CLINT

CLIMATE INTELLIGENCE

EU CLIMATE SERVICES ON THE IMPACTS OF EXTREME EVENTS

June 2022

This project is part of the H2020 Programme supported by the European Union, having received funding from it under Grant Agreement No 101003876

Programme Call:	Building a low-carbon, climate resilient future: climate action in support of the Paris Agreement (H2020-LC-CLA-2018-2019-2020)
Grant agreement ID:	101003876
Project Title:	CLINT
Partners:	POLIMI (Project Coordinator), CMCC, HEREON, CSIC, SMHI, HKV, E3M, TCDF, DKRZ, IHE, ECMWF, UAH, JLU, OGC, UCM
Work-Package:	WP6: AI-enhanced Climate Services to foster adaptation at the pan-European scale
Deliverable #:	D6.1
Deliverable Type:	Report
Contractual Date of Delivery:	30 June 2022
Actual Date of Delivery:	29 June 2022
Title of Document:	EU Climate Services on the impacts of Extreme Events
Responsible partner:	SMHI
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Content of this report:	Review of the existing EU Climate Services with a focus on Extreme Events' impacts on the water, energy, and food sectors; report suggestions and requirements gathered from stakeholders in dedicated meetings.
Availability:	This report is public.

Document revisions		
Author	*Revision content*	*Date*
Ilias Pechlivanidis, Ursula McKnight, Andrea Popp, René Capell (SMHI), Elena Xoplaki (JLU), Ioannis Mitsios, Alessia De Vita (E3M), Matteo Giuliani, Andrea Ficchi, Andrea Castelletti (POLIMI)	D6.1_v01	31 May 2022
Harilaos Loukos	Internal revision of D6.1_v01	16 June 2022

Carmen Alvarez-Castro	Internal revision of D6.1_v01	20 June 2022
Ursula McKnight	D6.1_v02	24 June 2022
Andrea Castelletti	Coordinator final check of D6.1_v02	27 June 2022
Ilias Pechlivanidis	D6.1_v03	28 June 2022
Guido Ascenso, Elena Matta (POLIMI)	D6.1_F (final version for submission)	29 June 2022

About CLINT

The main objective of CLINT is the development of an Artificial Intelligence framework composed of Machine Learning techniques and algorithms to process big climate datasets for improving Climate Science in the detection, causation, and attribution of Extreme Events (EEs), namely tropical cyclones, heatwaves and warm nights, droughts, and floods. The CLINT AI framework will also cover the quantification of the EE impacts on a variety of socio-economic sectors under historical, forecasted, and projected climate conditions and across different spatial scales (from European to local), ultimately developing innovative and sectorial AI-enhanced Climate Services. Finally, these services will be operationalized into Web Processing Services, according to the most advanced open data and software standards by Climate Services Information Systems, and into a Demonstrator to facilitate the uptake of project results by public and private entities for research and Climate Services development.

More information: https://climateintelligence.eu/

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Abbreviations

AI	Artificial Intelligence
BA	Bias-Adjustment
CS	Climate Service
CII	Climate Impact Indicator
DST	Decision Support Tool
ECV	Essential Climate Variable
ML	Machine Learning
SCF	Seasonal Climate Forecast
SWOT	Strengths Weaknesses Opportunities Threat (analysis)

EXECUTIVE SUMMARY

Climate Services (CS) are being recognized as valuable assets for supporting adaptation, mitigation, and disaster risk management today and under future climate change scenarios when Extreme Events (EE) are expected to increase in both frequency and intensity. Future projections of these EE are, however, more uncertain than the predicted thermodynamic changes, limiting the implementation of effective adaptation strategies on local and regional scales and the value of information required to meet the Paris Agreement. At the same time, CS can benefit from the unprecedented availability of climate data to strengthen our understanding of the climate system and processes. In addition, recent advances in Artificial Intelligence (AI) offer a unique opportunity for making the most out of these data with the aim of providing easily accessible, timely, and decision-relevant information to policy-makers and end-users and of contributing to sustainable development strategies across different socio-economic sectors that need timely and effective climate actions.

The main objective of CLINT is the development of a Machine Learning-based framework composed of a suite of AI techniques and algorithms to process the Copernicus climatological big dataset for supporting the detection, prediction and attribution of EE, such as tropical cyclones, tropical nights, heatwaves, and droughts, along with the quantification of their impacts on a variety of socio-economic sectors under historical and projected climate conditions and across different spatial scales, from the whole European to the river basin scale. CLINT will hence support users and local decision-makers to implement timely and effective adaptation and/or mitigation measures.

The document is initially an introduction to state-of-the-art Climate Services covering the pan-European domain. This is achieved through a presentation of various operational services that address (part of) the needs in the water, energy and food sectors. Moreover, the document reviews the identified barriers to Climate Services uptake together with a SWOT (strength-weakness-opportunity-threat) analysis of the European market. In addition, a user survey contributes to understanding the needs of users affected by climate variability. The survey has been co-designed to bridge the knowledge gap between climate service providers and users. The answers helped us to better understand the regional, national and continental contexts and user needs, and, finally, improve the basis upon which long-term decisions are made.

KEYWORDS

Climate Services; User needs; Seasonal predictions; Centennial projections; Extreme events; Water sector; Energy sector; Food sector

1 INTRODUCTION

1.1 Purpose of this document

The CLINT project aims to innovate and enhance existing Climate Services (CSs) and their impact-based products and consequently support several EU policies in the water-energy-food nexus. CLINT's work package (WP) 6 will be driven by Machine Learning (ML) tools and methods developed in other WPs and further used as input AI-enhanced EE predictions and knowledge gained in WP3-5. In line with the Copernicus programme (an EU programme aimed at developing European information services based on satellite Earth Observation and in-situ data) vision of 'products and services to serve specific national (or trans-national), regional or local information needs, as well as the needs of niche European and global markets, work in WP6 will be carried out on the pan-European scale, targeting products used in Climate Services to improve preparedness for extreme impacts on the water, energy and food sectors and their interconnections in a nexus perspective. These services will showcase seasonal and climate predictions for decision- and policy-making at the European level and will boost innovation in all three climate-sensitive sectors and beyond. Remarkably, the improved understanding of extreme impacts will result in a better assessing the needs and the gaps of current EU policies, including, among others, the Climate Adaptation Strategy, the Common Agricultural Policy, the EU floods directive, the EU Water Framework Directive, and the Clear Planet for all strategy. Service enhancement through AI and ML will, for the first time, offer products that today are only achievable with considerable efforts in terms of expert involvement and super-computing capacities. They will not only let the experts' judgement enter just in the last phases of the decision-making process based on the service but will also open new unexplored possibilities by analysing unforeseen connections and relationships existing in the data.

The objectives of WP6 are to:

- Evolve water-energy-food-related Climate Services for future time horizons by applying AI/ML tools and methods to characterise, estimate, predict, and project extreme impacts.
- Advance extreme impact predictions at the European scale through an evolution of the impact-based models and the use of state-of-the-art seasonal prediction systems and climate projections.
- Quantify the added value of developed products and services through a rigorous evaluation procedure and predictability benchmarking against existing Copernicus Climate Change Service products.
- Explore the AI-enhanced services and products to better understand the complex and dynamic interrelationships between water, energy and food (nexus) towards more coordinated management and use of natural resources across sectors and scales.

To achieve part of the objectives listed above, this document addresses a series of specific objectives that include:

- Setting up a list of terminologies used in CSs and by the machine-learning community.

- Listing strengths, weaknesses, opportunities, and threats in CSs, and providing the current research and innovation status.
- Presenting the state-of-the-art pan-European CSs for the water, energy and food sectors.
- Designing an online user survey that allows improved understanding of the long-term decision-making practices.
- Analysing the user survey results in order to better understand the regional, national and continental contexts and user needs, and improve the basis upon which long-term decisions are made.

1.2 Structure of this document

The deliverable is structured in five chapters:

- **Chapter 1** (current) is the introduction to the document presenting the scope.
- **Chapter 2** introduces the definition of Climate Services and presents the recently identified barriers and bridges, together with a SWOT analysis for the European market.
- **Chapter 3** presents the information found in state-of-the-art operational Climate Services for the pan-European domain. These services are specific to the water, energy and food sectors.
- **Chapter 4** presents the CLINT user survey that aims to bridge the knowledge gap between climate service providers and users. Moreover, it presents the analysis of the responses and provides insights.
- **Chapter 5** concludes the main body of the document.

2 BACKGROUND ON CLIMATE SERVICES

2.1 Introduction to Climate Services

Access to usable weather and climate information is critical for societies to prepare for, mitigate and adapt to risks and opportunities afforded by climate variability and climate change (Bruno Soares et al., 2018). Recent advances in modelling capabilities and data processing combined with vastly improved observation tools and networks have resulted in the expansion of available weather and climate information, from historical observations to seasonal climate forecasts, as well as decadal climate predictions and multi-decadal climate change projections. However, it remains a key challenge to ensure this information reaches the intended climate-sensitive sectors (e.g. water, energy, agriculture, health) and is fit-for-purpose to guarantee the usability of climate information by these users and downstream services. As a result, there is growing emphasis on tailoring climate information and services to these sectors, shaped by user-specific needs, as well as on overcoming identified barriers that continue to limit the uptake of climate information in society.

Climate Services, according to the European Commission's Roadmap for Climate Services (2015), cover *"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 services in relation to climate that may be useful for the society at large."*

Hence, CS providers develop science-based and user-specific information relating to past, present and potential future climate, assisting society in adapting to climate variability and change. Information about climate, climate change, and impacts on natural and human systems, as well as mitigation and adaptation strategies, are tailored to the specific user requirements. Climate Service users include economic, administrative, political and scientific stakeholders across sectors and disciplines in society. Notably, these users not only need access to this information but also need to better understand how to choose from among the many available datasets (e.g. often regional or local climate projections downscaled from global climate models) and assess their credibility in order to use them wisely in practice (Barsugli et al., 2013). This requires going beyond improving the technical and scientific capabilities to ensure attention while also refining and updating the usability of climate information for various user needs across the Water-Energy-Food (WEF) sectors and their nexus. Hence, there is a need for a direct assessment of the added value in decision-making and its impact from the generated CSs versus the "traditional" decision-making process (benchmark). This latter task is vital, considering the various and sometimes conflicting spatial and temporal scales of decision-making across these sectors.

2.2 Rational for Climate Services

Access to tools, products, data and services is essential in helping societies better prepare, mitigate and adapt to climate change. Consequently, the field of CSs has been developing rapidly, with many different types of services and service providers evolving worldwide (Panenko et al., 2021). Policy-makers, planners, investors and vulnerable communities need climate information in user-friendly formats so that they can prepare for expected trends and changes. They need good-quality data from national and international databases on, e.g., temperature, rainfall, wind, soil moisture, and ocean conditions. They also need long-term historical averages of these parameters, as well as maps, risk and vulnerability analyses, assessments, and long-term projections and scenarios (Buontempo et al., 2018). Depending on the user's needs, these data and information products may be combined with non-climate data, such as agricultural production, health trends, population distributions in high-risk areas, road and infrastructure maps for the delivery of goods, and other socio-economic variables. The aim is to support efforts to prepare for new climate conditions and adapt to their impact on water supplies, health risks, extreme events, farm productivity, infrastructure placement, etc.

The current landscape of CS is highly diverse, with an ever-growing range of programs, projects and portals involved in developing and/or providing CS at different administrative levels and spatial-temporal scales (Weichselgartner and Arheimer, 2019). This diversity, i.e. of producers, users and policy arenas, has furthermore generated a highly heterogeneous data- and information-oriented service landscape that will require efforts to harmonise and standardise key aspects (see ClimatEurope; https://www.climateurope.eu/), including the conceptualisation, operationalisation and evaluation of CS information and data (Weichselgartner and Arheimer, 2019). Thus, it is paramount to involve the user community - especially those responsible for climate-informed decision-making and climate-smart policy and planning - in producing, translating, transferring and using climate information and knowledge. This will lead to more effective engagement with users, also increasing the uptake of the best available climate science through improved confidence in scientific knowledge.

The World Meteorological Organisation (WMO) has set up the Global Framework for Climate Services (GFCS), a global partnership of governments and organisations that produce and use climate information and services, building on continued improvements in climate forecasts and climate change scenarios to expand access to the best available climate data and information. GFCS thus accelerates and coordinates the technically and scientifically sound implementation of measures to improve climate-related outcomes at national, regional and global levels. It seeks to enable researchers, producers, and users of climate information to join forces to improve the quality and quantity of Climate Services worldwide. Pooling expertise and resources through international cooperation is expected to help expand the production, distribution and use of relevant and up-to-date climate information, particularly in developing countries. It is envisioned that UN agencies, regional institutions, national governments and researchers will work together through the GFCS to disseminate climate data, information, services and best practices. This collaboration will build greater capacity in countries to manage the risks and opportunities of climate variability and change and adapt to climate change.

Information resources are urgently needed for building climate resilience and preparing adaptation plans. GFCS is currently focusing on developing and delivering services in five priority areas, which present the most immediate opportunities for bringing benefits to human safety and well-being:

- Water

- Energy
- Agriculture and Food Security
- Disaster Risk Reduction
- Health

Furthermore, the GFCS implementation plan guides the development of climate information resources with the additional aim of creating partnerships and building trust with users. The implementation of the GFCS has five components:

- Observations and Monitoring
- Climate Services Information System
- Research, Modelling and Prediction
- User Interface Platform
- Capacity Development

These components ensure the necessary infrastructure is in place for generating climate data and information which can further address user needs; enable the continued advancement of climate science (data, tools, etc.); create a platform for bridging producers with users to ultimately promote effective decision-making; and support capacity development (in terms of policies; institutions; human resources) to enhance the uptake of Climate Services worldwide.

2.3 Applied terminology in CSs and AI/ML

Climate scientists are increasingly asked to co-produce knowledge with actors from the user community to improve decision-making regarding climate change adaptation (Porter & Dessai, 2017). This critical interaction requires that users of these data are familiar with similarly evolving Climate Services terminology, often developed by scientists. Table 2.1 provides an overview of the latest set of terms and definitions typically used by CS developers, providers, and the AI/ML community. These definitions have been compiled by the CLINT partners, experts in the scientific fields of AI/ML and CSs. The definitions were tailored to bridge the communication gap (due to technical and/or programming backgrounds) between the two communities and set a mutual understanding.

Table 2.1 Overview of the latest set of climate service terms (with acronyms where relevant) and their respective general definitions and sources (where available and internally reviewed), together with AI/ML terms that are commonly found in CSs. The terms are organised according to their primary context category: either related to CS or, more specifically, to AI.

Term (acronym)	Definition	Sources, where available
Climate Services		
Application Programming Interface (API)	An API provides a set of interfaces from an application environment to an execution environment. The execution environment provides services to the application environment.	
Benchmark Climate Services	Existing Climate Services (including models and data) used as a benchmark (i.e. baseline for comparisons) for assessing the value of the enhanced Climate Services.	
Bias Adjustment in CSs	It is the effort to reduce the systematic errors (biases) that are observed in the outputs of both Global and Regional Climate Models (GCM, RCM). There can be errors in the timing or the amount of flux and are due to limited spatial resolution (large grid sizes), simplified thermodynamic processes and physics or incomplete understanding of the global climate system. The use of uncorrected outputs in impact models or climate impact assessments can often give unrealistic results, while the quality of the observational datasets determines the quality of the bias adjustment.	
Big Data Analysis	Scrutiny performed on a massive volume of data with the purpose of obtaining meaningful results, such as trends or preferences.	
Centennial projections	Simulations of Earth's climate typically until 2100 based on different emission scenarios.	

Term (acronym)	Definition	Sources, where available
(Un)Certainty in probabilistic prediction	The level of agreement between these ensemble members can be translated to a prediction certainty. If most members agree, then it is relatively certain. If many members do not agree, the forecast/prediction is uncertain.	
Climate Impact Indicator (CII)	CII is an aggregate quantitative measure used to show the impact of climate change and extremes on complex environmental phenomena in terms of trends and variability.	
Climate Services (CS)	According to European Commission's Roadmap for Climate Services (2015), CS cover "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 services in relation to climate that may be useful for the society at large." Hence Climate Services providers develop science-based and user-specific information relating to past, present and potential future climate and therefore assist society in adapting to climate variability and change. Information about climate, climate change, and impacts on natural and human systems, as well as mitigation and adaptation strategies, is tailored to the specific user requirements. Climate Service users include economic, administrative, political and scientific stakeholders across sectors and disciplines in society.	
Climate Projections	Projections are estimates of how the Earth system might change under different scenarios of CO_2 emissions.	
Cloud Computing	Paradigm for enabling network access to a scalable and elastic pool of shareable physical or virtual resources with self-service provisioning and administration on-demand. NOTE – Examples of resources include servers, operating systems, networks, software, applications, and storage equipment.	

