Climateurope2

Literature based guiding principles for high-quality Climate Services

Deliverable D4.1

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Table of Contents

List of tables

List of figures

About Climateurope2

Timely delivery and effective use of climate information is fundamental for a green recovery and a resilient, climate-neutral Europe, in response to climate change and variability. **Climate services address this through the provision of climate information for use in decision-making to manage risks and realise opportunities.**

The market and need for climate information have seen impressive progress in recent years and are expected to grow in the foreseeable future. However, the communities involved in the development and provision of climate services are often unaware of each other and lack interdisciplinary and transdisciplinary knowledge. In addition, quality assurance, relevant standards, and other forms of assurance (such as guidelines, and good practices) for climate services are lagging behind. These are needed to ensure the saliency, credibility, legitimacy, and authoritativeness of climate services, and build two-way trust between supply and demand.

Climateurope2 aims to develop future equitable and quality-assured climate services to all sectors of society by

- Developing standardisation procedures for climate services
- Supporting an equitable European climate services community
- Enhancing the uptake of quality-assured climate services to support adaptation and mitigation to climate change and variability

The project **will identify the support and standardisation needs of climate services, including criteria for certification and labelling, as well as the user-driven criteria needed to support climate action**. This information will be used to propose a taxonomy of climate services, suggest community-based good practices and guidelines, and propose standards where possible. A large variety of activities to support the communities involved in European climate services will also be organised.

Executive Summary

The market for climate services has developed rapidly over the past decade or so, originating from seasonal forecasts issued by public and private (weather) services to a crowded landscape with a wide range of applications for climate change adaptation and mitigation. To ensure quality, trust and usability in this emerging market the Climateurope2 (CE2) project aims to help develop future equitable and quality-assured climate services to all sectors of society by developing standards for climate services, supporting an equitable European climate services community and enhancing the uptake of quality-assured climate services to support adaptation and mitigation to climate change. One of the elements required to achieve these goals is the definition of (high-)quality climate services. What makes up a good climate service? Is there a common ground across the huge variety of providers, products and users of climate services? Can a climate service or parts of it be standardised to ensure and to improve quality, usability and trust?

In this deliverable, we define a first set of guiding principles for high-quality climate services based on a comprehensive literature review. Key elements of such guiding principles are that climate services should be science-based, user-centred, designed with transparent and collaborative processes, delivered in a timely and accessible fashion, and for public services also sustainable and equitable. This assessment was made through the analysis of a logic model based on input, process, output, outcome, in which the process for the field of climate services should be a co-production process. Due to the broad landscape of the climate service market and the variety of demands on climate services, the quality of climate services depends on many factors and there can be no “one size fits all” solution. Thus, further discussions about which parts of a climate service can be standardised and certified will at least partly be related to common (quality) features that can be identified in the market of climate services and state-of-the-art science for climate services. Throughout the project, this set of guiding principles will be revisited and refined within CE2 through community engagement by case studies, surveys and interviews with providers and users of climate services throughout the broad range of components of the climate service market.

Keywords

Climate services, high-quality, guiding principles, standardisation and literature review

1 Introduction

According to the European Commission (EU, 2015) climate services encompass "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". In Climateurope2 (CE2) (Deliverable D1.3), a slightly modified definition is under discussion within the project consortium: "The provision of climate information usually in combination with non-climate information and knowledge in such a way as to assist decision makers. The service component involves a demand-driven approach, appropriate engagement with the decision makers, an effective access mechanism and responsiveness to user-needs".

Climate services (CS) have gained considerable importance over the last 10-15 years. These services originated from products derived from medium-range weather and seasonal climate forecasts and were particularly useful for agricultural applications, e.g., for efficient irrigation planning, pest control, etc. (see Vaughan and Dessai, 2014 for a historical background of climate services). As the quality of these forecasts is constantly improving this has led to greater confidence and trust in the products among the users. In this part of the climate service market, which was originally dominated by publicly financed providers, nowadays a larger number of private providers are present. Nevertheless, many of these providers are often relying on data from National Hydrometeorological Services (NHMS) or Copernicus Climate Change Service (C3S) as the basis for their products (see: https://climate.copernicus.eu/sites/default/files/2022-08/ECMWF_C3S_06072022.pdf for a report on the use of C3S service).

In recent years, the market for climate services has rapidly expanded (Larosa & Mysiak, 2019; Cortekar et al., 2020; Le at al., 2020; Buontempo et al., 2022) as data from high-resolution model experiments and long-term climate simulations became available. They provide the basis for climate services on regional and local levels e.g., for climate change adaptation and mitigation, and/or risk assessments for various sectors (e.g., urban planning, forestry, energy supply, etc.). Furthermore, national and EU-wide regulations for the implementation of sustainable energy use or climate adaptation measures are creating new business sectors for climate services, which are increasingly also being covered by private providers.

Thus, the market for climate services is becoming increasingly larger, more complex and crowded, especially for users (e.g., Bessembinder et al., 2019; Bruno Soares & Buontempo, 2019). It is increasingly unclear for users to understand what climate services are available, which providers supply which products, whether these products can be intercompared, how good is the quality of the service, which providers and products are trustworthy.

Bremer et al. (2021) wrote: "Climate services, and research on climate services, have mutually developed over the past 20 years, with quality assessment a central issue for orienting both practitioners and researchers. However, quality assessment is becoming more complex as the field evolves, the range and types of climate services expands".

Thus, one of the key questions Bremer et al. (2021) stated is: "How can we comprehensively identify the characteristics associated with a climate service which determine its quality for particular functions in a particular context?"

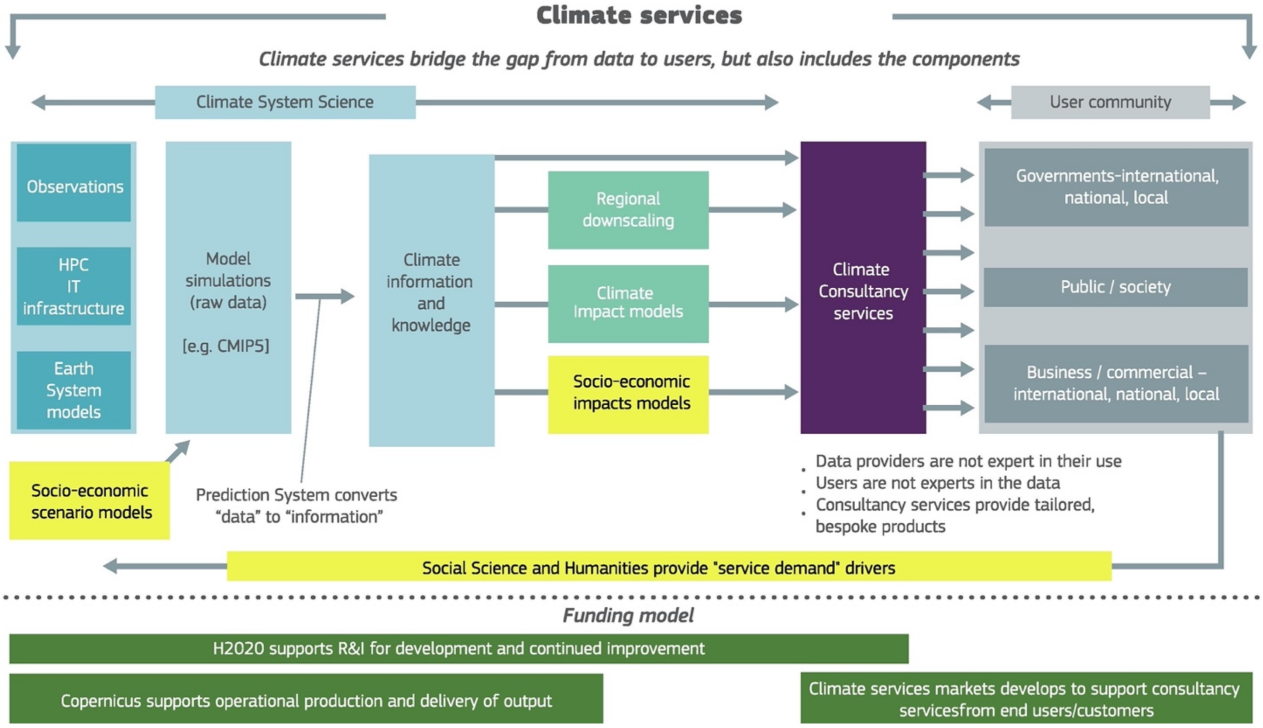

Figure 1: The essence of climate services. Source: European Commission, 2015.

The European Commission (2015) (see Figure 1) stated in the European research and innovation roadmap for climate services: "The enhancing the quality and relevance of climate services challenge seeks to engage users, providers, purveyors and researchers to identify and provide through co-design, co-development and co-evaluation the improvements and innovations in climate services that are needed to better inform decision-making processes and the resulting decisions". Brasseur and Gallardo (2016) identified "five conditions for climate services to be successful:

(1) the activities and elements of a climate service should be user-centric;

(2) the climate service function should be supported by active research;

(3) advanced information (including predictions) on a variety of space and time scales is required to serve national needs;

(4) the climate services knowledge base requires active stewardship; and

(5) climate services require active and well-defined participation by government, business, organised civil society, and academia.”

Hewitt et al. (2021a) made nine recommendations for future research priorities for climate modelling and climate services. Regarding climate services the authors recommended that high quality climate services required:

1) understanding requirements, decision-making and foresight,

2) innovate and enhance diffusion of information,

3) assess the value of climate services,

4) set standards for climate services and overall strengthen the links between climate modelling and climate service communities.

Major issues with the use of climate services are still deficits for instance in mutual understanding between providers and users, lack of trust, or problems with accessibility and sustainability. Although there are many ideals for successful climate services other literature findings have pointed out that the production and delivery of climate services are still primarily considered a natural science endeavour, even though the use of climate information is primarily a social science problem (e.g., Findlater et al., 2021; Máñez Costa et al., 2021; Steuri et al., 2022). Swart et al. (2021) addressed the so-called “valley of death” between providers and users. The authors stated that “value chains are often still underdeveloped and public providers with strong roots in upstream climate services attempt to reach downstream users without properly contemplated business models to do so”.

Bruno Soares et al. (2018) investigated the use of climate information across different economic sectors. They came to the conclusion that in order to increase the use and uptake of climate information a number of barriers have to be addressed and promoted such as: “i) better understanding of climate information, including its parameters, limitations and scientific uncertainty; ii) improve coordination and standardisation across fragmented sources of climate information and accessibility; and iii) address current gaps in information provision”. Guentchev et al. (2023) investigated the upscaling of CS as they “rarely make the transition from prototype to fully-fledged, transferrable and/or repeatable climate services.”

Recently a number of EU-funded projects have been trying to provide more orientation in this area for users as well as for providers. Within the framework of the MARCO (EU-MARCO, 2018), EU-MACS (EU-MACS, 2018) and Climateurope (Climateurope, 2017; Hewitt et al., 2017a; Hewitt et al., 2021b; Cortekar et al., 2020) projects, the market structures, potentials and developments were examined in detail.

The need to improve climate services has recently been addressed by the Fast Track Action Committee on Climate Services of the US National Science and Technology Council (NSTC) in the Federal Framework and Action Plan for Climate Services (NSTC, 2023) that contains a number of recommendations addressing the need for a more coherent strategy for climate services in the US. In the UK, the Climate Resilience Programme (UKCRP, 2022) defined fundamental principles, requirements and guidelines for climate services.

The aim of the Climateurope2 project (www.climateurope2.eu), beyond the strengthening of the climate service community in Europe, is to address the question of whether and for which parts of climate services quality criteria and standards can be defined in order to ensure higher uptake of CS through better and higher quality of the products. Based on a continuous analysis of the market for climate services, its development and potentials, quality criteria and standards are to be defined and expanded on the basis of existing structures.

Work Package 4 on “Market Development” of CE2 is concerned with the continuous monitoring of the market for climate services across all sectors (Task 4.1), facilitating market development (Task 4.2 and 4.4) and with the definition of standardised guiding principles for high-quality climate services (Task 4.3). In this deliverable the first attempt for these guiding principles is presented on the basis of an extensive literature research. In the course of the project, these guiding principles will be further refined and updated through community engagement, case studies, surveys and interviews with providers as well as users of CS.

The guiding principles for high-quality CS are being developed as a prerequisite for future standardisation, certification and labelling (Work Package 1). By defining quality factors for climate services, this process serves as a background information for future standardisation approaches. The guiding principles will also support other Work Packages of Climateurope2, such as Data & Processes (WP2), Business Innovation (WP3), Market Development (WP4) and Policy Support of CS (WP5).

The assessment of high-quality criteria and indicators is structured and defined along a value chain of CS, i.e., 1) input to the development of a climate service, 2) the co-production process, 3) output (characteristics of the CS as such), and 4) outcome (whether and how the climate service is used).

Based on these first results, recommendations for standards and guiding principles for high-quality CS will be exchanged and iteratively developed in order to create a broad consensus within the communities involved and to contribute to more trust and transparency. This deliverable can already build on an initial assessment on the existing landscape of initiatives and standardisation norms and approaches (Deliverable 1.1) and the draft framework (Milestone 1.1) of Climateurope2.

