Evolving Climate Services into Knowledge–Action Systems

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ABSTRACT

The current landscape of climate services represents a highly diverse and still growing range of programs, projects, and portals involved in developing and/or providing climate services at different administrative levels and spatial–temporal scales. The diversity of service producers, users, and policy arenas has created a highly heterogeneous data- and information-oriented service landscape, and the authors contend that the domain of climate services requires efforts toward agreed structures and forms of conceptualization, operationalization, and evaluation. It is proposed here that qualitative classification be applied into climate change adaptation products, services, and systems to better guide research, policy, and practice with a clear terminology and analysis framework. This differentiation allows the pinpointing of critical challenges associated with the production and application of climate-relevant information, as well as the identification of suitable metrics to assess the impact of climate services. The article concludes with recommendations to advance climate services into knowledge–action systems and increase their sustainability.

1. Introduction

The need of climate change adaptation (CCA) services became urgent with the Paris Agreement in 2015, where adaptation was highlighted as a pressing need alongside traditional mitigation measures (UNFCCC 2015). Accordingly, the increasing number of scientific, political, and public efforts to develop and implement climate services has led to substantial achievements in this emerging field. Several models and frameworks to design and evaluate climate services have been proposed (WMO 2011; Hewitt et al. 2012; Vaughan and Dessai 2014; Miles et al. 2006), and agendas have been set up by governmental bodies (European Commission 2015) and scientific (National Research Council 2001) and intergovernmental organizations (JPI Climate 2011; WMO 2014) around the globe. In parallel, international policy processes and mechanisms have been implemented to facilitate the dissemination and use of knowledge that would inform and support adaptation policies and practices such as national adaptation plans (NAP), nationally determined contributions (NDCs), and the Nairobi work program (NWP) (UNFCCC 2015, 2018). Scientific studies have highlighted barriers between producers and users of climate information (Moser and Ekstrom 2010; Dilling and Lemos 2011; Lemos et al. 2012; Biesbroek et al. 2013; McNie 2013), while climate service prototypes have been developed and analyzed to distill lessons learnt (Brasseur and Gallardo 2016; Buontempo et al. 2018). The scope, content, and design of climate services have been analyzed (Lourenço et al. 2016; Swart et al. 2017; Christel et al. 2018) as have specific products, such as seasonal climate forecasts (Bruno Soares and Dessai 2016), scenario platforms (Sigel et al. 2016), or web-based climate applications (Brown and Bachelet 2017). There are also numerous studies of specific countries (Goosen et al. 2014; Görransson and Rummukainen 2014; Máñez et al. 2014; Haque et al. 2017; Kundzewicz et al. 2017; Vincent et al. 2017), actors (André et al. 2017; Wilk et al. 2017), and sectors (U.S. Government Accountability Office 2015; Hauge et al. 2017; Buontempo and Hewitt 2018) in contrast to the limited number of analyses covering institutional and governance aspects (Biagini et al. 2014; Hakelberg 2014; Oberlack 2017).

So far, research has focused on producers (Kjellström et al. 2016; Harjanne 2017; Räsänen et al. 2017) and

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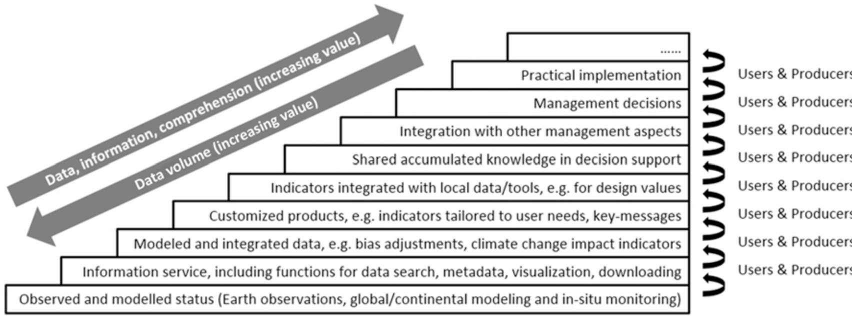

FIG. 1. Producer–user interplay: example of different steps in the climate service production mode, involving layers of different producers and users when going from data to information and finally to climate-relevant decision-making.

users of climate services (Cavelier et al. 2017; Golding et al. 2017a,b; Porter and Dessai 2017; Bruno Soares et al. 2018). An undifferentiated discourse about ''the producer'' and ''the user'' is problematic: while a large amount of research acknowledges that different users have different needs, too often the research does not distinguish between different categories of users (Swart et al. 2017). In practice, both groups are very heterogeneous, ranging from national meteorological services and research centers on the producer side to national policy makers, specific sectors, and the general public on the user side. Going beyond clear producer–user roles often reveals a continuous cascade of different users/producers replacing each other along the production chain, when refining data, in various layers of processing, to finally obtain information and insight for decision-making (Fig. 1). Today, the field of climate services is characterized by a confused provider and user orientation, ambiguous terminology, incoherent responsibilities, and ad hoc service content. There is a highly diverse and still growing range of programs, projects, and portals involved in developing and/or providing climate services at different administrative levels and spatial–temporal scales. Similarly, the existing literature on climate services is highly fragmented and often very context specific, which complicates any progress on fully understanding their nature. The rapidly increased number of studies on CCA measures has resulted in long lists of possible services for CCA, and accordingly, a lack of both coordination mechanisms (Hewitt et al. 2017b) and critical discourse (Harjanne 2017) in the climate service domain has recently been diagnosed.

