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Climate Services 17 (2020) 100151

Contents lists available at ScienceDirect

Climate Services

journal homepage: www.elsevier.com/locate/cliser

Original research article

Reflexive climate service infrastructure relations

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ARTICLE INFO

Keywords:
Service infrastructure
Climate data
Knowledge
Climate services
Interactive infrastructure approach

ABSTRACT

Exploring existing climate knowledge infrastructures as the important backbone of service endeavours, the authors analysed how climate knowledge infrastructures are organised, how (far) they take into account the 'end user', and how processes of data infrastructure governance function. Following these themes, we first catalogued and mapped relationships of organisations involved in the climate data infrastructure value chain and conducted interviews with representatives of some of the mapped organisations in order to corroborate the literature research and obtain additional insights. We suggest viewing climate service infrastructure in the four dimensions of instrumentation, information, communication, and service infrastructures. We argue that success or failure of climate services will be determined, firstly, by the ability to view and practically embed users as integral partners in the co-construction of climate services rather than treating them as 'external factors' (cross-boundary reflexivity). Secondly, we argue that it will be crucial for the growth of the climate service market, and therefore wider societal resilience to pay more attention to communication and service infrastructures intersecting. This may take in multiple ways with instrumentation and information infrastructures (infrastructural reflexivity) in the sense of a "value network" (not simply a value chain) given all the fluidity of the service infrastructure.

Practical implications

(1) The "vast machine" (Edwards, 2010) of climate services requires an enormous effort to develop infrastructures that allow for the translation of climate intelligence into specific use contexts. The complexity of this task can only be understood properly when climate services are conceived of in their inherent complexity.

(2) In order to create an integrated perspective on climate service and climate service infrastructure, we suggest viewing climate services infrastructure as encompassing four dimensions, all combining social and material aspects, referring to technology, negotiation, and governance to different degrees:

a) Instrumentation Infrastructure: allows for the collection of all kinds of climate-related data. It includes (but is not limited to) weather stations, radar, buildings, projects and partnerships, equipment such as computing facilities and satellites, as well as the practices and personnel, and the organisational set-up and institutional framework around these.

b) Information Infrastructure: Information is data plus meaning and organisation–that which is needed for qualifying (refining, processing) data for climate-related and service-related use, the structure of storage as well as its preparation (curation) for dissemination. It is often linked with non-climate data, and is based also on social practices, personnel, and the organisational set-up and institutional framework around these.

c) Communication Infrastructure: addresses the entire machinery of channels where exchanges of climate-related ideas and information take place, which are not considered to be services.

d) Service Infrastructure: refers to the socio-technical machinery of channels where the provision of climate services takes place; including the users, as they bring their sets of ideas about why and how they would use climate services. It includes the institutional and organisational structures as well as personnel needed for the service activities, and the technology as well as into which service interaction is woven.

(3) Besides structures of codified information, infrastructure refers also to the systems of hardware, networks and software via which they are made available, as well as to 'e-infrastructure'. Making these available and usable to a wider range of users creates a challenge regarding costs, longevity,

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https://doi.org/10.1016/j.cliser.2020.100151
Received 11 July 2019; Received in revised form 6 January 2020; Accepted 14 January 2020
Available online 01 February 2020

potential future use and user inclusion, and design.

(4) We suggest to view instrumentation and information as being based on devices and socio-technological systems that assist in turning information and knowledge into readable 'text' (in the broadest sense), while the entire complex of measuring, recording/gathering, administrating/curating is itself a deeply social process relying on technical, organisational, and political achievements that only allow for carrying out this work.

(5) Engaging in service relationship means going through a mutual learning process. This can take place at various instances of service networks: in end use contexts, scientific or infrastructure development contexts, and so on; it can be in an institutionalised collaboratory or during moments of occasional situated practice.

1. Introduction

In a knowledge-intensive economy (Felt et al., 2007), service provision, firstly, is a question of knowledge which allows for interaction and new links between disconnected areas and actors, e.g., commercial and public, science and user practice (Hipp and Grupp, 2005; European Commission, 2015, 3; Nightingale et al., 2015, 11; Street, 2016, 3; Perrels et al., in this issue). Regarding climate services, types of knowledge include climate data and knowledge, the knowledge *of* users (about their climate-related issues and the organisational requirements to deal with them, as well about external aspects, as regulatory conditions or mandates) and the knowledge *about* users (their demands, working conditions, climate knowledges, policies, by providers), and knowledge of technologies, actors, successful and failing enactments of services, and markets (Vigar-Ellis et al., 2015; Reinecke, 2015). Secondly, the most crucial objects that form a service are the boundary objects (Star and Griesemer, 1989; Stegmaier 2009). These are objects that allow for encounter and exchange (services, tools, products, problems, information, etc.), especially, when there are many different actors that need to come together regarding complex issues such as climate data and managing climate change: "*Once artefacts and material networks are in place, they are not easily abandoned and acquire a logic of their own* […]" (Geels and Kemp, 2007: 443; Walker, 2000). Typical of climate services is that their boundary objects are reasonably bulky and require a lot of specialized knowledge. Thirdly, infrastructure is the material, instrumental, and organisational structure underlying any service. Practices need to develop that provide a sound basis for service interaction. Social relationships, reciprocal expectations, vested interests, and organisational commitments establish and stabilise systemic structures (Geels and Kemp, 2007). Ultimately, these interactions have a negotiation character and are leading to arrangements on which each follow-up service interaction can build. The way such arrangements take form can be described in terms of governance. In this article, we emphasise the infrastructure dimension of climate services in the light of the above-mentioned knowledge-, social relations- and object-related angles.

This paper focuses particularly on our approach to conceptualise climate services infrastructure from a process perspective (Hamaker et al., 2017). We frame the issue against the background of relevant literatures on climate services, service innovation, co-construction, and infrastructure. Moreover, users are seen as integral partners in the co-construction of climate services (Bremer et al., 2019; Vincent et al., 2018; NASA et al., 2016; Vaughan et al., 2016; Steynor et al., 2016; Dilling and Lemos, 2011; Oudshoorn and Pinch, 2003). It would be hard to imagine climate knowledge infrastructure not as spanning across the continuum reaching from providers of raw data to end users with all intermediate forms. Thus, it appears only logical to pay more attention to communication and service infrastructures intersecting in multiple ways with instrumentation and information infrastructures. This has consequences for the notions of 'service' and 'infrastructure' that we use in order to conceptualise climate services infrastructures. To be clear, this analysis is neither about any infrastructure, nor can it be reduced to the infrastructure notions known from construction, engineering, military, informatics, or economic development. We are focusing on the socio-technical nature of infrastructure for and by services, and as such in the context of providing, purveying, and using of climate services.

Service infrastructure is, besides relevant data and knowledge, the basis to provide any service at all. The understanding of infrastructure related to climate services is threefold:

(1) most often, infrastructure is addressed as an *object external to climate services* (as in buildings, agricultural, water, or energy infrastructure), for which climate services can offer strategic intelligence (cf. Bruno Soares et al., 2018; Ceglar et al., 2018; van den Hurk et al., 2018; Damm et al., 2018; Jacob and Solman, 2017; Lappegard Hauge et al., 2017).