Term (acronym)	Definition	Sources, where available
Data Management & processing	Provision of calibrated datasets, data archiving, data certification, and data curation, e.g., provision of validated datasets to consultancies for further analysis.	
Data Ownership	Legal rights and complete control over a single piece or set of data elements governing the acquisition, use and distribution of data assets. NOTE: Normally, the data owner is the organisation or group of organisations that originally commissioned the data acquisition or compilation and retains managerial and financial control of the data, with legal rights over the dataset, intellectual property rights and copyright. Ownership implies the right to exploit or destroy the data.	General definition: Council-EN, based on: The Principles of Good Data Management, Intra-Governmental Group on Geographic Information, Office of the Deputy Prime Minister: London, July 2005 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/14867/Good_dataMan.pdf
Data Provenance	Information provides details about the source of data, such as the person responsible for the provision of data, functions applied to data, and information about the computing environment for data processing (e.g., operating system, description of the hardware, locale settings and time zone). Big data provenance is the information that records the historical path of data according to the data lifecycle operations in a big data ecosystem.	
Data Quality	Set of principles that assure that data have been processed fairly and lawfully, have been collected for specified, explicit and legitimate purposes, are adequate, relevant and not excessive, are accurate and, where necessary, kept up to date, and are kept in a form which permits identification of data subjects for no longer than is necessary for the purposes for which they were collected or further processed.	General definition: Definition 1: Article 5 of the GDPR and Article 4 of Regulation (EU) 2018/1725

Term (acronym)	Definition	Sources, where available
		Definition 2: EDPS data protection glossary, https://secure.edps.europa.eu/EDPSWEB/edps/EDPS/Dataprotection/Glossary
Data Validation	A system that facilitates data providers to check and validate their data against a set of validation rules to ensure data of the highest quality possible *usually carried out prior to processing and importing. In AI/ML: The process of ensuring data has undergone data cleansing to ensure they have data quality, that is, that they are both correct and useful. It uses routines, often called "validation rules", "validation constraints", or "check routines", that check for correctness, meaningfulness, and security of data that are input to the system.	General definition: *APPENDICES STRATEGIC PATHWAY 4: DATA. (n.d.). [online] https://ggim.un.org/IGIF/documents/SP4-Appendices-26Feb2020-GLOBAL-CONSULTATION.pdf. AI/ML definition: https://en.wikipedia.org/wiki/Data_validation
Decadal Predictions	Simulations describing the trends in climate for the next few years up to a decade. Decadal predictions are specifically designed to predict fluctuations in the climate system over the next few years to decades through knowledge of the current climate state and multi-year variability of the oceans.	https://www.metoffice.gov.uk/research/news/2013/decadal-forecasting
Decision Trigger	Value of a climate-related variable or indicators that triggers an action, e.g. a conditional expression "if the level raise above X threshold release a flood alarm	
Essential Climate Variable (ECV)	A physical, chemical or biological variable or a group of linked variables that contributes to the characterization of Earth's climate.	
Evaluation	The process used to determine the satisfiability of a solution with respect to its goal(s).	

Term (acronym)	Definition	Sources, where available
Flood Hazards	In Water-Energy-Food (WEF) context: Combination of the probability of flooding and corresponding exposure characteristics such as flood depth, velocity, duration, rise rate, period of occurrence and water quality	WEF definition: Definition reference: A Floods Working Group (CIS) Resource document Flood Risk Management, Economics and Decision Making Support, ARCADIS, October 2012, http://ec.europa.eu/environment/water/flood_risk/pdf/WGF_Resource_doc.pdf
Forecasting	Forecasting refers to a calculation or an estimation that uses data from previous events, combined with recent trends to come up with a future event outcome.	
Hazard Map	Map that highlights areas that are affected by or vulnerable to a particular hazard	WEF definition: https://en.wikipedia.org/wiki/Hazard_map Note: They are typically created for natural hazards, such as earthquakes, volcanoes, landslides, flooding and tsunamis.
Impact Model	Impact models used to transform the climate-related decision triggers into the sector-specific impact indicators (e.g. calculate the flood or drought risk, yearly energy production, yearly crop yield)	
Integrity	Property of accuracy and completeness.	
Interoperability	The ability of two or more systems or applications to exchange information and to mutually use the information that has been exchanged.	General definition:

Term (acronym)	Definition	Sources, where available
		[ISO/IEC 27729]
Metadata	1) Data about data or data elements, possibly including their data descriptions, and data about data ownership, access paths, access rights and data volatility. 2) Structured, encoded data that describe characteristics of information-bearing entities to aid in the identification, discovery, assessment and management of the described entities.	
Model Quality	A measure of how correctly the forecast/predictions/projections compare to the observations.	
Model Skill	The relative quality of a set of forecasts/predictions, with respect to some set of standard reference forecasts/ predictions, such as climatology, persistence, random forecast/prediction.	
Monthly/ Sub-seasonal Forecasts	Simulations predicting a variable typically up to 5 weeks ahead.	
Multi-hazard Early Warning/Alert Systems	The set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organisations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss. NOTE – This definition encompasses the range of factors necessary to achieve effective responses to warnings. A people-centred early warning system necessarily comprises four key elements: knowledge of the risks; monitoring, analysis and forecasting of the hazards; communication or dissemination of alerts and warnings; and local capabilities to respond to the warnings received. The expression "end-to-end warning system" is also used to	

Term (acronym)	Definition	Sources, where available
	emphasise that warning systems need to span all steps from hazard detection through to community response.	
Open Data	Data that can be publicly accessible to all through open standards and protocols or through other means. The use and redistribution of open data can be subject to rules.	
Prediction	An actual act of indicating that something will happen in the future with or without prior information.	
Real-time Data Streams	Data or services (e.g., broadcasting) that are transmitted with virtually no time delay to today's status.	
Reliability	Reliability (relating to performance) is the ability of an item to perform a required function under given conditions for a given time interval. NOTE 1 – It is generally assumed that the item is in a state to perform this required function at the beginning of the time interval. NOTE 2 – Generally, reliability performance is quantified using appropriate measures. In some applications, these measures include an expression of reliability performance as a probability, which is also called reliability. The probability and/or ability of a system, product or component to perform and maintain under stated conditions as required for a specified period of time.	
Risk	1) The relative impact that an exploited vulnerability would have on a user's environment. 2) Effect of uncertainty on objectives. NOTE 1 – An effect is a deviation from the expected – positive and/or negative.	

Term (acronym)	Definition	Sources, where available
	NOTE 2 – Objectives can have different aspects (such as financial, health and safety, information security, and environmental goals) and can apply at different levels (such as strategic, organisation-wide, project, product and process). NOTE 3 – Risk is often characterised by reference to potential events, consequences, or a combination of these. NOTE 4 – Information security Risk is often expressed in terms of a combination of the consequences of an information security event and the associated likelihood of occurrence. NOTE 5 – Uncertainty is the state, even partial, of deficiency of information related to, understanding or knowledge of, an event, its consequence, or likelihood. NOTE 6 – Information security risk is associated with the potential that threats will exploit vulnerabilities of an information asset or group of information assets and thereby cause harm to an organisation. NOTE 7 – Based on the definition given in [b-ISO Guide 73].	
Seasonal Climate Predictions	Predictions of average seasonal conditions (e.g., temperature, precipitation, discharge) over a region that are made many months in advance (typically up to 7 months ahead) due to slowly changing parts of the climate system.	
Validation	Evaluation of the simulated variable (forecasts / historic simulations) against hydro-meteorological observations (from gauges or remote sensing) or reanalysis datasets not used for the calibration of the forecast/simulator.	
Vulnerability	Characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard. Also, the weakness in the implemented measures and procedures which could be exploited to carry out an act of unlawful interference.	General definition: http://www.preventionweb.net/risk/vulnerability

Term (acronym)	Definition	Sources, where available
		- May be opposed to resilience [IATE:902747] - Related to risk management [IATE:765095] Regulation (EU) No 1291/2013 establishing Horizon 2020 - the Framework Programme for Research and Innovation (2014-2020), CELEX:32013R1291
AI and ML		
AI Ethics	Branch of applied ethics that focuses on the normative issues raised by the design, development, implementation, and use of AI, in terms of both the data used and the algorithms developed and trained.	General definition: Council-EN, based on: European Commission, Independent High-Level Expert Group on Artificial Intelligence, April 2019, Ethics Guidelines for Trustworthy AI AI/ML definition: Hellström, T., Dignum, V., & Bensch, S. (2020). Bias in Machine Learning--What is it Good for?. arXiv preprint arXiv:2004.00686

Term (acronym)	Definition	Sources, where available
Artificial Intelligence (AI)	ISO/IEC 2382-28 defines AI as "an interdisciplinary field, usually regarded as a branch of computer science, dealing with models and systems for the performance of functions generally associated with human intelligence, such as reasoning and learning". This includes pattern recognition, the application of machine learning and related techniques, as well as the development and study of "intelligent agents"—devices or programs that perceive their environment and take actions to achieve goals.	
Bias in AI/ML	1. A systematic difference in treatment of certain objects, people, or groups in comparison to others. 2. Average error between model output and ground truth.	General definition: ISO/IEC 22989 AI/ML definition: https://www.merriam-webster.com/dictionary/bias?utm_campaign=sd&utm_medium=serp&utm_source=jsonld
Biased Data in AI/ML	Data is said to be biased when it does not fully represent the statistical process that generated it, but only part of it. This may occur when a dataset is too heavily weighted toward specific attributes and/or unrepresentative of all use cases.	General definition: On The Semantics Of Data Bias: Reducing Bias Versus Creating Inclusive AI (forbes.com)
Big Data in AI/ML	Refers to datasets that have been created on a scale that is difficult to obtain, manage, and manipulate in a timely manner using traditional computing tools, but are instead handled with a "scalable architecture for efficient storage, manipulation, and analysis".	General definition: [1] University International Conference on Engineering, NUiCONE, 2012, pp. 1–5.

Term (acronym)	Definition	Sources, where available
		[2] NBD - PWG NIST, (2014).NIST Big Data Public Working Group. Draft of Big Data Definition.
Classification in AI/ML	The process of assigning data points to classes (e.g., distinguishing between objects within an image). Classes are also referred to as *categories*, *targets*, or *labels*.	AI/ML definition: https://towardsdatascience.com/machine-learning-classifiers-a5cc4e1b0623
Clustering in AI/ML	The process of partitioning a set of data points into disjoint and homogeneous meaningful groups, based on the proximity of the data points to one another.	AI/ML definition: Council-EN, based on: Official blog of Remi A.I - A walkthrough on A.I Clustering (23.2.2021)
Convolutional Neural Networks (CNN) in AI/ML	A neural network in which at least one layer is a convolutional layer (uses a mathematical operation called convolution in place of general matrix multiplication).	General definition: https://developers.google.com/machine-learning/glossary#c
Data Accessibility in AI/ML	Degree to which users can access data. Different users may have different levels of access. The degree of access is partly a function of the data which users are permitted to examine and partly a function of the software options for analysis.	General definition: Proposal for a regulation on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU of the European Parliament and of the Council AI/ML definition:

Term (acronym)	Definition	Sources, where available
		https://www.encyclo.co.uk/meaning-of-Data_accessibility
Data Annotation in AI/ML	The process of giving labels to data that an AI/ML method will then be asked to learn how to output from the input data.	General definition: https://appen.com/blog/data-annotation/
Data Cascades in AI/ML	Compounding events causing negative downstream effects from data issues, resulting in technical debt over time. Data cascades often result from applying conventional AI practices that undervalue data quality.	General definition: Nithya Sambasivan, Shivani Kapania, Hannah Highfill, Diana Akrong, Praveen Paritosh, and Lora M Aroyo. 2021. “Everyone wants to do the model work, not the data work”: Data Cascades in High-Stakes AI. In CHI Conference on Human Factors in Computing Systems (CHI '21), May 8–13, 2021, Yokohama, Japan. ACM, New York, NY, USA 15 Pages. https://doi.org/10.1145/3411764.3445518
Data Cleaning	The process of deleting irrelevant and duplicate data from a dataset, and potentially smoothing the data and dealing with missing values and outliers.	
Data Curation	The active and ongoing management of data through its lifecycle of interest and usefulness.	General definition: https://www.sciencedirect.com/science/article/pii/B9780128176368000053.

Term (acronym)	Definition	Sources, where available
Data Integrity	A property that indicates the data has not been altered or destroyed in an unauthorised manner.	
Data Lifecycle	A whole range of data processing phases including data planning, data acquisition, data storage, data sharing, data usage, data transmission, and data disposal.	
Data Supply Chains in AI/ML	The elements that constitute the data lifecycle: selection, procurement, transfer, quality assurance, warehousing/storage, data management, transformation, monitoring, and distribution — feeding data pipelines for use in data products.	AI/ML definition: https://towardsdatascience.com/learning-from-machines-the-data-supply-chain-4380f420bb2c
Data Visibility	The degree of ease through which one can monitor, search, display, and analyse data from different sources.	AI/ML definition: https://www.sentinelone.com/blog/data-visibility/
Internet of Things (IoT)	A network of electronic devices embedded with software and sensors that enable the interaction between machines. The connectivity between devices helps the collection of huge amounts of data which can be analysed by computer-based systems.	AI/ML definition: https://link.springer.com/content/pdf/bbm%3A978-3-319-94878-2%2F1.pdf
Epoch	One entire transit of the training data through the algorithm.	AI/ML definitions: https://deepchecks.com/glossary/epoch-in-machine-learning/
Long Short-Term Memory (LSTM)	An artificial recurrent neural network (RNN) architecture. Also, a type of cell in a recurrent neural network used to process sequences of data in applications such as handwriting recognition, machine translation, and image captioning. LSTMs address the vanishing gradient problem that occurs when training RNNs due to long data sequences by maintaining	AI/ML definition:

Term (acronym)	Definition	Sources, where available
	history in an internal memory state based on new input and context from previous cells in the RNN.	1) https://en.wikipedia.org/wiki/Long_short-term_memory 2) https://developers.google.com/machine-learning/glossary#l
Machine Learning (ML)	The process of extrapolating from data useful input-output mappings that generalise well to never-before-seen data, without explicitly encoding them into heuristic rules beforehand. Machine learning also refers to the field of study concerned with these programs or systems.	AI/ML definition: https://developers.google.com/machine-learning/glossary#l
Machine Learning Pipeline	A set of logical nodes, each with specific functionalities, that can be combined to form a machine learning application.	
Monitoring	Machine learning monitoring is the practice of tracking and analysing model performance to ensure acceptable quality as defined by the use case. It provides early warnings on performance issues and helps diagnose their root cause to debug and resolve.	AI/ML definition: https://towardsdatascience.com/machine-learning-monitoring-what-it-is-and-what-we-are-missing-e644268023ba
Robustness in AI/ML	The characteristic of a model when its generated output and overall performance are satisfactory and admissible, even though data may derive from various probability distributions, contain outliers and diverge from parametric distributions, expected data ranges and other model assumptions.	AI/ML definition: https://en.wikipedia.org/wiki/Robust_statistics

Term (acronym)	Definition	Sources, where available
Scalability in AI/ML	The ability of algorithms, data, models, and infrastructure to operate at variable size, speed, and complexity, as required by the task or as specified by hardware or software constraints.	General definition: https://www.techopedia.com/definition/9269/scalability AI/ML definition: https://resources.sei.cmu.edu/asset_files/WhitePaper/2021_019_001_735330.pdf
Segmentation (SGM)	The act of generating two or more derived PDUs (Protocol Data Unit) from an initial or derived PDU. The derived PDUs together carry the entire user data of the initial or derived PDU from which they were generated.	
Supervision in AI/ML	The process of training a ML model using labelled data.	
Training in AI/ML	The process of adjusting the parameters of a machine learning model so that they form a mapping from input to desired output that, on average, works well for all data points used during training.	
Training Data in AI/ML	The subset of the dataset used to train a model.	AI/ML definition: https://developers.google.com/machine-learning/glossary#t

2.4 Barriers and bridges in Climate Services

The need for Climate Services became urgent with the Paris Agreement in 2015, where adaptation came into focus as a pressing need alongside traditional mitigation measures (UNFCCC, 2015). Information about future climate variability can help inform decision-making by providing deeper insights into the potential risks and supporting actions to mitigate those risks. An analysis by Panenko et al. (2021) has shown that Climate Services and knowledge action systems within the EU were most developed in corporatist and/or decentralised countries (e.g. Austria, Denmark, Germany, Ireland, Spain), while statist and centralised countries (e.g. France) showed different degrees of integration of climate products and services within their respective adaptation governance. Users of Climate Services are expected to range from individuals or organisations with responsibilities for decisions and policies related to climate change mitigation and adaptation, to intermediary users such as consultancies, to societal actors (public) representing such as the media, non-governmental organisations and/or other non-profit organisations such as industry bodies (Cortekar et al., 2020).

However, the production and availability of Climate Services and information do not guarantee its use in decision-making contexts (Dilling and Lemos, 2011; Bruno Soares and Dessai, 2016). Indeed, it has been seen that more (climate) information does not necessarily lead to better decision-making or increased information use; on the contrary, there has been widespread recognition that the science produced is not necessarily informing decisions that could benefit from such knowledge (Kirchhoff et al., 2013; Meyer, 2011). Recognition has finally come that the target groups on the receiving end of CS and information are highly diverse, with different requirements (regarding the assimilation of CS data), levels of expertise and capacity for assimilating cutting-edge science and technology (over preference for the business-as-usual), and that these user-specific needs must be more fully addressed in order to capitalise on and continue advancing the field of CS. It has been demonstrated that links must be forged, bridging research and related assessments with decision-making practices to ensure information becomes "usable".

