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Perspective

Toward a multi-faceted conception of co-production of climate services

Scott Bremer[a,*], Arjan Wardekker[a,b], Suraje Dessai[c], Stefan Sobolowski[d], Rasmus Slaattelid[a], Jeroen van der Sluijs[a,b,e]

[a] Centre for the Study of the Sciences and the Humanities, University of Bergen, Bergen, Norway
[b] Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, The Netherlands
[c] Sustainability Research Institute and ESRC Centre for Climate Change Economics and Policy, School of Earth and Environment, University of Leeds, Leeds, United Kingdom
[d] NORCE Norwegian Research Centre, The Bjerknes Centre for Climate Research, Bergen, Norway
[e] Department of Chemistry, University of Bergen, Bergen, Norway

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ABSTRACT

Increasing numbers of scholars and practitioners appeal to procedural theories of ‘co-production’ as they work to transform climate science into climate services. Most work in this direction theorises co-production as an ‘iterative and interactive’ process between climate service providers and users, with success measured mainly in terms of the usefulness and usability of the information product for the user. But notwithstanding these first important steps, this perspective paper argues that the current study of climate service co-production is too narrowly framed, and fails to properly engage with the broad and rich literature that conceives of co-production processes in a diversity of ways. The authors suggest a fresh look on co-production as a process best examined simultaneously from several complimentary perspectives, with reference to recent work reconceptualising co-production as an eight-sided ‘prism’. Using an illustrative example of climate services developed to predict and visualise future flooding in the municipality of Voss, in Norway, the paper demonstrates how this prism concept of co-production can enable a more comprehensive view on co-production as a multi-faceted phenomenon, improve mutual understanding among actors and, ultimately, help design climate services that are better tailored for climate change responses in particular contexts.

1. Introduction

Climate services emerge from a process of transforming climate science into bespoke information products and decision-support for society. They represent one important way of linking climate knowledge and action at the science-society interface, at different levels. Climate services is an emerging field of work, growing and maturing according to iterative moves between theory and practice around this complicated and contentious transformation process. As such many aspects of design and evaluation of climate services remain ad hoc and while some best practices have emerged, a theory of practice has not been developed (Vaughan et al., 2018). There are numerous working definitions of ‘climate services’, but one widely used in Europe covers “*the transformation of climate-related data – together with other relevant information – into customised products such as projections, forecasts, information, trends, economic analysis, assessments (including technology assessment), counselling on best practices, development and evaluation of solutions and any other service in relation to climate that may be of use for society at large*” (European Commission, 2015). Climate services have increased in popularity over the past 15 years (Buontempo et al., 2014) with major initiatives at the global scale, e.g. through the Global Framework for Climate Services for example (Hewitt et al., 2012), regionally in Europe through the Copernicus Climate Change Service (https://climate.copernicus.eu/), ClimateKIC (http://www.climate-kic.org/) or Climate-Adapt portal (http://climate-adapt.eea.europa.eu/) for instance, and nationally through the emergence of national climate service centres. But there remain important barriers to realising the effective and reliable transformation of climate data into useable climate services.

Increasing numbers of scholars and practitioners have appealed to procedural theories of ‘co-production’ to shape the climate service transformation process (Bremer and Meisch, 2017). Co-production has in this field mainly meant the deliberate, collaborative product-development work between climate scientists, or producers of climate data, and practitioners, or users who require climate information, including potential or even ‘imagined users’ (Porter and Dessai, 2017). But there

* Corresponding author.
E-mail address: scott.bremer@uib.no (S. Bremer).

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is confusion about when climate services should be co-produced and what kind of process this involves, especially given that the nature of co-production can be highly case dependent. As a result it may range from informal discussions about climate science over coffee, to formal processes of multi-institutional negotiation. The first important steps in this direction have primarily theorized co-production as 'interactive science' (Lemos and Morehouse, 2005), which measures success mainly in terms of the usefulness and usability of developed climate services (Hewitt et al., 2017). However, in this perspective piece we argue that a narrow (albeit important) focus on co-production as a process of developing climate services misses other aspects of this complex, multi-faceted process. We assert that other things are simultaneously co-produced – deliberately or not – while we develop climate services; learning, empowerment, institutional capacity or new representations of nature and society for instance. We suggest a fresh look on co-production as a process best regarded simultaneously from several complimentary theoretical perspectives, in order to: (i) understand the context of climate services; (ii) design better performing procedures for co-producing these services, and (iii) (co-) evaluate their quality (fitness for function) and measure their impact.

This perspective piece builds on recently published work by Bremer and Meisch (2017) who re-conceptualise co-production as a prism. That is, a compound concept that integrates eight different 'lenses' on co-production; distinguishable by the emphasis they give to different aspects of co-production, their academic tradition, the work that they do, and the criteria for their evaluation. We suggest that this prism concept can help us see the different sides to the climate service co-production process, or to use another metaphor, help us unravel, interpret, and steer the different strands of work that are wound up in this process like a rope. This is a strong concept for broadening the study and practice of co-production in climate services in an ordered way, and by extension, offering up a multi-faceted portfolio of criteria for evaluating quality and impact of co-produced products and practices. We illustrate what such a research programme could look like with reference to an ongoing controversy, drawing on climate services to predict future flooding in the municipality of Voss, in Norway. We start in Section 2 by presenting the context for this discussion, before Section 3 discusses current work on climate service co-production, and Section 4 rationalises the use of the prism as a promising focus for the future. Section 5 presents our conclusions and suggest a way forward.