1.1 Objectives of the work

Task 4.3 of the CE2 proposal provides the objectives and concept for this deliverable:

To increase trust and transparency in CS, **this task will elaborate on guiding principles for high-quality CS as a prerequisite for future standardisation, certification and labelling**. These elements will be clustered in **four categories associated with climate services: 1) inputs to develop a climate service, 2) the co-design process, 3) output (characteristics of the CS as such), and 4) outcome (if and how the climate service is used)**.

As a result, the initial recommendations for standards and guiding principles for high-quality CS formulated in this deliverable will be shared with the CS community and then further developed iteratively to build a broad consensus within the communities involved and, thus, contribute to increase trust and transparency in CS.

These activities will be also linked to other tasks within CE2 such as Task 1.4 (Setting ground for standardising climate services), Task 2.3 (Verification) and Task 2.4 (Uncertainty and climate risk assessment) to ensure the traceability of CS and to feed into the development of a pre-standardisation process and the evaluation of future options for certification and labelling that will be performed in WP1.

1.2 Structure of this report

The report is divided into four sections. Following this introduction, Section 2 describes the concept and methodology for literature review on elements of high-quality climate services. Section 3 summarises the findings and discusses the results. Section 4 provides an overall summary and outlook to the next steps to be taken within this task of the Climateurope2 project.

2 Concept & Method

2.1 Definitions

What does "high-quality" mean in the context of climate services?

In Climateurope2, a number of fundamental terms and expressions were discussed within the consortium in order to reach common understanding and consensus. This is part of a basic framework described in the Deliverable 1.2 of CE2. A part of these discussions was also focused on the term high-quality climate service. An initial suggestion for a definition on the term high-quality climate service resulting from these discussions resulted in: "High-quality climate services shall fulfil a number of qualitative criteria and / or quantitative measures (well) above average." This is of course a very general statement with very limited explanatory power as whatever "average" is has to be defined and must reflect the qualitative and quantitative informational needs of the user community.

Furthermore, it was agreed that detailed criteria should be clustered along the complete value chain required for the development of a climate service. Elements of this value chain are **input** (e.g., data), a joint **co-production process** (user/provider interaction) to develop a climate service, **output** (the product as such) and **outcome** (usage of the CS). These categories, following the so-called "Logic-model" (OECD, 2002; Frechtling, 2015; Wall et al., 2017) (see Figure 2) were formulated in the CE2 proposal and origin from project management. Many evaluation approaches use this model, be it explicit or implicit (Schuck-Zöller et al., 2018; Bremer et al., 2021).

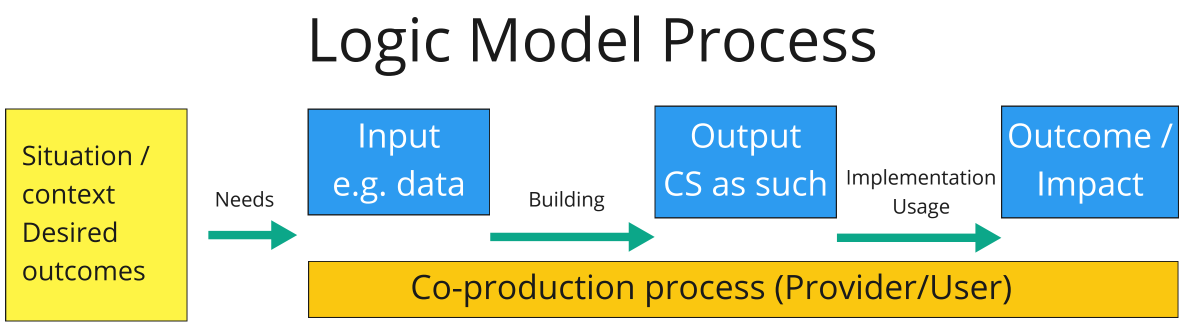

Figure 2: Conceptual diagram of the logic model for process management (modified from https://learningforsustainability.net/logic-models/)

In addition, assessment and evaluation of quality always depends on the demands and requirements of the users of climate information. For example, for a farmer a 70% probability of a seasonal rain forecast might not be sufficient for decision making whereas in urban planning this can be a sufficient threshold for water management planning. Nevertheless, all users rely on understandable and user-friendly information they can trust. Building of trust is of particular importance and can be a complex, demanding and fragile process that needs often more time than expected (e.g. Stern and Coleman, 2014; https://theclimatecommsproject.org/trust-and-its-role-in-climate-change-communication/).

Thus, elements like accuracy and reliability, tailoring to user needs, easy-to-use as well as credibility, accessibility and timeliness are important quality elements although different weighted following the related project objectives.

Based on these initial definitions and guidelines a comprehensive review of existing literature was performed to develop the first set of guiding principles for high-quality climate services. It is a qualitative and not a quantitative assessment but building on a large and comprehensive knowledge base. Nevertheless, gaps and uncertainties of this initial assessment are identified which will be further addressed during the lifetime of the Climateurope2 project.

2.2 Method

As the market for climate services emerged rapidly over the past decade or so (Cortekar et al., 2020; Le at al., 2020; Buontempo et al., 2022), the potential and performance of climate services have been discussed in the scientific literature quite extensively. Thus, these publications provide a sound basis to investigate and define a first set of guiding principles for high-quality climate services.

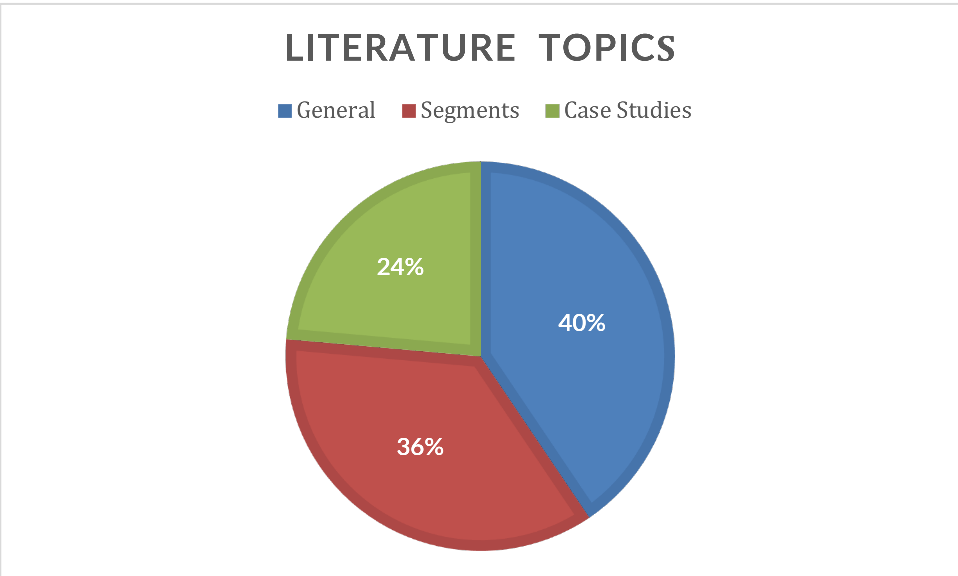

Figure 3: Topics covered by the literature review

The comprehensive literature and desk review of this study comprises a large set of overview and specific case study papers across the broad spectrum of climate services. In total, more than 100 papers (see Section 5) were included. Selection criteria for including papers in the review were **a) overview and review papers about climate services with respect to quality aspects** (noted “general” in Figure 3), **b) articles covering the different segments of the complete value chain of CS** (input, the co-production process, output, and outcome/impact) (noted “segments” in Figure 3) and **c) examples across different application sectors, products, providers and users of climate services** (noted “case studies” in Figure 3).

Commonalities as well as differences e.g., through the broad range of providers, products and users that have fundamentally different intentions and requirements were taken into account.

Nevertheless, the scientific literature has a bias towards public climate services due to the fact that the CS market is for many sectors still dominated by public funded activities or the private sector activities are not publicly displayed (Keele, 2019, Bruno Soares et. al., 2018; Tart et al., 2020; Larosa & Mysiak, 2020; Rubio-Martin et al., 2021). Thus, this literature review is a first step towards a more comprehensive assessment of high-quality elements of climate services. Throughout the lifetime of the CE2 project, the guiding principles will be refined using detailed case studies and community engagement through interviews, surveys and workshops.

Therefore, this first approach starts with a lower level of granularity and will be updated towards a more detailed and differentiated view throughout the project.

3 Results

According to the Task 4.3 of the Climateurope2 project (see section 2.1) the assessment for the guiding principles for high-quality climate services should be clustered in four categories following approaches in the scientific literature according to the Logic-Model approach (OECD, 2002, Frechtling, 2015, Schuck-Zöller et al., 2017, Wall et al., 2017) (see Figure 2: 1) **input** to the development of a climate service, 2) the **co-production process**, 3) **output** (characteristics of the CS as such), and 4) **outcome** (whether and how the climate service is used).

As these categories have to take into account the widespread landscape of climate services, we will initially discuss the different component of the CS landscape and the relationships to quality issues. This will then be followed by above-mentioned segments of the CS value chain.

3.1 Landscape of Climate Service

As mentioned earlier, the landscape of climate services has developed rapidly during the past decade. Here we will briefly review and discuss the landscape of climate services and players involved before starting with an analysis and assessment of quality factors of climate services based on the value chain of CS. A more in-depth review of the climate service market will be performed in Task 4.1 of CE2 and shared in Deliverable 4.2 (M14).

The landscape of climate services and players involved can be illustrated by the following three categories (see Figure 4):

1. Providers: Public, private, profit and non-profit actors
2. CS types and products: From publicly available product to custom designed application for specific users
3. Users: From individual customer to broad public

3.1.1 Providers: Public, private, profit and non-profit actors

Originally, climate services evolved mainly out of the public funded sector, i.e., NHMS, research organisations and universities (e.g., Cortekar et al., 2020; Le at al., 2020; Buontempo et al., 2022). Seasonal to interannual predictions but also climate projections built the basis for a variety of different products applied in various sectors such as agriculture, energy and water, etc. (e.g., Vaughan et al., 2018). Although the public sector is still dominating (Bruno Soares, 2018), more and more services are developed out of the private / commercial sector (e.g., industry, consultancy, SMEs and start-ups) and provide for instance specific consultancy services for the agricultural applications sector, or risk assessments products for the financial and critical infrastructure sector.

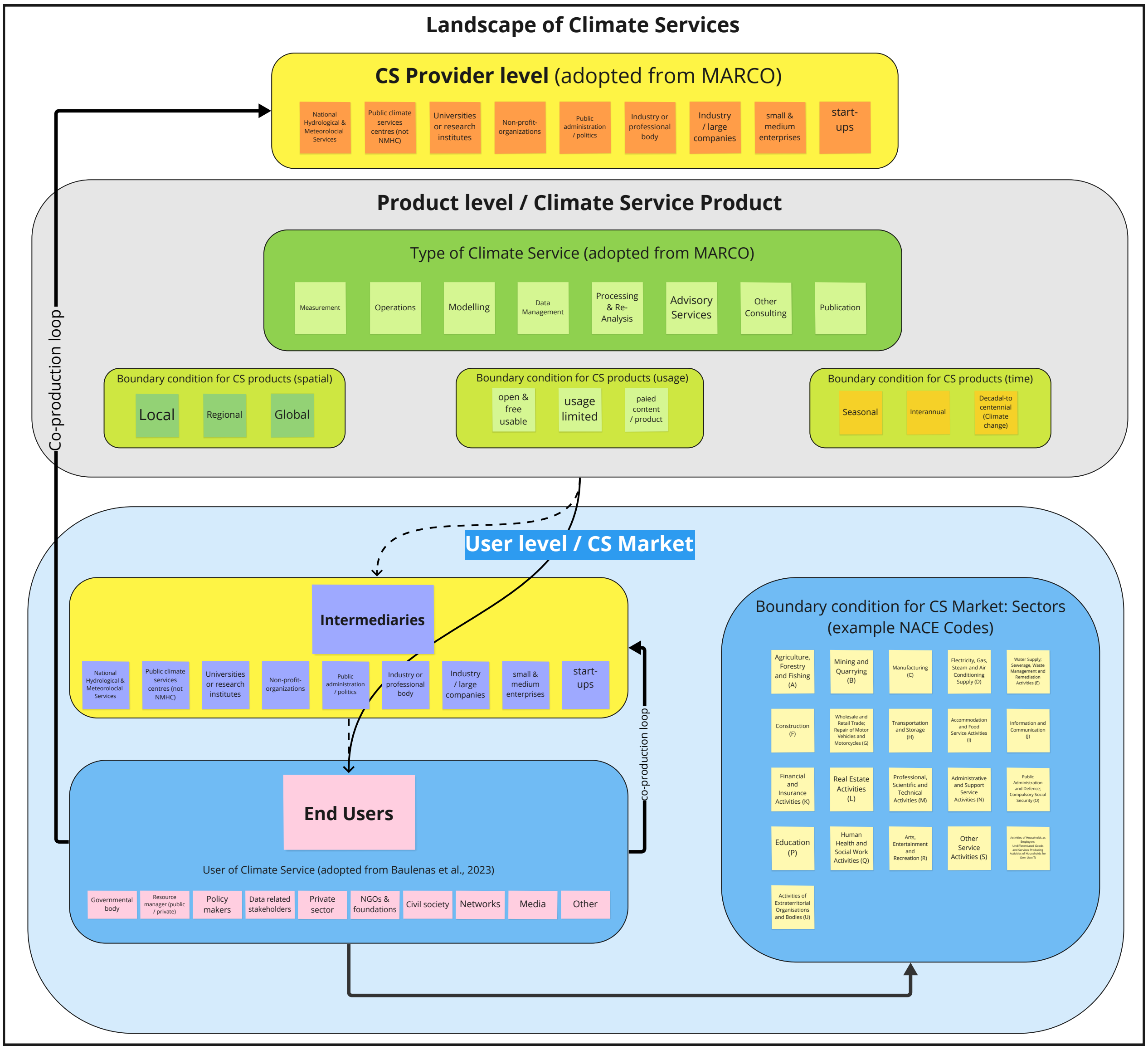

Figure 4. Landscape of Climate Services

Assessments within the MARCO project (EU-MARCO, 2018; Cortekar et al., 2020) suggested the following categories of the climate service provider landscape:

- National meteorological services (or extensions thereof)
- Public climate service centres
- Universities or research-performing organisations

- Non-profit-organisations
- Industry / professional bodies (e.g., chamber of commerce, intl. organizations)
- Public administration / politics
- Industry / large companies
- Small and medium-sized enterprises
- Start-ups

Note, that also other typologies are discussed in the literature (e.g., Clements et al., 2013; Bessembinder et al., 2019; Vischer et al., 2020).

