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Engagement, involvement and empowerment: Three realms of a coproduction framework for climate services

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A B S T R A C T

While knowledge coproduction between climate scientists and climate information users has become a common theme in the climate services discourse, the interface between climate service providers and users is an aspect of climate services projects that still calls for more attention. This is due in part to the dominance of the physical sciences in these projects, as well as the prevalence of an instrumental and narrow interpretation of coproduction. Following up on the World Meteorological Organisation's Guidance on Good Practices for Climate Services User Engagement, and incorporating insights from the social and human sciences, we develop a coproduction framework for climate services to help establish a smooth and effective interface between scientists and stakeholders. This framework is intended for research and innovation projects developing climate knowledge and services. The coproduction framework comprises three realms: (i) engagement using various communication channels; (ii) involvement through interviews, workshops and webinars; and (iii) empowerment of stakeholders and scientists through focused relationships. This incremental participatory process involves stakeholders in increasingly profound ways: from a broad stakeholder group identified through awareness-raising campaigns, on to potential users with whom we exchange knowledge, and then to a set of "champion users" who co-develop the service and pioneer its use in decision-making processes. This paper illustrates the application of the coproduction framework in PRIMAVERA, an EU H2020-funded project for designing, running and testing new high-resolution global climate models and evaluating their outputs. While PRIMAVERA provided ground breaking scientific findings that could potentially benefit various stakeholders and support climate risk assessment activities, these results are highly specialised and their added value has yet to be assessed. Accordingly, the user engagement component of the project faced the challenging task of both motivating stakeholders' participation in the project and motivating future users of potential services based on PRIMAVERA data. The trial of the framework in PRIMAVERA provided key lessons for enhancing coproduction in research and innovation projects. We demonstrate how the role of scientists gradually shifted in this coproduction cycle from masters of knowledge (Roux et al., 2017) to co-learners, and how the involvement of the project's interdisciplinary team and their interaction with stakeholders served to move the project towards transdisciplinary knowledge production.

1. Introduction

Climate services is a fast-growing research field and practice, assisting the transformation of vast and often diverse climate data into information and knowledge that can support decisions for which climate is a relevant factor (Haines, 2019; Hewitt et al., 2012; Terrado et al., 2018). Climate services enable the incorporation of science-based climate data and information into planning, policy and practice at all levels of society (Vaughan and Dessai, 2014). In the words of the European Commission (Street et al., 2015, p. 7): "Climate services have the potential to become the intelligence behind the transition to a climate-resilient and low-carbon society."

New climate data and climate services are increasingly being produced, yet it remains unclear how successful they are in connecting with the knowledge and needs of stakeholders and in supporting their decision-making. Efforts undertaken by the Global Framework for Climate Services (Hewitt et al., 2012), the Copernicus Climate Change Service (Bruno Soares and Buontempo, 2019; Swart et al., 2017) and other initiatives aiming to coordinate distribution and support access to reliable climate services aspire to achieve greater connectedness to stakeholders' needs by integrating participatory activities – commonly labelled as *user engagement* – into the climate services development agenda. User engagement goes beyond service distribution, however, aiming to improve the quality and relevance of climate services through the coproduction of usable knowledge (Bruno Soares and Buontempo, 2019).

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Although knowledge coproduction between climate scientists and climate information users has become a common theme in the discourse of climate services, there is still no broadly accepted understanding of what the term coproduction means in practice (Bremer et al., 2019; Harjanne, 2017; Norstrom et al., 2020; Vincent et al., 2018). Coproduction in climate services has often been used in the context of aiming for greater quality, compliance and usability of products and services (Lemos and Morehouse, 2005; Moser, 2016). However, this instrumental interpretation is only one aspect of knowledge coproduction (Daly and Dilling, 2019; Goldman et al., 2018; Lemos et al., 2018; Vaughan et al., 2018). The climate services field would benefit from going beyond this basic interpretation of coproduction to an understanding of coproduction as "a complex meeting place where several different academic traditions and practices converge, overlap, affect each other, come into conflict, or cooperate toward describing and effecting co-production" (Bremer and Meisch, 2017, p. 20). This "meeting place", i.e. the interface between climate data providers and users, is an aspect of climate services that needs further attention and improvement (Golding et al., 2019; Hewitt et al., 2017). This is partly due to the dominance of the physical sciences in climate change research projects when it is widely acknowledged that the field would benefit from being better grounded in social science theory and experience (Hackmann et al., 2014; Meadow et al., 2015; Palsson et al., 2013). A more central role for the social sciences could pave the way for an improved meeting place by providing experience, tools and methods for achieving a smooth interface between producers of science data and users (Charnley et al., 2017; Cvitanovic et al., 2014). A stronger recognition of the role of the social and the human sciences may lead to a more robust and complete understanding of the potential benefits of coproduction for a new generation of climate services.

Attempting a unique definition of coproduction would be a superfluous effort, since each coproduction approach emerges from creative social interaction in a particular context (Haines, 2019; Norstrom et al., 2020; Steynor et al., 2016). Nevertheless, much-needed guidance on how to conduct participatory activities with stakeholders and how to integrate scientific and other knowledge in climate services coproduction has emerged in recent years (Carter et al., 2019; Hewitt et al., 2017; WMO, 2018). In 2018, the World Meteorological Organisation (WMO) published *Guidance on Good Practices for Climate Services User Engagement* in an attempt to provide a more systematic approach to participatory activities in climate services development. Building on this guidance, and enriched with insights from the social and the human sciences, this paper presents a coproduction framework for climate services that offers an effective meeting place for information providers and intended users.

Our framework adds to the growing body of literature on knowledge coproduction in climate services that aims to improve upon traditional linear knowledge production in which scientists are on one side and knowledge users on the other. Publicly funded research and innovation projects that aspire to provide robust and salient climate knowledge and services continue to face challenges in moving on from a traditional linear understanding of user engagement. These projects are often constrained by the demand to define tasks and activities, including user engagement plans, before the project can be approved, and typically have limited time and resources available for such engagement. Taking these constraints into account, our framework provides guidance for research and innovation projects that aspire to produce climate services, such as projects granted under the European Union's framework programmes. In order to demonstrate the application of the framework in such a context, we applied it in PRIMAVERA, an EU H2020-funded project for designing, running and testing new high-resolution global climate models and evaluating the value added by their outputs.