2. Background: transformation at the science-society interface

2.1. Uncertainty and debate on the transformation to climate services

Climate services represent a move toward distilling scientific understanding of climate variability and change into useful products and services, tailored to support society's particular – often local – climate-related action. In this way they aim to embed scientific knowledge in societal decision-making contexts, and over the past 15–20 years have become a central part of countries' strategies to decentralise and strengthen climate governance at the local scales where impacts will be felt (Hewitt et al., 2012; Visbeck, 2008), and where decisions and policies are needed to support action. This has resulted in a transformation in how we organise and practice climate science at the science-society interface; the hybrid institutional spaces where science is mobilised in support of climate adaptation by different actors in society, from businesses to the public sector or individuals. This transformation has been driven by progress in both science and policy; (i) important advances in the science, with increasingly complex and precise climate assessments and projections at regional scales (Brasseur and Gallardo, 2016; Vaughan and Dessai, 2014), and (ii) steps by national policy to better incorporate climate science. This began with the US National Academy of Sciences report highlighting a need for climate information as "the timely delivery of useful products through direct and accessible user interface" to help manage risks and support decision-making (NRC, 2001). These national policy efforts have been further bolstered by international work by the World Meteorological Organisation, and the Global Framework for Climate Services (GFCS) (Hewitt et al., 2012).

Amid these institutional transformations practitioners and scholars alike recognise that, as an emerging field of work, there is uncertainty and debate about the development process and practices of converting climate science into 'something else' called a climate service. While we have seen important advances in the precision and reliability of climate information, this has not necessarily translated into better-informed adaptation, suggesting a persistent gap between the climate *science* and the required high quality climate *services*. Given the technological advances 'in the lab', this gap has, since the early conception of climate services, been more associated with how the science is communicated and used (Hooke and Pielke, 2000). Such transformation implies fundamental and potentially destabilising challenges for countries' climate services communities – networks of science providers and users in the public and private sectors, purveyors, policy and funding bodies, and other stakeholders working at the science-society interface – leading to mixed success. Many lament a 'valley of death' dividing science providers and users (e.g. Brooks, 2013). Providers often do not fully understand the contexts in which decisions are being made, and users are not fully aware (or expect more or different things) of what climate science can and cannot provide (Buontempo et al., 2014; McNie, 2007, 2013). Some of the persistent challenges to communicating and using climate services include: (i) defining high quality climate services (quality is currently quite case-dependent, but could encompass broad criteria like salience, credibility and legitimacy (Cash et al., 2003)) (ii) making climate services freely available (e.g., Webber and Donner, 2017); (iii) developing a market for climate services; (iv) increasing interaction between science providers and users; (v) improving the quality and communication of climate services for users' needs; (vi) increasing users' capacity to responsibly use climate services; and (vii) addressing legal, institutional and cultural barriers to using climate information (Hewitt et al., 2012; Kirchhoff et al., 2013; Lorenz et al., 2016; van der Sluijs and Wardekker, 2015; Vaughan and Dessai, 2014).

There are also signs of a broadening view on what climate services are, and who the users and producers might be. The limits to the climate service process are unclear; for instance, do climate services end with the delivery of an information product or do they extend to support for decision-making? Are they limited to communicating climate science, or can other knowledge systems develop climate services, communicating proverbs or stories, maps or artwork, or citizen science measurements for instance? Goosen et al. (2014) suggest that climate services currently focus primarily on information on basic climate data and impacts of climate change, but argue (like the European Commission, 2015) for more decision-driven and science-informed climate services. They propose a wider perspective, translating climate data to indicators, consequences and tools that are directly policy-relevant, such as those related to spatial claims and land-use or to local vulnerability (see also Giuliani et al., 2017). These might be more easily used in engaging stakeholders in discussions on adaptation. A climate 'service' in that respect could also include more than developing user-centric data and scenarios, and range from new tools to the facilitation of the impact assessment and adaptation process at the user organisation (i.e. climate *adaptation* services according to Goosen et al., 2014). Another observation is a blurring of the lines between traditional producers and users of climate services. Indeed, even the distinction between "users" and "providers" is subject to debate as it compartmentalizes participants into traditional roles and implies a unidirectional flow of information. Particularly, producers now not only include meteorological institutes but also private consultancies, and even citizens ('citizen science') (e.g. Van Vliet et al., 2014; Wildschut, 2017). Similarly, there is a broad range of users, from industries in sectors like agriculture, forestry and water management (see e.g. Specter, 2013), to governments working on adaptation, scientists and companies that tailor or (re)transform climate data for new applications, construction and housing companies, and citizen groups, as they take a more prominent role in implementing adaptation (e.g. neighbourhood greening initiatives).

Scholars and practitioners are working together to improve understanding of this transformation process, through iterative moves between theory and practice. A growing corpus of studies of climate service practices draw on theoretical lenses to analyse the conditions that promote high-quality, high-value services, in order to inductively build a body of climate service theory (see e.g. Dilling and Lemos, 2011; McNie, 2013; NRC, 2005; Prokopy et al., 2016). Such a dynamic approach to reciprocal theory- and practice-building is essential in a fledgling field, where scholars and practitioners are operating in *terra incognita*, and must pragmatically ‘learn-by-doing’. Linked to this, some scholars (Cash et al., 2006; Kirchhoff et al., 2013) are building theory through the comparative study of how climate services are organised, practiced and used in different countries to provide surprising insights on context, dynamics and success factors. Others convene practitioners from climate service communities in discussion about barriers to climate information uptake and how to overcome them (e.g. Buizer et al., 2016; Bruno Soares and Dessai, 2015; Cavelier et al., 2017; Laudien et al., 2018).