The usability of science is often evaluated according to its three main attributes: credibility, salience and legitimacy (Cash et al., 2003; 2005; Barsugli et al., 2013), all three of which are critical for ensuring "actionable climate knowledge" is produced (Meinke et al., 2006). A key barrier to CS uptake is thus related to the perceived credibility of the information in question. This was shown in the study by Bruno Soares and Dessai (2016), who conducted interviews with 75 organisations working across eight sectors - including water, energy and agriculture (food) - and in 16 European countries, with a focus on the use of seasonal climate forecasts (SCF). Most organisations interviewed did not use SCF at the time of the interview, citing especially the low reliability (here meaning trustworthiness) and skill of SCF in Europe. This barrier was often linked to existing perceptions of high levels of uncertainty and lack of forecast accuracy, preventing their use even as qualitative information. For those organisations using the information qualitatively, this perceived lack of reliability formed a major barrier preventing the integration of such data into, e.g., automated processes such as existing operational models. This was linked to issues with (lack of) capacity (resources) to perform both the required pre- and post-processing of the data in order to use it operationally.

Lack of relevance (i.e. salience) was another major barrier identified when the organisations lacked the capacity to incorporate such data into their daily work either because they were not responsible for activities related to this information or their organisation's focus was reactive rather than proactive in nature. Another non-technical barrier to the use of SCF was the lack of awareness regarding what information is even available, coupled with concerns at the level of financial investment (and other resources) necessary to allow them to pursue the use of CS in their organisation. In a few cases, preference for maintaining existing practices, also perceiving these [practices] to be more reliable prevented the uptake of such CS data, indicating a lack of understanding of the potential added value to be gained from incorporating new data sources. Similarly, the incorporation of such data, here SCF, was not compatible with their *modus operandi* or timing (of when these forecasts were made available to them, e.g. 2 months in advance), where they typically plan their work out in advance (up to 1.5 years).

Finally, financial barriers were identified as part of a SWOT analysis in the MARCO project (Tart et al., 2018), related to *suppliers* of and *inputs* to CS (see section 2.5 for definitions and details). For example, competition reported between European meteorological offices and private sector providers for commercial contracts has been identified as a barrier. This can be translated into a bridge, however, by strengthening collaboration between governments, research institutes and private companies and continuing to capitalise on Europe's ability to link research with societal change to develop tailored services. Restrictions for financing private R&D and a weaker venture capital scene (i.e. compared to the US, identified as Europe's biggest competitor) are additional barriers on the financing side that need to be addressed. Similarly, bridges can be created by enhancing cooperation/co-development opportunities between producers/providers and users of CS, and simultaneously building on EU suppliers' experience in internationalising quickly and dealing with different languages and currencies.

The main enablers supporting the use of SCF in the organisations interviewed by Bruno Soares and Dessai (2016) were related to relationships and interactions with the producers and providers of SCF. Thus, collaborations and ongoing relationships with CS providers greatly enhanced the accessibility to SCF. In addition, the level of organisational resources and (often in-house) expertise (capacity) were also seen as significant enablers of SCF, greatly enhancing their capacity to assimilate, process and use the CS data, which was also recognized as a competitive advantage for a few of the organisations. Other drivers for a few organisations were related either to their clientele being located outside Europe, or because their activities were largely knowledge-seeking (where SCF was perceived as a potential source of information, if only qualitative). The competence level of the user within the organisation (i.e. moderate or advanced) determined whether the data would be used qualitatively (as supplemental information, not used directly for decision-making) or quantitatively (e.g. for direct planning of activities, such as maintenance work or emergency planning).

Providing information that is readily usable for decision-making must therefore navigate and bridge between what scientists may think is useful (i.e. perception of usefulness) and what is actually usable in practice (actual capacity). This requires changing the paradigm of how scientists and practitioners/decision-makers have typically worked together in the past, i.e. moving from the “loading-dock model” where information is developed within the confines of the scientific community with the expectation that users will find that information usable (e.g. Feldman and Ingram, 2009; Lemos, 2015), to one of co-creation/co-production of both science and policy (Lemos and Morehouse, 2005) with a focus on capacity building where necessary to ensure uptake. These underlying narratives permeate much of the discussion to date around the production of CS and information, as well as its use in policy and decision-making contexts (Bruno Soares and Dessai, 2016).

2.5 SWOT analysis for European Climate Services

An analysis of EU climate service suppliers’ strengths, weaknesses, opportunities and threats (SWOT) is ideal for positioning European CS producers/providers and advancing in the global market. An analysis has been carried out within the MARCO project using Van de Ven’s Sources of Innovation model, which is ideal for considering all aspects of an immature market (Tart et al., 2018). The analysis explores four sources of innovation, thereby providing four perspectives in which to compare CS markets:

- Institutional arrangements, including standards, laws or regulations that can hinder or enable market growth;
- Users, who can impact market growth through their demand for such services, but who are largely influenced by both cultural norms as well as corporate strategies, tradition for competition, and individual competencies to handle/absorb CS information or technology;
- Suppliers, who encourage market growth by developing well-suited products, have the business prowess to address the market, and have access to adequate resources; and
- Inputs, including the availability of qualified labour, capital investments, and up-to-date research, technology and data - often linked to suppliers’ resources.

In Tart et al. (2018), both current and potential global climate service providers that may be a threat to European ones were assessed. Elements such as geo-climatic conditions, economic activity and urbanisation, political climate and investment power were considered, and a short list of potential competitors was generated. Global transactional competitive data supplemented the analysis, and further narrowed the list of competitors. While Asia was found to be a source of competition, it was not found to be the strongest competitor. Europe’s top global competitor was found to be Northern America and specifically, the United States, based on the multiple elements assessed. For this reason, the SWOT presented in Table 2.2 focused on comparing EU suppliers with US ones.

Table 2.2 The SWOT analysis for each of the four sources of innovation, including institutional arrangements, users, suppliers and inputs.

Institutional arrangements	
Strengths • Favourable legislation and policy with precise targets at the EU level • Accelerating development and sharing of codes and standards • Strong global outlook and investment strategies	**Weaknesses** • Lack of synergies between MS' policies • Lack of coordination and cooperation between EU initiatives • No single market entity • Lack of public-private partnerships (PPP), as commercial funding is limited in the EU
Opportunities • A growing market in developing countries	**Threats** • Strong commercial international foothold • Strong and clearly-regulated tradition for PPPs
Users	
Strengths • Accelerating awareness of user-driven approach • Increasing awareness of climate-related changes in societies	**Weaknesses** • High uncertainty in decadal climate predictions and limited skills in seasonal forecasting • Applications are too research-based
Opportunities • Building upon the growing environmental awareness among potential climate service users • Developing solution-oriented applications rather than focusing solely on risk assessments	**Threats** • Longer tradition for the use of seasonal climate forecasts in decision-making, due to more reliable climate variations • High awareness of value of Climate Services
Suppliers	
Strengths • Strong trend for user-driven, science-informed approach • Ability to link research with societal change	**Weaknesses** • Lack of coordination and exchange of best practices in technical networks
Opportunities • Further strengthening collaboration between governments, research institutes and private companies • Continuing to bridge climate information with social sciences to develop tailored services	**Threats** • Strong foothold in major markets such as China and Southeast Asia • Strong private-sector driven scene complementing and competing with public sector offers
Inputs	
Strengths	**Weaknesses**

Institutional arrangements	
• Strong funding of public programmes at EU level • Strong scientific and technological capabilities	• Lack of HPC (uneven across the EU) • Lack of specific instruments oriented towards SMEs and early-stage developments • Less developed venture capital scene
Opportunities • Building upon EU suppliers' experience in internationalising quickly and dealing with different languages and currencies	**Threats** • Result- and mission-oriented funding programmes • Strong innovative tradition and environment for user-driven tech start-ups

The weaknesses of the EU and the threats from the US were generally more evident than the strengths and the opportunities for the EU. Only the suppliers' perspective had more strengths listed than weaknesses. While this should not be discouraging, Europe must actively seek to close the CS market gaps if EU suppliers compete with their US counterparts. For example, it is unclear from an *institutional arrangements* perspective whether EU ambitions will translate into viable commercial products. This is largely due to a lack of coordination and cooperation between EU initiatives, and no single market entity. Markets are small, as are the incentives compared to those in the US. Current EU legislation favours change, however, and a strong global outlook and investment strategy in growing markets are equally promising.

For the *users*, a relatively shorter tradition in dealing with seasonal climate forecasts in Europe and a lower awareness of the value of CS can both be overcome through awareness-raising among potential CS users. Although European suppliers set services that have limited seasonal forecasting skills and are traditionally too research-based in their approaches, they have an increasing awareness of what users need. Extending their solutions beyond risk assessments could also help them grow their skills. We still note here that the EU is improving and enhancing these aspects, as seen by competencies collected in government agencies, e.g. in Sweden, Slovakia, Denmark, and Finland. This link between producers/suppliers and CS's users will be crucial for overcoming many of the existing barriers (see section 2.4), considering its importance in enabling CS uptake.

From the *supplier* side, the reported competition between European meteorological offices and private sector providers for commercial contracts is clearly a barrier when compared with the US traditional consensus agreement between public and private providers. The US has a much stronger foothold in both private and public markets, and private-sector actors keep the market alive by both cooperating with and putting pressure on their public-sector counterparts. European suppliers, on the other hand, lack coordination at a network level. Nonetheless, their experience in user-driven approaches and ability to link research with societal change can be applied to foster the relationships and networks they need to expand their reach.

In terms of *inputs*, the room for improvement is not negligible. The restrictions for financing private R&D and a weaker venture capital scene are just two of the many barriers on the financing side that need to be addressed. However, the EU Markets Union Plan is a step in the right direction. Looking at research and technology, HPC abilities are another weakness, as is a lack of instruments oriented towards SMEs. Fortunately, the EU is stepping up with ambitious public programmes addressing climate change impacts, including, for example, the Destination Earth initiatives (Destination Earth | Shaping Europe's digital future (europa.eu)). This set of initiatives will definitely work towards enhancing the coordination and exchange of best practices within key technical networks, currently seen as a weakness. This could furthermore serve as a momentum for EU Climate Services providers with experience in internationalising quickly.

In summary, Tart et al. (2018) concluded that, for European climate service providers to advance, innovation needs to happen along all four sources of innovation: institutional arrangements, users, suppliers, and inputs. The result of the SWOT analysis further indicated that the EU should try to gain an exporting market from the US, as well as seek to develop Climate Services in global regions of high demand.

2.6 Research and innovation for Climate Services

Many scientific efforts are directed towards innovating the existing Climate Services, for example, EU-funded projects like CLARA (www.clara-project.eu), CLIMATEUROPE (www.climateurope.eu) and MEDSCOPE (medscope-project.eu). Despite the various challenges, which were also addressed above, an added value has been demonstrated focusing on, among others, improving the predictability skill at long time horizons, ensuring robustness from the predictions and advancing the communication practices, including visualisation. Here we list the identified efforts toward research and innovation for Climate Services.

2.6.1 Extended time horizons

Climatic information from sub-seasonal (1-1.5 months ahead) to seasonal (6-12 months ahead) time scales (S2S) holds the potential to be of great value for a wide range of users who are affected by the variability in climate and who would benefit from better understanding and managing climate-related risks (Bruno Soares et al., 2018; van den Hurk et al., 2016). Climatic predictions at extended range (also known as sub-seasonal) and long-range (also known as seasonal) have witnessed improvements in forecasting skills (Scaife et al., 2014; Wetterhall and Di Giuseppe, 2018), although the skill of predictions of key variables for the impact sectors, such as precipitation and river flows, remains low. In Europe, there has been relatively little uptake and use of S2S forecasts by users for decision making, compared to other parts of the world, such as the USA and Australia, probably due to this relatively limited predictability at European latitudes (Mendoza et al., 2017). This challenge has prompted the development of new approaches, such as multi-modelling combinations and conditioning of forecasts to large-scale climate indices (Dobrynin et al., 2018; Wanders and Wood, 2016). Although investigated at pan-European scale services, these novel approaches have not yet been fully explored at the local scale in European user-targeted applications (Buontempo et al., 2018). S2S forecasts lack the necessary downscaling and tailoring, and hence effort is still ongoing to improve S2S forecast service predictability and usability. The predictability of S2S forecasts is subject to multiple sources of error and uncertainty, which are present in the various components of the production chain going from climate models (their parameterization, initialization, bias-adjustment, etc.) to the service that provides impact indicators (impact model setup, structure and parameterization). In addition, predictability is characterised by strong spatial variation and commonly a temporal degradation of its skill in longer time scales.

2.6.2 Cross-cutting Copernicus services

The Copernicus programme has been specifically designed to meet user requirements with the efforts toward a better understanding of the planet and a sustainable environment. Copernicus produces a wealth of data and information that address user requirements from a number of sectors with regard to, among others, monitoring the earth systems (satellite and in-situ observations), responding to emergencies, and mitigating/adapting to changes/variability in the climate. The information provided by the *Copernicus Climate Change Service* (C3S) is used for a wide range of applications in a variety of areas, including sustainable development and nature protection, agriculture, health, civil protection, infrastructure, as well as energy. The users are policy-makers and public authorities who need the information to develop environmental legislation and policies or to take critical decisions under extreme events. In addition, forecasters, commercial to private users, as well as the global scientific community have also benefited from these services to develop new methodologies and offer business products. Many value-added services have thus been tailored to specific public or commercial needs, resulting in new business opportunities and economic, societal and environmental benefits (EU, 2016).

CSs cover a range of spatial and temporal scales, but some information gap still exists for user applications that extend across multiple scales. These gaps could be filled with further services' evolution involving cross-cutting implementations of state-of-the-art scientific methodologies at local scale with the integration of in-situ data. A number of users are dependent on, for instance, hydro-meteorological forecasted information at different time horizons to increase the effectiveness of water-related hazard (flood and drought) response and enhance efficiency in decision-making. In many cases, hazard preparedness is a matter of trans-border and macro-regional cooperation; therefore, the timely and across-scale coherent provision of hydro-meteorological information is crucial.

2.6.3 Realising possibilities for Earth Observation products

There is a high potential for the use of Earth Observation (EO) in various applications in the water, energy and food sectors. EO data could address the increasingly complex and multidisciplinary challenges that users face today. EO technology and information can be a catalyst to promote and support climate service evolution. The GEO 2016-2025 Strategic Plan already identified climate and water, in general, to be among the priority actions for implementing the Global Earth Observation System of Systems (GEOSS) (GEO, 2015), while the European Earth observation programme of the Copernicus programme provides already a range of information services designed to support relevant topics including:

- Flood extent monitoring and forecasting
- Drought monitoring and forecasting
- River discharge monitoring
- Monitoring of water level in water reservoirs and dams
- Snow and glaciers extent monitoring
- Water extraction monitoring
- Irrigated areas mapping
- Water use and extraction monitoring
- Water availability assessment within climate change scenarios
- Digital Elevation Models and river discharge for hydropower production facilities

In particular, EOs have been used in the setup of impact-based models, i.e. dynamic forcing, land cover classifications and parameterizations of vegetation dynamics that are partially (or even entirely) derived from remote sensing products. However, EOs can add more value to the Climate Services by their integration into model validation and data assimilation practices (Demirel et al., 2018, Nijzink et al., 2018). Currently, opportunities for improvement of impact-based models within the Copernicus Climate Services include the use of a wide range of EO products in model setup, parameter estimation, model evaluation and data assimilation.

2.6.4 Purveying Climate Service knowledge

To increase knowledge and direct usefulness of data and information from Climate Services, a step-wise chain of information, from observations to decisions, needs to be refined. It is recognized that the recent opening of public sector data and EO products has not yet resulted in the expected massive innovations, economic growth and transparent governance, despite the available potential for such (Bruno Soares and Dessai, 2016). One reason for this discrepancy is that the data is still often too raw, of unknown quality and made available in various formats and resolutions (Bruno Soares et al., 2018). It, therefore, takes a lot of skill and time to actually use the data. Efforts were made for the European expertise of the climate community to collaborate on a process for systematically refining the data. By sharing tailored data, knowledge, development efforts and operational production, there has been progress on re-purposing the data into many different customised products and decision-support tools. These steps lowered the cost compared to developing each product separately and increased the quality of each resulting decision-support tool. This also opened new business opportunities. Although efforts were made to bridge the knowledge gap between data providers and users, there is still a need for strong user engagement through better communication of products and co-evolution of knowledge within Climate Services. To address this knowledge gap, Climate Services are in the process of introducing service purveyors, who are applied researchers, consultants or other intermediary actors working between science, policy and practice. They are key to the successful development and implementation of EU policies and large-scale services at regional and local levels. Purveyors act as knowledge brokers providing guidance on ways Climate Services can address regional problems. They also ensure that products, scientific results and business opportunities are adequately communicated to stakeholders. Policy-makers can support the growth of this knowledge brokerage market, simultaneously boosting climate resilience, jobs and the economy by helping to sustain the emerging knowledge sharing and learning network.