A major difference between the commercial vs. the public sector is that public providers (and some private non-profit ones) are mostly non-profit oriented. Public providers either receive funding project based (mostly time limited) or allocate a budget for the development of a climate service. Such projects are advantageous for the development of pilot or prototype studies, but are often limited to the duration of the project and therefore fail to deliver the long-term, sustainable provision of a CS (Bruno Soares & Buontempo, 2019). As profit-oriented organisations, commercial oriented providers only develop services that are economically feasible. This might be of disadvantage with respect to new, experimental prototype developments, however a service will be sustained as long as market perspectives are positive and promising. Further differences between public and commercial providers will be discussed in the context of input and co-production of a CS (see sections 3.2 & 3.3).

In summary, the provider plays a crucial role in the development of climate services. Scientific expertise, data quality and product development, and sustainability of the product highly rely on the provider side. In order to build confidence and trust, elements like a specific (quality) certification of providers may provide guidance for users of CS.

3.1.2 CS Types and Products: From publicly available product to custom designed application for specific users

The range of climate service types and products (e.g., see Climateurope, 2017; Hewitt et al., 2017a, EU-MARCO, 2018; Cortekar et al., 2020) is widespread from publicly available information and products to custom designed applications for specific user(s). The types of climate services suggested by EU-MARCO (2018) are given in Table 1.

Table 1: Types of Climate services (EU-MARCO, 2018, Cortekar et al., 2020)

Type	Description
Measurements	Instruments and technologies for measurement and calibration.
Operations	Collection and provision of raw data
Modelling	Modelling of data, both certified and non-certified
Data Manage-ment	Provision of calibrated data sets, data archiving, data certification and data sales
Processing & Re-Analysis	Provision of data analysis and retrieval services including data mining tools
Advisory Services	Advisory services, risk assessment and decision support tools provided to public and private sector organizations
Other Consulting	Consulting services not elsewhere covered
Publication	General publication of analysis findings

Further classification principles for CS types can for example include:

- temporal (e.g., seasonal, decadal, long-term scales),
- spatial (global, regional, local),
- accessibility (free, limited (available a limited period by subscription or fee), individual designed paid product) or
- a typology along application sectors (Bessembinder et al., 2019). On the latter point, there are various ways of dividing the market (sectoral division) (e.g., Cortekar et al., 2020; EU-MARCO, 2018; NACE (Nomenclature of Economic Activities)-codes: https://nacev2.com/en, see Figure 4).

Some climate services address only one or a subset of sectors (e.g., energy, urban planning or agriculture), while others are applicable across different sectors. This ultimately makes it difficult to derive quality criteria based on a specific CS typology.

The range of products developed by a specific type of climate service according to Table 1 is very broad: from seasonal rainfall advisories (e.g., https://climate.copernicus.eu/seasonal-forecasts, https://www.cpc.ncep.noaa.gov/products/predictions/90day/), web-based mapping tools (e.g., Soret et al., 2019), a freely available warning app for heat stress (e.g., Eggeling et al., 2022; Neset et al., 2021) to a consultation process designed for an individual city to adapt to climate change (e.g., Swart et al., 2021). See also Visscher et al. (2020) for a typology of CS divided into freely (or cheaply) available products vs. commercially ones (see also Table 4 in Section 3.4).

Quality criteria for the product itself have to address the product range of climate service applications in relationship to the intended users. Thus, the product quality also depends on the designated user. Does the product fit with the user's needs and requirements? How can the user determine the quality of a product?

Transparency, **easy-to-use** and **fit-for-purpose** are some key criteria with respect to the quality of CS products. Here, standards and certificates may play an important role for users of CS. See section 3.4 for further details.

3.1.3 Users: From individual customer to broad public

A "user" or "customer" (note, that both expressions are used interchangeable in this document) of a climate service can be almost anybody: politicians, policy and decision makers, scientists, commercial companies, journalists, and the general public (both informed individuals and those with a limited scientific knowledge base). Furthermore, we distinguish intermediaries (purveyors) as intermediate users that play an increasingly important role in CS, as they are serving as translators and communicators like journalists in the media world. Baulenas et al. (2023) suggested a typology of user categories to guide user identification (see Table 2). Stakeholders using climate services can act on local, regional, national and international levels. Thus, products have to be carefully adjusted to the targeted user community.

Depending on the product type and format, a climate service application either reaches out to users through a tailored co-design, co-production and co-implementation process by the provider. Or, on the other hand, users are provided with a climate service product that can be used, e.g., through a freely available website, without any mandatory training or detailed explanations and instructions.

This broad range of potential users or customers of CS products sets up specific requirements to the planning and design of a CS. Thus, quality and success of a CS not only depend on the quality of data or the product itself but also how it is perceived and used. A product used by the wrong person or in the wrong context can lead to consequences and decisions not expected or desired by the providers. "One size does not fit all", thus, quality factors of input, co-production, output and outcome are not independent of the designated user community and context and have to be defined by taking the whole value chain for a specific CS into account.

Table 2: Proposition of user categories with typologies to guide user identification (from Baulenas et. al, 2023)

Categories	Types
Policymaker	Local, subnational, national, and supranational level
Governmental body	Environmental and conservation agencies, climate change offices, and funding agencies
Resource manager (public)	Local, regional, and national authorities or resource authorities (e.g., river basin management authorities), public utilities, and resource suppliers
Resource manager (private)	Landowner associations, professionals, mediators, and practitioners
Data-related stakeholder	Data provision, supplier, purveyor, developers, and manager
Civil society/community representatives	Citizen associations, local communities (hybrid), consumer associations, citizen representatives, social movements, and youth representatives
NGOs and foundations	Local, regional, and national NGOs
Private sector	Companies, industry representatives, and associations
Networks	Transnational networks, global initiatives, and umbrella organizations
Media	Journalists and specialized media
Other	Non-project-related scientists, technologists (vendors, computing centers, etc.), and experts; educators

3.2 Input for the development of a climate service

An important basis for a climate service is (climate) data, which can originate from observations, model experiments or statistical analyses. Depending on the scope, resolution and quality of the model or method used, this basis can vary greatly in quality and is per se not suitable for every application, i.e., data depends on the context for which it is used. For the user it is often not clear and transparent to judge whether this basis, a climate service is designed and built upon, is really suitable for the application, i.e., good enough in terms of data quality and trustworthy (Zahid et al., 2020). This section focuses primarily on climate data. Nevertheless, many climate services use and/or incorporate other data (e.g., technical, economical, or social parameters) to their products. In principle, rules and indicators formulated in this section should also be applied for these non-climate datasets and information if they are part of the climate service product.

What measures can help on the input/data side to increase quality, transparency and trust?

Apart from data quality, a clear and understandable description of the data for the user, including uncertainties and limitations is required. For example, when using model data from a coarse-resolution global model or observation data in data-poor areas, the limited value when applied on a regional or local scale should be pointed out clearly as well as systematic model errors or measurement inaccuracies. Uncertainties and limitations of data are very important elements and crucial for building trust and acceptance on the user side. If users do not understand or misunderstand these information, decisions made could be wrong and trust in the products might be lost (https://theclimatecommsproject.org/trust-and-its-role-in-climate-change-communication/). Ultimately, however, it is up to the provider to use the best available data for the service and/or to clearly point out the corresponding limitations and uncertainties to the user.

For this category, the input / data side, Wilkinson et al. (2016) formulated the so-called FAIR principles. FAIR stands for: Findability, Accessibility, Interoperability, and Reusability. For details of the FAIR principles see Table 3 below.

Table 3. FAIR principles (from Wilkinson et al., 2016)

Principle	Elements
To be Findable	• F1. (meta)data are assigned a globally unique and persistent identifier • F2. data are described with rich metadata (defined by R1 below) • F3. metadata clearly and explicitly include the identifier of the data it describes F4. (meta)data are registered or indexed in a searchable resource

Principle	Elements

To be Accessible	• A1. (meta)data are retrievable by their identifier using a standardized communications protocol
	  ○ A1.1 the protocol is open, free, and universally implementable
	  ○ A1.2 the protocol allows for an authentication and authorization procedure, where necessary
	• A2. metadata are accessible, even when the data are no longer available

To be Interoperable	• I1. (meta)data use a formal, accessible, shared, and broadly applicable language for knowledge representation. • I2. (meta)data use vocabularies that follow FAIR principles • I3. (meta)data include qualified references to other (meta)data

To be Reusable	• R1. meta(data) are richly described with a plurality of accurate and relevant attributes
	  ○ R1.1. (meta)data are released with a clear and accessible data usage license
	  ○ R1.2. (meta)data are associated with detailed provenance
	  ○ R1.3. (meta)data meet domain-relevant community standards

Clear, comprehensible and good documentation is therefore a fundamental prerequisite for high-quality climate services. However, it is also important that the data used is suitable for the application to be developed from it. This "fit-for-purpose" issue is usually difficult for the user to judge, thus, the provider of the climate service has a special responsibility to fulfil this criterion.

Studies by the Copernicus Climate Change Service (C3S) (Buontempo et al., 2020) aim to improve the transfer of data into high quality usable products. Through the sectoral information system, C3S demonstrated successfully how the data infrastructure can be used to address specific user needs for different sectors (see https://climate.copernicus.eu/data-action for examples).

Climate data providers such as NHMS, and other public funded scientific organisations are already addressing **quality management** and **quality assurance** in a very comprehensive way. Some examples are:

1. Copernicus Climate Data Store: https://climate.copernicus.eu/quality-assurance-climate-data-store (see Figure 5)
2. Quality Management Framework for Climate Data Sets (Lacagnina et al., 2022)

3. Climate Forecast Metadata Conventions: http://cfconventions.org/index.html
4. WMO Climate Data Management Systems https://community.wmo.int/en/climate-data-management-systems-cdmss
5. German Weather Service (Kaspar et al., 2013 and https://www.dwd.de/EN/climate_environment/climatemonitoring/climatedatamanagement/qualityassurance/quali.html
6. German Climate Computing Center: https://www.dkrz.de/up/services/data-distribution/data-publication/quality-assurance-of-data
7. Climate Data Online (of NOAA) https://www.ncei.noaa.gov/cdo-web/

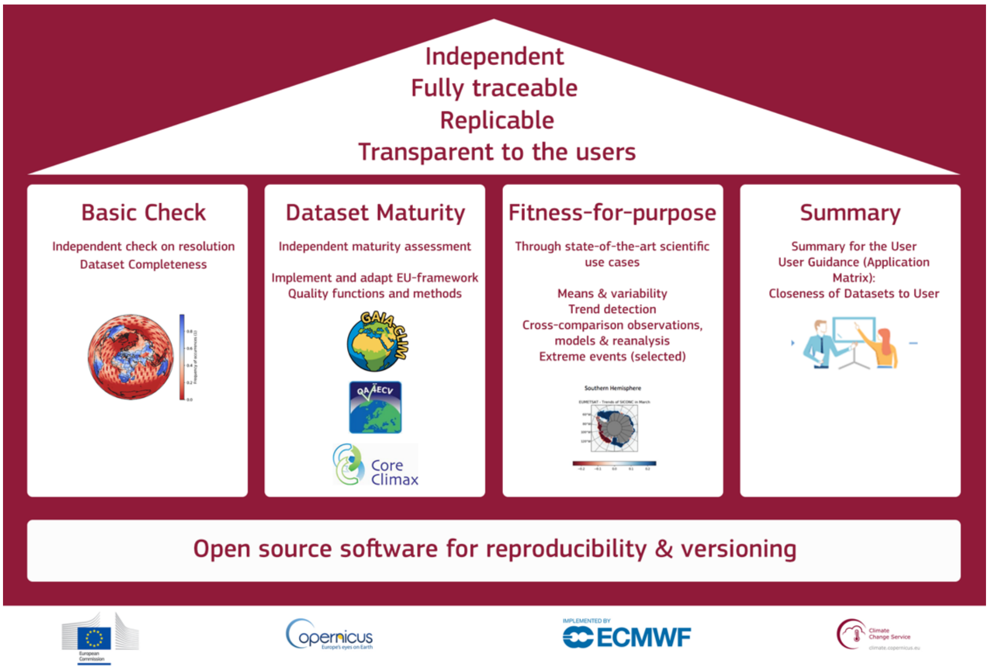

Figure 5. Assessment procedure of Copernicus Evaluation and Quality control

Climate services are often not developed by the main data provider (e.g., NHMS or research institution) but by intermediaries or commercial providers who use the data from the primary data producers as the basis for the climate service product. Even though the documentation of the data, etc. is available to these intermediaries, some of the primary expertise on the data might get lost or data might get modified in this part of the process. Thus, in order to keep the process transparent for the user, all steps from the data source to the product should be documented and be understandable and comprehensible for the user.