2.2. Climate services in action: the Voss controversy

Here we introduce an example of climate services in action, to illustrate one contentious and complicated process of climate service development. The township of Voss in Western Norway is currently appealing to climate services to inform a heated debate about future flooding in the Vosso river it sits beside. After a particularly damaging flood in 2014, Voss municipality commissioned information on future rainfall, and were told by the Norwegian Water and Energy Directorate (NVE) that there would likely be an elevated risk of flooding. The municipality then issued an open invitation for anyone to submit ideas for a solution to the flooding problem. In response, competing hydroelectric companies have offered to construct tunnels through the mountain range separating the watershed from the Hardanger fjord to channel water away, to simultaneously generating carbon-free electricity and reducing flooding. The decision of whether to support these works is locally and nationally contentious, because the river is legally protected from any works owing to its unique natural, recreational and scenic values as an iconic (largely unmanaged) wild Norwegian river. The polemic is drawn up: people are said to be “for the river, or for saving peoples lives”. Climate information is having an important and highly politicised role in this debate, revealing the challenges of finding the appropriate place for climate services in public decision-making.

Most prominent in this debate was an alarming fly-through 3D animation, shown at a public municipality council meeting, depicting the path and extent of a possible future flood through the centre of Voss, with massive damage to houses and infrastructure. This vivid climate service product was designed and developed by a private climate service consultancy under commission from two of the hydroelectric companies. It was designed to demonstrate the future impact of flooding on Voss in a no-action-scenario, contrasted to the diminishing impacts in three alternative scenarios ending with the measures proposed by the two hydroelectric companies. The consultancy used data provided by the Norwegian Water Resources and Energy Directorate (NVE), based on a 200-year flood with a projected 40% increase in extreme rainfall due to future climatic change (projected for the period 2071–2100 compared to 1971–2000). The data provided from the NVE was a scaled down projection based on the “business as usual”-scenario (RCP 8.5) from the 5th IPCC assessment report. The product was first presented as a 3D-image in the local newspaper, and then as an animation at the public meeting some months later, where it provided a turning point in the debate, translating numerical data into a visualised flooding event. In the ensuing public debate, the animation was referred to as 'a movie' representing the expert view of the watershed's future state. The animation was also critiqued in the public sphere, with some local residents and environmental NGOs condemning it as shock tactics favouring the interests of the hydroelectric companies and their supporters, while hiding the cascading uncertainties inherent to the scenario on which the animation was built. One Voss resident wrote in a local newspaper questioning whether the projection had allowed for the increased vegetation that might accompany a warmer, wetter climate, and the influence of this up-stream vegetation on reducing peak run-off and flooding. NVE responded, admitting the omission, but justifying their scenario, an example of how climate services are being appraised and challenged in the public sphere. The debate is suspended for the moment while the NVE review and assures the quality of the best proposals for dealing with the challenges caused by flooding. This case can be opened up to analysis from the perspective offered by co-production.

In sum, the 3D animation is a climate service in that it translates abstract climate data into a visualisation of a future flooding event, at a specific concrete location. It is co-produced as a response to a call by the Voss municipality for solutions to a concrete flooding problem, within the existing legal and economical constraints, and as a collaboration between the partners in the bid; hydroelectrical companies and the consultancy. The animation framed the following discussion by adopting a control and direct approach to nature to deal with the flooding problem. In turn, the animation was framed by municipality politicians as an argumentative resource supporting specific policies towards the problem.

3. Effecting and evaluating transformation to climate services through co-production processes

Co-production has been put forward as a promising procedural theory for better understanding and practicing the complex transformative process to climate services at the science-society interface. Co-production concepts can guide our iterative research between climate service theory and practice; steering climate service processes according to theoretical co-production principles and methods, in order to appraise and revise this theory based on practical experience. Co-production can also help us understand how climate knowledge is interpreted and exchanged in different social, decision-making contexts. It has rapidly grown in popularity in the academic literature (Bremer and Meisch, 2017; Moss et al., 2013) and is equally recognized in climate service policy, being incorporated into the GFCS (Hewitt et al., 2012), and endorsed by the European Commission’s Roadmap (2015) for instance. But, what shape has this concept taken so far?

Research on climate service co-production is mainly steered by theories of iterative and interactive science that emerged in the US about 15 years ago, in response to a policy imperative for more ‘useful’ climate information, ‘useable’ by decision-makers, to use the terminology of the National Research Council (NRC, 2001). In two seminal papers, Lemos and Morehouse (2005) and Cash and colleagues (2006) studied early American climate service initiatives according to how useful products should be deliberately co-produced at the science-society interface through direct interaction within networks of science providers and users. Lemos and Morehouse (2005, p. 58) defined this kind of co-production as, “the interaction between scientists and [users] to influence how scientists pursue science and how [users] understand the possibilities and limits of science…defined across three dimensions: interdisciplinarity, interaction with [users], and production of useable science”. These early studies analysed processes that promoted co-production at the interface – using principles of interdisciplinarity, interaction and usefulness for instance – and the characteristics of provider and user institutions that enable these processes – from flexibility and resourcing, to the establishment of boundary organisations. So seen, co-production becomes a normative challenge to better reconcile the supply and demand for climate science across the ‘useability gap’ (McNie, 2007), and tailor climate services to users needs through targeted, effective engagement. Unlike other perspectives on co-production, this approach is strongly iterative, pragmatic, and highly focused on the divide and interaction between supply and demand of information between producer and user.