(2) some address the *infrastructure needed for climate change adaptation* in terms of observational systems, climate models and portals, as well as economic and human resources (cf. Cavalier et al., 2017).

(3) There is an increasing attention for *infrastructure related directly to climate services* (cf. Buontempo et al., 2014; Bachelet et al., 2017; Giuliani et al., 2017; Street, 2016; Vaughan et al., 2016).

As it seems, the young science and practice of climate services is just about to develop a focus on climate service infrastructure (cf. CNR-ISTI, 2012). This is not surprising, as it may be seen more important to firstly outline the profile of climatological intelligence, its necessity as a means to realise climate policies, and societal ambition, and, secondly, explain the importance of climatological services, before questions of service infrastructure might become an issue of focus. We suggest that climate service infrastructure helps define what climate services are. The need for elaboration of a theoretical and empirical basis for climate services has already been acknowledged (cf. Climate Services Journal Editorial Brief, 2016).

There is a growing body of research and literature on infrastructures addressing their emergence, use, and evolution (Pollock and Williams, 2010; Hyysalo, 2010; MacKay et al., 2000; Williams et al., 2005). Our viewpoint is also inspired by the innovation studies literatures focusing on socio-technical systems (Geels, 2004, 2002; Geels and Kemp, 2007; Rip, 2012) and socio-technical regimes in particular (Rip and Kemp, 1998; Berkhout et al., 2004; Van de Poel, 2003; Geels, 2006; Nelson and Winter, 1982; Bijker, 1995; Unruh, 2000), which has also been looking into infrastructures (cf., e.g., Hoogma et al., 2002; Tushman and Anderson, 1986; Christensen, 1997). Vaughan et al. (2017) propose to determine enabling conditions for climate services in relation to innovation systems and not only in relation to value chains. Infrastructures, in this view, are of crucial importance for the stabilisation of systems, as are institutional arrangements, formal regulations, and adaptation of mundane practices.

In the following, after a methodological note, we will first elaborate on the notions of 'services' and 'infrastructures' and thereby emphasise their relational character (Section 2). This means they can be conceived as being subject to ongoing negotiations and ordering efforts between socio-technical, political, scientific, and producer-user aspects. Second, we explain climate services infrastructure as a communication machine (Section 3). Third, we report on the catalogued and mapped relationships of organisations involved in the climate data infrastructure value chain (Section 4). For this, we have conducted interviews with representatives of some of the mapped organisations in order to corroborate the literature research and obtain additional insights. Fourth, we discuss practical and policy implications of our key findings (Section 5). Finally, we conclude and provide an outlook on further research and governance needs (Section 6).

1.1. Methodological note

This paper is a further elaborated and focused reflection on climate services infrastructure, rooting in key parts of Deliverable (D) 1.3 'Analysis of existing data infrastructure for climate services' (Hamaker et al., 2017) of the EU-MACS project, in which we explored how the existing climate data infrastructure inhibits or stimulates the European climate services market. It is also informed by EU-MACS deliverables D1.4 'A multi-layer exploration on innovations for climate services markets' (Stegmaier and Visscher, 2017), D3.1 'Report on the results of explorations of climate service market development options for the tourism sector' (Damm et al., 2018) and D2.1 'Results of explorations of the climate services market for the financial sector' (Hamaker-Taylor et al., 2018). We followed an explorative approach to service and technology governance analysis (Yanow, 2000).

Firstly, empirical data was used. For D1.3, we carried out four intensive open interviews with experts from Centre for Environmental Data Analysis (CEDA), Joanneum Research, Barcelona Supercomputing Center and former Environment Agency of England and Wales; in the paper, we will refer to these directly. Two more sets of interviews are being used as background information not directly mentioned here: from D3.1, insights from 32 semi-structured interviews with tourism stakeholders and experts, as well as from one one-day workshop in Graz in September 2017 with 10 stakeholders; and from D2.1, insights from 65 semi-structured interviews are used, as well as from field observations at various public and corporate events with close connection climate service infrastructure issues.

Secondly, a database of climate services providers and users was compiled, cataloguing organisations ranging from observational data providers to downstream users. This was achieved by mapping actors to, for example, distinguish between entities who operate Earth observation (EO) satellites and/or weather stations (upstream climate services), and those who use satellite-based and other data for high-level complicated analyses or similar (e.g., forecasts, climate models) (downstream climate services). In addition, actors were mapped based on their influence on infrastructure in Europe. Mapping these actors elucidates the ways data is refined, allowing for further conclusions to be drawn out. Once initial findings were made, expert interviews were conducted to corroborate and fortify these findings.[1] While this catalogue and mapping exercise was not exhaustive, it allowed for useful insight into the broad range of actors present in climate services, their relationships, and highlighted how data is refined and processed along the value chain.

It was not possible to conduct an exhaustive characterization of the climate services data infrastructure as a whole, which is a limitation of the paper. The empirical data and the database remain the basis for a robust snapshot, though organizations may have been overlooked if, for example they have emerged as a provider since data was gathered in 2017–2018, or indeed if they are less well known. The review on the governance of data infrastructure is also not meant as an exhaustive stock-taking, but rather as explorative collection and first sorting of crucial issues identified in the expert interviews and from literature review, also meant to suggest a more processual angle on how service infrastructure is getting ordered than, e.g., a rather static lists of barriers and enablers would able to conceive.

[1] Throughout the research, expert interviews were conducted in order to corroborate preliminary findings and guide further research. When interview data is quoted, the following reference format is used: "(Int1-1; 160:3)". First, the anonymised name of the interview is given, then the number of the quotation that was coded in ATLAS.ti, a software package for managing qualitative data analysis.

2. Climate service infrastructure relations

Services and infrastructure in the context of climate service literature are usually addressed in the context of politics and governance (Wellstead et al., 2016; Golding et al., 2017; Bremer et al., 2019), highlighting the engagement for it as a logical, practical, and political consequence of the 2015 Paris Agreement (Swart, 2019; Cavalier et al., 2017), as a national and at the same time an increasingly international task, and as requiring a suitable and supportive regulatory framework (Cavalier et al., 2017; Pope et al., 2017) as well as support for building a community of people involved in climate services (Vincent et al., 2018). In terms of business, climate services require private and public investments and attention for both in sector-specific and cross-cutting ways (Cavalier et al., 2017; Hoa et al., 2018; Steininger et al., 2016; Street, 2016) and regarding the service value chain (WMO, 2014; Giuliani et al., 2017; Naab et al., 2019; Damm et al., in this issue). Emphasised is sometimes both the immaturity (Poessinouw, 2016) as well as the untapped potential (e.g., Golding et al., 2017; Vogel et al., 2017; Bremer et al., 2019) of climate services; although no signs of a gold rush have been detected as of yet. This means we are facing a highly heterogeneous and dynamic subject, a moving target that has many facets, with many more or less tentative efforts (Kuhlmann et al., 2019) to govern and manage it and to push and profit from it. We therefore presume that a notion of 'climate service infrastructure' that makes us simultaneously aware of fundamental properties, and is flexible enough to encompass diversity, would suit best for our analysis.