The input/data part of a climate service offers options for standardisation within the framework of Climateurope2. Here, Deliverable 1.1 of Climateurope2 "Current landscape of initiatives and standardisation norms and approaches" (Climateurope2, 2023) and the "Guidelines on Quality Management in Climate Services" of WMO (WMO, 2018b) provide a found basis.

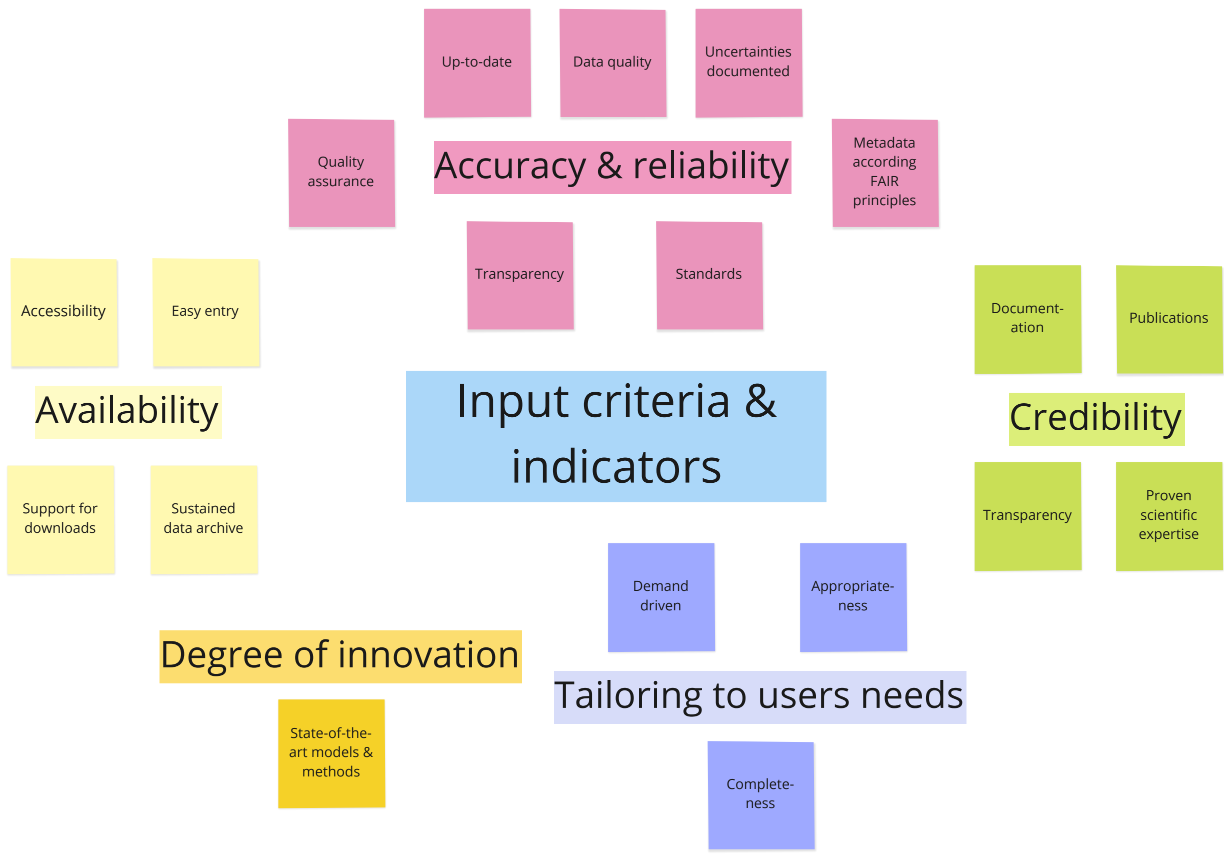

Figure 6: Summary of important criteria and indicators with respect to the input for a CS

In summary, frequently mentioned criteria & indicators for the (data) input of CS (see Figure 6) are:

- **Degree of innovation**:
  - Use of state-of-the-art models and methods
- **Accuracy and reliability -> Transparency & Trust**
  - Up-to-date high-quality data
  - (Meta)data are compliant with FAIR principles
  - Data conform with (international) standards
  - Uncertainties / error margins of the data are known and documented
- **Credibility, legitimacy & traceability -> Transparency & Trust**
  - Data source and methods well documented and published
  - Data basis and modifications are documented and comprehensible to the user
- **Availability**
  - Data freely available and easily accessible
- **Tailored to user needs -> Appropriateness**
  - Data basis suitable to address the problem / task

3.3 The Co-production Process

The interaction between providers and users in the development and design of a climate service is an essential part to ensure success and envisaged impact. Hewitt et al. (2017b) stated that there is growing recognition that the interface between the users and providers is the least-developed aspect of climate service and has to be improved. Hewitt and Stone (2021) (see also Figure 7) stated: "Through a consideration of the value chain for climate services, we emphasise the importance of dialogue and collaboration between those developing, providing and using climate information in decision-making, and stress that a climate service is only worth delivering if it is going to be used by someone to influence an outcome. Co-production can be highly useful for enabling the dialogue and collaborating across the value chain, helping create services based on credible, salient and legitimate knowledge.". Stegmaier et al. (2020) pointed out that "success or failure of climate services will be determined 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'".

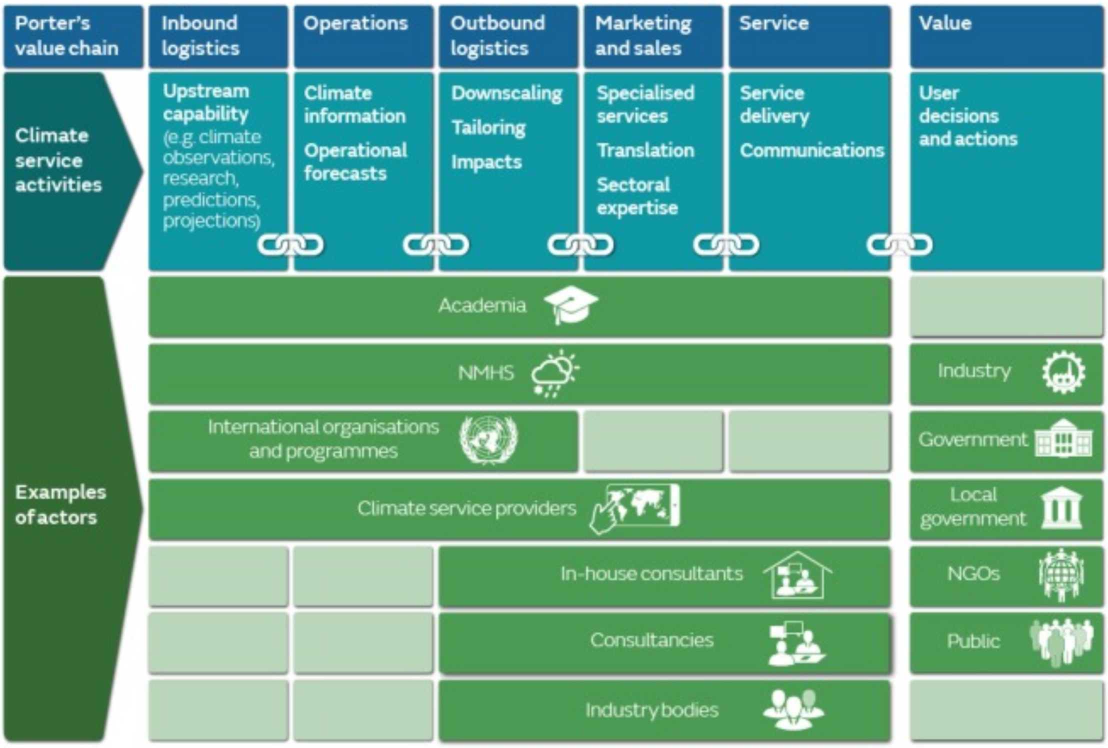

Figure 7. Value chain of CS. (from Hewitt and Stone, 2021).

The co-production process, which has already been discussed in detail in the literature, offers a multitude of facets and options. In the following a number of co-production approaches are introduced and displayed (e.g., see Miller and Wyborn, 2020 for a historical review, Dressel, 2022 for a review on science–society interaction models, Máñez Costa et al. (2021) for a review based on ERA4CS projects and Djenontin & Medow (2018) for a review on international practise).

Here some other co-production ideas & approaches from the literature:

- Mauser et al. (2013) (Figure 8) proposed a framework for interdisciplinary and transdisciplinary co-creation of a “knowledge castle”
- Bojovic et al. (2021) (Figure 9) and Terrado et al. (2023a) proposed a co-production framework which comprises three realms: (i) engagement using various communication channels; (ii) involvement through interviews, workshops and webinars; and (iii) empowerment of stakeholders and scientists through focused relationships.
- Bremer and Meisch (2017) and Bremer et al. (2019) (Figure 10) suggested a fresh look on co-production as a process best examined simultaneously from several complimentary perspectives, with reference to recent work re-conceptualising co-production as an eight-sided “prism”.
- Schuck-Zöller et al. (2022) suggested five principles: 1. common ground, 2. transparency, 3. professionalism, 4. enhancement of applicability and 5. theoretical and empirical foundation for a successful co-creation process.
- Carter et al. (2019) defined 10 principles for good co-production of an application in Africa with the following elements: 1. Tailor to context & decision, 2. Deliver timely & sustainable service, 3. Building trust, 4. Embrace diversity & respect differences, 5. Enhance inclusivity, 6. Keep flexible, 7. Support conscious facilitation, 8. Communicate in accessible ways, 9. Ensure value-add for all involved, and 10. Improve transparency of forecast accuracy and certainty.
- Vogel et al. (2019) and Grossi and Dinku (2022) used a 4-pillar concept for the co-development of a CS (Figure 11, adopted from IRI), based on continuous interaction between providers and users.
- Chambers et al. (2021) proposed 6 modes of co-production through a global analysis of 32 initiatives: (1) researching solutions; (2) empowering voices; (3) brokering power; (4) reframing power; (5) navigating differences and (6) reframing agency.
- Hewitt et al. (2020) (Figure 12) applied a concept with five stages (explore, exploit, expose, examine, expand) of co-development of a climate service prototype in China.
- Norström et al. (2020) (Figure 13) proposed a set of four general principles that underlie high-quality knowledge co-production for sustainability research: a) context-based, b) pluralistic, c) goal-oriented and d) interactive.
- Daniels et al. (2020) introduced a framework for co-designing “transdisciplinary knowledge integration processes” to build climate resilience and Stegnor et al. (2020) emphasized the need for a greater focus and value to be placed on the process elements of transdisciplinary co-production.
- Vincent et al. (2018) (Figure 14) suggested that a co-produced climate service product should be decision-driven, process-based and time-managed.
- Williams and Jacob (2021) (Figure 15) proposed an 8-step integrated approach of co-development of CS in the context of citizen science.

- The Climate Service Center Germany (Gerics, https://www.gerics.de/methods/prduct_development/index.php.en) has set up a co-development process for the design of prototype CS with continuous user-provider interaction.