PRIMAVERA provided state-of-the-art global climate model (GCM) simulations at high resolution (~25 km), including flagship simulations for the Coupled Model Intercomparison Project (CMIP6), that contributed to the latest set of climate models intended to inform the IPCC's Sixth Assessment Report. The combination of global coverage with high spatial and temporal resolution (typically only achievable in limited-area modelling to date) was expected to enhance the representation of processes relevant for understanding climate, with a principal focus on Europe but with a global modelling scope. The PRIMAVERA project has demonstrated that high resolution can lead to some improvements in the simulation of certain climate processes, for instance atmospheric blocking and the representation of tropical cyclones (Schiemann et al., 2020; Roberts et al., 2020). It has been shown that this can lead to a better understanding of extreme and highly impactful climate events both in the past and future (Bador et al., 2020).

As a research and innovation project, however, PRIMAVERA's activities constitute a first step towards evaluating these new models and their potential utility to users and stakeholders. For this reason, the communication, dissemination and stakeholder engagement component of PRIMAVERA involved the challenging task of transferring these ground-breaking but highly specialised scientific findings to various stakeholders. Given the high degree of scientific uncertainty and the fact that this new data was still developing (the assessment of its added value is ongoing after the end of the project), the task of motivating potential users of this information to collaborate on shaping this new knowledge required an innovative and creative approach.

This paper presents a framework for the coproduction of climate services and suggests ways in which to operationalise the interface between different knowledge-holders. The interface is facilitated by bridging agents who have both the social and technical skills to mediate the interaction between climate scientists and users of climate knowledge (Haines, 2019; Norstrom et al., 2020; Reyers et al., 2015; Steynor et al., 2016). By bringing together climate scientists, social scientists, communication and other experts, the framework supports interdisciplinary collaboration. By reaching out to stakeholders and bringing in their knowledge and experience of climate change to scientific projects, the framework moves from interdisciplinary towards a process-centric transdisciplinary knowledge production, by including non-scientific insights into knowledge creation processes (Daniels et al., 2020).

2. The coproduction framework for climate services

To construct our coproduction framework, we took as the point of departure the long tradition of participatory knowledge production and decision-making in various research fields, including in the environmental sciences and sustainability studies (see, for example: Pretty, 1995; Reed et al., 2018; Richards et al., 2004; Turnhout et al., 2020). We complemented this with the similarly long history of coproduction in the fields of public services administration, science policy and science and technology studies, as well as in knowledge and governance for global sustainability (Bremer and Meisch, 2017; Miller and Wyborn, 2018; Vincent et al., 2018). We also draw from the fact that participatory methodologies, as a cornerstone of the coproduction process, are developing together with emerging new communication spaces and tools (Bojovic et al., 2015). We believe that the pluralism and diversity of participatory methodologies can address emerging and uncertain complex problems such as those posed by climate change (Chambers, 2017; Norstrom et al., 2020).

The concept of coproduction, together with co-exploration, co-design, and co-development, belongs to a family of collaborative terms (Bremer et al., 2019). With coproduction we assume, in particular, an iterative, interactive and collaborative process that brings together a plurality of knowledge sources to mutually define problems and develop usable products to address these problems (Armitage et al., 2011; Sletto et al, 2019). Coproduction thus integrates both the process and product or service (Borie et al., 2019; Daniels et al., 2020; Vincent et al., 2018). Co-exploration happens at an early stage in the coproduction process and is a consultative process with a focus on fact-finding (Steynor et al., 2016). Co-exploration should be followed by joint framing of the challenge in the co-design process. The aim of the co-design phase is to reach

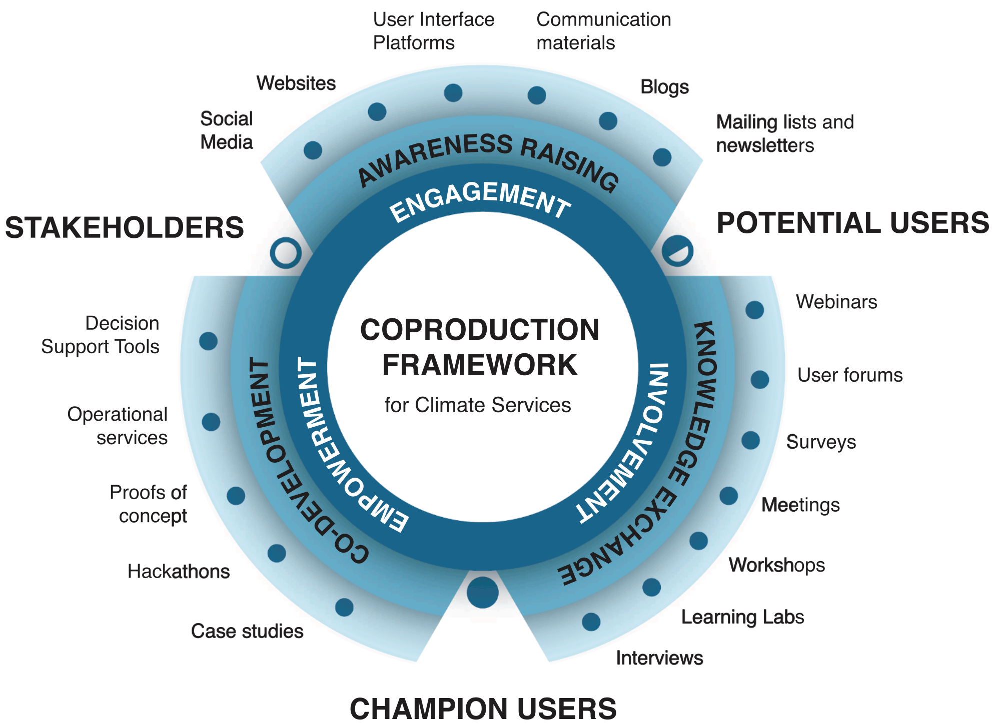

Fig. 1. The coproduction framework for climate services. The framework engages stakeholders by raising awareness through different communication tools (the *engagement* realm). It then involves stakeholders in knowledge exchange and co-learning, using various participatory approaches (the *involvement* realm). Finally, it empowers users of climate services, who take part in their co-development (the *empowerment* realm). The status of participants gradually changes as they move through the framework, from stakeholders, to potential users, to champion users.

a common understanding of the research goals and the roles to be played by different groups in the process of coproduction (Mauser et al., 2013). We define co-development as a phase of the coproduction process that involves collaboration on development and evaluation of the product or service.