3 STATE-OF-THE-ART PAN-EUROPEAN CLIMATE SERVICES

In this section, we identify the state-of-the-art pan-European Climate Services (e.g. that cover at least the European region) and categorise them depending on their major contribution to either the water, energy and food sectors. In particular, we aim to present the key features of these CSs by consequently addressing the following questions: *Who is providing Climate Services? Are these services operational or demonstration services? Which Climate Services-related activities are providers engaged in? Which types of Climate Services are provided? Who are the targeted customers/clients/users? Which sectors do Climate Services providers approach? Which geographic markets do Climate Services providers address?*

3.1 Water sector

Water-related natural hazards, such as droughts and floods, and inefficient management of water resources can have a life-altering impact on the society, with the effect being felt mainly at the local and regional levels, but depending on the magnitude of the event, sometimes also at the national and continental levels (Pappenberger et al., 2015; Blauhut et al., 2016; Carleton and Hsiang, 2016). Even when human communities are relatively unaffected, impacts can also be seen on the environment, with varying consequences. The recovery from an extreme event depends on the intensity of the impact and the level of preparedness and resilience of the subject impacted. Although the magnitudes of water-related hazards have increased (Blöschl et al., 2017; van Loon et al., 2016), practices demonstrating efficient management of water resources under changing conditions are still limited. They are challenged by changes in extreme events, i.e. floods, population growth, pollution, environmental response and rules of competition from many water uses, e.g. energy production, recreation, agriculture, ecosystem management, and drinking water (McDonnell et al., 2018; Zhou et al., 2015).

In the various existing Water and Climate Services, forecasts/predictions and projections covering different time horizons are usually driving the short and long decision-making, respectively, affecting further the adaptation strategies and policy-making. In daily applications and decision-making, typically in early warning and water resources management, medium-range hydro-meteorological forecasts (up to 10 days) have routinely been used (Ward et al., 2015), whilst for long-term decision-making (e.g. policy and planning), extended time horizons (sub-seasonal to seasonal forecasts, decadal prediction and centennial projections) are required (Hewitt et al., 2017). The numerical models that provide the forecasts, predictions and projections vary in process representation, spatial resolution and performance (White et al., 2017); however, under a robust method for information extraction and dissemination, outputs from numerical models can be capable of providing useful information to be used in impact models and further address user needs.

Below, we present a set of state-of-the-art pan-European Climate Services for the water sector with applications in water resources management, early warning services and disaster risk reduction.

3.1.1 European Flood Awareness System (EFAS)

To improve flood preparedness at the European scale, the European Flood Awareness System (EFAS) was developed, implemented and set fully operational in 2012. Over the years, EFAS has delivered accurate flood forecasts, while it has been strategically considered in the development of a more robust European Union disaster response. EFAS aims to deliver an added-value and complementary flood early warning information to the national and regional hydrological services while at the same time providing an overview of the current and forecast flood situation to the Emergency Response Coordination Centre (ERCC) of the European Commission's Directorate-General for European Civil Protection and Humanitarian Aid Operations (DG ECHO). Among other products, EFAS provides pan-European overview maps of flood probabilities up to 10 days in advance, as well as detailed forecasts at stations where the national services are providing real-time data. Currently, more than 70 hydrological and Civil Protection (national or regional) authorities in Europe are part of the EFAS Partner network, and additional 50 authorities are EFAS Third-Party partners. EFAS information also contributes to timely activation of the rush mode of the Copernicus Emergency Management Service (CEMS) - Mapping for an improved flood extent monitoring, see https://emergency.copernicus.eu/mapping.

Apart from the 10-day hydrological forecasts, EFAS provides extended and long-range forecasts, which comprise two model systems; sub-seasonal (based on the ECMWF extended-range system; ER) and seasonal (based on the ECMWF SEAS5 system; SEAS5). In both cases, the Lisflood hydrological model is forced with forecasts from the two meteorological systems. Figure 3.1 presents the production chain for the seasonal forecast, yet a similar one is valid for the sub-seasonal.

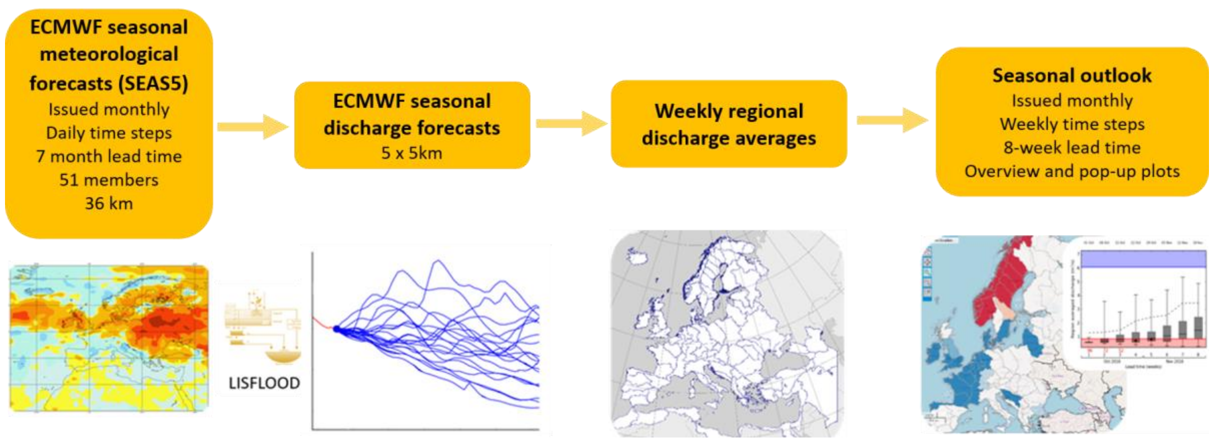


Figure 3.1 The EFAS production chain for seasonal time horizons.

The two systems use different meteorological forcing in their model chain and are issued with different frequencies, yet both provide 51 members. The SEAS5 forecasts are issued monthly, whereas the ER forecasts are issued twice weekly, on Mondays and Thursdays. EFAS sub-seasonal and seasonal forecasts provide hydrological outlooks showing the likelihood of high (and low) river flows within the coming six and eight weeks, respectively. Results are aggregated on the river basin level. They are created by comparing the forecast with EFAS low and high flow thresholds, each averaged over the defined regions. The thresholds for high and low flows: 90th and 10th percentiles of the weekly averages from the water balance simulation for 1990 to 2013. Results are presented as maps (Figure 3.2), while for every region, time series are available (Figure 3.3).

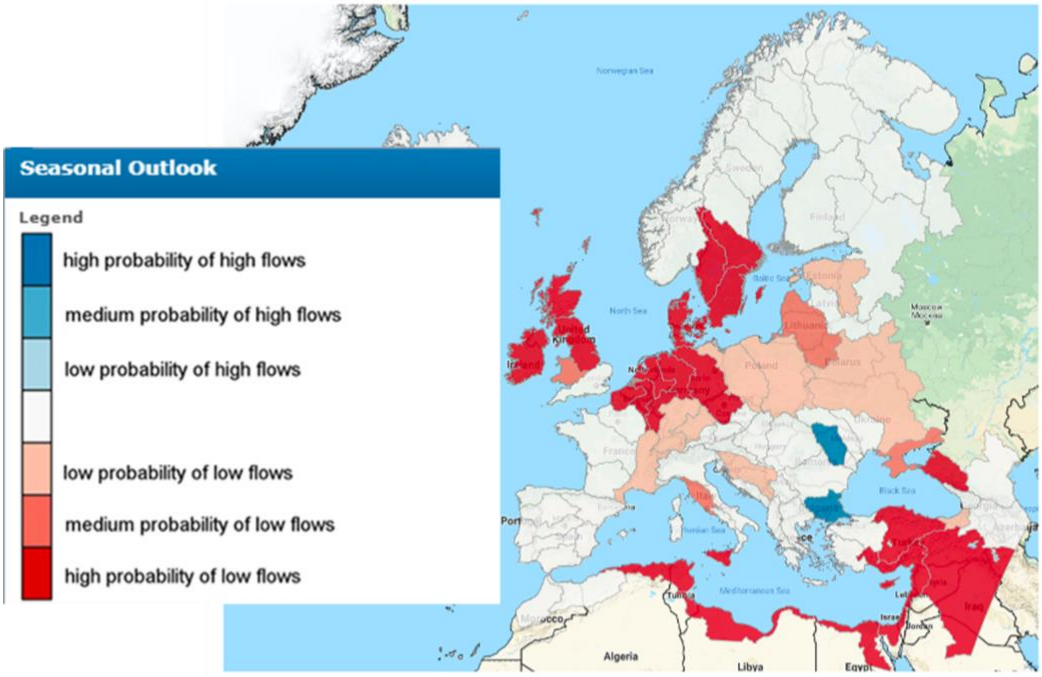


Figure 3.2 The EFAS seasonal hydrological outlook for high (blue) and low (red) flows. The intensity of the colour - the highest forecasted probability (percentage of ensemble members) of exceeding the high threshold within the forecast horizon.

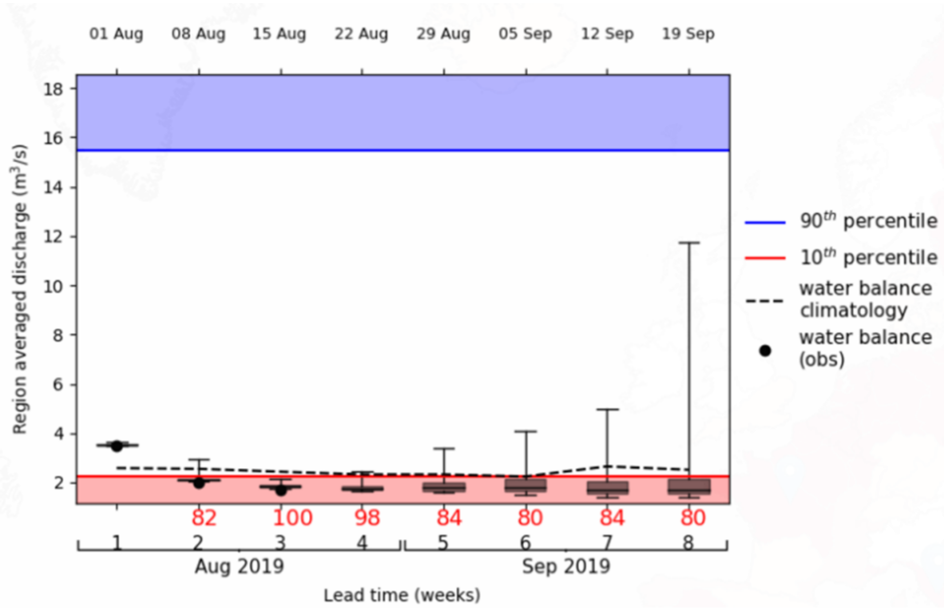


Figure 3.3 Boxplot indicating the weekly averages of ensemble discharge forecast over the first 8 (seasonal) weeks.

3.1.2 C3S Water Resources Management

The Operational Service for the water sector of the Copernicus Climate Change Service (C3S) aims to help a broad range of water managers plan their activities at seasonal horizons, as well as to adapt their strategies in order to mitigate the effects of climate change (https://climate.copernicus.eu/operational-service-water-sector). C3S thus supports water management by using climate data to anticipate, e.g., water stress, droughts and floods. The intended user is in the fields of, for instance, water allocation, flood management, ecological status and industrial water use, but the provided services and information are also relevant in adjacent sectors, such as energy and agriculture.

The service offers state-of-the-art hydrological climate information and seasonal forecasts for the water sector, available through high-resolution datasets and interactive web applications (e.g. maps and graphs of quality-controlled water and climate data). For example, the interactive web application “European hydrology and climate data explorer” provides easy access to a range of climate impact indicators for water quantity, water quality and relevant meteorological climate impact indicators. The climate impact indicators are derived from a state-of-the-art ensemble of regional climate models from the Euro-CORDEX (European Coordinated Regional Climate Downscaling Experiment). A bias-adjusted ensemble of eight models from the EURO-CORDEX EUR-11 was then used to force a multi-model setup of the hydrological model E-HYPE at a pan-European domain (5x5 km grid and on average 215 km^2 sub-catchments).

Also provided are time series, including future river flow and other water-related indicators, and seasonal hydrological forecasts (to guide planning). These datasets contain Essential Climate Variable (ECV) in the form of daily mean river discharge and a set of climate impact indicators (CIIs) for a total of 18 water quantity and quality CIIs and 1 water ECV. The river discharge ECV data meet the technical specifications set by the Global Climate Observing System (GCOS), as they are provided daily. Note these are model output data and not observation data, as is the general case for ECVs.

ECV datasets provide the empirical evidence needed to understand the current climate and predict future changes. CIIs contain condensed climate information which facilitates relatively quick and efficient subsequent analysis, thereby making climate information accessible to application focussed users within a sector. The CIIs are provided as mean values over 30-year time periods. For the reference period (1971-2000), data is provided as absolute values; for future periods, the data is provided as absolute values and as the relative or absolute change from the reference period. The future periods cover 3 fixed time periods (2011-2040, 2041-2070 and 2071-2100) and 3 "degree scenario" periods defined by when global warming exceeds a given threshold (1.5 °C, 2.0 °C and 3.0 °C). Global warming is calculated from the global climate model (GCM) used; therefore, the degree scenarios' actual time period will differ for each GCM. These datasets are produced and quality assured by the Swedish Meteorological and Hydrological Institute on behalf of the Copernicus Climate Change Service (see also Figure 3.4).

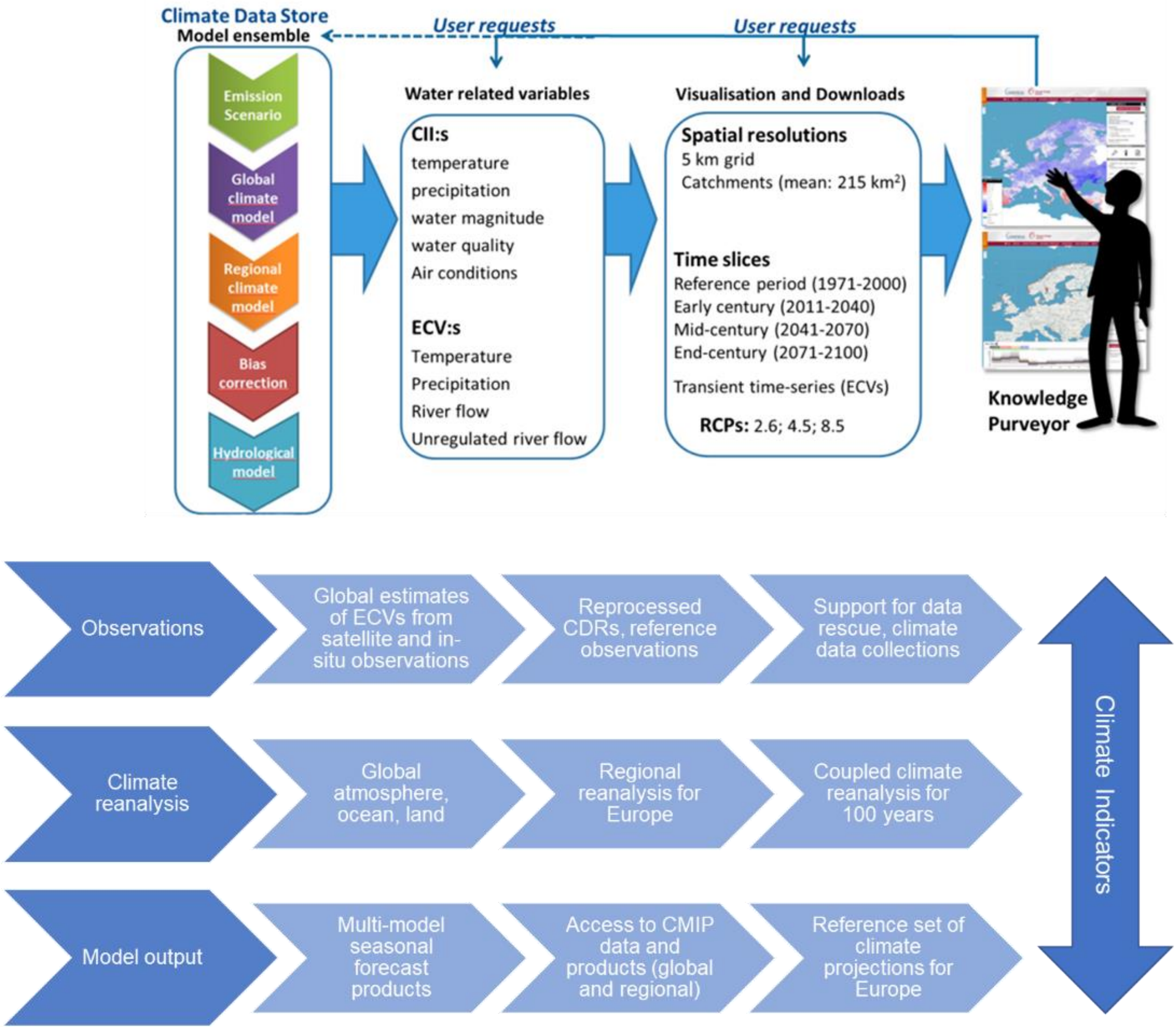


Figure 3-4 A conceptual overview of the C3S service for water resources management indicating the ECVs and CIIs.