Subsequent work on co-production as iterative interaction has been led largely by scholars from political science, geography and environmental science, influenced by work in 'science and technology studies' on the social context of science (Jasanoff and Wynne, 1998), and literature on science at the science-policy interface from interactive science (Scott et al., 1999), Mode 2 science (Gibbons et al., 1994), and boundary work (Guston, 1999) for instance. In this way, various authors (e.g. Dilling and Lemos, 2011; McNie, 2013) have further developed this theory of co-production, and it has come to underpin a large literature about overcoming limitations to the useful uptake of climate information, through: (i) co-production processes (Prokopy et al., 2016); (ii) boundary organisations (Cash et al., 2006; Buizer et al., 2016; Kettle and Trainor, 2015); (iii) understanding users' needs in decision-making contexts (Furman et al., 2011; Porter et al., 2015; Bruno Soares and Dessai, 2015; Lorenz et al., 2016); and (iv) building capacity to use climate information, and creating an informed community of users and providers to support future developments and evolutions of climate services (Diehl et al., 2015; Lorenz et al., 2015; Lowrey et al., 2009). For example, a number of papers have assessed the co-production of climate information in the NOAA Regional Integrated Sciences and Assessments (RISA) programme in the US, analysing the barriers to interaction and how they were overcome to build a engaged and informed community of users/providers (Bartels et al., 2013; Briley et al., 2015; Kirchhoff et al., 2013; Lemos et al., 2014; McNie, 2013).

The way we conceptualise co-production also has implications for how and who evaluates the quality of climate services. Given the significant technical advances that increasingly enable us to provide weather and climate information at smaller scales, most people see the bottle-neck to the transformation to climate services lies not in the lab-work but in the social work. There is a need for robust frameworks for (co-)evaluating the co-production of climate services where, with some exceptions (NRC, 2005; Vaughan and Dessai, 2014), there is generally a lack of work on evaluation frameworks. Vaughan and Dessai (2014, p588) note there has been, ***"relatively little evaluation of [climate services] performance…leav[ing] climate service users, providers, and funding agencies with very little information about the quality and relative value of climate services."*** The early frameworks that have been developed have mainly taken their lead from models of iterative, interactive co-production, and thus sought to distil key factors (or criteria) enabling the co-production of useful and useable information from comparative studies (Cash et al., 2006; McNie, 2013; Wall et al., 2017), and literature reviews (Dilling and Lemos, 2011; Kirchhoff et al., 2013). Others have tried bringing practitioners together to 'co-produce criteria of high quality co-production' (Buizer et al., 2016; Bruno Soares and Dessai, 2015). Some more comprehensive frameworks have been developed and tested. Ford et al. (2013) created a list of attributes of useable science from the literature, for assessing projects in Canada. Wall et al. (2017) defined a set of 45 indicators related to inputs, processes, outputs, outcomes and impacts of co-producing useable science from the literature, and tested them in two case studies.

If we (crudely and illustratively) apply the iterative, interactive perspective on co-production processes to the Voss case – and the animation product in particular – we see the ex-post analysis and evaluation it permits (that is, not applying this perspective to plan new co-productive processes, but to study how co-production was conducted). One focus goes to the *process* of provider-user interaction in negotiating the final form of the product, which in Voss extends to the complex and multi-tiered interaction between NVE as data provider, the consultant as animation provider, the hydroelectric companies that commissioned it, and Voss municipality as decision-maker (comprised of elected officials and municipality staff). What deliberate attempts, if any, were made to bring these four groups together in dialogue, what was the quality of this dialogue, and how did this dialogue iteratively evolve over the process? How were the different users' (hydroelectric companies and the municipality) needs and expectations, and different providers' (NVE and the consultant) interpretations of the science reflected in designing the animation? Which interested parties were excluded from this dialogue, like the Voss constituents for example, and how could their perspectives be incorporated, through elected officials representation for instance? A second focus goes to the *institutional elements and capacity* that shaped this negotiation process; how did the institutions of the four groups – NVE, the consultant, the hydroelectric company and Voss municipality – facilitate or hinder this negotiation process? Did any institution assume a 'boundary' role in initiating and facilitating this negotiation? A third focus will be on the usability and usefulness of the *animation product output* for supporting the public decision-making process. And a fourth focus might be on the *outcomes* for those involved in the negotiation; what was learned? By extension, an evaluation like that of Wall et al. (2017) would look at the extent to which the institutional framework and process gave effect to factors and principles that promote high quality interaction and dialogue, and some measure of the animation products usability and usefulness in the debate, perhaps according to criteria of legitimacy, credibility and salience.