WMO's *Guidance on Good Practices for Climate Services User Engagement* (2018) proposes a stepwise approach from passive to active engagement. In particular, this guidance specifies three categories of user engagement: (i) websites and web-based tools; (ii) interactive group activities; and (iii) focused relationships between providers and users. Building on the approach proposed by WMO (2018) and the combination of perspectives outlined above, we present a coproduction framework for climate services intended for research and innovation projects (Fig. 1). Encompassing the realms of *engagement*, *involvement* and *empowerment*, the framework combines multiple participatory approaches and communication tools while at the same time being formulated as an iterative process amongst the three main realms. Engagement is achieved through various communication channels for raising awareness about available or emerging climate information and possible climate services. Researchers and different knowledge agents, including potential users of the future service, are subsequently involved in a more profound knowledge exchange. In this phase they frame and co-define concrete problems and discuss potential solutions that could address different decision-making circumstances. Finally, the phase of service co-development is achieved in a tailored and often one-to-one interaction between scientists and users. In this coproduction process, more "specialised" service users are gradually involved: from the broader stakeholder group whom we inform through the awareness-raising campaign, on to potential users with whom we exchange knowledge, and finally on to a set of "champion users" who co-develop the service and pioneer its use. The rest of this section describes each of the three realms in more detail.

2.1. Engaging through communication

Building awareness about existing initiatives and available knowledge is the first step in facilitating access to climate data. Far-reaching web-tools have a key role in establishing this initial engagement of stakeholders. Information and communication technologies, epitomised by the Internet, provide an excellent opportunity for engaging citizens, raising awareness about climate information and scaling up participation (Bojovic et al., 2018; Galbraith et al., 2013; Kelly et al., 2012).

Scientists and other information providers often use websites and social media as a primary communication channel. However, other approaches such as interactive user-interfaces and blogs can be more effective by allowing for bi-directional and more dynamic engagement (Hewitt et al., 2017). The engagement realm should continue throughout the coproduction process. The more we learn from the knowledge exchange and co-development of new knowledge in the involvement and empowerment realms, the more customized material we have for sharing and engaging with new stakeholders.

2.2. Involving through consultations and meetings

A more involved and intensive approach includes interaction with stakeholders through surveys, interviews, and meetings. An online survey can easily reach a large number of stakeholders, provided they are motivated to participate (Calenda and Meijer, 2009; Vicente and Novo, 2014). Prior engagement activities can add to this motivation. To deepen our understanding of stakeholders' needs, perceptions and rationales, we need a more intensive and meaningful exchange that can be achieved through interviews. Although semi-structured interviews are time-intensive, they can encourage participants to speak freely and enable the emergence of new discourses and narratives (Haines, 2019; Luyet et al., 2012). In workshops, round-tables and focus groups, participants can actively exchange knowledge, confront opinions and sort out disagreements, build consensus and find common solutions for potentially conflicting interests and views. In addition, online meetings and webinars, which are not limited in space and are more flexible in terms of time, also provide spaces where participants can discuss pertinent issues and challenges (Dietz and Stern, 2008; Meijer et al., 2009). If skilfully facilitated, open online discussion spaces such as thematic online forums can also provide strong involvement, while the issue of the pre-selection of participants can be addressed by such spaces being made freely open for everyone to participate. In these involvement activities and events, participants can also share, discuss and query the knowledge co-developed in the empowerment realm.

2.3. Empowering through focused relationships

From the network of participants established in the previous steps, there are stakeholders who want to be more actively involved in problem analysis, exploring and identifying possible as well as preferred solutions, the so called "champion users". Building on the information-sharing and knowledge-exchange accomplished in the previous coproduction realms, this realm involves more thorough interaction with champion users.

Collaborating on a case study or a service prototype development allows data providers and champion users to co-develop a tailored service, test its usability and assess its added value (Christel et al., 2018; Golding et al., 2019). Only a service that proves useful and practical for users and that is tested with them can have a role in decision-making processes, meaningfully informing decisions that require consideration of past, current or future climate changes. In the process of coproduction, we aim at inclusive and flexible collaboration without predetermined hierarchies and power impositions, since it is essential that different knowledge sources should be acknowledged (Cook and Overpack, 2018; Vincent et al., 2018). Increasingly, hackathons and hackathon-like events, e.g. climathons (Kolstad et al., 2019), are being used to stimulate creativity in problem solving and enable co-development of new, shared knowledge. Good examples of results of co-development processes are decision support tools and operational climate services such as seasonal forecast services for specific sectors (Golding et al., 2019; Soret et al., 2019). If researchers position themselves as co-learners and contributors to shared knowledge production rather than as "masters of knowledge domains" (Roux et al., 2017, p.711), it is possible to reach the third realm of genuine climate service co-development. The boundary between providers and users becomes ever less distinct as we approach the co-development stage. By listening to and supporting holders of non-scientific knowledge and ultimately passing responsibility to them, this process mutually empowers scientists and stakeholders (Chambers, 1994). This part of the process is here termed "empowerment" and can include incremental or transformative learning (Mitchell et al., 2015). This process generates a sense of shared ownership, since responsibilities are redistributed among all the participants. When successful, individuals – both scientists and users – develop new capacities, while the expected outcome of co-development is larger and with more extensive impact than any individual contribution could achieve (Breda and Swilling, 2019; Fung and Wright, 2001; Hendriks, 2009; Rowlands, 1995). Finally, these newly built relationships can positively affect information-sharing and awareness-raising within collaborators' networks (Bond et al., 2012; Cundill et al., 2019).