A second interactive web application to be published soon, the “Hydrological seasonal forecast explorer”, presents monthly hydrological seasonal forecasts of river discharge from a hydrological ensemble using the ECMWF SEAS5 seasonal forecasting system. These forecasts present the probability of river discharge deviating from normal conditions. The seasonal forecasts are updated every month and extend seven months forward. Datasets include multi-model seasonal forecasts of river discharge for Europe from January 2021 to the present and multi-model seasonal reforecasts of river discharge for Europe. These datasets are produced and quality assured by the Swedish Meteorological and Hydrological Institute, together with Wageningen University and Research Centre (NL) on behalf of the Copernicus Climate Change Service.

Finally, the C3S platform includes real-life examples of decision-making in climate adaptation. Use cases cover, for example: (i) the Heineken brewery in the Netherlands, which uses C3S data to plan ahead using projections of future water supply and water quality in the source area; (ii) the Italian consultancy GECOsistema which used climate projections to determine the future growth of six vital crops for food production, as well as the existing capacity of irrigation systems to improve irrigation infrastructures and maximise crop yield under climate change; and (iii) AGHRYMET - the committee for drought control in the Sahel (West Africa), where extreme drought and flooding have become more common - who use C3S forecasts to provide information on the daily, monthly and seasonal rainfall and streamflow within the River Niger basin. This information is critical to food security - with more than 80% of the population relying on agriculture and livestock, thus supporting decision-making by dam managers, farmers and society.

3.1.3 SMHI's climate service

SMHI's hydrological climate change service provides several entry points to global and regional climate change impact web services, one of them being the 'Europe Climate Change' service (Figure 3.5). The service provides climate impact assessments based on the bias-adjusted EURO-CORDEX EUR-11 ensemble projections forcing three hydrological models; E-HYPE, VIC and Lisflood. The service provides information about water quantity and quality. Climate impacts are presented in the form of climate impact indicators, and projected changes are visualised for the early- (2011-2040; 2020's), mid- (2041-2070; 2050's) and end- (2071-2100; 2080's) century. The user is also provided with an outlook of the mean values for the reference period (1971-2000). Moreover, information is given for three emission scenarios (RCP2.6, RCP4.5 and RCP8.5), while the uncertainty in the projected CIIs can be interpreted through information on the minimum, mean and maximum values from the ensemble range.

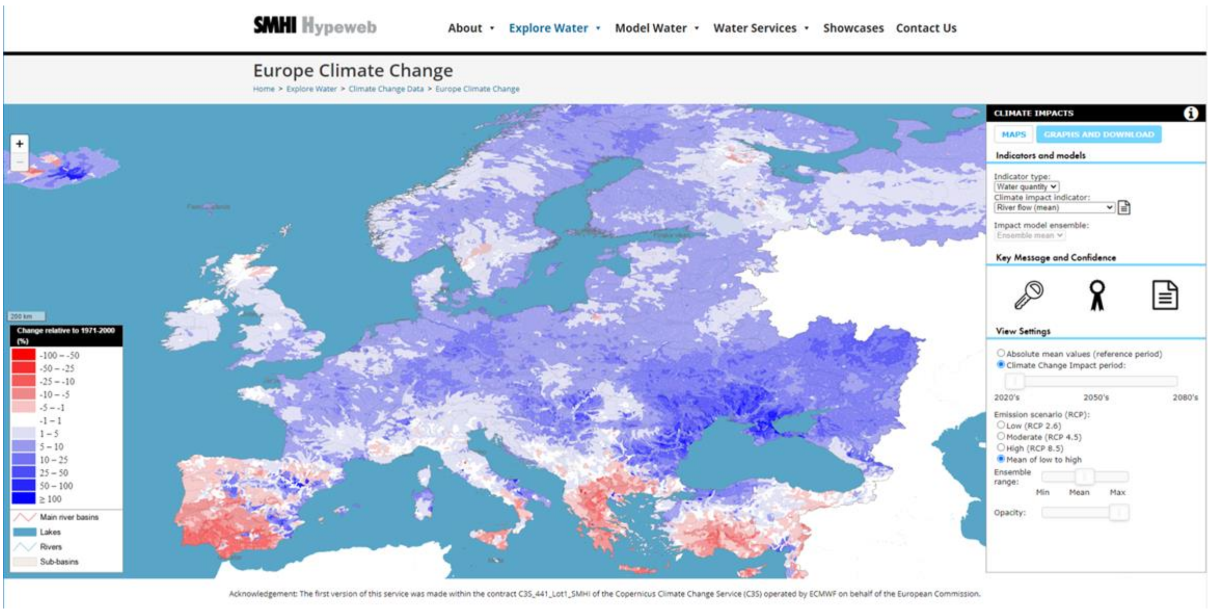


Figure 3.5 The outlook of SMHI's climate service based on centennial projections for water resources management (https://hypeweb.smhi.se/explore-water/climate-change-data/europe-climate-change).

In addition, SMHI provides a climate service based on seasonal hydro-meteorological forecasts (see Figure 3.6). Similar to the centennial projections, the E-HYPE hydrological model is forced with bias-adjusted ECMWF SEAS5 seasonal forecasts that provide operationally 51 ensemble members.

The bias-adjustment method belongs in the family of quantile mapping methods, and it is done for every initialization month and lead month. Seasonal forecasts of precipitation, temperature and river discharge are hence available on a monthly time step every month, and the data extend up to 7 months ahead.

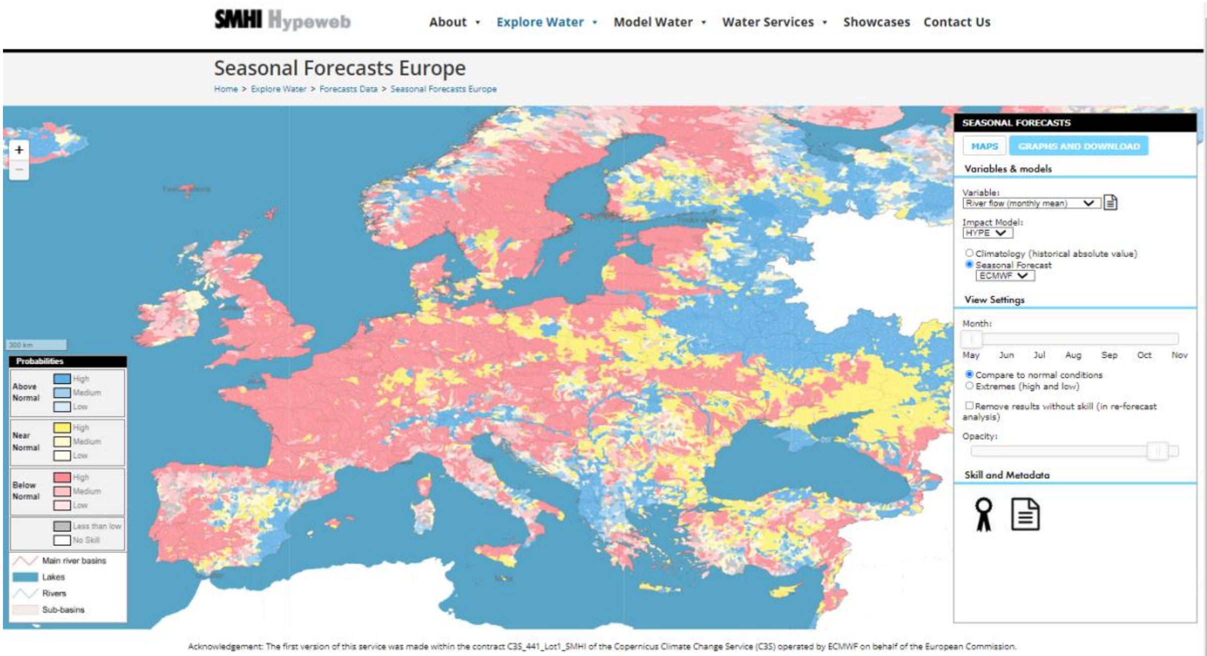


Figure 3.6 The outlook of SMHI's climate service based on seasonal forecasts for water resources management (https://hypeweb.smhi.se/explore-water/forecasts/seasonal-forecasts-europe/).

Both for the centennial projections and seasonal forecasts, the information is visualised in the form of a mapping tool as well as a site-specific tool which allows users to interactively select a point of interest on a map and receive an indicator-specific visualisation of change projections or forecast for that point. Users can also download model data from which indicators are calculated to enable users' own impact assessment workflows.

3.1.4 WMO's Climate Information Service

The WMO climate service named Climate Information provides global climate change summaries based on CMIP5 global model ensembles, optionally downscaled with CORDEX regional models for all CORDEX domains, including the European domain with the EURO-CORDEX EUR-11 (Figure 3.7). Hydrological impacts are calculated using the global WWH hydrological model. The target audiences for the service are regional to national decision-makers worldwide. The main goal of the Climate Information service is to provide easy access to state-of-the-art climate change information, with the service providing mapped climate impact indicators as well as pre-compiled site-specific summary reports for climate change impacts, and guidance on tools to calculate indicators based on a user's own local data series.

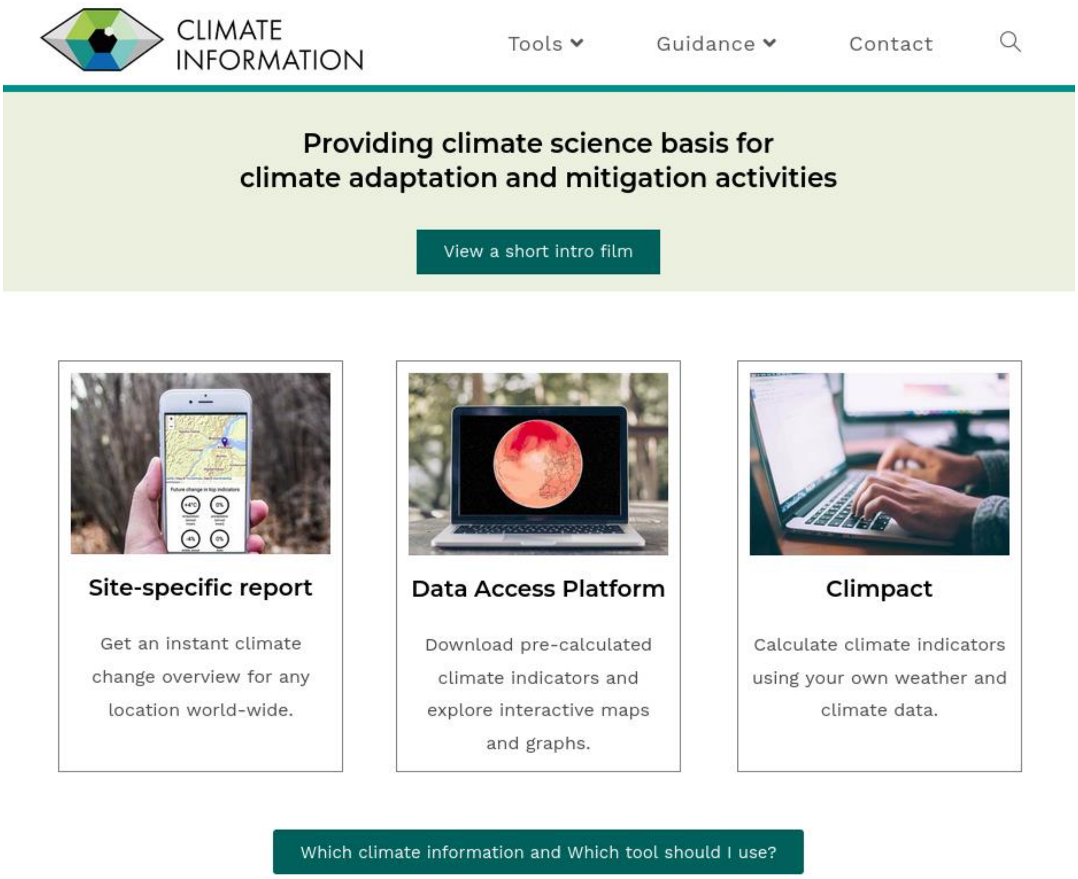


Figure 3.7 WMO Climate Information landing page with the main service parts (https://climateinformation.org/).

The "Site-specific Report" part of the service allows users to interactively choose a point of interest from a map interface, along with a greenhouse gas emission scenario and a target time period. Climate impact projections for the chosen point are then compiled into a web report which highlights projected changes in key indicators, as well as a detailed summary of all indicators available from the service in the form of map, boxplot and pie chart figures which illustrate change magnitude in a spatial context, ensemble spread, and projection robustness for each indicator. All figures are downloadable for integration in users' own assessment reports.

The "Data Access Platform" provides a global mapping tool for indicator projections, with a rich selection interface for users to interactively visualise different aspects of the projections, e.g. compare global CMIP5 runs with regional CORDEX ensembles, individual ensemble members, or different emission scenarios and impact time periods. Users can interactively select a point on the map to get a visualisation of the ensemble spread in the form of a box plot as well as downloadable model data.

The "Climpact" part of the service provides guidance on tools to compute climate impact indicators based on local data. The Climate Information service also includes extensive user guidance material to fulfil its goal to provide easy-to-digest climate information to a variety of decision-makers who are not necessarily climate experts themselves.

3.1.5 Summary

Here we summarise the characteristics of the operational pan-European Climate Services for the water sector (see Table 3.1).

Table 3.1 A summary of the characteristics of the state-of-the-art pan-European Climate Services.

Service	Time horizon	Meteo system	Bias adjustment	Impact model	Spatial resolution	Climate impact indicators	Aggregation	Max lead time
EFAS	Seasonal predictions	ECMWF SEAS5 (51 members)	-	Lisflood	5 km	River discharge (m^3/s)	Weekly averages	8 weeks
	Centennial projections	-	-	-	-	-	-	-
C3S WRM (WaterSIS)	Seasonal predictions	ECMWF SEAS5 (51 members)	Based on a quantile mapping approach	E-HYPEcatch and E-HYPEgrid	215 km^2 and 5km	River discharge (m^3/s)	Monthly averages	7 months
	Centennial projections	EURO-CORDEX EUR-11	Based on a quantile mapping approach	E-HYPEcatch and E-HYPEgrid	215 km^2 and 5km	Precipitation (mm/d) Temperature (°C) River discharge	Daily	2011-2040 2041-2070 2071-2100
SMHI	Seasonal predictions	ECMWF SEAS5 (51 members)	Based on a quantile mapping approach	E-HYPE	215 km^2	Precipitation (mm/d)	Monthly averages	7 months

Service	Time horizon	Meteo system	Bias adjustment	Impact model	Spatial resolution	Climate impact indicators	Aggregation	Max lead time
						Minimum temperature (°C) Mean temperature (°C) Maximum temperature (°C) River discharge (m^3/s)		
	Centennial projections	EURO-CORDEX EUR-11	Based on a quantile mapping approach	E-HYPE, VIC, Lisflood	215 km^2 and 5 km	17 CIIs derived from precipitation, temperature, water quantity and quality	Monthly	2011-2040 2041-2070 2071-2100
GCF	Seasonal predictions	-	-	-	-	-	-	-
	Centennial projections	CMIP5 and CORDEX	Based on a quantile mapping approach	WWH	1000 km^2	Various CII derived from precipitation, temperature, water quantity	Monthly	2011-2040 2041-2070

Service	Time horizon	Meteo system	Bias adjustment	Impact model	Spatial resolution	Climate impact indicators	Aggregation	Max lead time
								2071-2100

3.2 Energy sector

Extreme weather events such as heat waves, warm nights, and extreme droughts are likely to become more frequent and persistent in the future, exacerbated by global warming (Forzieri et al., 2018; Kornhuber et al., 2018). Analysis of impacts on the European energy sector under future climate conditions should include the risks of multiple climate extremes on different components of the energy infrastructure, such as power utilities, transmission, and distribution networks, as well as changes in energy demand sectors (Cronin, 2018; Rivers and Blake, 2020). Informed decision-making about climate adaptation options at the local level requires consideration of regional differences in power system infrastructure and available renewable resources, such as long-term hydrologic trends in river runoff, wind, and solar radiation. Adaptation measures must account for changes in power generation costs and reserve requirements, as well as conflicts over the seasonal water allocation for food and power production. Supply-side shocks include rising demand for cooling and heating-peak demand for electricity in most southern European countries already falls in the summer rather than winter months (Platts, 2018). Assessing necessary adaptation measures on a pan-European scale also requires foresight over long time horizons. Long-term analyses allow consideration of projected climate change pathways and the resulting increase in the likelihood of weather extremes. An approach to incorporating extreme events and long-term climate projections into energy modelling can be found in the literature. However, there are only a limited number of studies that thoroughly describe the complex and dynamic interactions between water and energy, focusing on the demand or supply side in selected sectors of the economy (Rivers and Blake, 2020). A comprehensive approach and integration of data from Climate Services are necessary to address the need for energy modelling frameworks to assess heat waves, warm nights, extreme droughts, and compound and concurrent extreme events for long-term policy assessments.