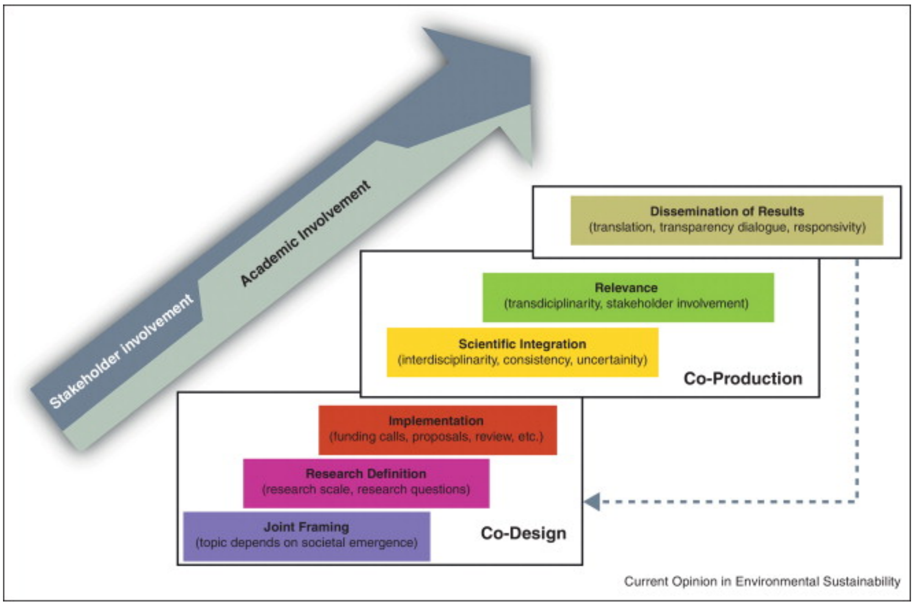

Figure 8. Framework for interdisciplinary and transdisciplinary co-creation of the knowledge castle (from Mauser et al., 2013).

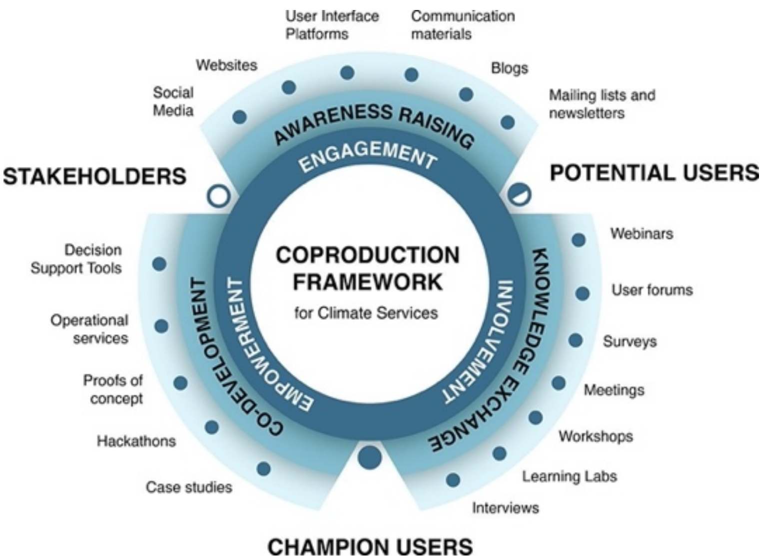

Figure 9. Co-production framework (from Bojovic et al., 2021). The framework engages stakeholders by raising awareness through different communication tools (the *engagement* realm). It then involves stakeholders in knowledge exchange and co-learning, using various participatory approaches (the *involvement* realm). Finally, it empowers users of climate services, who take part in their co-development (the *empowerment* realm).

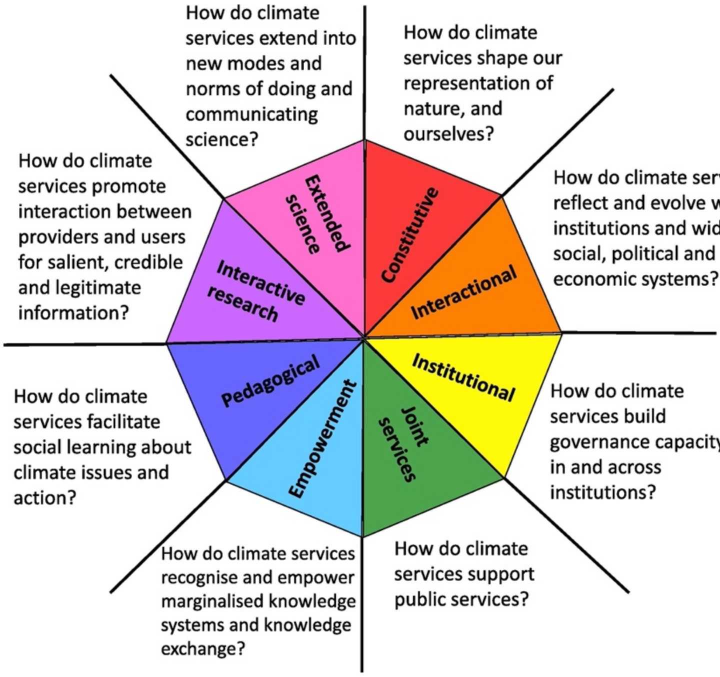

Figure 10. Co-production prism (from Bremer et al, 2019). The authors suggest a fresh look on co-production as a process best examined simultaneously from several complimentary perspectives, with reference to recent work reconceptualising co-production as an eight-sided ‘prism.

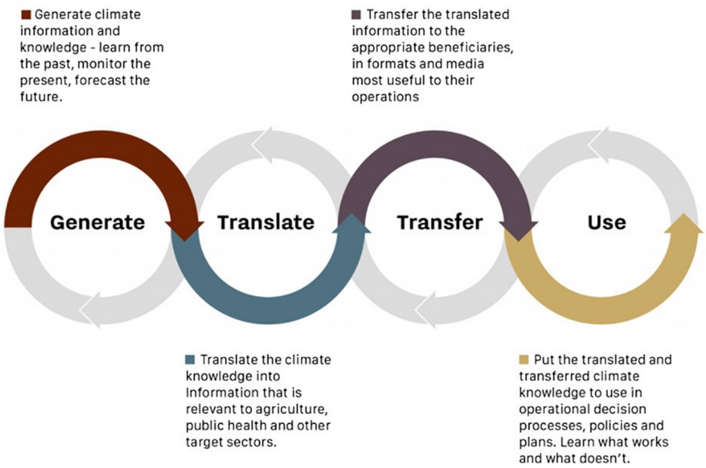

Figure 11. 4-pillars of CS (from https://iri.columbia.edu/actoday/, see also Vogel et al., 2019, Grossi & Dinku, 2022). Co-production is foundational for both locally led and locally owned climate services and important for ensuring climate services are both useful and usable.

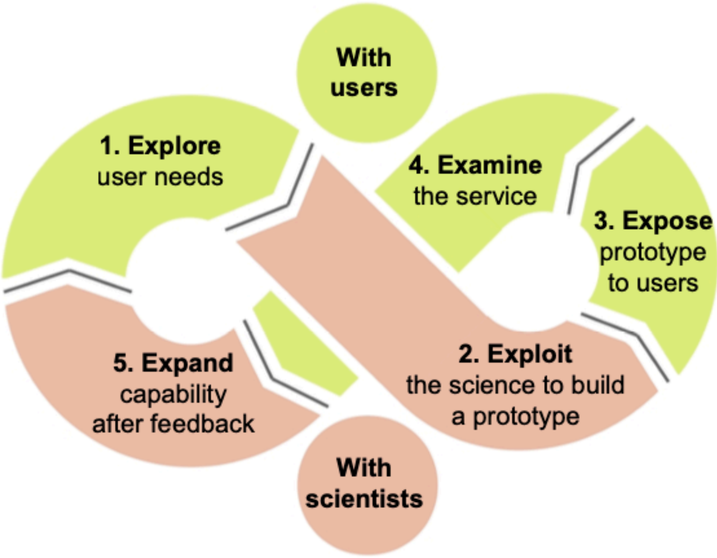

Figure 12: Concept of five stages of development of a climate service prototype (from Hewitt et al., 2020).

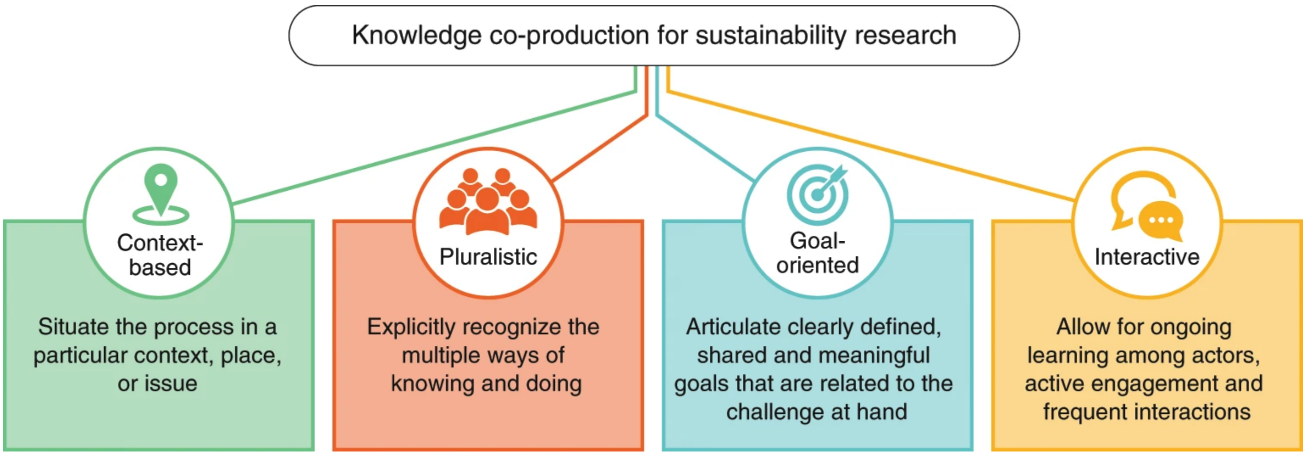

Figure 13: Principles for knowledge co-production in sustainable research (from Norström et al., 2020)

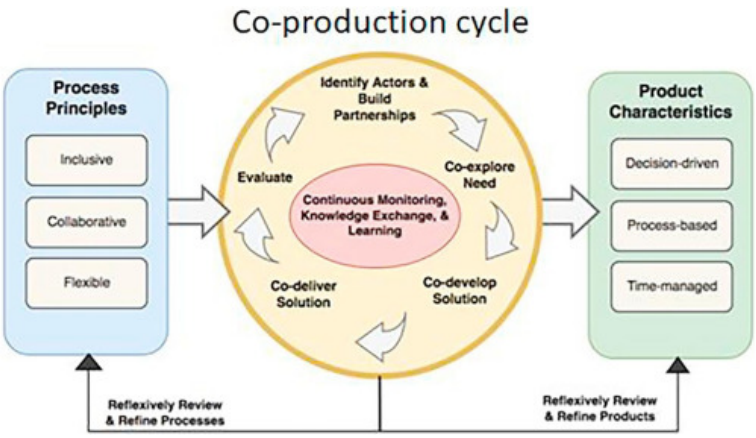

Figure 14. Co-production cycle (from Vincent et al., 2018)

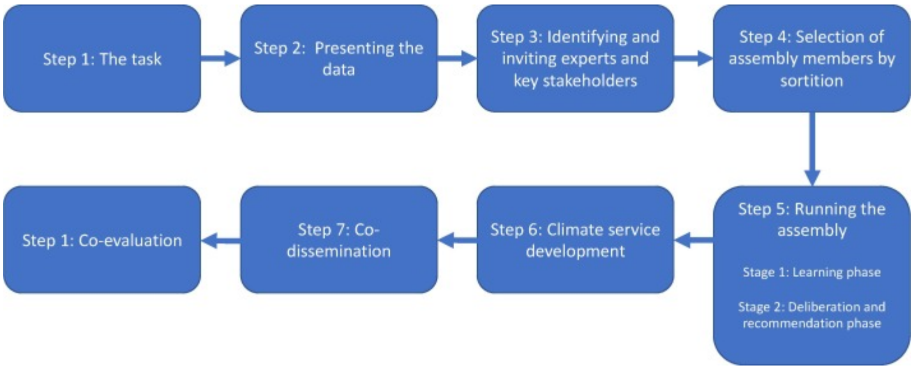

Figure 15. An eight-step sequential process, responding to the need for integrating citizen science and vernacular knowledge for inclusive climate service provision (from Williams and Jacob, 2021).

A vital co-production process can avoid failures in the creation of a CS (e.g., Kolstad et al. (2019) for a critical assessment of a case study) and it is characterised by a constant exchange with (potential) user groups (e.g., Hewitt et al. (2020), Terrado et al. (2023b), Blair et al. (2022), Rubio-Martin et al. (2023)) right from the beginning. The user group is involved as continuously as possible in the process, from creation to test phases to the final product. Through continuous dialogue, the product can be optimally adapted to the user's needs. This ensures mutual transparency and trust.

The exchange and transfer of information within a co-production process would be done by a "neutral" moderator who can also ensure a common and understandable language for all participants. Suhari et al. (2022) call it a boundary manager who serves as a mediator between a CS provider and a user community. In this way, problems of misunderstanding could be effectively encountered.

Buontempo et al. (2018) stated that the interaction with the users during the development of a climate service cannot be sporadic and cannot simply occur at the beginning (e.g., service definition) and at the end (e.g., service evaluation) of the service development.