2.4. From three realms to an incremental framework

The three realms that form the coproduction framework for climate services are not discrete phases but rather a continuum: they build on and interact with each other as the coproduction process builds throughout the cycle.

Eliciting stakeholder feedback throughout the process of service design and development should ensure that no important discourses or perspectives are overlooked. This enables more robust and evolving participation, becoming ever more profound over time and leading towards relationship-building and true partnerships. Bridging agents have the role of facilitating smooth interactions. Those in the role of bridging agents should thus possess broad knowledge across different domains in order to understand both stakeholders and climate scientists, as well as the skills needed to enable mutual learning and, ultimately, co-development (Norstrom et al., 2020). In research and innovation projects, this role is typically assigned to user engagement teams. Ideally, these teams or individuals would have social science skills to help them conduct effective and power-balanced participatory processes.

The status of participants changes through the three realms. At the beginning of the cycle we cannot speak of "users" but rather of stakeholders who might find the future service relevant and usable. By agreeing to become more profoundly involved in knowledge exchange, stakeholders become potential users who contribute to the maturing of the climate service at the same time as researchers endeavour to better understand and address their needs. Finally, the participants become users or champion users who co-develop with researchers a service that can truly inform their decision-making needs. To close the cycle, or rather to enter a new cycle, this new service is then used to motivate other stakeholders, or new users (Otto et al., 2016). Champion users often act as ambassadors in their sector or societal group, promoting broader uptake of the climate service and contributing to a new cycle of activities in the engagement realm.

In this maturing process of the participants and the service itself, the fields of expertise of the team involved and the roles of scientists also change. Science communicators guide the work related to awareness-raising while social scientists have the bridging role of involving different knowledge-holders in knowledge exchange. Data scientists and data visualisation experts are particularly important in the service co-design, e.g. in the technical development and user-testing of a visual interface that will exhibit climate information or the service (Christel et al., 2018; Mauser et al., 2013). Without the involvement of climate scientists, however, more profound interaction and understanding at the coproduction interface cannot be achieved. The interdisciplinary structure of the project teams is therefore crucial for smooth and effective interaction between all these disciplines. Finally, sustained interaction between scientists and stakeholders should occur throughout the whole lifecycle of the service.

3. Applying the coproduction framework in PRIMAVERA

The PRIMAVERA example illustrates the benefits and limitations of applying the coproduction framework for climate services in the context of research and innovation projects where climate knowledge and service are already predetermined in the project preparation phase and no prior consultations are held with stakeholders. Although PRIMAVERA engages stakeholders from different economic sectors, we focused on the energy sector in order to illustrate our framework in practice. Both energy consumption and production, and renewable energy generation in particular, are strongly dependent on weather conditions. The energy sector is thus pioneering the use of climate services for energy planning.

3.1. Engagement

Engagement in the project has been done through various (online) communication approaches. Websites often serve as an entry-level user interface (Hewitt et al., 2017); however, it is not easy to gain attention and pass on new information in our information-rich world. Intending to diversify from commonly used project websites, PRIMAVERA thus went beyond such simple information dissemination and built a User Interface Platform (UIP). This platform provided project findings and other communication materials in a user-friendly manner to complement the project website which presented more scientifically-focused information. The communication materials comprised a range of topics and formats, including story maps, sectoral and scientific factsheets, a project video, presentations, recordings and reports from meetings and webinars, as well as a glossary. In general, the uptake of these materials by UIP visitors has been quite good (e.g. more than 3000 downloads of factsheets). (For more details on the content of the UIP, see Appendix A of Supplementary Data.) A Data Viewer was implemented to provide an easy comparison between data obtained from different climate models and with different model resolutions used in PRIMAVERA, engaging more specialised data-driven stakeholders whilst also providing material in a visually attractive and interactive manner. Applying a heuristic evaluation approach – a usability inspection method that helps to identify usability problems in the user interface design and define approaches to address these problems (Nielsen, 1994) – in six in-depth interviews with stakeholders with different backgrounds, we obtained recommendations for improving the initial and building the final PRIMAVERA Data Viewer interface. The content provided and regularly updated at the UIP was promoted through social media (Twitter) and a mailing list. In fact, the tweet that introduced the Data Viewer was one of the most popular PRIMAVERA posts.

While contributing to awareness-raising about the PRIMAVERA project and the climate services it produced, the UIP helped us to identify an online community that could be involved in more profound levels of participation. The success of this engagement was evidenced by the number of responses and different profiles participating in the activities conducted under the involvement realm, as well as by the growing project mailing list, which counted 125 members by the end of the project (Fig. E1 in Supplementary Data provides coproduction activities in numbers).

3.2. Involvement

As a first step for involving stakeholders, we conducted an online survey that we distributed to the project partners' stakeholders and through different channels such as newsletters and Twitter accounts. The survey was undertaken with the aim of improving our understanding of stakeholders' needs for information related to climate variability and climate risks affecting the work of different sectors. The survey explored the influence of weather and climate change on participants' work and the most important natural hazards faced in each sector, the use of data and information, lack of information and knowledge gaps, the perceived applicability of high resolution climate data to the participants' work, and the most appropriate form of information distribution (the survey is available in Appendix B of Supplementary Data).

Although we used all available channels to distribute the survey, the sample of respondents (83) was far from impartial (see Figs. D1 and D2 in Appendix D of Supplementary Data). Clearly, our communication channels mainly attracted people with an interest in climate change and/or expertise in the field. The survey results confirmed that the respondents had both a wide range of knowledge of weather and climate change and experience of using weather and climate information to the users' and sector's advantage. The most advanced sectors in this respect were those of energy and insurance (Bojovic et al., 2017). For more than half of the participants (55%), weather and/or climate were very important for their personal work or for the professional decisions they made. They cited extreme rainfall, rainfall-related flooding, and high winds as hazards with the largest effect on their work. It was, thus, not surprising that most of the participants were familiar with climate information, which they obtained from national or European hydrometeorological or environmental agencies, research institutes, but also from the private sector. Participants mainly used this information and data for research activities, immediate or short-term planning and operational activities, but also for other purposes, such as strategic, long-term decisions or to inform investment strategies. As the main obstacle for using weather or climate information that could help fulfil their professional roles, the survey participants mentioned technical and knowledge barriers, rather than availability of this data and information per se. When it comes to the form in which information is best understood, participants showed interest in descriptive information and guidance on how to select the right information from the wealth of what was available. They also expressed interest in more technical information and easy and direct access to data. Finally, there was an appetite for more information about climate impacts and a better description of uncertainty. Consequently, out of 14 factsheets published on the UIP, the one about uncertainty in climate projections was the most downloaded.