Understanding the effects of EE on the energy sector can improve our short and long-term projections and facilitate policy decision-making. It will expand our ability to characterise, estimate, predict and project impacts on energy prices and energy infrastructure driven by EE. Improving impact-based models with better seasonal forecasts, climate projections and extremes improves our ability to address the needs and the gaps in current EU energy and climate policies.

Below, we present several pan-European Climate Services for the energy sector and impact-based models that consider the demand and supply-side impacts of climate change, incorporating water resources management, sub-seasonal to seasonal climate predictions of renewable energy production and changes in the energy demand for heating and cooling.

3.2.1 The S2S4E Decision Support Tool

The S2S4E Decision Support Tool (DST; https://s2s4e-dst.bsc.es/#/dashboard) is an operational climate service that integrates sub-seasonal to seasonal climate predictions with renewable energy production (solar, wind and hydropower) and electricity demand (Figure 3.8). The DST was created within the Horizon 2020 project S2S4E (Sub-seasonal to Seasonal Climate Predictions for Energy), which aimed to provide more reliable and usable climate forecasts to help increase the resilience of the solar, wind and hydropower energy sectors to climate variability and extreme events.

The DST map viewer displays the forecasts according to the impact indicator (see Table 3.2). Tailored energy-relevant climate information is provided through energy indicators derived from the essential climate variables (ECVs) as listed in the table. These indicators provide robust information on the future variability in wind, solar and hydropower energy generation, as well as electricity demand, both at grid point level, and country or basin scale. The tool is user-friendly and interactive, i.e. includes an explanation of the variables, filters, sidebar information etc.

Both the sub-seasonal forecasts produced by ECMWF Extended Range and the seasonal ECMWF SEAS5 forecasts have 51 ensemble members, hence they account for the uncertainty in the forcing meteorological input. The outputs of these climate forecast systems have been used for the generation of forecast products that combine climate prediction with scientific knowledge to guide the users in its interpretation. In the DST, the information provided by the ensemble members has been used to provide the probabilities of tercile events and the probabilities of extreme event occurrence, hence there is a focus on both averaged conditions and extreme events.

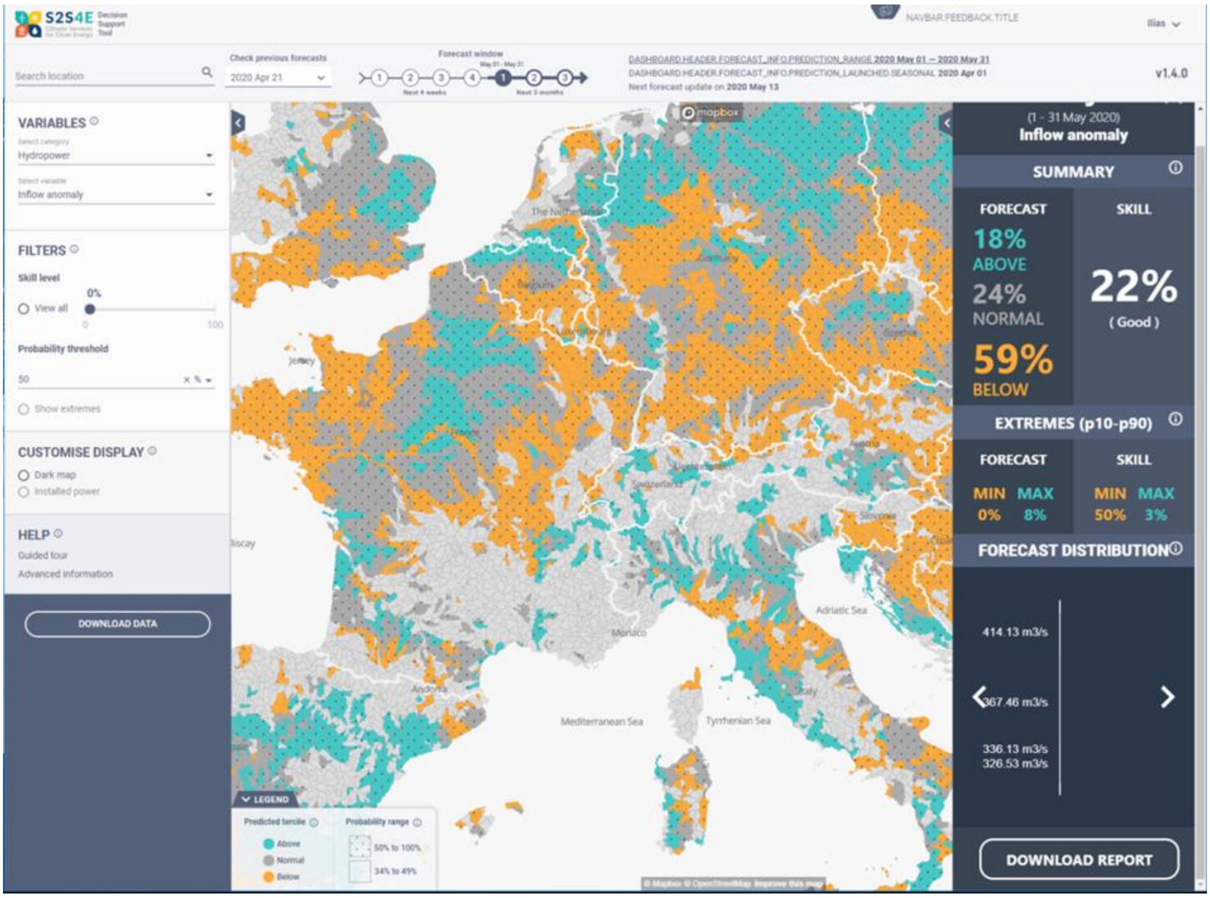


Figure 3.8 The map viewer of the S2S4E DST, which provides information for the renewable energy sectors and sub-seasonal to seasonal scales.

Table 3.2 The list of derived energy indicators that are available in the S2S4E DST, grouped under the four categories.

Category	Variable description (unit)	Aggregation level
Wind	Wind speed (m/s)	Grid
	Wind speed by country (m/s)	Country
	Capacity factor IEC1 (%)	Grid
	Capacity factor IEC2 (%)	Grid
	Capacity factor IEC3 (%)	Grid
	Sea level pressure (hPa)	Grid
Solar	Solar radiation (W/m^2)	Grid
	Solar radiation by country (W/m^2)	Country
	Capacity factor (%)	Grid
	Sea level pressure (hPa)	Grid
Hydropower	Precipitation (mm)	Grid
	Precipitation by country (mm)	Country
	Temperature (°C)	Grid
	Temperature by country (°C)	Country
	Inflow anomaly (m^3/s)	Sub-basin
	Snow max anomaly (mm)	Sub-basin
	Sea level pressure (hPa)	Grid
Energy balance	Electricity demand (GW)	Country
	Wind energy production (GW)	Country
	Demand-net wind (GW)	Country

3.2.2 The PRIMES model

The PRIMES model simulates energy supply and demand, CO_2 emissions, investment in demand and supply side of the energy market. At the same time, it also simulates the energy technology penetration and prices and costs on a country-by-country basis and across Europe for the entire energy system (see Figure 3.9). The model has been applied to carry out impact assessments for the European Commission, including the EU Long-Term Strategy and is being regularly used to create the "Reference outlook for EU energy, transport and GHG emission trends to 2050". Within the ongoing GOEXUS project, the improved PRIMES modelling framework is being extended to include the risks of limited water availability to energy production in Europe and contribute to policy dialogue for adaptation measures necessary to increase the resilience of the European energy system to future water availability constraints in Europe. The PRIMES model for power generation can be further modified to include EE in its detailed unit commitment model to assess the impacts of EE over Europe.

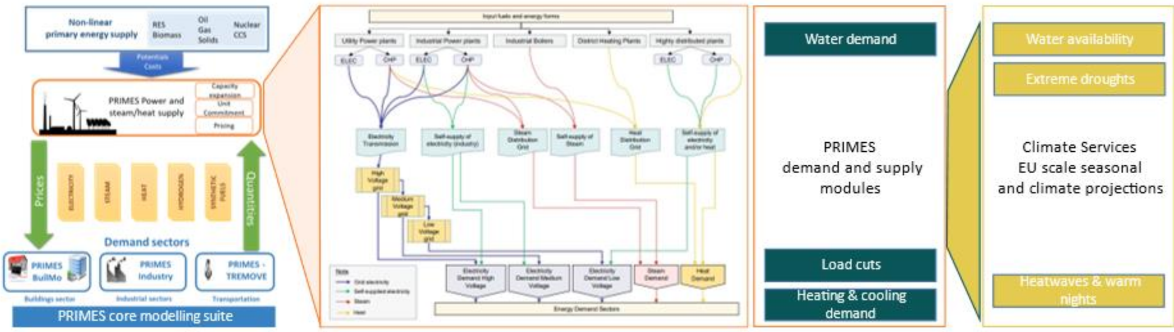


Figure 3.9 The PRIMES model framework designed to include Climate Services data for the energy sector.

The long-term energy scenarios will benefit from the modification of the PRIMES modelling suite to include EE effects on the energy system and especially power supply modules. The PRIMES core modelling suite can integrate both supply and demand-side effects of climate change on the energy sector, considering current and planned EU climate and energy policies. The model applies constraints associated with water supply for hydropower production and feedstock supply curves for biomass production and can also be extended to taking into consideration such EE as tropical cyclones and extreme droughts. PRIMES demand module can reflect structural changes in the industrial and domestic demand for energy and electricity for heating and cooling services induced by EE, such as an increased occurrence of heatwaves and warm nights.

3.2.3 Proof-of-concept on pan-European Climate Services in the energy sector

Completed and ongoing EU-funded projects have aimed to set proof-of-concept services and further address the development of climate and weather services that contribute to the analysis of climate change in the energy sector. Most of them focus on the short- and medium-term forecasts (days, weeks and months) of renewable energy sources (wind and solar radiations) as well as hydrological trends in runoff volume and seasonality: CLARA project for climate forecasts[i]; CLIM2POWER will integrate seasonal weather forecasts into decision making in the electricity sector[ii]; IMPREX addresses the future of hydropower in Europe and provides long term hydrological trends in runoff volume, extremes, and seasonality[iii].

[i] http://www.clara-project.eu/
[ii] JPI Climate - CLIM2POWER (jpi-climate.eu)
[iii] IMPREX (Improving predictions and management of hydrological extremes). Horizon 2020 project: Hydropower | IMPREX

The limited number of Climate Services for the energy sector address the long-term effects of climate change, focusing on the analysis of changes in the power and energy demand, as well as solar and wind potentials within the projected greenhouse gas concentrations pathways, see Figure 3.10 for e.g., the European energy and climate data explorer[iv].

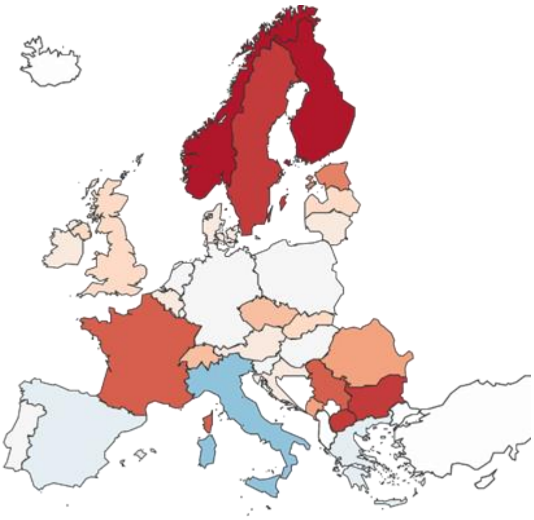


Figure 3.10 Changes in power demand in 2050 under RCP4.5 (left) and changes in solar radiation in 2050 under RCP4.5 (right).

3.3 Food sector

3.3.1 Global Framework for Climate Services (GFCS)

The agricultural and food security sector of the GFCS (https://www.gfcs-climate.org) provides climate variability and climate change insight coupled with relevant services. It performs scenario-based risk assessments and services on extreme events such as droughts and floods for monitoring, early warning systems, resilience and impact evaluations.

The agricultural and food security exemplar objectives are the development of effective partnerships and dialogue between Climate Services and agricultural and food security users at all levels to enhance these sectors' climate resiliency. Moreover, the organisation aims to monitor and respond to the changing needs of the agricultural community by developing and incorporating Climate Services into core agricultural functions (e.g., phenology, crop surveillance, preparedness and risk management, multi-sectoral food security), as well as advocating that the provision of sustainable agriculture and food security is considered an end-goal of other sectors such as climate, disaster risk reduction, water, and health. Furthermore, the exemplar intends to provide adequate and timely information and services to agriculture decision-makers to integrate environmental and climate factors into agriculture planning strategies. Finally, the example aims at improving

[iv] European energy and climate data explorer, Copernicus Climate Change Service (C3S) [European energy and climate data explorer (copernicus.eu)]. The data explorer gives projections under RCP 2.6, RCP 4.5 and RCP 8.5 for power and energy demand, hydropower reservoirs and rivers, as well as onshore and offshore wind speeds.

operational and technical collaboration on environmental, disaster risk, and climate issues so that coordinated actions can be taken to ensure sustainable agriculture and food security.

3.3.2 JRC Agri4Cast

Agri4Cast (https://agri4cast.jrc.ec.europa.eu) are operational Climate Services provided by the Food Security Unit of the European Commission's Joint Research Center (JRC). Within Agri4Cast, the Monitoring Agricultural ResourceS (MARS) Crop Yield Forecasting System (MCYFS) provides daily 25x25 km gridded agrometeorological data with a unique set of weather indicators, yield forecasts and crop conditions, also reported within certain administrative regions and sub-regions, i.e. based on the NUTS for Europe delineation.

The MCYFS monitors crop growth conditions and weather conditions affecting crop development and provides yield forecasts alongside an information and warning system for crop damages, shortages or failure in support of the food security objectives. Near real-time data such as weather, weather forecasts and remote sensing data are used alongside ancillary data such as soil maps, crop calendars and administrative yield statistics in order to simulate crop conditions. These crop simulations, coupled with weather and remotely sensed data, are used to make crop-specific end-of-season yield forecasts. Additionally, MARS provides monthly reports (bulletins) for crop monitoring in Europe with agrometeorological quantitative and qualitative analyses based on the outputs of the weather and crop models (Figure 3.11).

Overall, the Climate Services that are provided in relation to the food sector are: (1) The generation of agro-meteorological indicators for a direct evaluation of alarming situations such as drought, extreme rainfall during sowing, flowering or harvest etc.; (2) The development and use of simulation methodologies and models for crops behaviour and the evaluation of the effect of weather on crops. The crop growth models used are mainly WOFOST and WARM, along with others such as the CropSyst and CANEGRO. The crops simulated are winter wheat, grain maize, spring barley, rye, sugar beets, potato, field beans, winter rapeseed, sunflower and rice.

The major MARS activity sectors are agricultural monitoring, crop yield forecasting, food security, agricultural biodiversity, rural development and climate change. MCYFS provides monthly bulletins forecasting crop yields in support of the EU's CAP. The developed system on early warning of crop shortages or failure provides timely and quick information for EU development aid activities to encounter food insecurity. Additionally, Agri4cast performs assessments of the effectiveness, efficiency, relevance and sustainability of policy measures related to rural development, climate change adaptation and possible mitigation by agricultural-related policies.

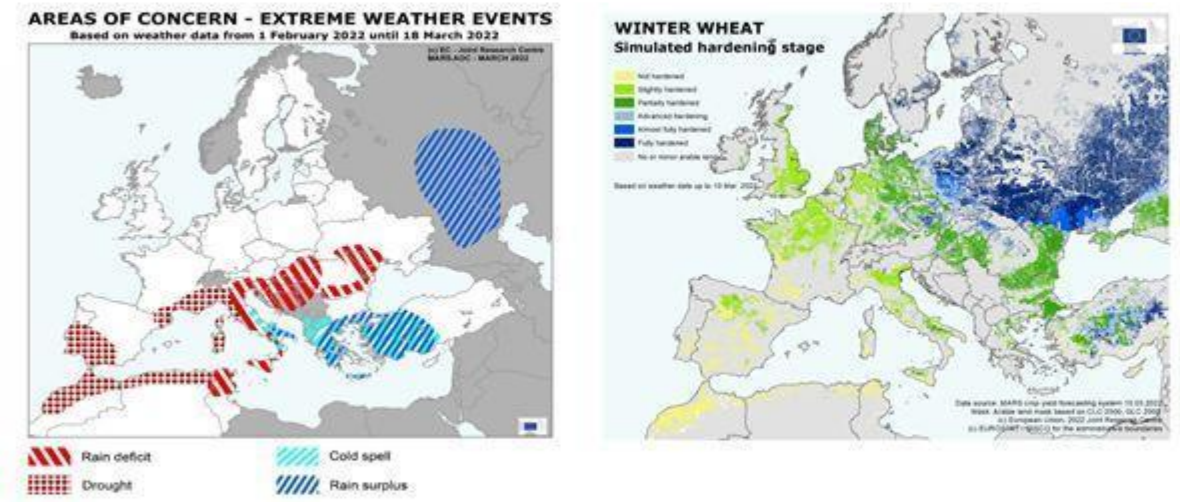


Figure 3.11 Agrometeorological overview and areas of concern in Europe (left) and winter wheat status (right).