Considering the ongoing societal efforts in establishing climate services, the authors suggest concentrating efforts toward agreed structures and shared understanding of interplay between various actors and sectors. The fragmentation of producers, providers, and purveyors has resulted in a clouded, ineffective service landscape with an unbalanced emphasis on the supply of data and information. Potential users are confused by the variety of providers and services available, making it difficult to evaluate providers' saliency, credibility, and legitimacy, and to assess the quality and usability of products. Consequently, the epistemic community is struggling to convert climate science into climate services and effective CCA actions. Fundamental questions remain unanswered: How can we insure that the information provided by research influences climate-relevant decisions, policies, and actions, that is, the use of climate services? How can we evaluate the quality of changes implemented by climate service users, that is, the success of climate services?

This paper surveys state-of-the-art literature and the future prospects in the domain of climate services and delineates relevant findings from present research. Services that aim at *adapting to* climate change impacts, that is, the process of adjustment to actual or expected climate and its effects (IPCC 2014a), are the focus. Climate services that aim at *mitigating* climate change, that is, a human intervention to reduce the sources or enhance the sinks of greenhouse gases (IPCC 2014a), are not considered [for this, we highlight a recent call from Obersteiner et al. (2018) for a discourse on effective climate change mitigation strategies]. According to the authors' review, the term ''climate service'' is undifferentiated and thus confusingly used for numerous items and activities, ranging from an online mapping tool for precipitation forecasts to guidelines for energy efficient households and the national meteorological agency's web portal. Climate services are provided by universities and research centers, public and private bodies, governments and nongovernmental organizations (NGOs) alike. Depending on the country or provider, services cover only specific sectors, such as ''agriculture'' or ''disaster risk reduction,'' at the expense of other sectors, such as ''energy'' or ''health.'' Given the range of actors, entities, and activities that are subsumed under the term ''climate service,'' the authors begin their attempt to structure the domain by clarifying key terminology (see the appendix). Subsequently, this article explores critical challenges for climate services in the way they are produced and used. However, climate services are not scrutinized from the traditional climate perspective focusing on information, but from a decision-making perspective focusing on quality by differentiating between products, services, and systems for CCA.

This distinction highlights a main message of this article: it is not only the lack of climate information that limits current CCA processes, but also the lack of addressing the questions of *what* kind of information is available, *how* and for *whom* is it produced, and to *whom* is it delivered in *which* form? Although several authors have emphasized barriers hindering effective knowledge production, transfer, and implementation (Lemos and Morehouse 2005; Moser and Dilling 2007; Jasanoff 2010; Moser and Ekstrom 2010; Weichselgartner and Kasperson 2010; Lövbrand 2011; Naustdalslid 2011; Weichselgartner and Marandino 2012), so far there has been little effort to increase the effectiveness of engagement between climate information providers and users and to better link climate information with decision-making (Hewitt et al. 2017c). In fact, the last review of this topic scrutinized the climate information usability gap and proposed strategies for narrowing it (Lemos et al. 2012), followed by constructive commentaries on ‘‘demand-driven climate services'' (Lourenço et al. 2016) and ‘‘improving the use of climate information in decision-making'' (Hewitt et al. 2017c) that emphasized the need to debate advancing the climate service concept. Lately, the climate research community admitted that ‘‘data are published in specialist terms and may not be relevant or robust enough to support reliable services'' and, consequently, ‘‘researchers need to make their results more accurate, useful, and readily available'' (Hov et al. 2017). A recent review of more than 100 climate service activities concluded that ‘‘strategies to design, diagnose, and evaluate climate services remain relatively ad hoc—and while a general sense of what constitutes ‘good practice' in climate service provision is developing in some areas, and with respect to certain aspects of service provision, a great deal about the effective implementation of such service remains unknown'' (Vaughan et al. 2018, p. 373). Hence, it is timely to review our understanding of climate services and necessary to structure the interplay between actors and sectors.

There is no blueprint for designing climate services; however, we believe that the producer and user communities will benefit from a more consistent terminology and system analysis as the field of CCA evolves. The authors' argument is that we need to extend our focus from CCA products to services and, ultimately, to systems that support effective preparation for climate change impacts. This includes not only enhancing our understanding of how climate information is generated, provided, and implemented in decision-making, but also fine-tuning our efforts on ‘‘what information can be produced'' and ‘‘in which format it can be delivered'' toward ‘‘which decision-making processes need what kind of information for which specific purpose.'' The first goal of this article is to stimulate and advance the current discussion on objectives, scope, and content of climate services by highlighting their fundamental attributes. The authors will do this by proposing a qualitative classification of ‘‘services.'' The second goal is to identify critical barriers and bridges in producing and using climate services. We believe that accentuating the connections between knowledge-making and decision-making and adjusting the modes of production and use accordingly, will advance the quality and usage of climate services. Moreover, it facilitates identification and application of reliable metrics that allow for the indispensable assessment of their impact and success. The article concludes with recommendations for effective CCA knowledge–action systems.