An advantage of this approach is that it takes a focused look at whether providers and users understand each other and whether or not the climate services actually contribute to addressing the challenges faced by, and meeting the goals set by, the user. A disadvantage is that this strong focus on immediate client satisfaction can miss the broader societal impacts and qualities (whether positive or negative) that are inherent when working within a public arena. This risks developing climate services that are highly politicised and highly vulnerable to changes in the political leadership of the user. Inherent to developing any service is framing its focus, goals and problems. This is not only a technical, scientific matter, it is also political and part of the policy process (e.g. Robards et al., 2011). Consequently, the policy process can become 'scientized' or the science 'politicized' (Sarewitz, 2004) if the technical tools overshadow or obscure the political process. Moreover, political and social understandings of climate change and adaptation can change, with consequences for the perceived legitimacy, salience and credibility of adaptation policies and the climate services that support these (Offermans et al., 2011; Offermans, 2012). In Voss this also appears to be the case. The animation was developed to support a specific, highly political adaptation solution, and was consequently attacked as uncredible and illegitimate. In other words, this provider-client oriented approach risks delivering climate services that have low societal and political robustness (cf. Nowotny, 2003).

4. Broadening the study of co-production processes using a 'prism'

There are important opportunities for broadening the study of climate service co-production. As shown, the dominant conception of co-production is mainly founded in the American experience, and on one (albeit important) *'normative'* theoretical tradition, promoting direct, iterative, interactive processes between providers and users for developing useable products. But this fails to account for other normative approaches to co-production as collaboration that may have different emphases, on creating spaces for learning, or empowering vulnerable local groups for instance (see for e.g. Klenk et al., 2017). Nor does this include a proper regard for *'descriptive'* perspectives on co-production processes, which help analyse and interpret how climate services are more indirectly formed by the context (institutions, political debate) in which they are produced, but also concurrently shape this context; asking 'what else is being simultaneously produced when we develop climate services?' like power relationships or institutional norms (see e.g. Corburn, 2009). While a tight theoretical perspective is undoubtedly important to make sense of a complex reality, by using a limited lens of co-production this can equally limit the phenomena we

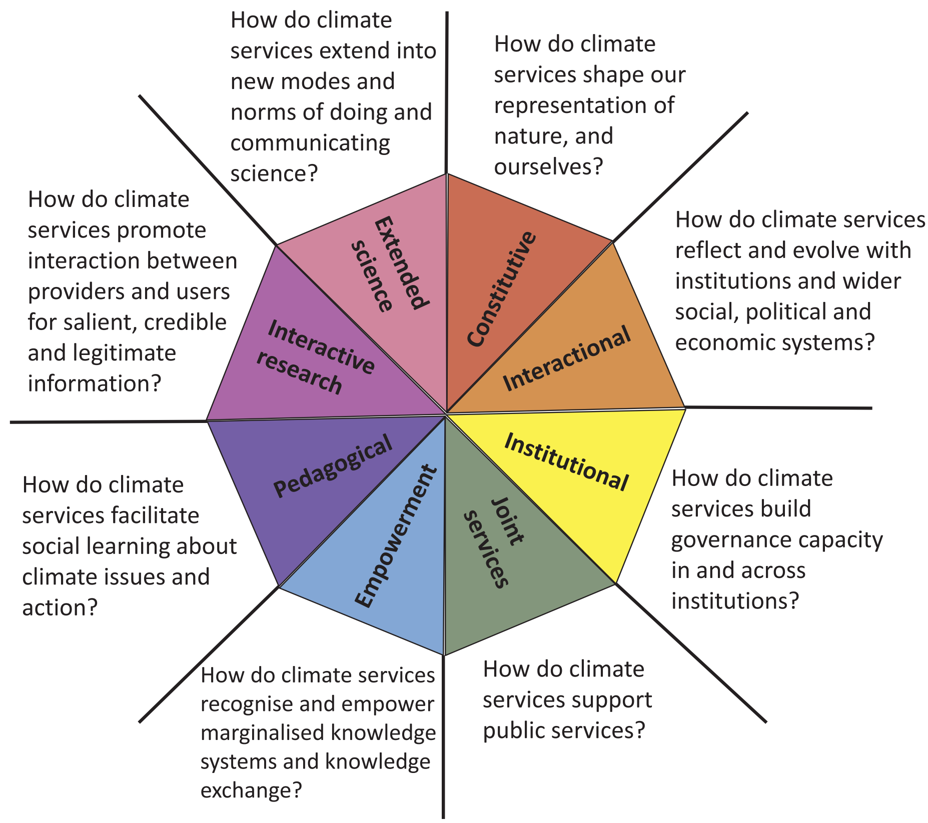

Fig. 1. Applying the co-production prism to climate service research questions (adapted from Bremer and Meisch, 2017).

can observe, and the ways we can learn from and steer climate service practice. Co-production study in climate services is arguably conceptually poor.

Co-production is itself part of an extended family of related collaborative, or 'co-' terms. Sometimes co-production is used synonymously with terms like co-creation, and sometimes as subsidiary or relational to these other terms (Lang et al., 2012; Mauser et al., 2013). Mauser and colleagues (2013) for instance, presenting discussions within the Future Earth programme, talk about the *'co-creation'* of science along three phases of a transdisciplinary research process: (i) the *co-design* of the research; (ii) the *co-production* of science through conducting the research work; and (iii) the *co-dissemination* (and co-evaluation) of the results. The level of involvement, including who has a leading role, can vary between stages as well as studies.