2.1. Services

Definitions of services are manifold, and there is hardly consensus. So, the service notion chosen here corresponds with typical features of climate services. When focusing on climate service infrastructure, it is useful to clarify what is meant with the notions that shape this composite term: 'climate service' and 'infrastructure'. The term 'climate services' is relatively new and as such has no set definition. Often, though, the European Commission's definition[2] is used (European Commission, 2015). Harjanne (2017: 1) suggests the climate services concept is ambiguous and offers a broader alternative to the Commission's definition, stating climate services can be defined as "*the production and delivery of climate-related information for any kind of decision making*". Similarly, but less broad, Vaughan et al. (2018: 373) define climate services as "*the production, translation, transfer, and use of climate knowledge and information in climate-informed decision-making and climate-smart policy and planning*". Referring to an official definition such as the Commission's does not exempt one from struggling to find a more suitable definition that has less normative implications alone through its mere political condition as being authoritatively coined by a suprastate body and being part of the EU climate governance (Stegmaier and Visscher, 2018). Parts of the EU framework are also rather disentangled from general environmental concerns (Stegmaier and Visscher, 2018). There is also neither 'user community in sight' (which would imply a rather coherent group of users), as suggested in the 2014 Advisory Group Report (European Commission, 2014), nor can we yet be certain how coordinated, coherent and pervasive the climate service building approach of the European Commission and the Member States to date is (Stegmaier and Visscher, 2018). We have discussed elsewhere several

[2] "For the scope of this document, we attribute to the term a broad meaning, which 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 the society at large. As such, these services include data, information and knowledge that support adaptation, mitigation and disaster risk management (DRM)." (European Commission, 2015: 12)

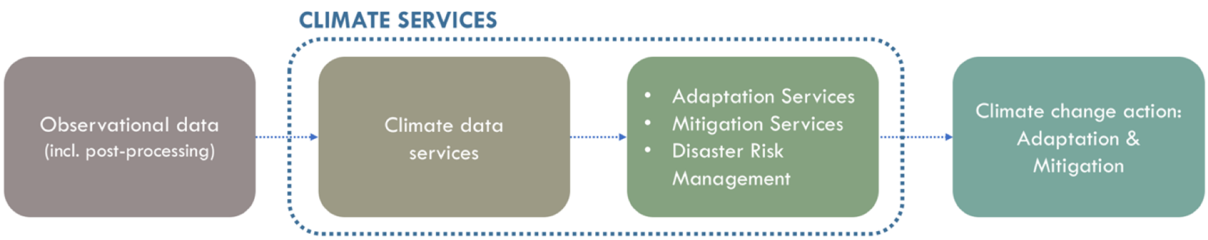

Fig. 1. Simplified climate services diagram based on European roadmap for climate services (Hamaker et al., 2017: 11).

different political- or business-led scenarios in which the EU would have a greater or lesser role in building and maintaining a system of climate services (Stegmaier and Perrels, 2019), as well as a typology of business models for climate service provision, underpinned by empirical findings from the EU Horizon 2020 funded EU-MACS project (Visscher et al., in this issue).

Climate services can be first conceptualised as a combination of climate data services, projections, forecasts, and climate models (Hamaker et al., 2017). Second, climate services include vulnerability and risk analyses, recommendations for climate change action, and more refined information, such as adaptation, mitigation and disaster risk management services. Fig. 1 illustrates how climate services includes these two main grouping of services (climate data services and adaptation etc. related services). The dotted line symbolises the fluidity of the climate services boundaries, driven by numerous technological, scientific and market-based forces.

Though the boundary around climate services is relatively fluid, services not based on data on climate variables (e.g., temperature or precipitation) are not considered climate services. Carbon footprinting, energy efficiency analyses, and logistics optimization, therefore, are not climate services, in our view.

Similarly, definitions for the term ‘climate data’ are ambiguous and still under debate. This often leads to misunderstandings, for instance, when the term ‘climate data’ is used colloquially connoting an array of different kinds of data, from observational data and climate data records to climate models and climate projections. Thus, ‘climate data’ is not a definite term. Rather, it is used for a spectrum of data products that somehow relate to climate (cf. Hamaker et al., 2017).

According to Troccoli (2018), climate services are not fundamentally different to other types of services even though they do have relatively high levels of risk with regards to the accuracy of their outputs. Thus, climate services are considered here through the lens of more general service literature as well. As such, service activities can be seen as ongoing negotiations, during which providers and users interact for tackling a service problem. Service providers supply services in a service relationship, which leads to tailored information—they establish a give-and-take-relationship (Gadrey, 2002). The service product or good can materialise in more than one situated activity; services can be things to be taken home (to a public or private body, or even by an individual citizen), refined or used, shared with others. The fit and the quality of a service rely substantially on whether there is anybody on the user side that can engage, for instance, in communication about climate data as well as on the kind of data the users need to link with climate data in order to aim at context-specific decision-making.

The market of ‘co-produced’ climate services is expected to grow and develop fastly in the near future, with many climate services being produced by the private sector for the private sector (Lourenço et al., 2016). As Alexander and Dessai (2019) note, service management and marketing literature put emphasis on service delivery and co-production as integral and intrinsic components. This also implies that the value of the service is not just determined by the quality of the output but rather the interactions between user and provider (i.e., communication), how users subjectively feel their expectations are being met, and the experience of consuming the service whereby users create value in-use (Alexander and Dessai, 2019).

From this point of view, the climate services infrastructure could ideally be conceived as a set-up to which users a priori belong, instead of being considered as ‘external factors’ to a closed system. If this view is shared, one can argue success or failure of climate services will depend on the ability to embed users as equal and integral partners in the co-construction of climate services—in direct collaboration on the development of services and on the basis of a mutual willingness to interact. Climate service customers may be seen as ‘outsiders’ in terms of climate expertise, but certainly not in terms of their specific interests and usages for climate data (cross-boundary reflexivity). Involving users seems a prerequisite of providing services that take users’ demands seriously; however, success is never guaranteed. Engaging in service relationship means going through a mutual learning process.

2.2. Infrastructure

Infrastructure often refers to the physical structures on which people, goods, and information travel. We are interested in a more complex understanding of climate services data infrastructure, the structures behind the collection of climate data, matching, its storage, distribution, refinement into further products, further distribution, and processing. Edwards (2010) termed this complex as the ‘climate knowledge infrastructure’. We will emphasise the negotiation character of these activities (cf. Kuhlmann et al., 2019). The provision of climate services relies on an infrastructure as an underlying foundation and framework, while the infrastructure itself is subject to construction, maintenance and further development in exchange with the various different users. It is not yet clear what an infrastructure and service innovation climate services will develop (cf. Van den Ven, 1999).