Furthermore, the process of co-producing a climate service should be inclusive, collaborative and flexible. Martinez et al. (2022) pointed out that "when co-designing climate services, it is vital to understand users' needs, based on their values and experiences with climate and weather and to seek ways to influence, alter and change them".

Blair et al. (2022) stated: "Our results showed that both users and producers emphasise the importance of producer reputation, trial period, peer-recommendation, co-production with users, user-friendly design, consistent terminology and ensuring that users are aware of the full range of already available products." This is supported by Barnet et al. (2021): "Research demonstrates that stakeholder participation in the production of CS is a necessary condition for the successful implementation of CS, and effective user engagement in the co-production of climate services is critical to guarantee its value and impact (e.g., Vincent et al., 2018; Bremer et al., 2021; Vollstedt et al., 2021, Georgi et al., 2016). User-provider engagement is one of the most fundamental activities in the preparation, development and application of climate information for decision-making. In addition, the collaboration between decision makers, climate scientists and specialised academics offers an opportunity to leverage the expertise of all parties to better serve the problem-solving process (Briley et al., 2015; Golding et al., 2017)".

However, the resources in terms of time, personnel and funds required for the co-creation-design and implementation of a service is often a limiting factor, in particular on the user side. Condon (2023) cited a mayor of a small Alabama town on the Gulf of Mexico: "I don't have a big planning staff or any resources. So how can I even know the size of the threats we are facing, and what can I do to protect the people of my town?" Bruno Soares and Buontempo (2019) stated that although co-production has become somewhat of a pre-condition in climate services, depending on the aim and purpose of the service it can be more productive and effective not to implement such a process, (e.g., general products available through a NMHS website). WMO (2018a) stated that the level of engagement will vary depending on the use of the service and should be determined by the users' needs. They distinguish three categories: (i) websites and web-based tools; (ii) interactive group activities; and (iii) focused relationships between a provider and a user. Within these categories the user involvement can range between passive to active.

Wilby and Lu (2022) point out that the user willingness and ability to play an active role in co-development and production processes can be quite diverse, from "off-the-peg" customers to very individual and active ones. Thus, they claim that therefore "providers should allocate time and resources to deepen their understanding of what really matters, better communicate key risks and uncertainties, develop more practical advice, improve sectoral knowledge and find ways to maximise the legacy/impact of their services". Biswas et al. (2022) investigated in a literature review why urban water organisations are still lacking climate change adaptation in their water security management and planning, the key barriers and how they could be solved and enabled. "Lack of support from stakeholders, lack of holistic guidelines and ambiguous policy frameworks were identified as the most critical barriers", the authors stated.

Máñez Costa et al. (2021) analysed co-production processes in 26 ERA4CS projects and identified three levels of intensity of engagement: 1) Low level of intensity: users take up the information from science 2) Balanced level of intensity: mutual influences from science and practice, 3) High level of intensity: Ownership is given to the users in practice (see also Figure 16).

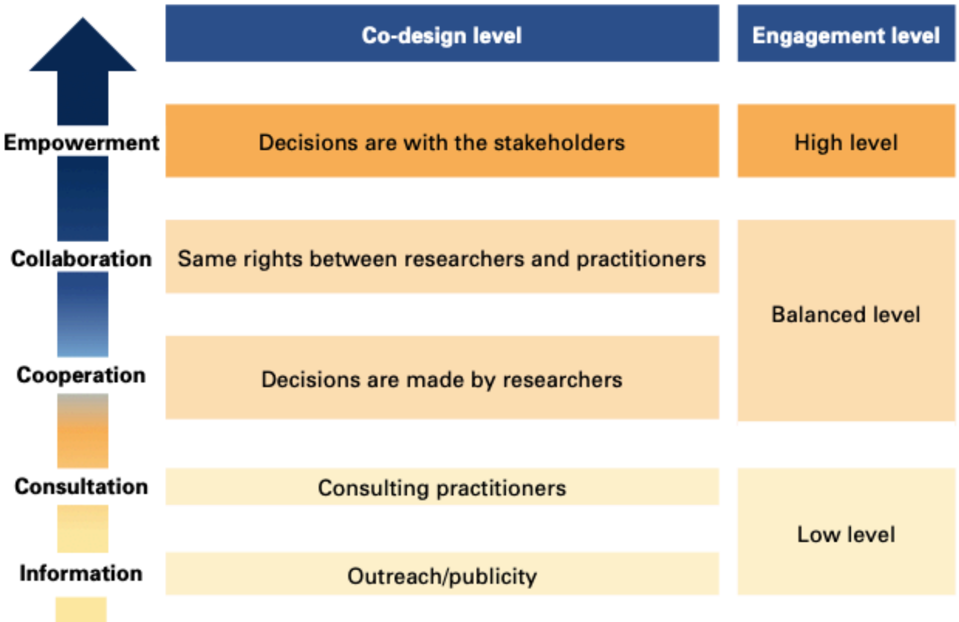

Figure 16: The correlation between co-design and levels of engagement intensity observed in the ERA4CS projects (from Máñez Costa et al., 2021)

WMO's Guidance on Good Practices for Climate Services User Engagement (WMO, 2018a) also categorises the different levels of user interfaces for CS from a more passive to active user engagement (s. Figure 17).

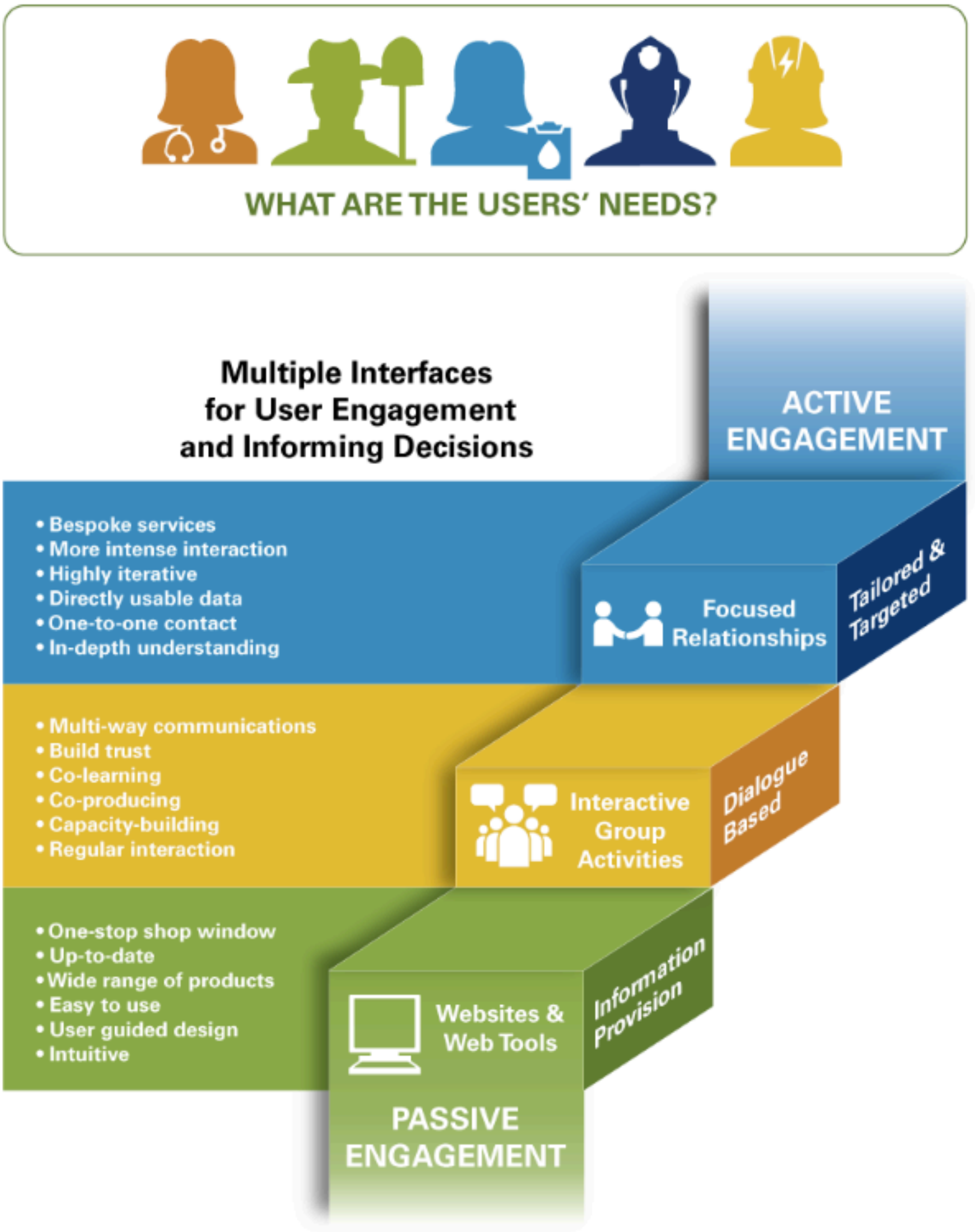

Figure 17: The different levels of user interfaces for climate services (from WMO, 2018a)

Hermansen et al. (2021) summarises four key lessons learnt from engagement in climate services research projects: "i) all end-users have pre-established decision-making processes and tools for their purposes, hence all new information needs to be adapted, ii) one size fits none – and tailoring takes time, iii) building trust between different actors, processes and confidence in new information is key in the tailoring process – and resource-demanding, iv) purveyors and intermediaries can facilitate tailoring processes but need to finance their activities until end-users demonstrate willingness to pay and/or the climate service is readily implemented". The authors stated that more attention needs to be paid to the demand-side of climate services to help viable climate services make it through the innovation "valley of death" (see also Section 3.5).

In summary, almost all co-production models discussed in the literature start the interaction with the users of climate services at the very beginning of the process. Either the question that such a service is supposed to answer is posed directly by the user to the provider or the provider involves possible users of such a service from the beginning in order to create the best possible product.

Most of the literature on co-production focuses on CS designed by public providers. Nevertheless, there are differences in the development of a CS between public and private providers as illustrated in Figure 18. Regardless of the kind of provider, the first consideration within the development of a CS will address the question: which product could be useful for whom, in order to create value (financial or economic but also social or societal values) for the user.

Further differences between public and commercial providers occur during the planning and development phase, as not every approach to create a climate service will be successful. In Figure 18, a number of decisions throughout the development process of a CS may lead into an "exit-strategy", e.g., either due to the lack of a market or of (financial) resources or an incompatible or unsolvable problem. A service provider as an honest broker of climate information will (should) not develop or release a product which is not reliable or fit-for-purpose. Not applying this rule will lead to a loss of trust and credibility for the provider but possibly also to the whole community.

In addition, for commercial (private) providers, the co-production / participation procedure will likely have a different character than for publicly funded providers. Especially with regard to transparency, a commercial provider will not (be able to) disclose all details (Keele, 2019, Condon, 2023), for example, if it is a software product that is not created specifically for an individual customer (-> e.g., products of the start-up Repath (https://repath.earth). On the other hand, Condon (2023) stated that "without transparency behind both data and methods, an end-user cannot properly evaluate the right application of climate risk tools." Máñez Costa et al. (2021) stated that the principles of knowledge co-production are alike if not more relevant for private sector providers because the creation of a useful and used service is the basis for economic success of any private sector concern.

Webber & Donner (2017) argue "that a shift away from the commercialised model of climate services may be necessary to ensure the creation, and consistent delivery, of products that practitioners in the developing world are able to employ in making adaptation decisions."