Some scholars have suggested employing other models of co-production for guiding climate services. Some have put forward alternative normative models of co-production as 'extended modes of science' where co-production aims to reorganise ways of doing science; from epistemological representations, to methods and norms. One key approach put forward is 'transdisciplinarity', which begins from assertions that complex societal challenges like climate change involve multiple disciplines and research should integrate these rather than exploring them separately (interdisciplinarity). However, when analysing societal challenges, non-scientific actors also hold key knowledge, and involving such actors is described as transdisciplinarity (going beyond scientific disciplines) (Nicolescu, 2002). This implies working with stakeholders at all stages of the research process, from problem framing and research design, to knowledge generation, or knowledge dissemination and application (Lang et al., 2012; Mauser et al., 2013; Wamsler, 2017); an approach that has been promoted within co-production efforts in Future Earth networks. Another similar approach put forward is 'post-normal science' (PNS) (Buontempo et al., 2014; Bremer, 2017; Kirchhoff et al., 2013; Krauss and von Storch, 2012; van der Sluijs et al., 2010; Van der Sluijs, 2012). PNS is both a critical concept for describing the limits of climate science in the face of uncertainty and high stakes, and a normative inspiration for a participatory mode of science. It promotes co-production as an extended mode of scientific inquiry, integrating users and other stakeholders into the scientific peer community jointly developing climate services. Central to such extended peer review is the systematic appraisal of the *quality* of climate service products, where quality is contingent to the context and use of the product – its fitness for function – and goes beyond standard scientific measures to incorporate other disparate considerations; from political legitimacy, to legal defensibility, and practical implementation.

Others have argued for more attention to descriptive models of co-production, analysing the more indirect social and natural orders at once influencing and influenced by climate services. This means looking beyond the direct collaborative work to consider the shaping influence of wider policy frameworks, institutions, societal needs, political discourse, cultural frameworks or markets for climate information (Lövbrand, 2011).

4.1. Seeing climate service co-production processes through a prism

A recent review by Bremer and Meisch (2017) argues that the co-production concept is a meeting place for a number of over-lapping traditions. They distilled eight different perspectives on co-production processes in climate change research; distinguishable by the aspect of co-production that they emphasise, their academic tradition, the work that they do, and their evaluation criteria. From these perspectives they conceptualised a 'prism' model of co-production comprising eight 'lenses' that span the descriptive/normative divide, and offer eight unique but complimentary ways of looking at the production of climate science. There is not the place here to go in detail through each lens, but suffice to note most co-production work in climate services falls under 'interactive research', transdisciplinarity and post-normal science fall under the 'extended science' lens, and the 'constitutive' and

Table 1
Examples of different aspects of climate service co-production, visible at different stages, through different co-production lenses.

Lenses	*Understanding context and co-design*	*Process of co-producing climate services*	*Co-disseminating and co-evaluating*
Constitutive	• How climate services relate to long-held ideas of weather and seasons as natural order, and how this influences their acceptability	• The role that surprises, tipping points, non-linearities and wildcards play in climate service development.	• How climate services redefine local understandings of the climate and climate action, and how communities' constitute their place in nature and broader society.
Interactional	• How institutional structures, processes, cultures, interactions, and legal frameworks currently shape the context in which climate services are produced and used.	• The social and political processes at play in dynamically renegotiating the development of climate services. • How climate change issues are (re-) considered relative to the other issues institutions face.	• The impact of climate services on institutions, including the power they exert in institutions. • The co-evolution of markets for climate services with other social, legal, political and economic systems
Institutional	• The various institutional capacities, experience, expertise and resources needed as inputs to • co-produce climate services, and how to mobilise them.	• How climate services are integrated with other information, actor networks, and on-going decision-making processes of institutions.	• How climate services contribute to a more adaptable (or fragile) body of climate knowledge for decision-making in institutions. • Impacts on expertise and capital (human, social, institutional, political) in institutions.
Joint services	• Understanding the relationship between private and public climate services, and how these competing markets provide context for developing new climate services. • The economic and institutional processes that are transforming public organisations into producing private climate services.	• Co-evolution of climate services as private and public goods and emergent tensions. • Proprietary challenges to private climate services produced for profit, using public data.	• Trustworthiness and legitimacy of public vs private climate services, or use of private climate services in public arenas. • The impact of climate services on traditional public services like weather forecasts.
Empowerment	• How stakeholders might be meaningfully engaged from the beginning in the joint design, production, evaluation and use of climate services	• How non-scientific knowledge is integrated with scientific knowledge in developing climate services. • Alternatives to science-based climate services, based on other anticipatory technologies associated with local and traditional knowledge.	• The influence of climate services on other knowledge systems in a place, like traditional or local knowledge.
Pedagogical	• Barriers to understanding and using climate services among key user groups. • Perceived knowledge gaps	• How climate service processes and products create spaces for learning and building competencies, and what collaborators learn about	• How climate services are used in educational institutions like universities or schools
Interactive research	• How collaborators negotiate across conflicting motivations, expectations, values, assumptions, vocabularies, scales of operation, and demands of climate services, and their goals of working together.	• Ways to create high quality dialogue through iterative interaction between climate service users and providers. • The role of boundary institutions in brokering knowledge partnerships	• The usefulness and usability of the final climate information product for users and their institutions, and any limits to its uptake. • Collaborators' perceived success of co-producing a high-value high-quality product
Extended science	• Reflections on an 'ethics of climate services' and what constitutes the 'responsible' production and use of climate services. • The epistemological status of climate services as a mode of practicing science, and its unique paradigm of representations, rules and methods.	• Alternative scientific practices, processes and technologies for collaboratively conducting scientific enquiries for climate services • The potential for new forms of 'citizen science' in climate services	• How scientific processes incorporate diverse criteria of knowledge quality and value, and how these criteria are layered in a final climate information product.