2. Structuring climate services

a. *Refining terminology*

The various interpretations of climate services, ranging from specific products to entire organizations, reveal the different scientific disciplines, intellectual traditions of stakeholders, and functions of the institutions that produce and/or provide climate services (Table 1). This diversity, however, hinders coherent communication across the increasing number of societal actors and sectors engaged in climate services, often contributing to misunderstandings and misinterpretation of climate information (Brown and Bachelet 2017; Hjerpe et al. 2017). ‘‘Knowledge'' and ‘‘service'' mean different things to different people, and it is important to make distinctions explicit. For instance, this article explicitly uses the term ‘‘research based'' knowledge to acknowledge that there are also other, equally important ways of knowing (e.g., experiential and tacit, local situational awareness). Furthermore, the term ‘‘climate relevant'' data is used to highlight the fact that climate services may need other environmental and socioeconomic data in addition to climate data. Likewise, ‘‘decision relevant'' information for climate-related decisions is not only about climate. The intention behind the clarification of terms is not to leverage individual terminology systems or to propose ‘‘better''

TABLE 1. Selected definitions of climate services (presented chronologically)

Definition	Author
The timely production and delivery of useful climate data, information, and knowledge to decision-makers.	National Research Council (2001, p. 14)
A national climate service identifies, produces, and delivers authoritative and timely information about climate variations and trends and their impacts on built and natural systems on regional, national, and global space scales. This information informs and is informed by decision-making, risk management, and resource management concerns for a wide variety of public and private users acting on regional, national, and international scales.	Miles et al. (2006, p. 19 616)
User-driven development and provision of knowledge for understanding the climate, climate change and its impacts, as well as guidance in its use to researchers and decision-makers in policy and business.	JPI Climate (2011, p. 44)
A climate service can be considered as the provision of climate information in such a way as to assist decision-making. The service needs to be based on scientifically credible information and expertise, have appropriate engagement from users and providers, have an effective access mechanism and meet the users' needs.	Hewitt et al. (2012, p. 831)
Climate services are boundary organizations that provide and facilitate knowledge about climate, climate change, and climate impacts for planning, decision-making, and general societal understanding of the climate system.	IPCC (2014b, p. 200)
A climate service is considered here to be the provision of climate information in such a way as to assist decision-making by individuals and organizations. The service component involves appropriate engagement, an effective access mechanism and responsiveness to user-needs.	WMO (2014, p. iii)
Climate services involve the direct provision of knowledge and information to specific decision-makers. They generally involve tools, products, websites, or bulletins.	Vaughan and Dessai (2014, p. 588)
Transformation of climate-related data—together with other relevant information—into customized products such as projections, forecasts, information, trends, economic analysis, assessments (including technology assessment), counseling on best practices, development and evaluation of solutions and any other service in relation to climate that may be of use for the society at large. As such, these services include data, information and knowledge that support adaptation, mitigation and disaster risk management.	European Commission (2015, p. 10)

definitions but to offer a common baseline from which constructive discussions can emerge.

As a shared point of departure for advancing structured interdisciplinary and cross-sector collaboration on climate services, the authors propose to differentiate between components of research-based knowledge production: facts, data, information, knowledge, and, ultimately, wisdom (Table 2). We know from the literature of organizational theory and information science (Polanyi 1966; Cleveland 1982; Ackoff 1989; Nonaka and Takeuchi 1995; Pentland 1995) that it is critical to distinguish different forms of knowledge and qualitative levels of comprehension, and we believe it provides a sound basis from which climate-related researchers can better communicate with climate-relevant policy makers and practitioners, and vice versa. Therefore, when defining climate services, we suggest considering facts as a set of objective but meaningless observations and measurements, and data as processed facts, the processing directed at giving structure. Both can be converted into information if intentionally processed and organized in a functional way so that one can draw conclusions. While facts and data do not have any inherent structure, information has context. Knowledge is created by accumulating and organizing information with respect to breadth, depth, and amount and through social interaction and personal experience, with the result that facts, data, and information are considered and evaluated from different perspectives. Wisdom can be seen as a reflected, judged understanding, that is, reflexive knowledge. As with knowledge, wisdom operates within people and involves exercises of evaluation, reflection, and adjustment. Experience that creates the building blocks for wisdom can be shared, but it needs to be communicated with even more understanding of the personal contexts than in the case of knowledge sharing. We note that each component—despite different qualitative levels of comprehension—can be decision relevant if it yields deeper understanding of a choice or if, incorporated in making a choice, it yields better expected results for decision-makers and their constituencies

TABLE 2. Components of knowledge production, adapted from Weichselgartner and Pigeon (2015, p. 109)

Component	Narrative	Key activities	Comprehension
Facts	Objective measurements	Observe, record, measure, register	Elements
Data	Structured facts	Pool, gather, categorize, classify	Structures
Information	Functionalized data	Compare, connect, analyze, organize	Correlations
Knowledge	Contextualized information	Synthesize, combine, interrelate, assess	Patterns
Wisdom	Reflexive knowledge	Evaluate, reflect, judge, adjust	Principles

than would be achieved if the choice were made without that knowledge.

A precise use of terms prevents the incorrect labeling of the process of ''providing information'' with the term ''knowledge,'' as is frequently done in both the climate service literature and practice. It also elucidates that an increase of information does not inevitably result in an increase of knowledge. Indeed, the advancement of information technology is progressively producing and providing facts and data (Edwards 2017), but much of the information remains unorganized, untapped, or unused, thus is not contextualized and turned into applicable knowledge. Since adaptation requires that individuals and entities alter their standard practices and decision routines to account for climate change, the terminological differentiation must be accompanied by a more precise view of decision support than currently done. Decision support consists of a set of processes intended to create the conditions for the production of decision-relevant information and for its appropriate use. According to the U.S. National Research Council (2009), a climate service thus needs to be equipped with training and user support to be effective, as well as feedback mechanisms for co-design with the service provider. Ongoing communication and interaction between the climate service producers, providers, and users is at the center of these processes, and while information products are one result, they are most likely not the critical one. Both the differentiation between components of knowledge production and the specific connection of these components to decision-making are critical characteristics of climate services that should be reflected in the definition. Hence, the authors use the term ''climate service'' for organized efforts to produce, provide, and use climate-relevant knowledge that can improve climate-related decisions and increase an entity's capacity for taking effective action to mitigate climate change or adapt to climate change impacts.