In climate data practice, information and communication technologies are omnipresent. Codes and algorithms affect the knowledge and directionality of innovation. In many ways, technology affects and changes the ways how such systems as services and infrastructures are governed (cf. Dolata, 2013). At the same time, policies and governance approaches are literally inscribed into software, hardware, and climate data technology: *“[…] code, protocols, software, and algorithms are not only technologies to be governed but also full-blown governance actors enacting regimes of inclusion/exclusion from innovation processes”* (Pelizza and Kuhlmann, 2017: 3). What occurs in crisis or rupture—for instance, when a services infrastructure does not (yet) run smoothly or a service market is under development and far from maturation—is *description*, the opposite of inscription: the inscribed rules and other patterns become visible and even negotiable (Pelizza and Kuhlmann, 2017: 8). *Interoperability* is constitutive for any infrastructure, facilitating inter-organisational relationships (Pelizza, 2016: 307). The *building and maintaining* of it entails institutional reordering (Pelizza, 2016: 305). What a national meteorological office, a supercomputing centre, or a city environmental office does and means for collaboration partners, is closely connected to the data conventions, ports, depository policies, software codes, firewalls, ethics schemes, business models, etc. that characterise their operations. It appears only fair to ask whether climate services would wish to consider who should take part (or not) in this process, and how.

In this understanding, infrastructure is constantly being created in interaction among those giving and taking services, and thus more than a structure upon which services operate that is obsolete once built. It emerges in connection with organised practices. From a practical point of view, climate services knowledge infrastructure is "*something that emerges for people in practice, connected to activities and structures*" (Star and Ruhleder, 1996: 112). It includes technical and business-related, as well as social and material, scientific and governance dimensions on which climate services travel. Tasks like processing or visualization of data may be interwoven with more than one dimension, correlative to whether the aim is to build a meaningful corpus of data (information dimension) or rather to exchange within the climate research and services community (communication). The mentioned tasks may even address both. Besides structures of codified information, the infrastructure concept refers "*qua information also to the hardware, networks and software systems via which they are increasingly stored and accessed*" (Pollock and Williams, 2010: 522), as well as to so-called 'e-infrastructure' (Edwards et al., 2007, 2009; Hine, 2006). Making these available and usable to a wider range of users creates a challenge regarding costs, longevity, potential future use and user inclusion, and design.

3. Infrastructure as a communication machine

3.1. Established and evolving instrumentation and information dimensions of climate services infrastructure

'Climate knowledge infrastructure', is used by Edwards (2010) to mean the "*many interlocking technical systems*" around the collection and assembly of observations and models of physical systems, which are used to collect knowledge about the climate. He refers to the infrastructure which collects land, sea, air, and space observations and models atmosphere and ocean systems as a 'vast machine' that is now nearly complete. Edwards explains that the current climate data and knowledge infrastructure was built on existing weather information systems and has undergone many "*rounds of revision*" (Edwards, 2010: 432). Climate data and information infrastructure, however, has been the subject of much more scrutiny than weather infrastructure, as its data and components have been debated much more than weather information (Edwards, 2010: 431–432).

Despite this scrutiny, the climate data infrastructure has continued to grow and now includes much more than a collection of historical data (Overpeck et al., 2010). The 'vast machine', for example, includes model-based reanalyses which assimilates vast amounts of observed data into physically-based climate models. Other important advancements include sophisticated coordination efforts between climate data and modelling communities. The Coupled Model Intercomparison Project (CMIP) brings together climate modelling groups from across the world to promote a standard set of climate model simulations. Similarly, the US-based Earth System Grid Federation catalogues and publishes climate data to make it useable for the international community (Williams et al., 2009), by including metadata and security standards, data transport, aggregation, sub-setting, and monitoring of system and services usage. The European Network for Earth System Modelling (ENES) and Programme for Integrated Earth System Modelling (PRISM) are European examples (ENES, 2011).

The vast climate data machine (Edwards, 2010) is now amassing vast quantities of data: phase six of the CMIP to be between 20 and 40 petabytes resulted in 36 terabytes of model data alone (Eyring et al., 2016). Overpeck et al. (2010: 702) summarize the key issue with ever-increasing quantities of data, in stating that the question of "*how to actually look at and use the data, all the while understanding uncertainties*" persists. Additionally, there are other fundamental challenges to maintaining the actual physical infrastructure (or instrumentation infrastructure) that provides and processes climate data. Bojinski et al. (2014) point out that meeting certain standards also implies continuous "investments in instrumentation and in the generation, validation, and intercomparison of datasets". Existing instrumentation does not just need maintenance but will need (or already needs) upgrading to meet increasing demands for accuracy. Furthermore, it should be noted that in large parts of the world instrumentation infrastructure for recording and archiving climate data in order to deliver climate services remains fragile and incomplete (Bojinski et al., 2014). This is also linked to the fact that many developing and emerging countries lack strong national weather services which lead to incomplete observational records, lack of trained staff, and insufficient computing power to run climate simulations (Brasseur and Gallardo, 2016).

So, while it is safe to say the instrumentation and information dimensions of the climate services data infrastructure are sophisticated and mature in some regions more than others, the communication and services infrastructures are still under development, as evidenced by the following section.

3.2. Developing communication dimensions of climate service infrastructure

The Royal Netherlands Meteorological Institute (KNMI) called for the need for the development of tools aimed at decision-makers, which would better inform them about climate change, as early as 2005, having started building such tools as their Climate Explorer in 1999 (Van der Wel, 2005). In those early days, data policies around various datasets hindered the development of climate-related tools (Van der Wel, 2005). By calling for these tools, which use large amounts of spatio-temporal data, KNMI was one of the first organizations to foster the development of the communication dimension of the climate services knowledge infrastructure (see discussion of dimensions in Section 1.4). Their call for the further development of 'tools' has likely contributed to a plethora of upstream portals now present in the climate services market in Europe, rather than other downstream products and services such as guidance and processed forms of raw data.

Web-based climate data portals, or more upstream climate services, have been portrayed in the literature as effective means for communication of large and complex datasets. When discussing the Earth System Grid, Williams et al. (2009), a web-based portal was proposed as an ideal solution to address the needs to assemble, analyse, archive, and access climate modelling datasets, for example.

A more recent investigation into the ways in which the U.S. government can improve the usability of its climate data has found, however, that the communication dimension of the climate services infrastructure is progressing beyond upstream portals. The study found that neither data sets nor portals per se are enough, and instead, accompanying aides, manuals, assessing tools, personal support are needed alongside the data (NASA et al., 2016).

In the European context, a study around various aspects of the European Commission's flagship Earth observation programme, Copernicus, highlighted the need for the further development of the communication infrastructure. Key barriers for user uptake of climate data include lack of user-friendliness of data and information, as well as the fragmented nature of Copernicus portals—Copernicus portals are not centralised and are dispersed over several websites. The study also finds the various Copernicus websites lack content which reflects the knowledge levels of users and provide a limited amount of information for private sector stakeholders (European Commission, 2016a). Various solutions could include a Data Access Information Kit for potential users, as well as open data discovery functions on the data portals (European Commission, 2016a).

A further study echoes the findings of the American and European studies, in that it highlights the fact that there is a strong need to bridge the valley of death between climate service providers and users; that is, providers should work toward co-designing and co-generating climate services alongside users (Buontempo et al. 2014).