'interactional' lenses do the descriptive work. We argue that this prism concept has significant promise for broadening the study and practice of co-producing climate services beyond a one-dimensional process of product development; it is a strong concept for doing this in an ordered way. By re-framing co-production as multi-dimensional, the prism enables us to ask and answer new questions about how best to study and practice this complex transformation (see Fig. 1).

Bremer and Meisch (2017) do caution against tensions between some of these lenses, but point out that owing to their overlapping nature, they are largely complimentary in what they reveal about processes of co-production; "As each lens permits only one narrow observation on the complex processes of co-production, certain scholars (deliberately or not) define co-production in a way that combines several lenses to provide a more comprehensive view" (Bremer and Meisch, 2017: p. 12). Indeed, there is a great potential and precedent for using two or more lenses in concert for a more comprehensive analysis, without necessarily making the analysis over-complicated (see e.g. Armitage et al., 2011). The prism systemises a way of looking at eight dimensions of the co-production process in an organised, stepwise fashion (see Table 1). It can help us study and learn lessons from on-going co-production practices; looking at what each lens reveals about what is going on in this complex process, and comparing across the lenses for new and surprising insights. As such, it promotes and enables integrated and nested systemic analysis of the people, institutions and processes that come together, affect each other, come into conflict or cooperate in co-producing climate services and defining their value in a context. At the same time, it gives us more latitude in planning new co-production processes, with consideration for different types of co-production work; emphasising policy products or science, learning or institutional capacity.

Arguably such integrated study could improve both the way we *observe* and interpret the role of climate services in a context, *intervene* to effect co-production approaches, and *evaluate* the impact of climate services within that context. Here we echo the three phases of Mauser et al. (2013) in concretely demonstrating the value of the prism, and how it could contribute to designing better performing climate services in practice.

4.1.1. Understanding climate issues in context and co-designing climate services

Scholars and practitioners have been ill-equipped to describe the contexts where climate services are introduced, or interpret how context can shape the way they develop. But we can draw on the descriptive work of Science and Technology Studies scholars, in the 'constitutive' and 'interactional lenses', for seeing how science is produced from institutions, politics and socio-cultural frameworks. Proper consideration for context is vital for designing climate services that address the real need, and with different co-production perspectives, this opens up more design options. Does a policy-making process need a single number (e.g. of average rainy days), when an 'interactive research' approach is best? Or are climate services part of a long-term effort to involve vulnerable groups in decision-making, using an 'empowerment lens?' Or do we need spaces where community members learn about their local climate ('pedagogic lens')? Understanding context is equally important for developing climate service markets.

4.1.2. The process of co-producing climate services

Methodologically, the prism assembles the toolboxes of approaches that are associated with each of these perspectives on co-production, which in many cases show significant overlap. This enriches the ways we can practice climate service co-production. There are new methods from 'extended science', like citizen science, or convening an extended peer review for example. Or participatory policy approaches for building institutional capacity from the 'institutional lens'. Or institutional economic research on economic tools for involving local people in 'joint public service provision' for instance.

4.1.3. Co-disseminating climate services and co-evaluating their impact

Climate services has seen a lot of work on communication and dissemination, but including 'pedagogical' and 'empowerment' perspectives could present new opportunities; targeting services to vulnerable groups, and helping them 'learn to learn' about climate. Evaluation of wider impact, beyond the usefulness of a product, is another key value in adopting different perspectives on co-production (see Section 4.3). It admits a wider spectrum of evaluation criteria associated with sets of intended and unintended impacts. So while a particular climate service product – like an animation – may formally be useless to a decision-making process, the learning from developing it, or the political conflicts it triggers, may be seen as important and worthwhile.

Finally, we can challenge the adequacy of the prism's eight lenses for covering all facets of co-production; are there aspects of co-production overlooked by this concept? Bremer and Meisch (2017) do note that the eight lenses resulted from their own synthetic interpretation of a rich and overlapping literature, which could potentially have been interpreted differently. For instance, the impact of co-production on policy-making seems under-stated in the public service and institutional lenses, and could have stood alone. But these weaknesses notwithstanding, the prism is already a first big step away from the one-dimensional focus on product development, and can be subject to refinement and challenge later.

4.2. Looking at the Voss case through the co-production prism

The prism takes clarity and definition when applied to particular cases, so what kind of analysis might we conduct by turning it on the Voss case? We have already seen how the iterative interaction lens can help us study the co-production of climate services in Voss, but how might the other seven lenses help to build a more comprehensive understanding?

4.2.1. Constitutive lens

We see how climate services connect with on-going debates in Voss about how to represent and live with the river. One group sees the river as part of an inherently wild and untameable nature that should be left in its natural state; that rivers will always flood, and society needs to live with this risk. Another group sees the river as a feature to be controlled through engineering, to eliminate or reduce the flooding risk. The animation demonstrated flooding risk without any works to control the river, presenting a highly precise scenario that gives an impression of exact knowledge of the future river.

4.2.2. Interactional lens

We see how climate services, combined with other influences, were used to re-frame Voss municipality's (and other institutions') underlying representations of weather and natural phenomena in terms of global climate change. Flooding is reframed from being a normal impact of climate variability, to being a harbinger of pervasive climate change. This in turn can influence the type of information seen as salient and legitimate for addressing flooding, with for instance a shift in emphasis from modelling past flood events, to more predictive models of future flooding events that in this case included flooding supposedly beyond local experience.