b. *Classifying climate services*

In addition to a more specific view of what counts as climate knowledge, we need to scrutinize the transfer mechanisms of climate-relevant information into adaptation actions. With the concept of climate services rapidly climbing research and research-funding agendas worldwide, a steadily increasing number of climate services are being produced for an expanding group of decision-makers both in policy and practice (Lourenço et al. 2016; Vaughan et al. 2018). Alongside this expansion there is an increasing recognition that the interface between the climate service providers and users is the least-developed aspect of climate services, and therefore urgently needs improving (Kirchhoff et al. 2015a,b; Hewitt et al. 2017c). Consequently, we need to review the modes of production and use of services assisting decision-making related to CCA. Given the many forms of information and variety of knowledge products that are labeled ''climate service,'' the authors suggest classifying them according to the quality of decision support (see the appendix) and to distinguish between climate change adaptation products (CCAP), services (CCAS), and knowledge–action systems (CCAKAS). A classification that takes into account the different forms of knowledge as well as the qualitative value of these forms for decision-making appropriately reflects the fact that knowledge transfer is an iterative and highly social process. Studies have detected the limitations of prevalent models of research production and use that suggest rational, linear processes of transfer (Mitchell et al. 2006; Kirchhoff et al. 2013; McNie 2013). Knowledge as the capacity to act implies not only making climate change impacts visible through the specialized scientific lens but linking them via people's perceived reality to socially meaningful actions. Weichselgartner and Marandino (2012) speak of ''priority knowledge'' to emphasize characteristics and abilities, which make implementing findings possible, that is, the realization of knowledge. As research-based climate knowledge is complex and specific to identified issues, a ''service'' can never be designed to fit all. We recognize that in the past, climate services have focused on producing data of environmental conditions, while at present they are extended to include impacts, also in a societal context (Fig. 2). To become more efficient and effective, a synergetic approach is needed to evolve into CCAKAS of diverse actors and sectors, which will also allow more proactive decision-making from a holistic perspective.

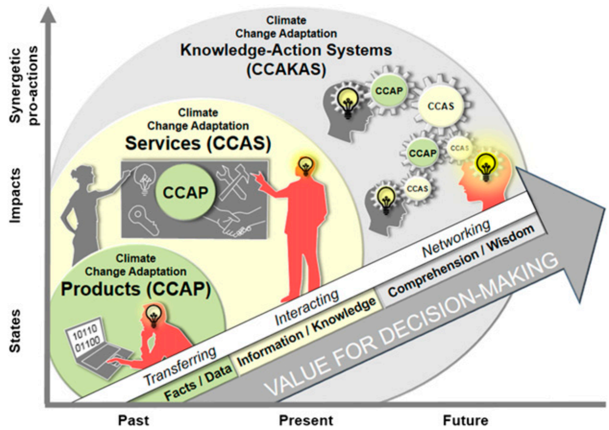

FIG. 2. Development of CCAKAS: a service-focused, context-driven, and decision-oriented coproduction mode of tailored CCAP and CCAS requires transformative changes in the knowledge infrastructures and producer–user interfaces, but offers a higher relevance, credibility, and legitimacy for decision-making than a product-focused, academic-driven, and data-oriented production mode. Working together in synergy on CCAS and engaging in interactive governance, which involves the active involvement and empowerment of societal stakeholders and negotiating and implementing mutually agreed-upon rules, is a feasible way to enhance relevance and usability of products and services.

3. Barriers and bridges in climate services

a. Scrutinizing the production of climate information

Evidently, climate-relevant information is useful for decisions only when it is timely, accessible, and understandable to decision-makers (National Research Council 2009). In decision-making processes, however, more information does not necessarily lead to better decisions. Research has highlighted diverse functional, structural, and social factors that limit the production, dissemination, and use of scientific information; many of these factors are psychological, institutional, socioeconomic, and infrastructure related and are not resolved with more and/or new information (Weichselgartner and Kasperson 2010; Biesbroek et al. 2013; Rayner and Caine 2015). Such barriers influence the use of information in decision-making and reveal a lack of, for instance, data accessibility, direct relevance to management objectives, credibility of information providers, or sufficient background knowledge (about climate science among managers and about management practices among scientists). Climate-relevant information must be tailored to reach the right person in the right form at the right time. Neither does a unilateral supply-side push result inevitably in more useful information, nor does the availability of climate-relevant products guarantee their use (McNie 2013; Hauge et al. 2017; Swart et al. 2017; Wilk et al. 2017). Reoccurring factors that have limited the success of provided climate information are (i) insufficient awareness by societal actors of their vulnerability to climate change; (ii) the lack of relevant products and services offered by the scientific community; (iii) the inappropriate format; and (iv) the inadequate business model, which is insufficiently adapted to the culture of users (Brasseur and Gallardo 2016; Bruno Soares and Dessai 2016; Bruno Soares et al. 2018).