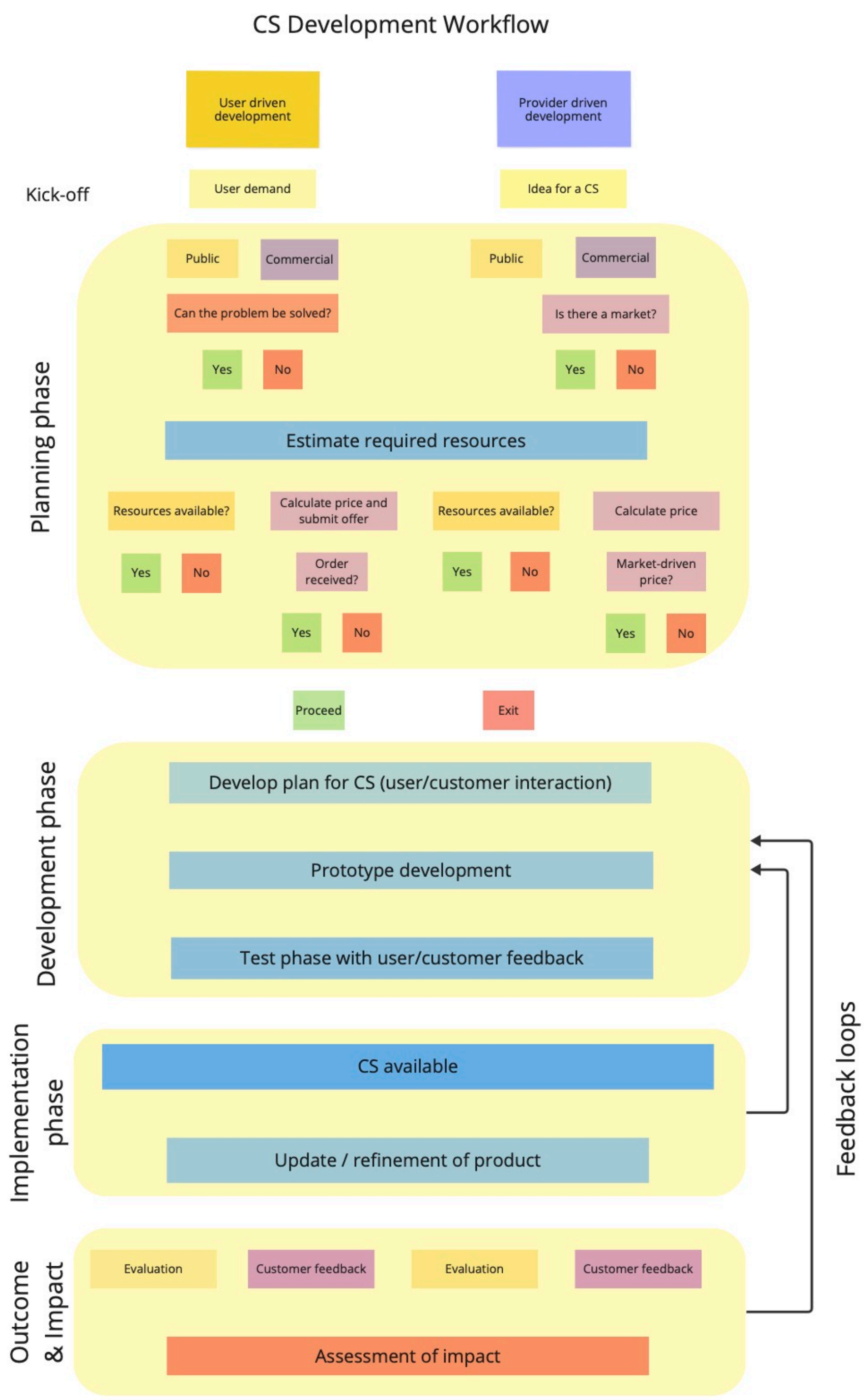

Figure 18: Conceptual diagram of a development workflow for a CS of user (left) or provider initiated (right) CS, and further distinguishing between a public and private / commercial CS.

The co-production process does not end with the completion of the product. User feedback and evaluation should lead to a continuous further development of the service. Ideally, the provider also supports the user in the implementation of the changes announced by the climate service. Boon et al. (2022) commented: “Studies that assess the results of climate services tend to focus on evaluating (perceived) usability, though uptake, impacts and outcomes of services are rarely assessed systematically”. Englund et al. (2022) proposed four methodological guidelines to evaluate co-produced climate services: “(i) engaging in adaptive learning by applying developmental evaluation practices, (ii) building and refining a theory of change, (iii) involving stakeholders using participatory evaluation methods, and (iv) combining different data collection methods that incorporate visual products”.

Vaughan et al. (2019) summarises evaluation procedures in various case studies and recommended a three-phase approach to evaluation, beginning with “(1) rigorous efforts to understand who accesses their information; developing (2) a nuanced understanding of how that information is used; and culminating with (3) a characterization of the utility and value of the information in context”. Schuck-Zöller and Keup-Thiel (2018) provided a comprehensive list of criteria and indicators for the evaluation of output and outcome of CS (see sections 3.4 and 3.5).

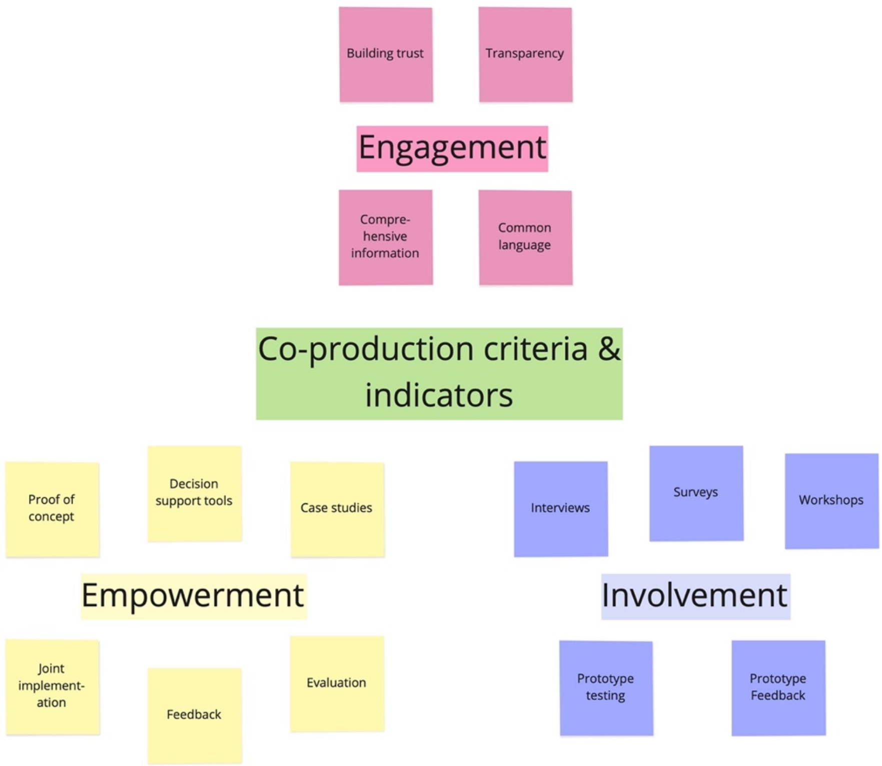

Figure 19. Elements of a co-production process of a CS

Figure 19summarises important criteria and indicators of a co-production process of a CS, based on the input of the above-mentioned literature. Along the three major criteria mentioned in Figure 19, high-quality co-production can be characterised by:

- **Engagement**
  - User participation from the beginning or a user-initiated process
  - Develop of a mutual understanding and communication between providers and users
- **Involvement**
  - Continuous exchange between user and provider
  - Joint testing of the climate service
- **Empowerment**
  - Feedback loop for improvements (Empowerment)
  - Evaluation of user behaviour and user satisfaction

Which parts of a co-production process have potential for standardisation? Most of the criteria are qualitative measures. Nevertheless, it should be further discussed whether and which key elements of a co-production process are required for a successful CS.

3.4 Output (characteristics of the climate service as such)

Climate service products and applications are developed on the basis of the input / data described in section 3.2 and ideally within a co-production process as discussed in section 3.3. The range of CS products is very broad, from general and freely available products, which do not address a specific clientele (e.g., a seasonal outlook), up to individual and specific applications developed together with/for a user. This latter option is in particular frequently found for applications from the private sector, e.g., by consulting companies but also in prototype services developed by specific research projects (e.g., Abegg et al., 2021, or the strategy of the Climate Service Center Germany: https://www.gerics.de/methods/prduct_development/index.php.en)).

Since the character of these applications can be very diverse, the market for climate services has become extremely broad and diversified within a very short time period and has thus also become very crowded and opaque, especially for users (Perrels et al., 2020). For an overview of the CS market and products see Section 3.1 and previous projects such as MARCO (EU-MARCO, 2018), EU-MACS (EU-MACS, 2018) and Climateurope (Climateurope, 2017; Hewitt et al., 2017a, Cortekar et al., 2020, Larosa & Mysiak, 2019).

Weichselgartner and Arheimer (2019) note that "It is ill-advised to believe that the success of climate services can be increased only through "more accurate data" or "better targeted information." Instead, what is important in the context of the product is its usability for the user/customer, i.e., ensuring the data that is available can be transformed into the necessary information that users need. A broad variety of products exists ranging from purely web-based information offerings, through interactive tools and apps, to individually designed applications and advisory services (see Fig. 19). Visscher et al. (2020)

suggested a typology of CS divided into freely (or cheaply) available products vs. commercially ones (see Table 4).

Thus, usability of the product for the envisaged purpose and user is an important quality factor of the product. Is the targeted user / customer satisfied with the product? Ultimately, the use and satisfaction of the user/customer is of elementary importance. Only a service that is used and even recommended to others has evidence of high acceptance and can be regarded as a high-quality product. Hence, evaluations / assessments by users are of considerable importance (see section 3.3). For meaningful and comparable evaluations, it would be desirable to define a minimum standard for evaluations. DeGEval (2017), defined a set of major criteria for evaluation: usefulness, feasibility, fairness and accuracy, with detailed indicators for each of those criteria. (Note: publication in German only)

Furthermore, a high-quality product is also characterised by regular product maintenance, including updates and long-term availability. Here, in particular, publicly funded project-based pilot services often lack continuity because no sustained funding for updates and maintenance is available once the project is completed. (Bruno Soares and Buontempo, 2019). Thus, sustained funding of CS beyond pilot and prototype developments of products are also an important quality factor for CS.

Table 4: A Typology of Climate Services (from Visscher et al., 2020)

	Generic	Customised
Focused	• **Maps & Apps** • General climate services • For all users • Made freely or cheaply available	• **Expert Analysis** • Mono- or multidisciplinary climate services • Tailored to specific decision-making situations • Offered commercially
Integrated	• Mutual climate- and climate policy services • Among knowledgeable peers • Made freely or cheaply available	• **Climate-inclusive Consulting** • Interdisciplinary management, engineering, or policy services including climate data • Tailored to specific decision-making situations • Offered commercially

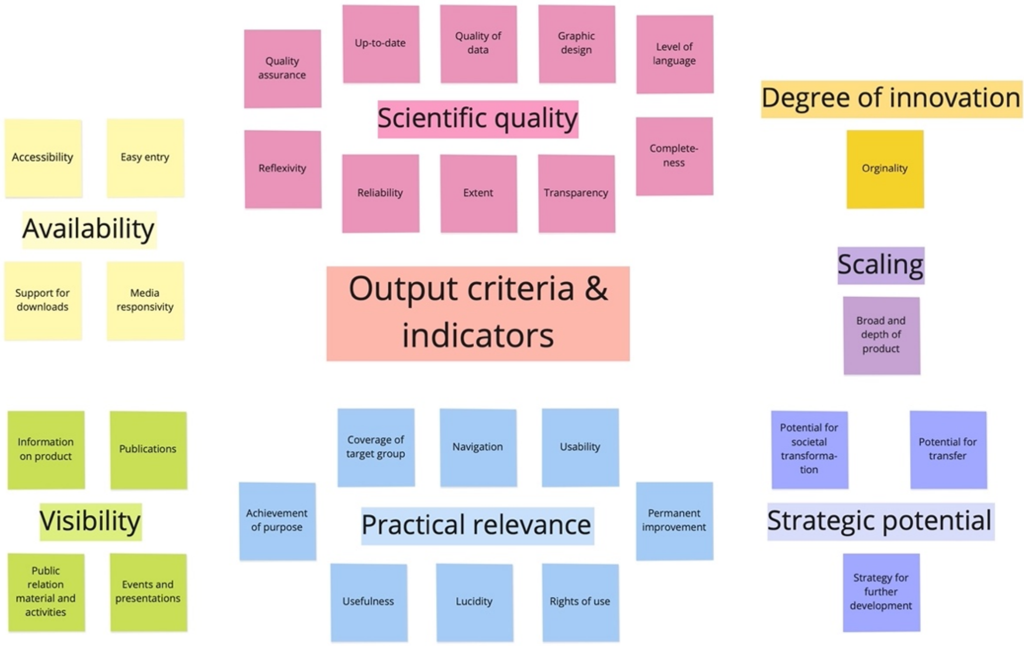

Figure 20. Output criteria and indicators (after Schuck-Zöller and Keup-Thiel (2018)

The possibility of certifying a CS product would be very helpful for both providers and users of climate services. Providers, especially those in the private sector, could use this for advertising purposes, and users could use the certification to increase confidence and trust in the quality of the product and also enable better comparability in the diverse market. In this respect, a certification / standardisation procedure for a climate service (if applicable / possible) could be a step forward for everybody. Nevertheless, not all CS products (or parts) will be suitable for standardisation (see D1.1 & D1.2 of WP1).

Schuck-Zöller and Keup-Thiel (2018) put together a detailed checklist of key criteria and output indicators for a high-quality climate service (see Figure 20). The major (high-)quality criteria for the output part of a climate service can be summarised as follows:

- **Scientific quality**:
  - Climate service product is based on up-to-date high-quality data, which is suitable for the application. **-> Reliability**
  - Limitations and uncertainties of the product are well documented, accessible and understandable for the user **-> Transparency**
- **Fit-for purpose**:
  - The information provided by a CS is easy to understand, ready to use and provides usable results and guidance. -> **Lucidity & clarity**
- **Availability:**
  - The product is easily findable and accessible

- The product is freely available or the user has appropriate rights of use
- Timely delivery of the product to allow appropriate and timely action by the user

(Note: different policies of public and private providers have to be taken into account)

Which quality indicators and parameters of a CS product can be standardised? For some criteria and indicators such as scientific and methodological quality standards (see also Section 3.23.2) are already available (see Deliverable 1.1 of CE2) or could be developed, for others like strategic or practical criteria further discussions and investigation are required.