Together these studies indicate that while the communication dimensions of the climate service infrastructure has developed rapidly since the first call for climate data 'tools', important work is still underway to evolve this infrastructure to allow for more effective communication of climate data and information, i.e. work which has the user perspective as the starting point rather than an afterthought. Copernicus has launched a Europe-wide training program, which aims in particular to improve access to data usage for users who are even less fluent with this data.[3]

3.3. Heuristic framework

In the light of the hitherto reflections on 'service' and 'infrastructure', we suggest viewing climate services infrastructure as encompassing four dimensions (Hamaker et al., 2017: 57–60), all combining social and material aspects, referring to technology, negotiation, and service relations to different degrees:

Instrumentation Infrastructure (Inst-I): allows for the collection of all kinds of climate-related data. It includes (but is not limited to) weather stations, radar, buildings, projects and partnerships, equipment such as computing facilities and satellites, as well as the practices and personnel, and the organisational set-up and institutional framework around these.

Information Infrastructure (Inf-I): Information is data plus meaning and organisation—that which is needed for qualifying (refining, processing) data for climate-related and service-related use, the structure of storage as well as its preparation (curation) for dissemination. It is often linked with non-climate data, and is based also on social practices, personnel, and the organisational set-up and institutional framework around these.

Communication Infrastructure (Com-I): addresses the entire machinery of channels where exchanges of climate-related ideas and information take place, which are not considered to be services. Before any service is given, the collectors and processors of data and information need to be in meaningful exchange about data and information (share all this or first of all exchange ideas about what could be worth sharing or using for particular purposes; conventions and other shared rules of use are negotiated by communication). The fora, platforms, arenas where personnel work in and are interested in, relating to climate data and information; including the institutional and organisational structures as well as personnel needed for the service activities.

Service Infrastructure (Serv-I): This refers to the socio-technical machinery of channels where the provision of climate services takes place; including the users (clients, customers, business partners), as they bring their sets of ideas about why and how they would use climate services (either in mere reaction to which services are offered or in an attempt at co-production); including the institutional and organisational structures as well as personnel needed for the service activities, and the technology into which service interaction is woven. This infrastructure is the most complex dimension as it relies on, and intersects with, the other three dimensions entirely, but add another level of knowledge, practice and quality.

This approach to climate service infrastructure integrates the social and material aspects of 'doing climate services'. We suggest to view instrumentation and information as being based on devices and socio-technological systems that assist in turning information and knowledge into readable 'text' (in the broadest sense), while the entire complex of measuring, recording/gathering, administrating/curating is itself a deeply social process relying on technical, organisational, and political achievements that only allow for carrying out this work. This includes contracts, commissions to build apparatuses and databases, conventions for data and collaborating on instruments and data, as well as for distributing and using results of this work. Since the area of climatology and all the intersecting areas have grown increasingly complex, communication is no longer just a side-aspect of science or service, but a central task. Since an entire service world is being built and actually in use, the infrastructure underlying these service and use relationships has also become a task of its own right, especially as the service relations have diversified enormously (cf. the many climate service areas mentioned in Alexander et al., 2017). The order of this socio-technical world (cf. Strauss, 1993; Strübing, 2005) is subject to ongoing governance or "processual ordering" (Strauss, 1993: 254–255).

This resonates with the five pillars of the World Meteorological Organization (WMO)'s Global Framework for Climate Services (GFCS)[4] that comprise (1) a user interface platform, (2) climate service information system, (3) observation and monitoring, (4) research, modelling, prediction, (5) capacity development (Vaughan et al., 2016). Instead of generalising one particular structure, as the WMO's we suggest thinking in terms of a smaller, more cross-cutting, and integrative framework (Hamaker et al., 2017) that can capture the main features of what doing climate services entails. We would also point at the interactional aspect of services going far beyond thinking in terms of information systems and platforms, although this framework provides numerous important pointers. GFCS is speaking of countries' capacities, which is at a very general level, because at the end of the day it is about specific people in specific organisations that need to develop know how about how to use climate services. We emphasise the practice level, while in the annex of the GFCS more the policy framework is addressed. Both perspectives complement each other.

4. Mapping climate service providers and users

Climate data and knowledge are an integral part of the climate services infrastructure, thus, we included a mapping of climate services providers who are primarily responsible for processing relevant data by applying their specialist knowledge to it. Since data forms the evidence base of climate services, the considerations in this section as most of this paper, focus mainly on the upstream segments of the value chain. In this section, we portray the climate services map from a European standpoint and with regards to value chain and market.

Climate data is gradually processed from being recorded (upstream) to producing reports or analyses that feed into private-sector adaptation strategies, the national adaptation plans (NAPs), of governments, and a wide array of climate-action-related decisions (downstream). Most actors identified during the research do not fit neatly into one of the segments of the climate services value chain as seen in Fig. 1. Often, they cover more than one of the steps in the data refinement process leading to the blurred nature of the climate services value chain and its components.

Fig. 2 shows a simplified mapping of data providers and users with a sample of organisations and actors present in the climate services value chain, helping illustrate the fluidity of the service infrastructure. Table 1 indicates climate services products typically associated with each of the four main boxes shown in Fig. 2.

The categories of infrastructure that we propose in the heuristic framework roughly map on to Fig. 2. Upstream observational data is collected by the instrumentation element of the infrastructure (*Inst-I*) and little manipulation or interpretation of it occur to produce climate services products such as datasets. The other areas of the climate services map presented in Fig. 2 relate to the information infrastructure *(Inf-I)* as well as the communication *(Com-I)* and service *(Serv-I)* infrastructures as the raw (upstream) datasets get translated, interpreted, communicated, and indeed provided in order to aide decision-making relating to climate and its changes.

4.1. The upstream segments of the climate services value chain

4.1.1. Observational data

Observational data from space-based and in situ instruments can

[3] Cf. https://climate.copernicus.eu/user-learning-services.

[4] https://gfcs.wmo.int/components-of-gfcs.