Examination of the factors that contribute to climate scientists' struggle to respond to users' requirements emphasized various barriers (Lemos et al. 2012; McNie 2013; Meadow et al. 2015) and, consequently, resulted in different suggestions for narrowing the gap between information providers and prospective users. Current proposals range from analyzing the potential market for climate services (Brasseur and Gallardo 2016) to determining new institutional priorities (Porter and Dessai 2017), and from altering the form and content of guidance material (Hauge et al. 2017) to improving climate education (Brown and Bachelet 2017). While many of the aspects identified by research clearly restrict the use of climate information, the suggestions provided by research will have only limited impact on decision-making as long as they tackle only specific symptoms, but not the root causes that are responsible for the restricted effectiveness and usability of many CCAP.

Here it is argued that the current production practice is not the most effective mode to enhance CCA and propagate a shift from a product-focused, academic-driven, and data-oriented production mode to a more service-focused, context-driven, and decision-oriented one. Despite reports of severe limitations in the academic-initiated and discipline-based knowledge production model (Funtowicz and Ravetz 1991, 1993; Gibbons et al. 1994; Hessels and van Lente 2008), a large number of present "climate services" are produced in the same conventional mode, with little consideration of the decision-makers' context and insufficient attention to usability and applicability (Buontempo et al. 2018; Vaughan et al. 2018). Failing to treat "climate services" as social and communication processes, and expecting that the "knowledge product" will be taken up by users without additional effort, is a common pitfall (Cash et al. 2003; Lemos and Morehouse 2005; McNie 2013; Weichselgartner and Kasperson 2010). We know from a series of studies that applicability, comprehensiveness, timing, and accessibility of scientific research have an influence on decision-makers (Dunn and Laing 2017; Tangney 2017), and that saliency, credibility, and legitimacy are critical attributes for effectively informing policy and decision processes (Cash et al. 2003; Mitchell et al. 2006; Meadow et al. 2015). These findings indicate that a CCAP will more likely influence decision-making when the producers manage boundaries between knowledge and action in ways that simultaneously enhance the scientific credibility, political saliency, and practical relevance of the information they produce. This is not only because sustained interaction is essential to transmit product-relevant information between producers and users, but also because persistent collaboration contributes to the creation of legitimacy and trust (Feldman and Ingram 2009; Kirchhoff et al. 2013; Golding et al. 2017b; Bruno Soares et al. 2018).

It is ill-advised to believe that the success of climate services can be increased only through ''more accurate data'' or ''better targeted information.'' The history of global climate negotiations reinforces our assertion that information alone cannot dictate policy choices and that ''value for decision-making'' is a significant guiding principle for CCAP. According to the last IPCC Assessment Report (IPCC 2014b, p. 837), there is empirical evidence to suggest that linking CCAP more directly to particular decisions and providing information tailored to facilitate the decision-making process will lead to more effective adaptation measures. There are also indications that climate science would profit from a more self-conscious critical review of the knowledge systems mobilized in support of action, in particular with regard to methodology, collaboration, and transparency (Haque et al. 2017; Knapp and Trainor 2013; Nielsen and D'haen 2014). Since the information sources used by scientific producers and nonacademic users are habitually quite distinct, scientific institutions may need to reevaluate their incentives and structures for producing decision-relevant climate information. Adjustments are already necessary since modes of collecting and delivering climate information are evolving, businesses and nonprofit organizations are increasingly supplying new services, and data now stem from a broader range of sources, such as mobile-phone apps and smart devices (Hov et al. 2017).

It is partially recognized that top-down management practices are not the most suitable for developing climate services, and the way in which users are involved in climate service projects should be changed (Buontempo et al. 2018). Promising and worth exploring is, for instance, the architecture around a chain of responsibilities, products, and users for climate services as proposed by Brasseur and Gallardo (2016). Each level of service—international, national, and regional—should address the needs of different customers and provide different types of services. At each level, partnerships with supporting research or development organizations and with intermediate and end users should be established in an effort to develop an iterative collaborative process. Donnelly et al. (2018) showed, for instance, that more general and large-scale climate services can be valuable also at the local level; however, comparative studies show that more tailor-made assessments for a specific location and issue are preferred for decision-making at the local scale. Local users normally need specific variables to support their decision, and moreover they trust data and information that can be validated locally for historical time periods. Therefore, it is important to identify, extract, and analyze case by case the most relevant variables from climate models and merge the projected data with local observations (Donnelly et al. 2018; Krysanova et al. 2018), thus asking for tailored production of climate information at this scale. Another example of good practice when developing climate services is to broaden the diversity of expertise involved in climate service production, including engineering, economy, social management, and communication. With a focus on the situation in Europe, the analysis of user engagement methods by Swart et al. (2017) yielded valuable insights for improving user consultation and engagement processes, using such a multidisciplinary approach.

The suggested coproduction mode allows for extended participation in decision-making and more socially robust and context-sensitive CCAP. Simply adjusting the format of CCAP without paying attention to what users consider as usable information in their decision-making is a short-term approach. Producers need to look at the users' perception of information fit, how new knowledge interplays with other kinds of knowledge that are currently used by users, and the level and quality of interaction between producers and users (Lemos et al. 2012; Meadow et al. 2015). The essential next step toward CCAS is to increase the proportion of policy- and decision-relevant information.

b. *Scrutinizing the use of climate information*

While from a producers' perspective all information generated is potentially useful, information moves from useful to usable only when users effectively incorporate this information into a decision process. Lemos et al. (2012) illustrate the path between usefulness and usability and describe the critical factors and actions that change users, producers, and the character of information to increase use. Hence, various factors restrict usability, and others, such as interaction, retailing, customization, and value adding, enhance it by changing producers' and users' perceptions both of the information and the character of the information itself. We also know that the characteristics of users matter in shaping their ability to access and make use of knowledge and that a research's formal output, be it a scientific report or predictive scenario, is only *one* visible indicator of a larger social process (Mitchell et al. 2006;

Weichselgartner and Truffer 2015). Thus, analyzing the content or format of a CCAP without capturing the regulatory and cultural conditions of users can never fully ascertain the real source of its influence. For example, climate policy has impact on the funding, production, and interpretation of climate research (Lövbrand 2011) and also the quality of public services and institutions is an influential factor (Fankhauser and McDermott 2014).