The survey participants responded favourably to concepts of higher spatial and temporal resolution (70% of responses). Those who evinced a more cautious reception tended to be more experienced users who were conscious of the fact that higher resolution does not automatically mean better information (Palin et al., 2018). Some participants were also aware that higher-resolution data would demand greater computational capacity, which was not always available to them. These findings validated our initial intention of shaping the project outputs and testing their usability in close collaboration between project scientists and users.

More than half of the survey participants from the energy sector confirmed their interest in being contacted for interviews. To facilitate more profound discussion in one-to-one interactions, we developed a semi-structured interview protocol (Appendix C of Supplementary Data) to allow space for new issues and discourses. With this approach we intended to go beyond the assumptions and aspirations that were predefined in the project. Instead of imposing the predetermined agenda of the project, the interviewers were interested in new points of view and shared understanding within expanded networks (Daniels et al., 2020). The project's user engagement team, comprising a range of scientific expertise, including social scientists experienced in the engagement of stakeholders, conducted 65 interviews. We illustrate here results from 15 interviews with participants from the energy sector, which were divided into three thematic groups of five participants: (a) management, research and consulting: electricity system/power sector, (b) consulting: renewable energy and (c) research and development.

Apart from the three most important weather related hazards found in the survey, interviewees from the energy sector also cited low precipitation and high temperature within the most important hazards for this sector. The hazards that were listed as most important in the survey and interviews were presented using climate indices in the PRIMAVERA Data Viewer. All the participants confirmed using past climate data from various data sources, including observations from commercial companies, data from national hydro-meteorological services, universities, and reanalysis datasets. "[We need] 30 years' worth of historical data to understand what a typical day in terms of electricity demand generation looks like and to understand what the size of the fluctuations in the demand is according to weather variables." (Interviewee #3[a]). However, participants also reported issues with past data, e.g. interviewee #1[b] said "An issue with past data is that stations were sometimes moved or relocated and this brings errors to datasets. Or, they changed the equipment and measuring apparatus. This is a problem with long data series". PRIMAVERA provided both historical and future climate model runs. Moreover, high resolution historical data was available from the project before future data, and strong interest in past data was an opportunity for an early co-development activity with champion users, even before the project's "key results" – the future climate runs – were produced.

Interviewees from the research and development group often used future climate data given its importance for understanding energy systems of the future. As interviewee #3[c] explained: "the energy systems will behave in the future with larger share from the renewable energy that strongly depends on climate variability". From the power sector group, an interviewee reported using future climate data for analysing extreme weather and understanding safety risks. Another participant reported the use of climate projection data for hydropower analysis. Apart from these examples, interview participants did not use future climate data. Future climate data would, however, be very useful for the wind power plant consultancy as it could inform the type of plant, infrastructural concerns such as the type of turbines and the foundation that are suitable for the future wind conditions in a given region, as reported in an interview.

Data quality and accuracy were the most important characteristics and, hence, the participants only considered climate data from trusted sources. One of the aims of the coproduction process in general, and the co-development realm in particular, was to develop trust between scientists and users of scientific knowledge. For most of the participants, data resolution was perceived as problematic at the moment (some reasons are given below). Finding data for certain parts of the world was also challenging. In particular, this data was normally not downscaled and thus low-resolution data from coarse global models presented a gap in knowledge for some geographic areas. Indeed, one of the co-developed case studies was for South East Asia, a region that is characterised with insufficiently robust regional climate data. High-resolution global climate data was the key motivation for this champion user to apply PRIMAVERA data.

We learnt from the interviews that the use of data was sometimes restricted or that there was a considerable time lag between data production and the time when the data was made available for broader use. Participants from all three sub-groups were interested in having access to raw data, as stated by one of the participants (interviewee #5[a]): “Often we just want access to raw data because that’s what is usable for us”. Moreover, having data in a format compatible with users’ software was very important. Many participants stated their interest in using PRIMAVERA data for in-house impact models rather than relying on processed diagnostics and pre-produced figures. This indicated the possibility of these stakeholders taking a more active role in using and processing the data according to their needs and thus an important opportunity for continuing collaboration in the co-development realm. When speaking about preferable interactions with the project, the interviewees recommended that we include a user-support email address, and this was subsequently provided on the UIP and all the prepared communication materials. Interviewees also expressed an interest in participating in workshops where they could learn more about available data and experiences from using this data.

The survey and the interviews were key activities in the involvement realm of the framework and we complemented these with workshops and meetings, including online meetings (webinars) and meetings organised as side events at conferences. Face-to-face meetings, such as a splinter session organised at the General Assembly of the European Geosciences Union in 2018, provided an arena for the project stakeholders (mainly scientists of various profiles), champion users, and project climate scientists to meet. Sharing insights from the climate scientists’ work on generating PRIMAVERA data and the perspectives of champion users on using this data enabled iteration between the empowerment and involvement realms of the framework, allowing direct knowledge-sharing between the scientists and champion users involved in the co-development process and potential future users. Furthermore, such sessions were recorded and later featured on the UIP, enriching the communication materials for the engagement activities with new stakeholders and ensuring a sustained effort in awareness-raising. This shows how the realms of the framework are not discrete but part of a continuum of activities rather than a sequential set of actions.

The PRIMAVERA project had the objective of augmenting the initial modelling experiments with further experiments. The second set of experiments was informed by findings from the first set of experiments, obtained by both scientists and engaged stakeholders. An interesting insight informing the second set of experiments was the participants’ clear distinction between their need for spatial and/or temporal resolution, with the energy system researchers and planners clearly expressing a strong demand for better temporal resolution (e.g. three-hourly data). Following this knowledge exchange, one of the aspects improved by the second round of modelling experiments was the provision of high-frequency surface output data as part of the standard output package.