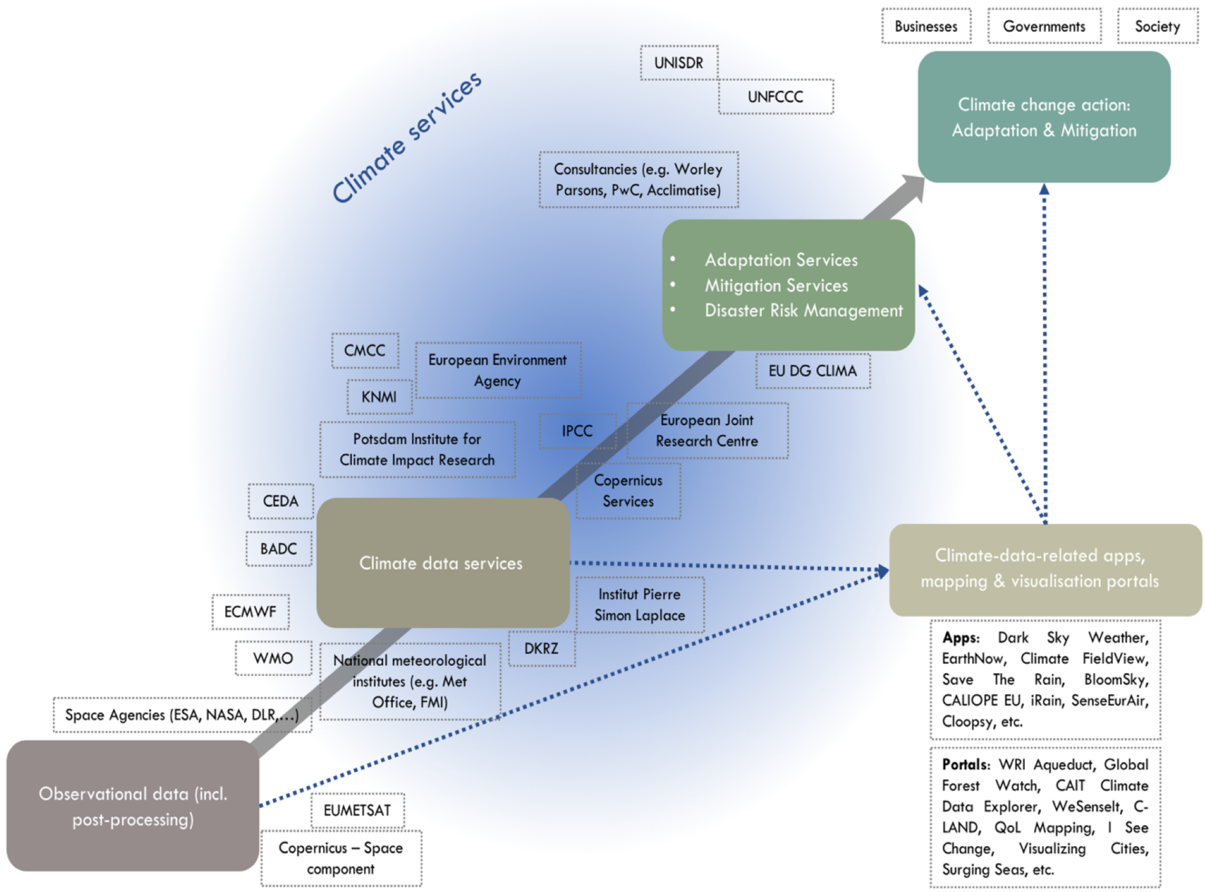

Fig. 2. Exemplary map of climate service actors (Hamaker et al., 2017: 21).

Table 1
Examples of climate service products in each step of the supply/value chain (Hamaker et al., 2017: 22).

Observational data (satellite & in-situ based)	Climate data services	Adaptation & mitigation services, disaster risk management	Climate action
Satellite imagery, atmospheric measurements, precipitation, temperature, humidity, …	Climate data records, climate models and projections, seasonal/medium range forecasting regional downscaling, mapping and analysis tools, portals for accessing and processing climate data, …	Climate risk assessments, vulnerability assessments, synergies with disaster risk planning and relevant mitigation efforts, …	National Adaptation Plans (NAP), specific adaptation action, resilience building, renewable energy investments, …
Inst-I. Inf-I	Inf-I, Com-I, Serv-I	Inf-I, Com-I, Serv-I	Inf-I, Com-I, Serv-I

either be used and provided separately or combined to produce climate data records. Instruments mounted on satellites provide complete spatial coverage of various parameters but can be less accurate recording certain ground conditions, like precipitation (Sun et al., 2018). Combinations of data from both in-situ and space-based instruments are, thus, important for comprehensive climate data records. This is also evident in, e.g., the Copernicus Programme which puts an enormous emphasis on its satellites, but also uses data from in-situ instruments.

Observational data are most commonly processed by the space agencies operating Earth Observation (EO) satellites and the meteorological institutes who run weather stations and participate in satellite missions. However, following the processing of data is a challenge even at these early stages because a lot of satellite and, sometimes, weather-station data can be acquired with very low or no levels of processing applied to it, open and free from, e.g., European Space Agency (ESA), National Aeronautics and Space Administration (NASA), NASA's National Centers for Environmental Information (NCEI), and Copernicus.

4.1.2. *Climate data*

The 'climate data services' segment of Fig. 2 refers to activities mainly focussed on climate modelling, climate projections, and forecasting. These are highly specialised and typically undertaken by research-orientated organisations, many of which are also represented in the earlier segment of 'Observational data (including post-processing)', e.g., NASA. In addition to staff with a very specialised skill set and education, climate modelling requires significant computing power, which is in itself an entry barrier into the provision of this type of climate service (cf. sections 3.2 and 3.3 below).

In Europe, Earth System Grid Federation (ESGF) members like the British Atmospheric Data Centre (BADC), Centro Euro-Mediterraneo per I Cambiamenti Climatici (CMCC), German Climate Computing Centre (DKRZ – Deutsches Klimarechenzentrum), and Institut Pierre Simon Laplace (IPSL) are some of the well-known organisations that manage and analyse climate data. Others include Barcelona Supercomputing Center (BSC), the University of East Anglia Climate Research Unit (CRU), Potsdam Institute for Climate Impact Research (PIK) and meteorological institutes such as the Royal Netherlands Meteorological Institute (KNMI), or the Finnish Meteorological Institute (FMI).

4.1.3. Climate-data-related applications and visualisation portals

As can be seen in Fig. 2, a large number of mobile and web-based applications that use observational data and/or satellite climate data have been and are being developed. Often the root data sources behind these applications, e.g., free an open climate data, cannot be easily identified, but it is reasonable to assume that small companies and start-ups often use free and open climate data, and profit from it. Many portals and apps, however, are developed by the data providers themselves (cf. Visscher et al., in this issue).

The purposes of apps that use climate data vary widely. Some operate as simple data visualization tools, e.g. NASA's EarthNow offering "visualizations of near-real-time global climate data from NASA's fleet of Earth science satellites" (NASA, 2012). Others have more specific functions, for example, Future Everything's and Barcelona Supercomputing Center's app Ukko was developed as part of the European research project EUPORIAS (EUPORIAS, 2019; Project UKKO, n.d.) and offers an interactive interface for the wind industry to explore probabilistic wind speed predictions.

While these apps and tools (cf. Visscher et al., in this issue) can be used free of charge, businesses are also developing commercial climate-data-related apps and tools. For example, the Dutch company Miramap offers an app called Droughtscan in which users can map underground soil moisture variations derived from satellite data (Miramap, 2019). Another example is Acclimatise's Aware for Projects™ which uses post-processed climate model outputs, observed natural hazard data, and data about current and future water scarcity. Aware™ is an online climate risk screening tool used by development finance institutions and other finance actors during the early stages of project and infrastructure investments (Acclimatise, 2019). This is a fast-moving market, with commercial apps and tools, including dashboards, likely reaching the hundreds; these are only but a few examples.

4.2. Considerations regarding the development, access, and uptake of climate services

In the actor mapping and analysis, several themes stood out as being instrumental to the understanding, development, access, and uptake of climate services. This includes the refinement of data within the climate services value chain, e.g., from relatively unprocessed data to an app, but also offering climate services to users and customers outside the value chain. The following should be considered for a successful co-construction of climate services. This implies an extra effort in cross-boundary reflexivity (cf. Stegmaier, 2009): thinking beyond the confines of one's own expertise and understanding of what climate services are.

4.2.1. Value chain boundaries are fluid

The boundaries of the climate data service value chain are fluid. Climate service actors, especially further upstream, do not exclusively stay in one segment of the infrastructure. Rather, they often also provide more refined services and products through additional processing and interpretational analysis, which Visscher et al. (in this issue) call 'Climate-inclusive Consulting'. Researchers and personnel move between these clusters of activity; as indicated by experts consulted for this research, they also have worked in various clusters shown in Fig. 2 throughout their careers (also cf. Vincent et al., 2018). Recognising this fluidity is crucial to understanding the climate services value chain and also presents an opportunity for increased knowledge exchange. In this respect, one might rather think of a value network than a value chain.