Likewise, providing a ''service'' is more than information transfer of prepackaged climate research findings to passive user audiences. There is a transformation process alongside any information transfer, and, importantly, it varies depending on the type of information, user, and user requirements (Davies and Nutley 2008). Despite this fact, ''end users'' frequently appear as one box in very complicated schemes of information sources and software tools, leaving the label of ''user'' open and inclusive, indicating that climate services can be useful to anyone. The literature recognizes numerous service customers, generally referred to as *the* users: individual policy makers, explicit organizations, entire sectors, and even yet unknown users for an envisioned prospective service market. While it is acknowledged that different users have different needs, in practice—even when a sectoral approach is applied—the diverse CCAP are not adequately differentiated, and the various types of users within a sector are not further distinguished (Swart et al. 2017). The fundamental problems on the user side are frequently considered to be a lack of climate literacy, interest, or skills to utilize the available information (Christel et al. 2018; Harjanne 2017; WMO 2014). Since perception, motivation, trust, and/or preferences may vary substantially—depending on whether the user is a climate impacts researcher, consultant engineer, business manager, or policy maker—more empirical studies are needed that systematically evaluate the extent to which climate services really meet the needs of the targeted users, and how social, cognitive, and behavioral processes influence the use of climate services in decision-making. As a consequence, our understanding of contextually relevant decision-making frameworks remains limited. Empirical studies of how climate-relevant information is used and valued in decision-making, in particular with regard to its impact on attitudes, decisions, and behavior of people, is thus a pressing need. A recently conducted analysis of climate service users in Europe, including 80 in-depth interviews and an online survey, revealed that climate services are often inadequate for users' decisions and many users struggle to understand or use climate model output (Hewitt et al. 2017a). It is also important to start recognizing the reusing and repurposing among users and producers and that there is normally no ''end user'' but a never-ending cascade of users.

The importance of active stewardship of both the ''product'' and ''service'' has been acknowledged in guiding principles (National Research Council 2001) and design elements (Vaughan and Dessai 2014) for climate services. In practice, however, it is still challenging to sort through the huge number of products and usually guidance is insufficient to lead a potential user to the most appropriate CCAP. As a result, products are selected on the basis of availability, convenience of format, and familiarity with the provider (Barsugli et al. 2013; Goosen et al. 2014), rather than on appraisal for decision-making. Besides the user's dilemma of identifying an adequate and credible product, there is evidence for an unsatisfied demand for ''nonclimate services'' explaining the use of information (Räsänen et al. 2017). A recent study on CCA user guides for buildings and infrastructure stresses typical features of the current situation: the overwhelming amount of user guides create uncertainty among users; none of them describe decision processes in depth; and a large proportion does not specify target groups and/or communicates background information rather than practical measures (Hauge et al. 2017).

Given that the current development of climate services is largely framed from a data provider point of view, the usual provision is through digital information portals, which are a useful component of CCAS, but by themselves insufficient to reduce the usability gap (Swart et al. 2017; Hewitt et al. 2017c). In contrast, adverse effects of magnifying gaps between science and policy can be observed because of commercialized mechanisms through which climate services are governed, and the political economic circumstances within which they are produced. For example, Webber (2017) identified inherit tensions in the commercialized ''service'' model, including contradictions between ''objective'' and ''entrepreneurial'' science and a focus on competition and circulating CCAP at the expense of collaborative relationships. The latter is particularly adverse since the quality of interaction between producers and users critically affects the success of CCAS (Buontempo et al. 2018; Christel et al. 2018; Feldman and Ingram 2009). Yet, with few exceptions, neither the effectiveness of user engagement methods nor the actual usefulness of the resulting portals is systematically evaluated in most portal development projects, neither during nor after their implementation (Swart et al. 2017).

Lately, efforts place more emphasis on the user dimensions of climate information. For instance, the analysis of climate information portals and the processes of engaging users in their development revealed important factors concerning harmonization of products and sustainability of providers (Swart et al. 2017). Likewise, the study of different engagement categories yielded useful recommendations for improving services by better linking information with decision-making (Hewitt et al. 2017c). Valuable insights into the design of services were gained by developing a climate service prototype together with potential users, applying different engagement methods and deploying various communication channels (Christel et al. 2018). These studies advance the quality, usability, and applicability of CCAP, but simultaneous efforts are needed to increase the diversification of expertise and social learning in the service development. The challenge of designing effective CCAS has two dimensions: first, bringing users into the front end of service production, an arena from which they have been so far mainly excluded; and, second, institutionalizing polycentric, interactive, and multipartite processes between knowledge and decision-making, among actors that have worked so far largely discretely. Given the important role of organizations in bridging science and decision-making (Guston 2001; Kirchhoff et al. 2015a) and the evidence that decision support is most effective when it is sensitive to context and the diversity of decision types and processes (IPCC 2014b; National Research Council 2009), the essential next step toward CCAKAS is to strengthen social collectives that jointly generate, organize, and apply knowledge.