4.2.3. Joint services

We see potential tensions between climate services as public or private goods, and how they are used in public and private arenas. Climate services are continuing a long trend toward the privatisation of previously public weather services. The Voss animation was privately commissioned, but built using public data, and used to stimulate debate in a public decision-making process. To what extent can the product be considered a public good, and then, what standards should it meet to be a public piece of information?

4.2.4. Empowerment

We see an ambivalent attitude to engaging non-scientific knowledge systems and social groups in the public debate in Voss. On one hand, alternative knowledge systems (local, traditional and craft knowledge) were not involved in the production of climate information for the decision-making process, including the animation; this despite a rich local knowledge and records of flooding events over the past 100 years. It is also recognised that when climate services are used in a public arena to inform publicly relevant decisions (decisions for which there is a broad constituency) local actors should have a critical voice in challenging these climate services (e.g. through local environmental and recreational groups).

4.2.5. Extended science

We see a limited recourse to alternative modes of science in Voss, but the animation shows the technologies available for creating sophisticated information products. It also shows the importance of extending ethics to climate services, for promoting responsible production and use (see e.g. Adams et al., 2015). Some argued that the animation was irresponsible in its shock tactics, in the way it portrayed damage, and in hiding the significant uncertainties underlying the animation. For these critics, this lack of transparency seems to undermine the legitimacy of the animation for public decision-making.

4.2.6. Institutional

We can see how the animation has contributed to the knowledge base, representations, and culture of the Voss municipality, and argue whether it has made that institution more 'adaptable'. In one sense, the animation may form part of a precautionary master plan, to steer development away from potentially flood-prone areas. In another sense, the animation is a snapshot of one uncertain distant scenario, which does not allow for incremental change and surprise along the way, or the ability to learn from future floods. Sticking rigidly to the animation could blinker Voss municipality to the other changes they may be experiencing even now, and may be taking Voss towards alternative scenarios.

4.2.7. Pedagogic

We see how the Voss public debate enables learning along several different dimensions. We see discussion of the future climate of Voss, but also reflection on the quality of the science and climate service products themselves. It also reveals procedural learning about the decision-making process itself, and how information is used in support of positions.

This is only a cursory analysis of the Voss case, but it serves to illustrate the many dimensions to co-producing climate information in a

Table 2
Criteria for evaluating good or successful co-production of climate services (from Bremer and Meisch, 2017).

Co-production lens	*Evaluation criteria*
Constitutive lens	The diagnosis of climate services role in rebuilding representations of climate, and the social orders for living with this climate
Interactional lens	The exposure and critical challenge to dominant social forces steering climate services
Iterative interaction lens	The usability of climate information products in a decision-making context
Extended science lens	The social robustness, accountability, and legitimacy of climate information in the face of uncertainty
Public services lens	The efficient and effective provision of public services
Institutional lens	The building of adaptive capacity in institutions
Social learning lens	The creation of a setting for learning to learn
Empowerment lens	The empowerment of marginalised knowledge systems for governance

place.

4.3. Evaluating the multi-faceted co-production of climate services

By employing a richer understanding of climate service co-production processes, there are also opportunities for building more comprehensive evaluation frameworks. Most current frameworks are structured around interactive research (Lemos and Morehouse, 2005), which has usability as the central criterion of quality. This is a good starting point, but with a regard for the other perspectives on co-production comes a greater appreciation for the other disparate criteria that underpin the quality and value of climate services; where quality is socially construed and value socially constructed. Usefulness alone is arguably insufficient. This literature suggests that at the very least, issues like scientific credibility, legitimacy of co-production processes and ensuring sustained commitment of actors should be critically scrutinised (Armitage et al., 2011; Cash et al., 2003; Dessai van der Sluijs, 2011; Hegger et al., 2012). Conceptually, Bremer and Meisch (2017) also engage with how each different lens evaluates 'good' co-production, highlighting the need for more multi-faceted evaluation frameworks of climate services too (Table 2).

Methodologically, assembling multi-faceted evaluation frameworks is itself an exercise in co-production. We need to co-produce frameworks for evaluating co-production if we are going to be true and consistent with the concept. This implies going back to climate service communities and exploring with them how they appraise quality and value. For instance, if we opt for post-normal science, this means actively engaging all stakeholders about the principles, processes, people, purposes and pedigrees that together determine quality and value in a context (Funtowicz and Ravetz, 1993; Kloprogge and Van der Sluijs, 2006). Related to quality, co-production concepts can render insights into how value is layered on climate services, and how we can evaluate value according to different criteria. Understanding direct and indirect co-production processes, and layers of value, is a critical step towards mainstreaming climate services and developing its markets.

5. Conclusions and the way forward

In this perspective piece we have argued for extending our understanding of the process of 'co-production' in climate services. We claim that recognising knowledge co-production as a multi-faceted phenomenon, able to be worked on along several different dimensions, could help climate services scholars and practitioners more fully realise the potential of this process. A more nuanced approach to co-production can potentially reform the way that the field understands the needs and interpretations of climate science, transforms climate science into climate services, and evaluates the quality of these climate services as salient, legitimate and credible. On one hand, it allows more explicit attention to the contexts where climate services are being produced, and how producing climate information is re-shaping these contexts, with implications for its social legitimacy. On the other hand, it opens up for a wider spectrum of creative methods and tools for co-production, which can be borrowed from neighbouring fields of research; unlocking exciting ways for 'learning to learn' about climate and climate action, extending voice to marginalised communities, or extending into alternative modes of doing science with non-scientists – like citizen science – for instance.

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Appendix A. Supplementary data

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