4.2.2. Open and free access to data: funding and tracking

There are different sources of open and free observational and climate data. In Europe this includes the Copernicus Climate Change Service (C3S) or services like the KNMI Climate Change Atlas. The requirement to purchase data likely limits its use due to economic barriers (Borowitz, 2018; European Commission, 2016b), so being able to access it free of charge can provide an incentive to develop new climate services, especially to smaller businesses with less capital.

Free and open data can also lead to tensions within the climate services sector. Having major actors like C3S offering a large range of free and open climate data is likely to felt by others who might provide similar data at a cost. At the same time, the issue of funding free and open data networks also remains. As pointed out in Section 1.2, the instrumentation alone is expensive and requires constant maintenance. Continual funding of this infrastructure will require at the very least strong political will (e.g., funding for Copernicus needs approval from the European Parliament), and could, at some point, involve cost recovery (Int 1-3; 163:101).

Furthermore, tracking how open and free data is processed can be difficult unless some type of registration process exists. US data archive center, NCEI, explained that until recently, it was not able to track which sector their users came from and the reasons users accessed NCEI data. Tracking users, however, has improved NCEI's understanding of which sectors use the data, what products they prefer, and, consequently, how best to meet their needs (NOAA's NCEI, 2016). So, while time consuming registration processes with very detailed questions can put potential users off at first, they also allow the data provider to paint a more accurate picture of the user base and thus cater to it more effectively, leading to a better service for users. Blockchain, as a means of governance by technology, may be an option going forward (cf. Stegmaier and Visscher, 2017: 34–35; UNFCCC, 2017).

4.2.3. Portal proliferation

A frequent means of data dissemination is via web-based portals, indicated in Fig. 2. The strong reliance on portals is what one expert termed as 'portal proliferation' (Int 1-3; 163:3). The logic behind these portals is often based on a simple conclusion: if an organisation collects large amounts of data, a portal allows users to access the data they need at their convenience. As a basic principle this makes a lot of sense, but the practicalities of well-functioning portals are often underestimated.

One commonly observed aspect of many, though certainly not all, existing portals is that prospective users are rarely consulted, leaving their actual needs to be assumed. Portals are of particular concern to the uptake of climate services since they are crucial boundary objects of encounter and exchange. Thus, genuinely co-constructing them with prospective users is key to their success. On the other hand, this also means that successful portals are tailored to specific audiences and that there is no 'one size fits all' approach. There is still much to be achieved in developing user-segment-specific data portals, but at the same time we might see increasingly diminishing returns in the value of launching more 'general' climate data portals.[5]

4.2.4. Businesses are increasingly using data to develop products

While climate data is still predominantly used by universities and research facilities, there is an increasing number of private businesses using climate data to develop products for profit. This is likely connected to a shift toward more user-driven and tailored services that may require industry-specific knowledge and networks. It is possible that this development is connected to recent developments such as the release of the final recommendations of the Financial Stability Board's Task Force for Climate-related Financial Disclosures (TCFD). The TCFD is an industry-led initiative, involving large corporate and financial institutions. Its recommendations present a voluntary climate risk analysis and disclosure framework for any type of organisation to follow. The TCFD recommendations have sparked a widespread interest in climate risks in the finance sector, among others, helping evolve the perception of climate risks as ethical concerns to financial concerns—therefore warranting investment in tools and capacities to

[5] For a more detailed discussion of this issue, refer to the explorative usability survey on climate data portals in Hamaker et al. (2017).

manage them. As finance actors are increasingly aware of climate risks as financial risks, they cause further awareness and action in the wider economy, by engaging with their counterparties (those they lend to and invest in) on the management of their own climate risks in their operations and supply chains. Simply put, the private sector, are awakening to climate change as a notable financial threat and are now increasingly interested and willing to pay for commercial climate services. Climate-specific consultancies, and the service sector more widely, has taken note and are rapidly responding with new offerings.

Finally, the rise of phone and tablet technologies has opened a whole new realm of opportunities where developers can, easier than ever before, put a new product in front of a large audience. This new paradigm is shaping many markets, including that of climate services.

4.2.5. Standards for supporting infrastructure

Data with low levels of processing has also been noted by experts to often have resolution or formatting issues (see section 3.3 below). In the UK, for example, obtaining data for a certain variable in a certain location may require the download of all files for that variable for the whole of the UK for that time period (Int 1-3; 163:12). There are, however, efforts like the climate4impact portal which provide search filters for a more user-friendly data retrieval experience.

As a further example, the Global Historical Climatology Network (GHCN) works to integrate and standardise climate summaries from surface stations from data 100+ years old into contemporary data formats. The Infrastructure for Spatial Information in Europe (INSPIRE) Directive in Europe addresses 34 spatial data themes needed for environmental applications and allows for sharing of environmental spatial information to the public and between organisations. With regards to climate data stemming from model output, linking and matching is completed by organisations such as ESGF and European Network for Earth System Modelling.

Despite such efforts, data formatting is not yet completely standardised within data storage, despite concerted efforts toward this, slowing the ease of moving and storing data at times (Int 1-1; 160:31, 38), for example. Data storage is an area of the instrumentation infrastructure that interlinks with all areas of climate services, and important standardisation problems relating to data storage remain unsolved. This also includes the underfunding of data managers or gatekeepers who could help avoid formatting issues. The lack of standards in this area could be hindering the uptake of the climate services market in Europe simply by slowing data dissemination (cf. Vollebergh and van der Werf, 2014).

5. The climate services knowledge infrastructure: practical and policy implications

The arguments developed so far have practical and policy implications for the further evolution of climate service knowledge infrastructure. We suggest perceiving of climate service knowledge infrastructure in terms of the four dimensions 'instrumentation infrastructure', 'information infrastructure', 'communication infrastructure' and 'service infrastructure'. In combination, these form the array of structures upon which climate services operate and which need to be integrated for a service to operate. Practically, common data formats and conventions for data records and exchange could boost services and the popularisation of climate data use. A standardisation and quality assurance institution as from all sides accepted intermediary could help institutionalise better interoperability and a common sense for shared rules. Obviously, this is at the same time a complex governance task, given the existing heterogeneity alone within Europe, and a policy task for negotiating and defining viable options how, e.g., the EU and separate countries could foster an infrastructure that fits together and evolves with the technologies and sciences, politics and institutional arrangements: meaning an *infrastructure that is capable of learning*. For climate service infrastructure governance, this implies a meta-governance—a governance framework for infrastructure self-governance (cf. Jessop, 2011)—that is learning, too.

Engaging in a service relationship means going through a mutual learning process. This can take place at various instances of service networks: in end use contexts, scientific or infrastructure development contexts, in exchange with brokers of climate intelligence, and so on; it can be in an institutionalised collaboratory[6] or during moments of occasional situated practice in which climate service is created or used in some way or another. The idea of world regions in which the necessary resources and infrastructures are not available shows how enormous the task of developing a knowledge infrastructure for climate services actually is. In addition to service innovation, policies need to be developed that allow such regions to be reasonably involved by sharing services with them. Climate change doesn't stop at borders, so why should climate services and their use?