4. Evolving climate services into knowledge–action systems

Before suggesting ways to enhance effectiveness of CCAKAS, we briefly outline some challenges that need to be addressed from both the producer and user perspective. The production and provision of CCAP and CCAS through legitimate and sustainable governance mechanisms are facing the challenge of addressing questions of responsibility and quality. At present, the support for climate services is generally organized on a governmental level and within determined projects. According to a recent survey, the most common type of service reported involved seasonal climate information provided by national meteorological services, in conjunction with research institutes, to agricultural actors over the Internet (Vaughan et al. 2018). A climate information system with federal leadership has several advantages, specifically for decision-makers to justify the costs of incorporating climate-relevant information into planning efforts, thereby reducing long-term federal fiscal exposure (U.S. Government Accountability Office 2015). Anchoring the production and provision of CCAS in temporary scientific projects is problematic. While the "project mode" is sufficient to achieve a limited set of objectives, it also leads to redundancy and duplication of efforts, inconsistency regarding terminology and information, and fragmentation of provider and user communities (Hewitt et al. 2012; Lourenço et al. 2016; Hewitt et al. 2017b).

The effectiveness of decision support can be judged by the extent to which it increases the likelihood that decision-relevant information is produced and enables and empowers decision-makers to use it appropriately (National Research Council 2009). Reliable metrics for CCA effectiveness and progress are difficult to develop, given the varying climatic conditions at the global scale, the different institutional settings at the governmental/national scale, and the diverse and changing conditions at the local level. There are conflicting views concerning the choice of metrics, as governments, institutions, communities, and individuals value CCA needs and outcomes differently and many of those values cannot be captured in a comparable way by metrics. Studies of knowledge use generally focus on assessing its impacts on a range of intermediate variables that are linked to those important outcomes. For example, assessments may focus on the influence of knowledge use on patterns of service delivery, without necessarily examining the full impacts of these service patterns on CCA outcomes. However, it is crucial to understand the connections of these processes, influences, and impacts, through time and through intermediary variables (Meadow et al. 2015). Decision support systems are a step forward in efforts to account for the social and spatial dimension in climate-relevant decision-making and the different ways of knowledge integration and learning (Nieuwenhuijs et al. 2016; Rodela et al. 2017). Furthermore, metrics for evaluating the extent to which targeted CCA outcomes (rather than CCAP) are occurring assist budget allocation and priority setting.

Contemporary transformations in social and environmental systems call for different forms of governance and new mechanisms to steer social systems toward CCA (Chandler 2018; Taylor and McAllister 2015). Interactive CCAKAS require more effort and resources to create a legitimizing collaborative work space and incentivize the production and use of CCAP, but have significant benefits with regard to institutional stability, learning mechanisms, and identification of decision needs and critical decision points. First, with their established links to different societal sectors they support sustainability of climate services and, because they reside at the producer–user interface with lines of responsibility and accountability to each, they have the ability to both bridge and to protect the boundary between knowledge-making and decision-making (Guston 2001; Kirchhoff et al. 2015b). Second, they can create synergies with other networks with related goals—in particular those addressing disaster risk reduction and risk adaptation (Kruk et al. 2017;

TABLE 3. Recommendations for developing effective CCAKAS.

- Pay attention to the differing perception, motivation, preferences, and requirements of producers and users to reduce discrepancies and avoid misinterpretations.
- Create dense social networks that provide bidirectional links across spatial scales and societal sectors to enhance soundness and value of products and services.
- Include diverse actors and combine multiple information sources to enhance legitimacy and credibility of products and services.
- Emphasize a service-focused, context-driven, and decision-oriented knowledge production mode to enhance relevance and usability of products and services.
- Create polycentric, interactive, and multipartite processes in a sustainable dialogue between knowledge- and decision-making to obtain a more consensual view of what is both feasible and desirable.
- Establish space and mechanisms for social learning and experimentation to enable new practices that may be needed under changed contexts.
- Start building nonhierarchical knowledge–action systems at the local scale, where context-appropriate measures can be implemented in a timely manner.
- Enhance links to other networks with related objectives to create and use synergies and diminish redundancies.
- Provide multidisciplinary education and cross-sectoral training in climate-relevant science and policy.

Willner et al. 2018)—and create boundary chains to reach a wider range of users more efficiently and effectively (Kirchhoff et al. 2015a; Guido et al. 2016). For instance, Feldman and Ingram (2009) demonstrate how, through construction of knowledge networks and their institutionalization through boundary organizations focused on salient problems, climate information can positively affect water resources decision-making. Third, they can facilitate monitoring the use of climate services and evaluating the quality of changes implemented by their users. A current survey on climate services conclude that efforts to sample climate services will need to be expanded, and kept up to date, if researchers are to be able track changes to the climate service community as a whole and keep tabs on the extent to which such services contribute to society's efforts to adapt to climate variability and change (Vaughan et al. 2018). Recent scientific studies on CCA knowledge emphasize the fact that more meaningful decisions can be taken in an arena where different agents provide knowledge of specific domains and that the emergence of new knowledge can be sustained by combining scientific and policy expertise (Olazabal et al. 2018). Van der Molen (2018) demonstrate that enabling well-informed environmental governance is not just a matter of managing the interfaces between knowledge and governance, but also a matter of capacity building in order to bring about reflexive governance arrangements.