Overall, through the activities in the involvement realm of the framework the PRIMAVERA project achieved an intensive knowledge-exchange that helped us shape the later phase of the project experiments, in this sense influencing the final product of the project. The knowledge the project scientists gained from stakeholders also helped us understand how to share this knowledge more effectively and to identify which aspects promised greater usability and added value. However, the experience from PRIMAVERA also clearly showed some limitations of the involvement realm within the context of this project. Given that the new climate knowledge was pre-determined in the project, both the co-exploration of the challenges and the co-design of opportunities for new climate services were limited.

3.3. Empowerment

The interviews and the follow-up meetings enabled us to identify a sub-set of champion users, those who had declared their interest in co-developing the PRIMAVERA outputs. Together with the impact science researchers in the project, five project champion users developed case studies in which they applied the project output data, pioneering their use in real-world problems and exploring their role in decision-making (Bojovic, et al., 2020a). Although the champion users were from different sectors, they all had scientific backgrounds. PRIMAVERA simulations were used in the case studies developed through the co-development process for: (i) applying hydrological and hydropower impact research to inform water managers and the hydropower sector; (ii) estimating the adequacy of the future power generation to meet the demand to inform energy planners; (iii) analysing drought in Central and Western Europe to inform water managers; (iv) exploring the characteristics of the changing rainy season in Southeast Asia to inform climate change adaptation plans and (v) developing a windstorm event set and application in catastrophe modelling for insurance and risk management.

We illustrate here in more detail the first case study, which investigated the use of PRIMAVERA data for hydrological and hydropower impact research in the Upper Danube basin. After initial meetings, and having established a common interest, the project team and the champion user continued with periodic calls, regular exchanges of data and results and face-to-face meetings at research venues (Bojovic et al., 2020b). This case study presents the earliest and longest collaboration with a project champion user, that lasted over the last two and a half years of the project, and has been maintained after the project ended. The similar pattern and the experience we obtained from the collaboration with this first champion user was applied in the other four collaborations. According to the testimonial of one of the champion-users: “the thing that worked really well was that [the PRIMAVERA impact scientist] was happy to chat with me over the phone and explain [to] me more about the data”.

The champion user in the Upper Danube case study was a consultant from a water management and hydropower consultancy company, acting as an intermediate user providing tailored information to regional or national stakeholders. The case study was developed from previous impact studies of the Upper Danube basin that generated hydrological climate change scenarios to support decision-making for water management authorities in Austria and Germany (Stanzel and Kling, 2018). One important objective of the previous studies was to update the climate scenario information with new climate model data, e.g. from the ENSEMBLES regional climate model (RCM) data to the CORDEX RCM data (Stanzel and Kling, 2018). As stated by the champion user, the application of high-resolution GCM data from PRIMAVERA was seen as an opportunity to provide a further update of climate scenarios for the Upper Danube based on the latest modelling efforts. Another objective of the champion user, as he explained in the initial phase of the study set up, was to enhance the knowledge of this new global data set and thus facilitate the data application in future projects. As the champion user’s company is active in impact research globally (see, for example: Kling et al., 2014; Stanzel et al., 2018), early and detailed knowledge of new global high-resolution climate data was regarded as an expected benefit of the collaboration.

The specific objectives of the Upper Danube case study were as follows: (i) to evaluate the skill of GCM simulations with different spatial resolutions to represent the regional climate at the scale of the Upper Danube hydrological model; (ii) to provide climate change impact scenarios for discharge and hydropower production in the Danube based on high-resolution GCM data; and (iii) to compare the GCM-based results with previous results based on ENSEMBLES and CORDEX RCM data.

Investigations of the historical simulation runs of three PRIMAVERA GCMs at different spatial resolutions confirmed the importance of high-resolution GCM information for impact research. Methods of downscaling and bias correction specifically developed for the Alpine terrain of the Upper Danube basin could be re-applied to high-resolution GCM data but not to the GCMs with typically coarser resolution since the grid size of the latter was too large. A comparison of various approaches of model evaluation showed markedly different results from methods averaging over the entire basin domain (as typically carried out in climate research) compared to methods focussing on spatio-temporal climatic patterns within the basin (as applied in impact research). These results highlighted the relevance of including an impact application perspective in model evaluation, i.e. the perspective provided by a champion user, as was facilitated in this coproduction framework.

Nevertheless, the mutual influence of climate scientists and impact scientists on their respective approaches was partly limited in this co-development process. Feedback from the champion user about a specific time period that would be useful but not covered by available data, for instance, could not be used to induce new climate simulations since the model runs had previously been defined and were part of the common modelling protocol of CMIP6 HighResMIP (Haarsma et al., 2016). The hydrological impact modelling framework that the champion user had previously applied limited analyses of all available PRIMAVERA data since some methods were not compatible with coarser GCM data. However, the tailored collaboration on this specific climate service and the open dialogue between "data producer" and "data user" expanded the knowledge of each other's requirements and limitations, providing valuable feedback on the usability and added value of data produced in the project. "When we provide climate services for climate change adaptation, our clients need to have trust in the data we use. And we can achieve this trust, if we know why the data shows specific characteristics, if we know about process representation in the models, if we also know about model artefacts and weaknesses. In the Upper Danube case study, we could discuss about the climate models in detail." (champion user from hydropower).

Generally, the case studies development confirmed that applying PRIMAVERA data for in-house impact models by potential users (which was a need expressed in the interviews) would demand collaboration between users and project scientists. The work performed in the co-development phase illustrated the amount of data produced with the high-resolution models and what technical preparations are needed to ingest these in regular decision-making processes. "It's not even an issue of not having computational capacity, but simply an issue of time and effort needed. You need to pre-process data before you use it. No user would want to have several Terabytes of data for all variables and the whole globe." (champion user from hydropower). Through the co-development process, users were supported by the project scientists to preserve the wealth of information provided by this new climate data. Hence, champion users had both support to address technical and knowledge barriers and direct access to data, as requested in the interviews. At the same time, the project team learnt how to put this data in the service of real-world activities. Although the project results will eventually be freely available, e.g. as part of the international CMIP initiative, it is difficult to imagine their application in real-world circumstances would have been possible at this stage without the direct interaction between project climate and impact scientists and champion users. The co-development realm in this way bridged the time lag between data provision and its availability for broader use, which was a barrier for climate data use raised in the interviews.