While it makes sense that free and open climate data is made accessible through a portal, it needs to be flanked by (ideally personal) support and tutorials that enhances inclusivity of a broader user base. Portals need to increase user experience to maximise impact. Freely available data, when not combined with appropriate levels of support, can be problematic. Finding aides (e.g., effective search functions and clear navigation) already pre-structured for typical users (e.g., already/not yet interested, types of problems climate services can tackle/problem types beyond climate services), offered with real human interactive support, could make the difference for successfully establishing and maintaining data provider/user relationships. Well-developed boundary objects for service could offer the potential to converge disparate knowledges and interest, positions and conventions. There are numerous items that may enhance cooperation across the boundary of climate sciences into other domains (e.g., the boundary between the practices of climate science and law), for example use cases that show the value of climate services (i.e., the business value) to users operating in other, non-climate services, sectors (e.g., aviation or road engineering). Such boundary objects may be existing, but purposefully and strategically used it could be a challenge for smart innovation that allow for collaboration with users and among the many stakeholders along the value chain (or in the value network) from the outset.

In these ways, service infrastructure could emancipate from technical-technocratic restrictions of specialists' mono-disciplinary views into a 'knowledge infrastructure' (Edwards, 2010) with greater usability and real-world application value across different sectors (e.g., use of data by the mining sector), but also specific enough for particular sectors. Translating climate data and information into other fields of practice and expertise (e.g., finance, insurance, agriculture, energy production, urban planning and housing) is such a complex endeavour that it could be too late to start with use orientation only at service infrastructure level; the other dimensions will have to anticipate this outward orientation instead of naval gazing. This implies the shaping of a practice-oriented meta-service: service in form of infrastructure provision, service for service providers, and finding/using aides for climate services themselves—a systematic effort to build a portfolio of means for communicating and translating climate intelligence into services.

All in all, it could be risky reducing the building of a services market infrastructure to efficiency and cost effectiveness, linear supply chain logics and processes of engineering and procurement. Rather, "*digital infrastructure requires understanding the relationships between the technological and social elements of such systems*" (Barns et al., 2017, 21). We suggest thinking of such a service infrastructure as a *reflexive* one—-being able to scrutinise own practice and structures, to learn, and to work for the convergence of perspectives among providers, purveyors,

[6] https://web.archive.org/web/20120806205400/https://adapt.nd.edu/, http://sts.hks.harvard.edu/research/biosocietycollaboratory, https://researcher.watson.ibm.com/researcher/view_group.php?id=4023, www.ncbi.nlm.nih.gov/books/NBK44967/.

and users.

6. Conclusion and outlook

In this paper we have linked climate service scholarship with science, technology and innovation studies. This nexus allowed us to feature a variety of aspects along the service journey as an innovation journey that sees infrastructure as an ongoing process of ordering. The ordering is no purpose in itself. The more complex the service and its foundations, the smarter the infrastructure must be. Smart means using the wealth of novel technological and business possibilities while embedding the wisdom of the practitioners who provide services everyday: a service infrastructure that does not just serve itself.

We argue success or failure of climate services will be determined, firstly, by the ability to view and practically embed users as integral partners in the co-construction of climate services rather than treating them as 'external factors' (cross-boundary reflexivity). Secondly, it will be crucial to pay more attention to communication and service infrastructures intersecting in multiple ways with instrumentation and information infrastructures (infrastructural reflexivity). The notion 'reflexivity' is used here not only in terms of thinking, but also in other forms of relating things and actors to each other: reflecting different properties and qualities of services and data, usages and context. It has to do with dialogue as talking about climate data in nested service relationships with different depths of climatological and contextual knowledge.

The usability of more downstream climate services interfaces could be studied in follow-up research. Moreover, since websites hosting climate models and output, for example, were too complex to navigate for a novice user—which was the intended frame of reference, it was not possible to survey every type of data portal. Doing this could make for another area of interesting research and assessment, especially given the expected growth trajectory of climate model datasets and analysis (Overpeck et al., 2011).

From a governance point of view, we suggest investing resources in further reflection what all this means in the broader context. Such has been outlined in terms of three governance scenarios (Stegmaier and Perrels, 2019), called 'state-centred', 'business-centred', and 'network-centred'. While the *state-centred-scenario* assumes climate service innovation and fostering would be driven by equity and safety concerns, aiming to ensure sufficient resilience across society, in all regions to the extent needed and deemed affordable with strong public intervention, the *business-centred scenario* presumes the creativity of free markets, and public climate services would largely be limited to basic data, services meant for citizens, and climate change scenarios. Almost a hybrid of both, but actually rather taking public and private as integral elements of a greater arrangement, the *network-centred scenario* roots in the observation that adaptation and resilience often require a strong role for the regional and local levels and benefit from bottom-up initiatives, actually giving local actors (citizens, civic groupings, companies, regional collaborations, etc.) a central role, even though facilitated by broader public (instrumentation) or corporate facilities (big data companies, software, and web applications) and/or support.

All three governance approaches can be found in the different EU Member States. Policy mixes tuned to the governance approaches will have considerable influence on how climate service infrastructure is (being) shaped. A 'state-centred' infrastructure may rather align with needs assessments of public authorities, use (or depend on) impulses from legislation, and base client-provider relations on procedural rules and administrative handbook quality definitions, while a 'business-centred' infrastructure may be seeking market opportunities, develop corporate soft law and align quality assurance with profit considerations first and foremostly. The 'network-centred' infrastructure may use combinations from both approaches, but with a stronger orientation towards local/regional stakeholder and citizen involvement leading to a welfare and well-being orientation that has neither the state nor the business as main beneficiary in mind. The latter may, for instance, see a climate service infrastructure that needs docking points for citizen and broadly distributed small and medium scale organised efforts to provide or use climate data and services. Climate concerns everyone. Linking all kinds of citizens into climate services (be it more in terms of citizen science and political citizen participation), can mean to be in a situation where budget, organisational, and infrastructural means are not available in the same (professionalised) way as when business or public bodies are involved. This is especially true, since the latter are themselves often struggling with adapting to complex climate intelligence related capabilities and capacities. Creative payment and crowdsourcing schemes as well as grant programmes/tenders may need to be developed to enable smaller and less organised groups of climate service users to participate. When depending on high costs and high levels of training, broadening or eventually democratising climate services may not reach a broader network beyond the "usual suspects" from business and public hand. Participation, e.g., at (city) district level may also lead to new forms of organising and of tendering resources for users less equipped with financial resources and knowledge. Unheard developments might occur.

CRediT authorship contribution statement

Peter Stegmaier: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Project administration, Funding acquisition. **Robin Hamaker-Taylor:** Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing - original draft, Writing - review & editing, Project administration. **Elisa Jiménez Alonso:** Formal analysis, Investigation, Data curation, Writing - review & editing, Project administration.

Declaration of Competing Interest

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

Acknowledgments

This research is based on the EU-MACS project that has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grants agreements No. 730500. We are also grateful for the constructive comments of two reviewers.

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