Given the functional, structural, and social factors that limit a collaborative production of knowledge (see Weichselgartner and Kasperson 2010), specific research on individual or project level is not sufficient to overcome existing barriers. Science organizations and funding agencies, from the WMO and Europe's "Horizon 2020" to the National Academies and the World Climate Research Programme, to mention a view prominent ones, possess adequate tools and incentives to strengthen collaboration between climate service bodies (or boundary organizations) and national meteorological services. However, to be successful and accelerate actions based on climate knowledge, communication between various stakeholders is urgently needed. The proposed qualitative classification will help improving communication and thereby concerted actions. We anticipate that the added value from this new knowledge–action system is threefold, as it will facilitate 1) resources allocated where they are most effective in bridging between science and practice, 2) services developed in cogeneration between many stakeholders for increased user uptake, and 3) user navigation among existing services with merging and tailoring information to specific issues and sites.

5. Conclusions and propositions

The domain of climate services needs to address two key matters to be more efficient: one is to adjust the modes of production and use of climate-relevant information, and the other is to evaluate the effectiveness of this information in decision-making. Achieving the first goal requires agreed forms of conceptualization, operationalization, and evaluation. The proposed terminology and clear distinction between CCA products, services, and systems enable a comparable analysis of CCA actions. A higher transparency and comparability of climate services will reveal shortcomings in the scope and content of CCA measures and more efficiently guide researchers, policy makers, practitioners, and civil society.

Developing CCAKAS with multiple layers of producers and users from different sectors is an effective method of tailoring decision-relevant information to different decision environments (Table 3). They can more easily overcome barriers to information adoption such as stovepipes, pipelines, and restricted decision space, and more effectively address issues of saliency, credibility, and legitimacy. In-depth research describing how particular knowledge–action systems are structured, detailing both challenges and successes, and describing whether or how new CCA products are integrated into management decision-making can help future producers and users better understand the dynamics of collaboration and set reasonable goals for the use of new climate-relevant information.

Achieving the second goal requires mapping and monitoring the information use in decision-making processes to trace the impacts of climate services on CCA. Without shared forms of conceptualization and operationalization it remains difficult for governments and climate funds to check and compare the impacts of their actions and projects and to mainstream CCA in the broader activity portfolio. Both goals call for transformative changes in knowledge infrastructures and producer–user interfaces. While the climate knowledge infrastructures of the twentieth century were usually constructed in a top-down, purposeful, and aggregative manner, we propose to arrange the twenty-first-century data-intensive production mode of climate knowledge more bottom-up and polycentric, driven by practice rather than design, and organized across societal sectors rather than in scientific isolation. These are pivotal shifts because climate services are complex and multidimensional social processes, and without a more structured and holistic enquiry to reassemble producer–user relations in creative and sustainable forms, we run the risk of making inadequate decisions and taking ineffective actions. Given the findings of a recent examination of the diachronic impact of climate-related disasters on ancient societies (Peregrine 2018), these shifts are by no means trivial: societies allowing greater political participation in decision-making and having more community coordination and governance organizations appear to provide greater resilience to climate-related catastrophes.

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APPENDIX

Key Terminology Suggested for a Structured Discussion When Analyzing Climate Services

Given the focus of this article, we note that we consider only climate services for climate change adaptation (CCA), which we classify into three categories: *Climate change adaptation products* (CCAP) are the organized efforts and tangible deliverables that contain data and information to support decision-making for adaptation, including efforts to identify information needs, encourage the use of climate-relevant products, and produce and disseminate climate-relevant data and information, among others. CCAP are not only documents, maps, projections, images, brochures, tools, models, or web pages, but also the media and channels developed to provide data and information. *Climate change adaptation services* (CCAS) are activities, consultations, or other forms of interaction that enable decision-makers to make better use of CCAP, including efforts to increase the quality, usability, and applicability of products; educate and train product users; improve the relationships between producers, providers, and users; facilitate adaptation decisions and actions, among others. CCAS are not only products, but also the mechanisms for interaction and knowledge exchange between producers, providers, and users. *Climate change adaptation systems* are networks of individuals, organizations, coordinating bodies, and institutional and communication structures that cooperatively design, produce, provide, and use CCAP and CCAS. They include not only products and services, but also mechanisms for new ways of thinking, understanding, learning, and behaving needed to produce, provide, use, and advance CCAP and CCAS according to their impact and success. The authors suggest calling them climate change adaptation knowledge–action systems (CCAKAS).

Climate service producers generate climate-relevant data, information, and knowledge; *climate service providers* supply climate-relevant data, information, and knowledge. Producers may also supply and disseminate climate-relevant data, information, and knowledge, making them both producers and providers, just as providers that also generate climate-relevant data, information, and knowledge (note: purveyors are a special type of climate service provider that uses climate-relevant data available from others and add value for users). *Climate service users* employ climate data, information, and knowledge for decision-making. They may or may not participate in designing and/or producing the product and/or service themselves and they may also pass data and information along to others, making them both users and providers. Producers, providers, and users may operate on international, national, regional, and/or local levels and in different sectors; they may be public or private, or some mixture of both. In addition, *climate service bodies* (or boundary organizations) operate at the interface between science and policy to create and sustain mutually beneficial connections between climate service producers, providers, and users. By integrating differing epistemic communities, knowledge systems, and societal sectors, they excel at providing space and mechanisms to support climate-relevant products and services in particular contexts, hence brokering knowledge to decision-making.

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