3.5 Outcome (whether and how the climate service is used)

As indicated in section 3.4, the success of a climate service depends on the extent to which the product is actually used enabling the user to make informed decisions and actions and to which consequences and impacts the use of the service leads. Bridging the so-called "valley of death" between technical invention and (commercially) successful innovation (Hermansen et al., 2021 and Swart et al., 2021, Figure 21) is an important issue in this context.

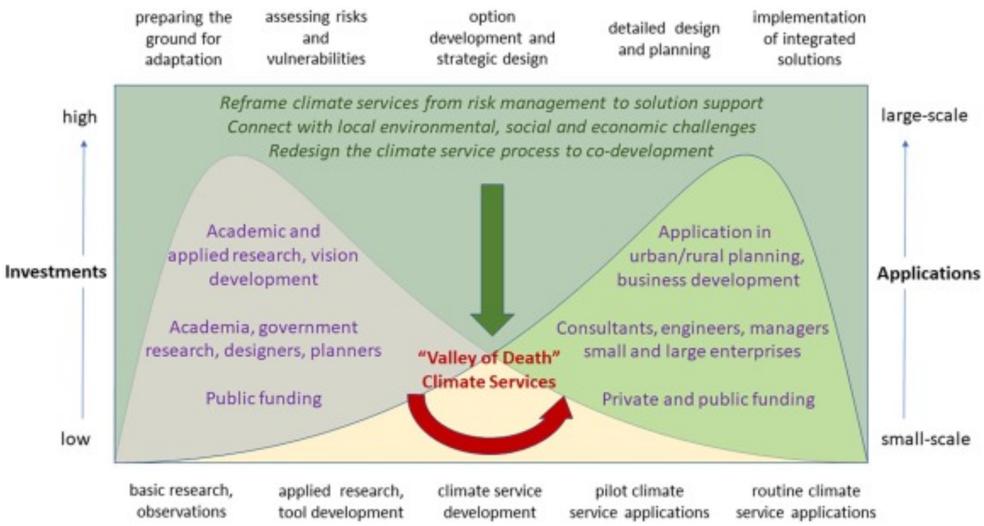

Figure 21. Bridging the valley of death (from Swart et al., 2021).

Problems often occur at this interface so that viable climate services developed "upstream" by (public) providers do not reach the "downstream" part. Damm et al. (2020) stated in a study of the tourism sector in Austria: "The main barriers to the use of CS in tourism include wide- spread low levels of risk awareness, a certain degree of risk denial, a lacking sense of urgency due to (yet still) little financial pressure, and rather short business decision cycles, which lead to a low prioritisation of climate issues. Furthermore, lack of knowledge of existing services and their benefits, lack of applicability, and distrust in climate services restrict their use". Guentschev et al. (2023) addressed the following issues of "up-scaling" a CS from the prototype to a fully-fledged CS: "Barriers include problems with leadership (e.g., the absence of a long-term vision and/or strategy for upscaling); limited funding or lack of a business model for the service at scale; issues with the enabling environment for upscaling (e.g., poor policy context, inadequate governance systems); and poor user engagement".

Thus, a climate service is only valuable and useful if it can be successfully applied by the user and/or represents an (added) value for them and ultimately changes actions in a (positive) way. Examples can be found in the area of seasonal forecasts of temperature and precipitation, on the basis of which farmers can prepare irrigation measures or pest control and thus minimise yield losses or optimise yields (e.g., MEDGOLD project: Dell'Aquila et al., 2023; Terrado et al., 2023a). The management of water reservoirs for energy production or drinking water supply also fit in this category (Delpiazzo, 2022, WMO, 2021, 2022b, https://aquaclew.eu/climate-services-in-hydropower-sector/). In view of the changes to be expected as a result of climate change, long-term decisions on climate adaptation and mitigation are necessary in order to minimise economic and social risks. This includes protection against extreme events (heat, storms, extreme precipitation, droughts) (e.g., WMO, 2020), but also long-term urban planning, flood protection or forest conversion (e.g., Climate ADAPT (https://climate-adapt.eea.europa.eu), UNHSP, 2014, Rizvi et al., 2015).

In addition to the pure information about expected (climate-related) changes, the development of options for action based on this information together with the users is of particular advantage for the successful application of a climate service. In this context, it is particularly important for users to be informed about the uncertainties in statements on climate predictions and future climate developments. Due to the long-term nature of some processes, measuring the impact of such climate services is often only feasible and meaningful on longer time scales.

Another aspect in evaluating the success of climate services are recommendations of the service by users. Furthermore, direct or indirect user feedback is very helpful for the provider to further improve the products.

As described in section 3.3 regular evaluation procedures help to assess the outcome and quality of the climate service, in particular from the user side. See Zahid et al. (2020), Schuck-Zöller et al. (2017), Vaughan and Dessai (2014), Wall et al. (2017) for details on evaluation procedures. Schuck-Zöller and Keup-Thiel (2018) (see Figure 22) provided a number of criteria and indicators to check the quality of the outcome of a climate service.

In summary, major quality criteria for the outcome part of a climate service can be summarised as follows:

- **Use of the Service**:
    - Climate service is used successfully (several times) by the customer
    - Use of the climate service fulfils expectations and to envisaged impact

- **Satisfaction**:
    - User recommends the climate service to others
    - User provides positive feedback
    - User provides suggestions for further improvements of the product
- **Valorisation**:
    - The service becomes operational, can be applied and widely used
- **Users Learning effects**:
    - The usage of the CS leads to the desired societal transformation or changes (impact)

Which parts of outcome parameters have potential for standardisation? Outcome criteria are by far more difficult to quantify, thus, it will be much more difficult to develop standardised procedures to measure the outcome of a CS.

Figure 22: Outcome criteria & indicators (after Schuck-Zöller and Keup-Thiel, 2018)

4 Discussion / Conclusions

Summarising the quality criteria found in the literature for the different components of the value chain of CS, a number of indicators for “high quality” were presented in section 3. The Word-cloud below displays the content of Table 5 that summarises criteria and indicators of the different components of a CS along the logic model used in this study.

Figure 23: Quality criteria and indicators for the components of CS along the value chain discussed in section 3.

Table 5: Summary of quality criteria and indicators for the components of CS along the value chain discussed in Section 3.

	Input	Co-production	Output	Outcome
Accuracy & reliability	Data quality	Comprehensive information	Data quality	Scientific connectivity
	Quality assurance	Proof of concept	Quality assurance	
	Uncertainties documented	Tailored to user needs	Completeness	
	Metadata according FAIR principles		Reliability	
	Transparency	Transparency	Transparency	
	Standards		Reflexibility	
	Up-to-date		Up-to-date	
Availability	Accessibility	Adequate resources	Accessibility	Timely delivered
	Easy entry	Timely delivered	Easy entry	
	Sustained funding		Sustained funding	
	Support for downloads		Sustained support	

	Input	Co-production	Output	Outcome
	Sustained data archive		Media responsiv-ity	
	Free or afforda-ble data		Affordable prod-uct	
Degree of inno-vation	State-of-the-art models	Equitable meth-ods	Permanent im-provement	Degree of inno-vation
			Inventive	Evaluation
			Strategy for fur-ther develop-ment	
			Sustainable prod-uct	Sustainable solu-tion
Credibility & le-gitimacy	Documentation	Building trust	Information on product	Licensing
	Transparency	Transparency	Events & presen-tations	Transferability
	Proven scientific expertise	Evaluation	PR material & ac-tivities	Operationalisa-tion
	Publications	Feedback	Publications	Recommenda-tions
Tailored to user needs	Demand driven	Common lan-guage	Level of language	Duration of use

	Input	Co-production	Output	Outcome
	Appropriateness	Joint implementation	Achievement of purpose	Depth of use
	Completeness	Decision support tools	Lucidity	Frequency of use
		Case studies	Coverage of target group	Suitable for target group
		Demand driven	Usefulness	Applicability for education
			Rights of use	Relevance
			Potential for societal transformation	Societal transformation capability
			Potential for transfer	Improvement of expertise
				Impact of product
				Value for user

Most of the criteria are qualitative and often depend on the user (group) and the context the service is used. Thus, a climate service product (or the co-production process) might not be universally rated to be good or bad, as it might be suitable for a specific user group but not suitable for a different audience, in particular, if the product is not confined or designed for a specific user group (e.g., a free web-portal or mobile application) (see WMO, 2018a).

Nevertheless, there are also clear quality indicators that are independent of the user group, e.g., data quality and usability for the problem to be solved or comprehensive meta data information. And an end-to-end co-production process ensures to the extent possible that the CS product is fit-for-purpose and can be applied as desired by the user.

The major criteria and indicators for high-quality climate services can be grouped under a set of principles, taking into account the scientific basis (input / data) and the co-production process (user focus, collaborative and transparent processes) to ensure the development of accessible, sustainable, and equitable products that fulfil the user needs.

4.1 Initial Guiding principles for high-quality Climate Services

Based on the literature review performed for this study, high-quality climate services should be designed and delivered in accordance with the following guiding principles:

1. **Science-based**: Climate services should be based on credible science and evidence. Service providers should use the best available scientific data, models, and methods to develop and deliver climate information. References to peer-reviewed literature and / or official certificates (e.g., Certified Consulting Meteorologists of the American Meteorological Society (https://www.ametsoc.org/index.cfm/ams/education-careers/careers/ams-professional-certification-programs/certified-consulting-meteorologist-program-ccm/) can build confidence and trust in the user community.

2. **User-focused**: Climate service providers should engage with users and stakeholders to understand their needs, priorities, and decision-making contexts. This will help ensure that climate information is relevant, usable, and actionable.

3. **Transparent**: Climate services should be transparent about their data sources, methodologies, and assumptions. Climate service providers should clearly communicate the limitations and uncertainties of climate information to users and stakeholders to build and increase trust. Here standards and guidelines (e.g., such as the FAIR principles) can help the user community to develop trust in the product and to be aware of the limitations.

4. **Collaborative**: Climate services should be developed and delivered through collaboration among different stakeholders, including scientists, policymakers, practitioners, and users. Service providers should engage in regular dialogue with users and stakeholders to ensure that climate information is useful and relevant. Feedback by the users provide valuable information to further improve the quality of the product. Thus, feedback and evaluation processes should be a vital part of the CS development.

5. **Timely and accessible**: Climate services should be provided in a timely and accessible manner. Service providers should use user-friendly formats and platforms to deliver climate infor-

mation to users, taking into account differences in literacy levels, languages, and technological infrastructure. Information should be easily locatable and (to the extent possible), be freely accessible.

6. **Sustainable:** Climate Services should be designed to be sustainable over the long term. Service providers should ensure that their services are adequately resourced over time, and that they have the capacity to adapt to changing user needs, new scientific developments, and evolving policy contexts.
7. **Equitable**: Climate service products should be freely accessible and usable to the extent possible, to ensure that they are available to users with limited resources. The outcome of a climate service should (to the extent possible) take equitable measures into account.

By following these guiding principles, climate service providers can help ensure that their services are of high quality, and that they support effective decision-making and action on climate change. As pointed out in the discussions, the overall quality of a climate service depends on a number of factors and the context in which a specific service and product is used. Thus, even though many quality criteria might be fulfilled, a success cannot be guaranteed.

Which elements of a climate service development could be a subject to standardisation or certification?

Standardization and / or certification of processes has different goals: e.g., it ensures comparability, maintains quality, provides transparency and builds trust. As climate services are very inhomogeneous and complex, a common standardization procedure which can be applied to all CS is certainly unrealistic. On the other hand, certain elements and procedures of a CS might be feasible to be standardized. Standards can pave the way for certification of elements of climate services such as:

- Certification of provider (e.g., based on requirements for scientific expertise, standards for input data quality, etc.)
- Certification of products (based on product quality, standards for metadata information, sustainable product)
- Certification of elements of a (co-production) process (e.g., based on standards for user-provider interactions, or feedback and evaluation processes)

As pointed out in this document, parts of the value chain of a climate service can be standardised or might have potential to be standardised in future. Most advanced are parts and processes related to data and quality control of input parameters of a climate service. Here, standards already exist or are under development (UKCRP, 2022). As co-production is a widely accepted method to improve / ensure high quality products and outcome of a service, it should be discussed which parts of co-production e.g., quality control, quality assessments and evaluation procedures can be standardised.

Although one goal of standardization is to maintain comparable quality, standards are not necessarily based on the highest achievable quality of certain parameters. Nevertheless, criteria and indicators for high-quality provide a sound basis for the development of standards and certifications.

4.2 Next steps:

These guiding principles for high-quality climate services are based on a comprehensive but qualitative literature review. During the lifetime of the Climateurope2 project we will add further information and knowledge obtained by further desk research, community engagement, case studies, surveys and workshops covering more aspects of the climate service landscape. These results will be summarised in D4.4 and D4.11 at month 24 and 48 respectively.

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