Agri4cast data collected for research activities are freely available for access and reuse. Agri4cast data and indicators can be used in policy support (e.g. EU and the Common Agriculture Policy (CAP)), education, consulting and business related to the agricultural and food security sector, covering the following regions: Europe, Russia/Kazakhstan, China, India, South America, Africa while maintaining a global window.

3.3.3 The INTERSUCHO Climate Service

The INTERSUCHO Climate Services (https://www.intersucho.cz/en/) are operational services provided by the global change research institute CAS and the Mendel University in Brno. The services provide maps of climate data analysis for the past four weeks and predictions for up to 9 days ahead. The maps are provided for the Czech Republic, Slovenia and Central Europe. The maps display estimator estimation of drought intensity, water deficit, relative soil saturation, vegetation condition, impacts on yield and impacts on forest (see Figure 3.12). The end-users of such services range from national to international agencies and stakeholders concerned with agriculture and forestry, food security and climate response.

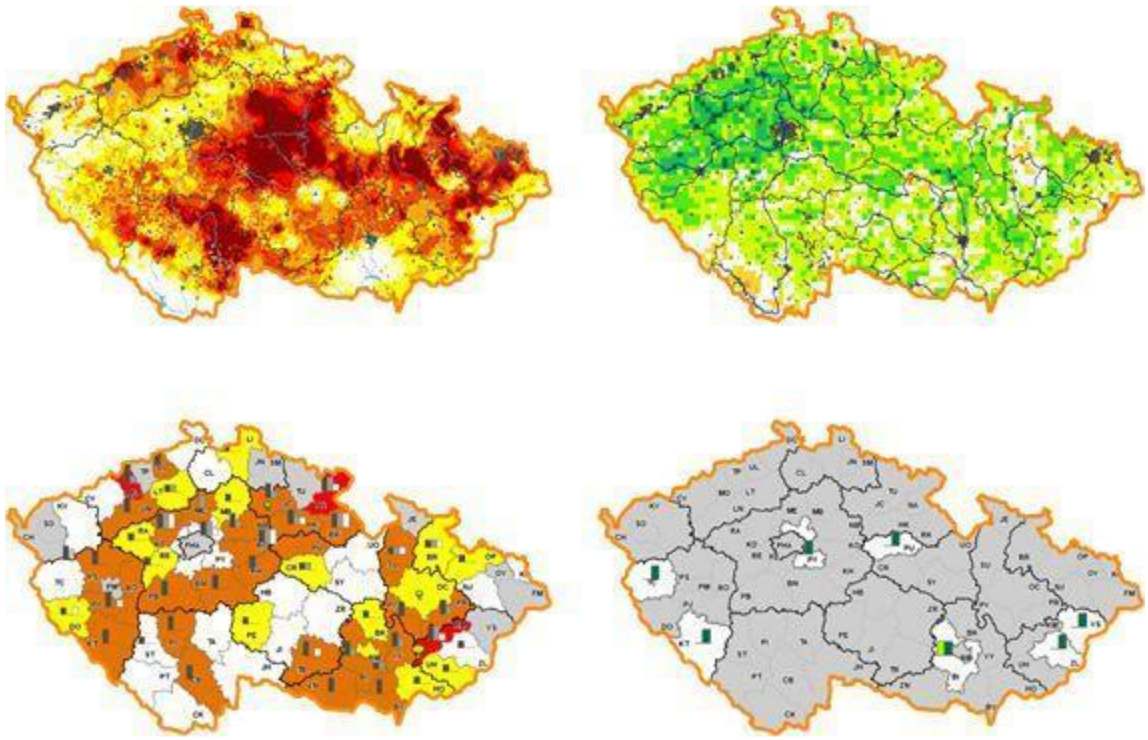


Figure 3.12 Drought intensity on 2022-05-15 (top-left), vegetation condition on 2022-05-15 (top-right), estimated drought impacts on yield on 2022-05-12 (bottom-left), and impacts on forests on 2022-05-12 (bottom-right).

3.3.4 MED-GOLD

The operational MED-GOLD Climate Services (https://www.med-gold.eu) are developed and maintained by the MED-GOLD consortium partners. MED-GOLD provides Climate Services for grapes, olives and durum wheat in Europe and coffee in Colombia. These services include data, information, knowledge and modelling platforms to support adaptation, mitigation and disaster risk management (see Figure 3.13). It offers risk management tools for pests, yield and quality losses and other climate-related threats. These services offer support for decision-making on two different timescales: a seasonal and a longer outlook over the next few decades. More specifically on the European part and crops, the services are as follows:

- For olives: Olive fruit fly infestation models for short and long-term time scales and yield modelling approaches for seasonal and projections;
- For grapes: Short- and long-term analysis of relevant climatic, bioclimatic and extreme climate indices affecting field management operations (choice of plantation site, grapevine variety, setting harvest dates, operational farming planning);
- For durum wheat: Seasonal and long-time-scale forecasting for yield, risk of diseases and operational farming management.

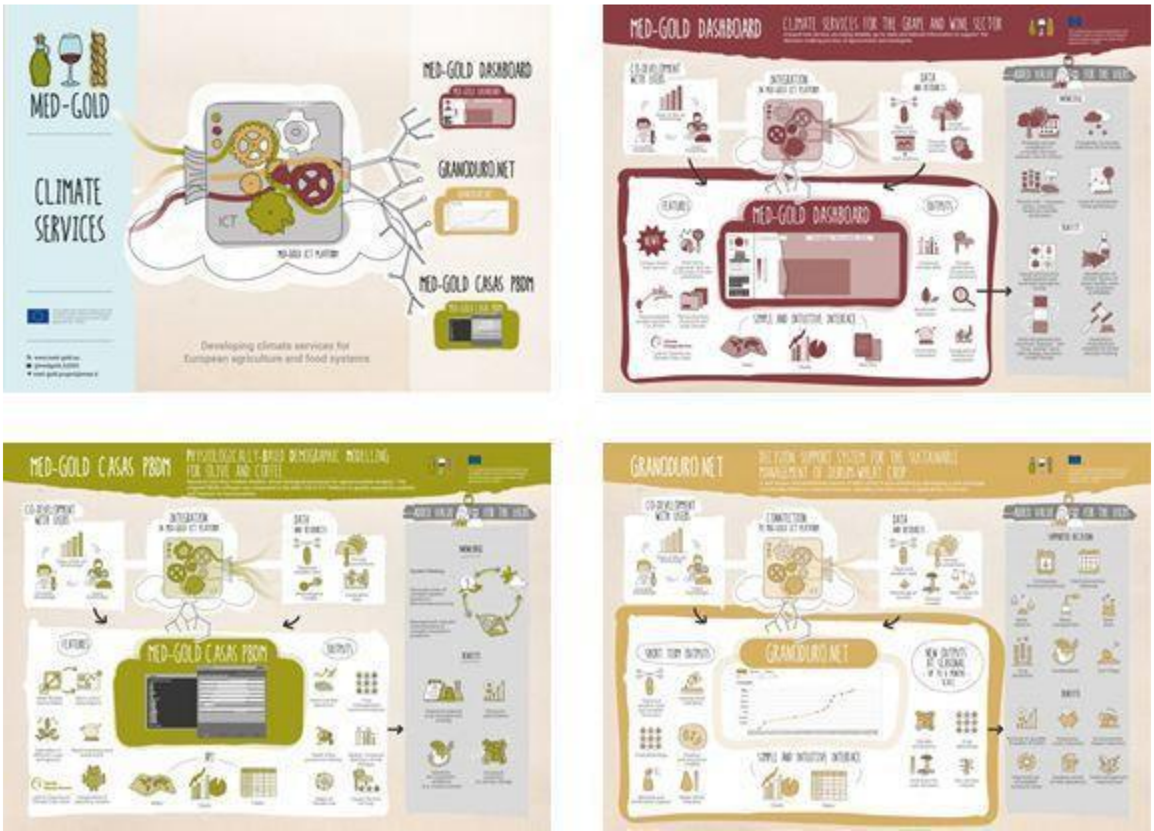


Figure 3.13 Infographical overview of the MED-GOLD project and the individual bundles of Climate Services.

The MED-GOLD services are related to agricultural monitoring, food security and climate change and are of major interest to public agencies and administration, academia, IT services, producers, companies, large-scale producers, farmers and SMEs. The MED-GOLD services cover mainly the European market and secondarily the Colombian market. It has a worldwide potential for durum wheat, a primary European potential for olives, and a grapes mixed market potential between Europe and the rest of the world.

3.3.5 The C3S on Agriculture and Forestry

The C3S services on Agriculture and Forestry deliver bioclimatic indicators and climate projections tested on crops such as wheat, rice, soybean, maize, cotton and permanent crops (https://climate.copernicus.eu/agriculture-and-forestry; see Figure 3.14). C3S uses climate data and climate change indicators for the generation and maintenance of impact models on agriculture and forestry. Furthermore, they are developing indicators for crop productivity and growth and for water resources and droughts, while providing customised data for climate resilience in these sectors. Additionally, C3S provides decadal projections to provide further, at least for demonstration/prototype projects, future climate knowledge, which is critical for adaptation strategies such as agriculture-related strategic policies, from regional to EU's common agricultural policy (CAP).

The C3S on Agriculture and Forestry mainly concerns farmers and farming associations, the textile industry, traders, biopesticide manufacturers, policy-makers and the agriculture/forestry involved public and private agencies, among others. C3S provides real-time climate information enabling day-to-day decisions, and seasonal forecasts to support medium-term adaptive decisions (e.g. choosing crop varieties, the best time to cut down trees, crop grazing balance and preparing for food emergencies). Furthermore, past and future climate comparisons help support transformational decisions such as breeding new crop varieties, investing in irrigation, and relocating production areas. The markets that mainly benefit and are targeted by the C3S services are, in principle, European but can be utilised globally.

More specifically, specialised and targeted programs have been developed under the C3S framework and utilising its services. Textile manufacturers, merchants, and apparel brands need specialised information to better grasp long-term climate-related risks. This information is delivered using the Climate Change Impact on Cotton application built with Copernicus data and tools, including seasonal forecasts. Examples are:

- HarvesterSeasons is a mobile and web application that integrates seasonal climate forecasts with a hydrological model from the Finnish Meteorological Institute to help the forestry sector make optimal decisions.
- BioSuccess combines the commission's temperature data with biological models of insect growth and biopesticide efficiency. The purpose is to aid biopesticide makers, users, and legislators in establishing the appropriate application timing for insect population control in various settings (see Figure 3.15).
- Climate Scale provides on-demand high-resolution global climate change estimates based on state-of-the-art climate downscaling models to help a wide range of sectors assess and manage the physical hazards of climate change.
- CLIMTAG is a web-based program that provides users with historical, current, and future agro-climatic indicators based on quality-assured C3S climate data. The number of dry days and the start of the major rainy season are among the agro-climatic indicators provided (see Figure 3.15).
- Climadjust is a tool that provides CMIP and CORDEX climate projections by applying state-of-the-art bias-adjustment methods to local reference data sets (e.g. WFDE5, ERA5-Land, GSOD).
- The Agricultural Climate Advisory Services (AgriCLASS) project developed data sets and tools to help the agricultural sector adapt to climate change by providing region-specific products providing a combination of climate and agriculture data.

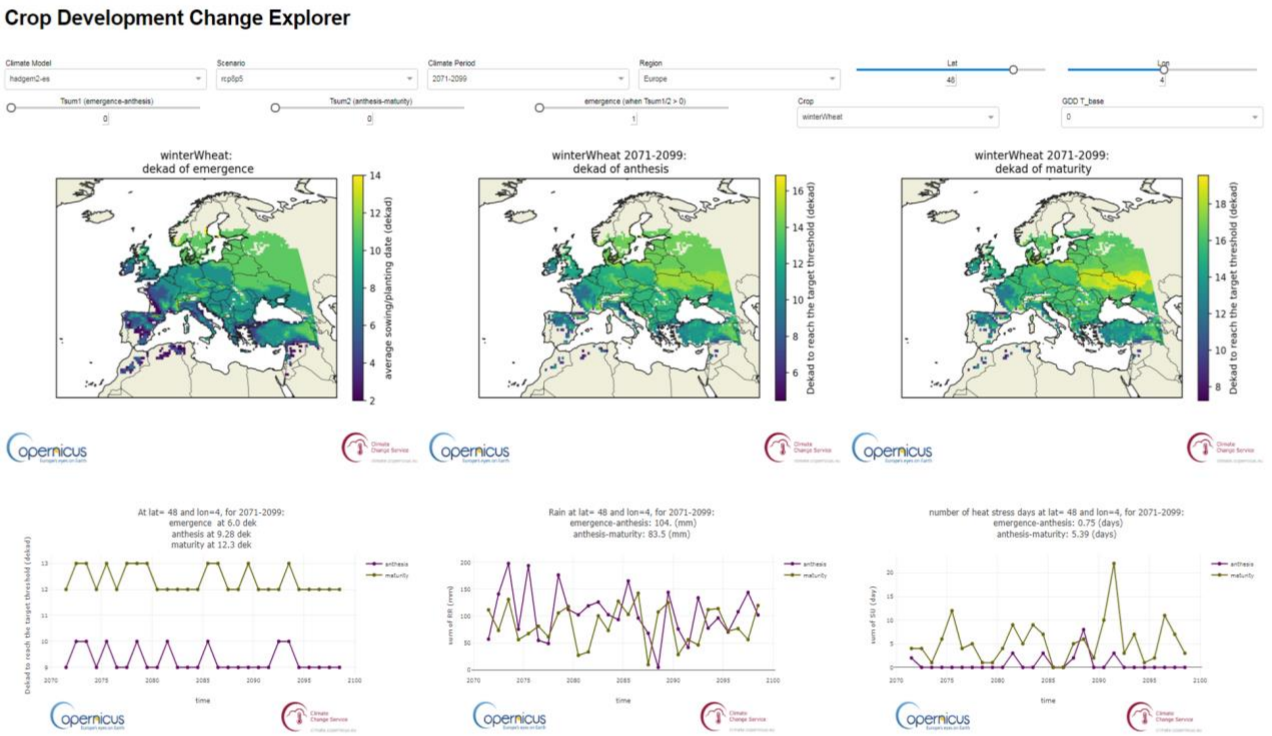


Figure 3.14 The Global Agriculture (https://climate.copernicus.eu/global-agriculture-project) project and the Crop Development Explorer app.

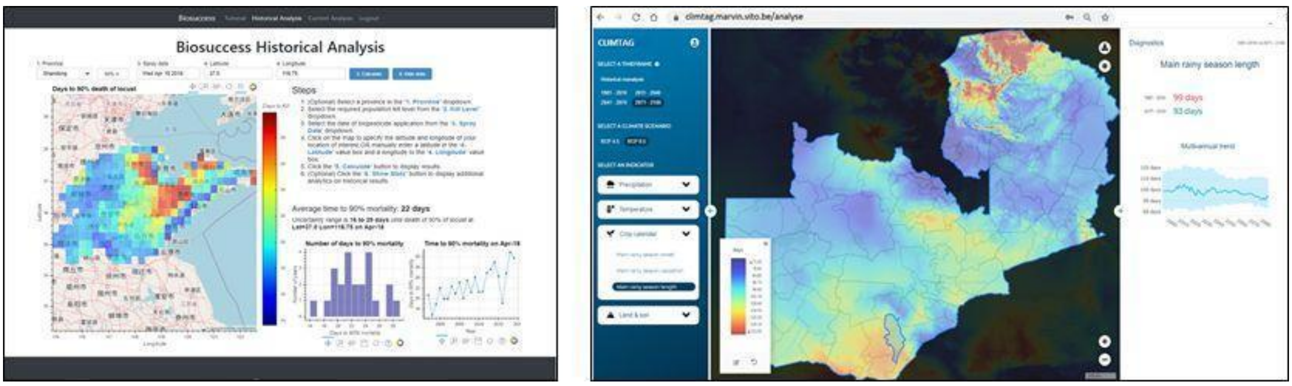


Figure 3.15 BioSuccess analysis showing days to 90% death of locusts, following biopesticide application (left) and the CLIMTAG screenshot showing the agro-climatic indicator 'Main rainy season length' for the Choma district in Zambia for 2041–2070 (right).

3.3.6 GEOGLAM Crop Monitor

The Group on Earth Observations Global Agricultural Monitoring (GEOGLAM) provides an operation bundle of Climate Services, the Crop Monitor for Early Warning (CM4EW) (https://cropmonitor.org; see Figure 3.16). The CM4EW is a consensus assessment of crop production conditions in food-insecure regions, supporting early warning for food security response and focusing on a wide range of crops that have regional food security implications. It provides monthly reports containing (1) information on crop conditions as a classification-type overview of the development and yield expectations on a regional scale (East Africa, West Africa, Middle East and North Africa, Southern Africa, Central and South Asia, Southeast Asia, Central America and the Caribbean), (2) a global climate outlook with two-week forecast of areas with above or below-average precipitation, (3) climate influences information in regard to the El Niño-Southern Oscillation, and (4) a regional climate outlook with two-week forecast of areas with above or below-average precipitation.