The profiles of the project's five champion users clearly showed that the co-development realm was limited to more "technical" users with pre-existing knowledge, skills and interests. The quantitative decision-making scheme in which these users were interested was also the one that better aligned with the project climate scientists' dominant epistemology. Although the bias in the sample of champion users is evident, the earlier realms of the coproduction process also allowed other involved stakeholders to deepen their understanding of the project and to build trust while at the same time assuring the project's comprehension of the needs and capacities of stakeholders.

The new partnership established in the co-development phase empowered both the champion users and the project with new knowledge and capacities. "Having access to one of the leading scientists in the field and outputs that we can easily digest and relate to was invaluable." (champion user from insurance). For the users, the application of the data in a case study resulted in detailed knowledge of the new global climate datasets before these became available to the broader public. As witnessed by the champion user from the hydropower consultancy, the new capacities allowed early and efficient data use in future applications for impact assessment studies globally, which was expected to provide a competitive advantage by "being better than competitors and showing to clients that we know about the issue more than others". In return, the project scientists received valuable feedback from the champion user about the usability of the project's results, which helped in gaining a better understanding of the added value of the high-resolution climate data produced in PRIMAVERA compared to commonly used lower resolution or regional climate data. "As a scientist, I became more aware of the data needs and further assumptions required to complete the impact studies." (project impact scientist). Close collaboration also built trust among the project scientists, who were initially more reluctant to share modelling outputs freely before these had been published in scientific journals.

4. Discussion

Publicly funded research and innovation projects such as PRIMAVERA demand a well-defined project structure with predefined tasks and activities. This often limits flexibility for making changes throughout the lifetime of the project. Coproduction is an intensive process in terms of human, technical and financial resources (Hegger and Dieperink, 2014; Kolstad et al., 2019) and should be an integral part of project design. Unless a project has time and resources allocated to coproduction it is overly optimistic to expect that the project's inflexible structure will facilitate optimal knowledge coproduction. An optimal coproduction process would enable the unpacking of problems emerging from climate change and the co-exploration and co-design of solutions to the concrete challenges to be addressed with the climate service (Beier et al., 2017; Carter et al., 2019). However, our application of the coproduction framework for climate services to PRIMAVERA demonstrated that it is possible to integrate coproduction elements in research and innovation projects where coproduction was not part of the initial design. The key lessons learnt also provide insights for preparing and integrating coproduction processes in a more structured way in future projects. This section first discusses what was achieved in PRIMAVERA in spite of the project-related limitations and then goes on to identify the remaining challenges.

First of all, by applying the coproduction framework to the PRIMAVERA project we expanded the boundaries of the project which had initially aspired to show the scientific added value of new high-resolution global climate data. We achieved this in the following ways: (i) by increasing the project's visibility and sharing knowledge about new trends and novel concepts in climate modelling; (ii) by co-learning about the needs for and outcomes of high-resolution modelling; (iii) by building the second phase of the project experiment on the basis of stakeholders' needs and expectations; and (iv) by building trustworthy relations between climate scientists and the champion users who moved this new knowledge from the scientific realm to real-world decision-making processes.

The smoothness and effectiveness of the collaboration in this coproduction framework was, according to the project impact scientist who worked closely with a champion user "reflected in the joint determination of research objectives as well as of data needs and formatting requirements, but also in other aspects such as the prompt discussion of issues and preliminary results, through quick chats and phone calls". Maintaining this smooth coproduction interface demands skilled facilitators. Bridging agents or facilitators can be members of the project team, if they have the requisite facilitating skills and understanding of the languages and cultures of both the scientists and the stakeholders while maintaining a neutral role in this process (Carter et al., 2019). An important step in this direction is the integration of different disciplines in climate services project teams. However, many climate services projects are designed and coordinated by climate scientists with an already framed epistemology, e.g. of vulnerability and adaptation and needed climate knowledge (Carr and Owusu-Daaku, 2016). Prioritizing a particular way of knowing limits the integration of other epistemologies in climate services (Goldman et al., 2018), which can hinder effective interdisciplinary collaboration unless well facilitated. This means we cannot simply "add" social and other sciences to climate services teams; what is needed instead is a framing shift enabling interdisciplinary and transdisciplinary processes. Interdisciplinarity in climate services should bring balanced and better-integrated intellectual partnership across different disciplines (Palsson et al., 2013; Weaver et al., 2014). Building on this, transdisciplinarity will provide a more constructivist approach to knowledge coproduction, with acknowledgment and integration of a plurality of knowledge as well as emphasis on problems and the process of solving them (Daniels et al., 2020; Hirsch Hadorn et al., 2006). A few skilled social scientists in PRIMAVERA mobilized multiple experts and stakeholders, with roles ranging from climate scientists to business consultants, and guided them through the structured coproduction process, approaching the goals of interdisciplinarity and transdisciplinarity.

The framework helped the whole team to rethink the concept of *user* (or *end-user*), as one of the entrenched terms in climate services. This term itself enforces a linear model of interaction, presuming that stakeholders should use what scientists produce even if this information does not necessarily address their needs, fit their decision-making contexts or account for non-scientific but relevant knowledge and experience. The term "user" also suggests that the process ends when someone uses a product or service, disregarding the importance of receiving and acting upon feedback from users. Our coproduction framework for climate services facilitated the evolution from someone as a stakeholder who might be interested in the topic under research to an active co-developer and future user of the climate service, i.e. a stakeholder with agency. This transition from relatively passive to highly active participation was clearly experienced in the PRIMAVERA project.

The incremental nature of the framework supports relationship-building as a continuum. The time dimension allowed the experts to mature their understanding of the stakeholder community and build trust (Cook and Overpack, 2018). The framework unfolds through building, maintaining and deepening the relationship between scientists and stakeholders. In the *Engagement* and *Involvement* realms, relationship-building is the key purpose of the interaction. With its summative approach, the framework allows for a reflective process and consideration of knowledge that constantly evolves through interactions, as recommended in the climate services literature (Daly and Dilling, 2019; Goldman et al., 2018; Lemos et al., 2012), supporting continuous transformational change (Burnes, 2005; Termeer et al., 2017). "After being involved in this project, I might frame my work with a new lens: this experience will condition how I conduct this type of impact research in the future" (project impact scientist).

There has been growing criticism of coproduction processes for depoliticizing power dynamics and for ignoring this important factor often present in knowledge-production processes (Daly and Dilling, 2019; Goldman et al., 2018; Turnhout et al., 2020). Certainly, in contexts characterised by high levels of complexity, inequalities, and conflicting views and positions, the research process would need to be more flexible (Breda and Swilling, 2019). Under such complex circumstances, the research process promoted in PRIMAVERA and similar projects, as well as in our coproduction framework, would be less successful. An interesting aspect of uneven power dynamics we faced in PRIMAVERA was related less to unequal knowledge than to the time and resources available to the scientists for the coproduction process as compared to the stakeholders, who were expected to volunteer their time (Turnhout et al., 2020), as observed by a champion user: "We collaborate on our own expenses. Scientists sometimes underestimate the effort needed for this coproduction." In spite of our efforts to open access to information to everyone and the attention we paid to engagement and involvement processes, our champion users were not randomly selected. The project scientists co-developed results with experts from the energy field, and other users with scientific backgrounds, who not only had the curiosity and capacity to examine new data but also support from their institutions to devote time to coproduction. Our case studies confirmed that the institutions and businesses with whom we have long-standing collaborations are usually those that are more proactive in the co-development stage (Frantzeskaki and Rok, 2018; Lemos et al., 2019; Roux et al., 2017). This inclination is bidirectional. Scientists often find it easier to collaborate with like-minded stakeholders such as those in research and development roles who are often former academics themselves (Porter and Dessai, 2017). As a consequence, the achieved empowerment is limited insofar as it remains confined to the project boundaries and is often inclusive of a limited number of individuals. This prevents the coproduction process in the described context from contributing to broader societal transformation (Carter et al., 2019; Harvey et al., 2019; Turnhout et al., 2020).

Finally, we have demonstrated that climate service is not the only outcome of the complex and iterative knowledge exchange process (Fazey et al., 2014). Our case studies confirmed that other important outcomes of a coproduction process include building new capacities, networks, and partnerships that outlived the project (Bremer et al., 2019; Norstrom et al., 2020). Through this process the project scientists learnt that there is no such thing as a 'user' but that instead we can only speak of *stake(& knowledge)holders* (Turnhout et al., 2020). Developed partnerships and scientists' new perceptions can influence the way in which stakeholders are integrated in research projects in the future (Wall et al., 2017). Indeed, we can see a tendency in new climate services projects of including stakeholders in project teams where they can influence the research question and design from the beginning, even under current funding schemes (see, for example: López et al., 2018; Vigo et al., 2019). This approach to building more diverse project consortia would increase interdisciplinarity and shift attention from the scientific abstraction to local experience, knowledge and practices (Krauß and Bremer, 2020), while addressing the discussed issue of uneven power dynamics. Perhaps, we should not look at research and innovation projects as a research work finishing after 3–5 years, but rather as a continuous transformational change. In projects that coproduce climate services (often prototypes) with stakeholders, these closely involved champion users can recognise the added value of climate information and have capacity to bring climate services to the next level: to an operational service, a service more tailored to their needs, or one that integrates additional stakeholder perspectives, by the subsequent engagement of new stakeholders. This involves a paradigm shift in our understanding of projects, moving from projects developed in silos to understanding projects as connected pieces of the same puzzle. Tendencies in this direction are already emerging, as witnessed by project clusters, such as the EU Polar Cluster, that currently comprises more than 20 projects that work closely together on issues related to climate change in the Arctic and Antarctic.

5. Conclusions

Addressing the recognized weakness of the interface between "providers" and "users" of climate services, this paper presents a framework that operationalises this interface and gives structure to the coproduction of climate services in research and innovation projects. These projects often have inflexible structures with a desired project outcome (e.g. new climate knowledge and services) predetermined prior to any user interaction, and such conditions do not allow for an optimal coproduction process that would result in exactly the climate service that the users need. Nevertheless, this paper shows how by applying the coproduction framework for climate services we managed to expand the boundaries of the project and integrate stakeholder knowledge and perspectives in the final outcomes. The framework comprises three interconnected realms. First, the stakeholders are recognized and involved in the engagement realm, a realm that is gaining ever more possibilities with new communication tools and spaces. The involvement realm was essential for achieving a shared understanding of the problem and of what PRIMAVERA can offer to address stakeholder needs. The empowerment realm is where the co-development of the final climate service happens, together with the establishment of new partnerships and capacities. The implementation of the coproduction framework in PRIMAVERA helped facilitate the evolution from a general stakeholder to an equal knowledge-holder and co-designer of the service. Although limited and confined to project boundaries, the empowerment phase shifted perceptions and built better understanding across communities. Building partnerships and achieving a shift in understanding and epistemologies across academic traditions and different practices can bring about the substantial change needed for transdisciplinary climate knowledge coproduction.

CRediT authorship contribution statement

Dragana Bojovic: Conceptualization, Data curation, Formal analysis, Investigation, Supervision, Visualization, Writing - original draft, Writing - review & editing. **Asuncion Lera St. Clair:** Conceptualization, Formal analysis, Writing - original draft, Writing - review & editing. **Isadora Christel:** Conceptualization, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Marta Terrado:** Conceptualization, Visualization, Writing - original draft, Writing - review & editing. **Philipp Stanzel:** Investigation, Writing - original draft, Writing - review & editing. **Paula Gonzalez:** Investigation, Writing - review & editing. **Erika J. Palin:** Data curation, Investigation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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