CM4EW provides insight for utilisation within the food security sector, mainly national agencies responsible for food security policy and response programs, being essentially a global service with targeted areas of concern, namely the African continent, the Middle East, Central America and Central/South Asia (see Figure 3.17). The target markets and end-users of the CM4EW products and reports are global, regional and national entities.

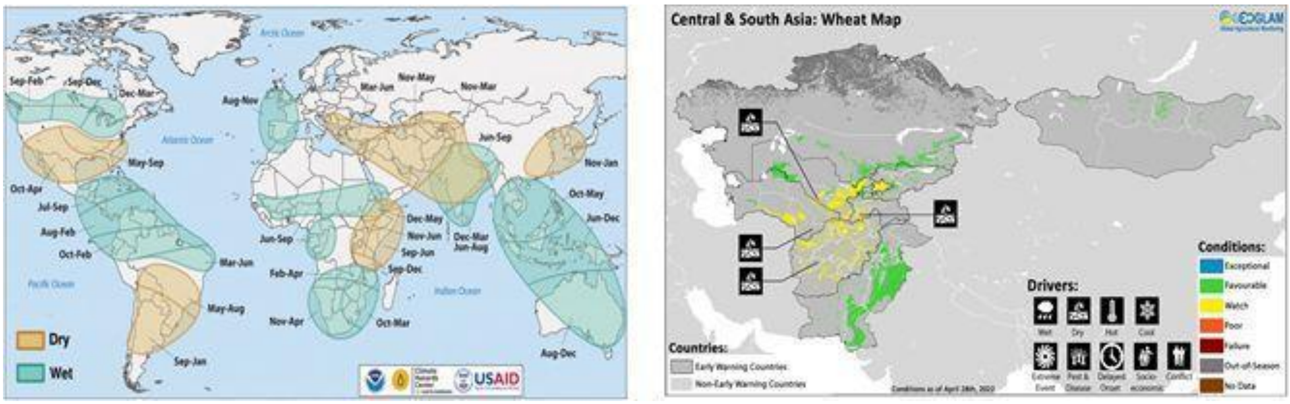


Figure 3.16 Timing of wet and dry conditions related to La Nina (left) and wheat conditions and drivers in Central and South Asia as of April 28th 2022 (regional) (right).

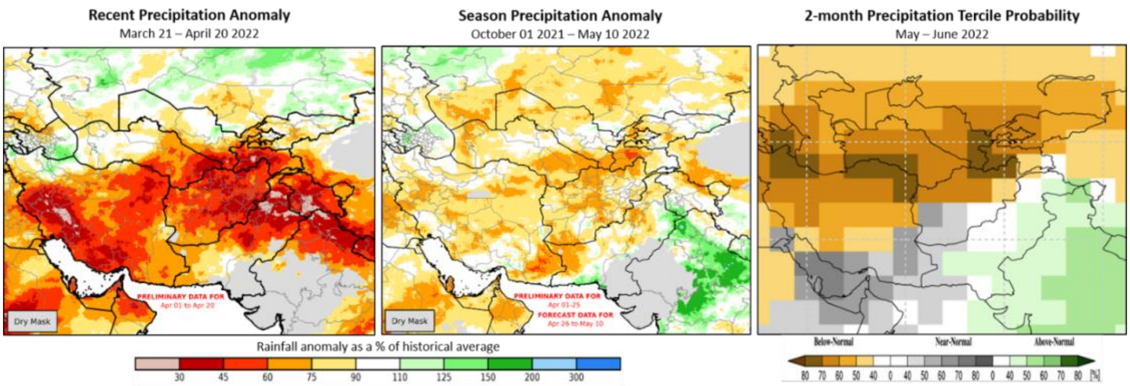


Figure 3.17 30-day and October 1st-to-May 10th precipitation anomalies, and a 2-month precipitation probability forecast for May-June 2022.

3.3.7 Drought Management Centre for South-eastern Europe (DMCSEE)

The DMCSEE (http://www.dmcsee.org/) provides operational Climate Services, which are provided by the United Nations Convention to Combat Desertification (UNCCD), WMO and the South-East European network (Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Greece, Hungary, Moldova, Montenegro, North Macedonia, Romania, Serbia, Slovenia, and Turkey). This project intends to coordinate and aid the development, appraisal, and deployment of drought risk management instruments and policies across South-eastern Europe to enhance drought preparedness and decrease drought impacts. The drought bulletins for SE Europe have been published monthly since 2010 and present the most relevant information on the current drought condition in South-eastern Europe (see Figure 3.18).

On the basis of several drought indices, a drought watch tool (as an open web-based application) was built to provide near-real-time monitoring of drought conditions over the Danube region. The data is based on remote sensing and modelled data and is provided on a daily, weekly, or 10-day basis. The Climate Services provide insight for stakeholders from the South-Eastern European Network countries, public and private bodies and interested parties mainly related to the agricultural sector, food security and environmental management.

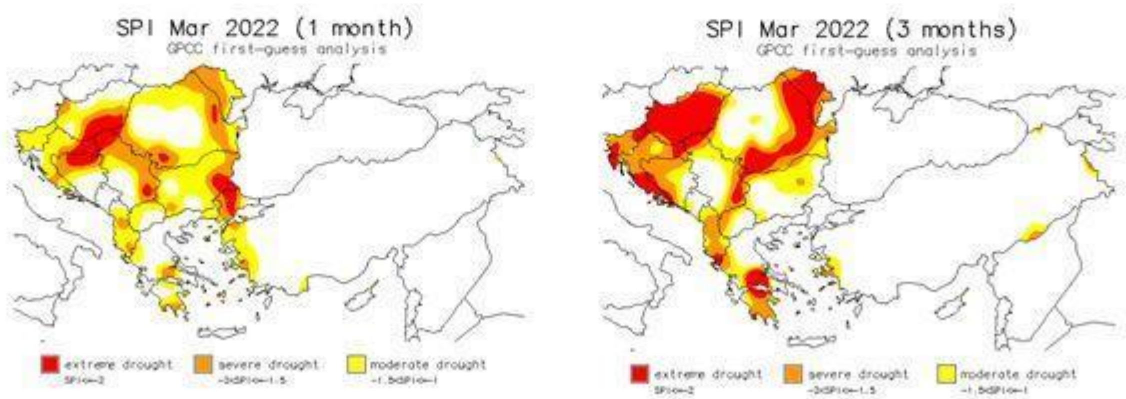


Figure 3.18 One-month standardised precipitation index for March 2021 (left) and three-month standardised precipitation index for March 2021 (right).

4 USER SURVEY

4.1 Introduction and Methods

CLINT's mission is to improve the Climate Science of extreme events fostering cooperation and knowledge transfer between climate service providers and users. In this phase of the project, we want to better understand the regional, national and continental contexts and user needs to improve the basis upon which long-term decisions are made. To this end, we created a survey consisting of twenty questions designed in the survey tool Questback (in English; see Annex for the complete overview of the questions). We distributed the survey via social media (i.e., Twitter, LinkedIn) and emailed it to reach relevant users, including stakeholders, researchers and other service providers, in order to further distribute it to their network. All answers were recorded anonymously in accordance with the General Data Protection Regulation (GDPR).

In total, 74 respondents completed the survey. However, we will continue collecting survey responses throughout the project's lifetime, hopefully increasing the statistical significance of the results. To understand the strategy and rationale behind the survey, we briefly explain its structure and implementation hereafter.

In the survey, we used 'rated response/scaling' answer options to quantify responses as well as 'open answers' to obtain individual feedback. This way, we could cover all major areas of interest and ensure a form of structural unity among the responses while also providing respondents with the opportunity to give individual feedback. The variety of answer types is critical for this survey because we expected Climate Services users to have various backgrounds and user needs. Moreover, we used conditional questions so that participants were automatically moved to a different set of questions depending on their previous responses. The majority of questions in the survey are tabulated and allow either single or multiple responses.

The survey is organised into two parts, with the first half including compulsory questions and the last part being optional. The first section aims to identify the respondents' decision-making context, such as their background and years of work experience. We consider this information important since the background of users may likely influence how they use Climate Services. In addition, we included questions on how the predicted information fits into their decision context, on their main interests concerning additional prediction information, data and predictions usage and what kind of improvement they envision for the future. In the second part, participants could express their interest in various issues related to their operational practice, such as accounting for uncertainties, data access and preferences for data visualisation.

Since many questions had multiple answer options, the number of answers does not necessarily refer to the total number of participants (i.e. 74). If the number of participants (from here on, referred to as "*n*") is not explicitly stated, then *n* refers to the total number of survey participants (i.e. 74).

4.2 Background of survey participants

The survey participants are primarily based in Europe, with some responses from the USA, Africa, Asia and Australia (Figure 4.1a). Almost a quarter of the survey participants have a background in engineering, followed by the fields of hydrology and environment with 17% and 16%, respectively (Figure 4.1b). The remaining participants have backgrounds in fields such as agronomy, economy and meteorology. Some participants also indicated working in art, culture and communication (added in the answer option “other”). The majority of survey participants are senior professionals with more than 11 years (69%) of work experience (Figure 4.1c), and most (53%) work as researchers within their organisation (Figure 19d). The remaining people are consultants (22%), decision-makers (11%) and other professionals such as team leaders or IT developers (“other” option).

Figure 4.1 Characteristics of the respondents: (a) the geographic background, (b) the professional background, (c) the years of experience, and (d) their role in their organisation.

The surveyed participants work primarily in the water (38%), energy (20%) and food (18%) sectors (Figure 4.2). Other sectors people indicated to work in include sustainability and science communication (“other” option). Among those who primarily work in the water sector (*n*=28), the vast majority (89%) indicated working on “water resources management”, and more than half (57%) work on “hydrometeorological risk reduction” (Figure 4.2a). 77% of those who primarily work in the food sector (*n*=13) reported working in "agriculture", followed by "livestock (meat and dairy)" with 40% (Figure 4.2b). In the energy sector (*n*=15), the sub-sector with the highest percentage was "renewables (wind)" (73%), followed by "hydropower" (60%) (Figure 4.2c).

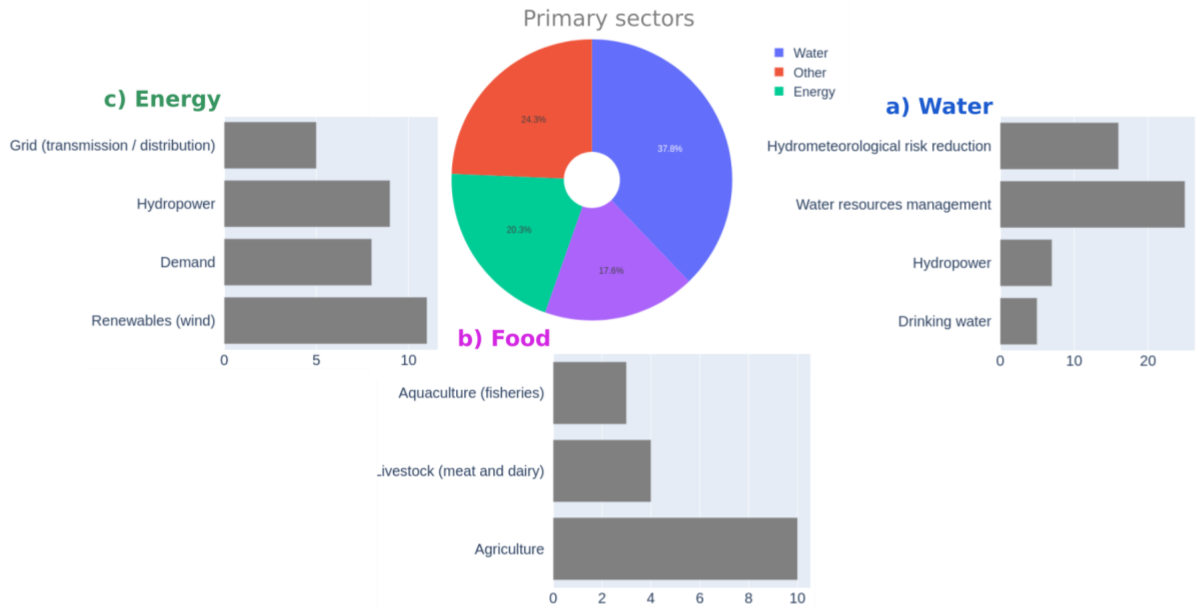


Figure 4.2 Characterisation of the sectors that respondents come from and their primary work for the: (a) water, (b) food, and (c) energy sectors.

To assess the nexus across sectors, we asked whether the survey participants also considered working in other sectors. Figure 4.3 shows the summary information in a word cloud, which indicates that professionals work across multiple fields such as tourism, rural development, forest management, art, circular economy and climate justice.

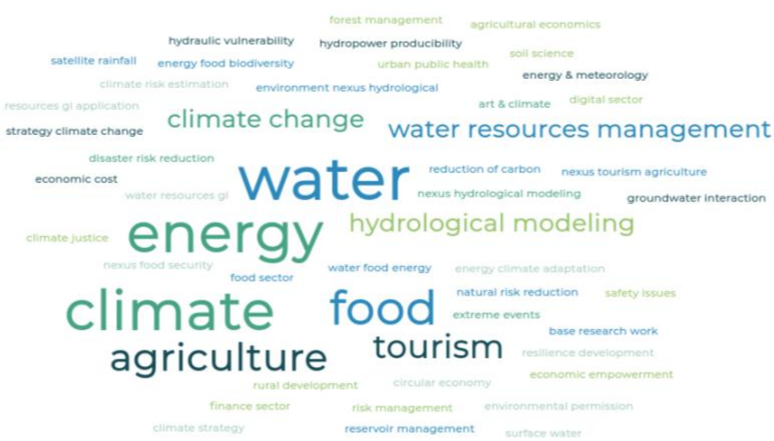


Figure 4.3 A word cloud showing the professional work of the respondents.

4.3 Benchmarking the use of climate information

Asked on what basis the respondents make long-term (i.e. a month ahead and beyond) decisions, the majority (51%) reported making decisions based on climatology, followed by forecasting (47%), real-time (34%) and decadal predictions (31%) (Figure 4.4a). The data types they (*n*=24) use are primarily model-based (96%), in-situ data (79%), and remote sensing (42%) (Figure 4.4b). Forecasting is done on a seasonal (75%) and monthly/sub-seasonal timescale (66%) (Figure 4.4c; *n*=35).

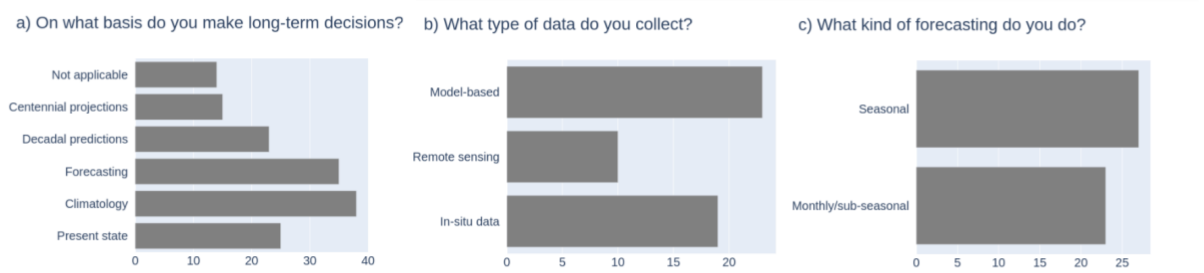


Figure 4.4 Analysis towards understanding of climate information being used.

Results show that the majority of survey participants (62%) use Climate Services for decision-making. When asked which Climate Services they are using, responses provided diverse answers, including weather web pages, satellite rainfall data, IPCC, CMCC, NASA and EU Services such as ECMWF forecasts. There was no clear differential signal among the remaining ones who do not use Climate Services for decision-making.

4.4 Spatial and temporal resolutions of Climate Services

The highest spatial and temporal resolutions of services participants use most are 2-10 km (28%) and 24 hours (27%), respectively (Figure 4.5). When the participants were asked what they considered an ideal spatial resolution of climate/hydro-meteorological predictions, they primarily responded with 1x1 km^2, 5x5 km^2 and 10x10 km^2. Similarly, when they were asked what they considered an ideal temporal resolution of climate/hydro-meteorological predictions, they mainly indicated monthly, daily, hourly and yearly (in order of relevance).

Figure 4.5 Analysis of the responses regarding the resolution of climate information that is needed in (a) space and (b) time.

4.5 Lead times of interest and use of predictions

The survey also aimed to understand the forecast horizons (lead-time) that the participants are interested in for the different variables. Figure 4.6 shows all relevant prediction horizons (named here as lead-time) for each variable used by the participants. Most lead times (i.e., days, weeks, months, years, decades) seem to be similarly relevant for key parameters such as precipitation, temperature and streamflow, except for seasons, which might have been considered as part of months. Biomass productivity and crop development seem to be the least relevant variables.

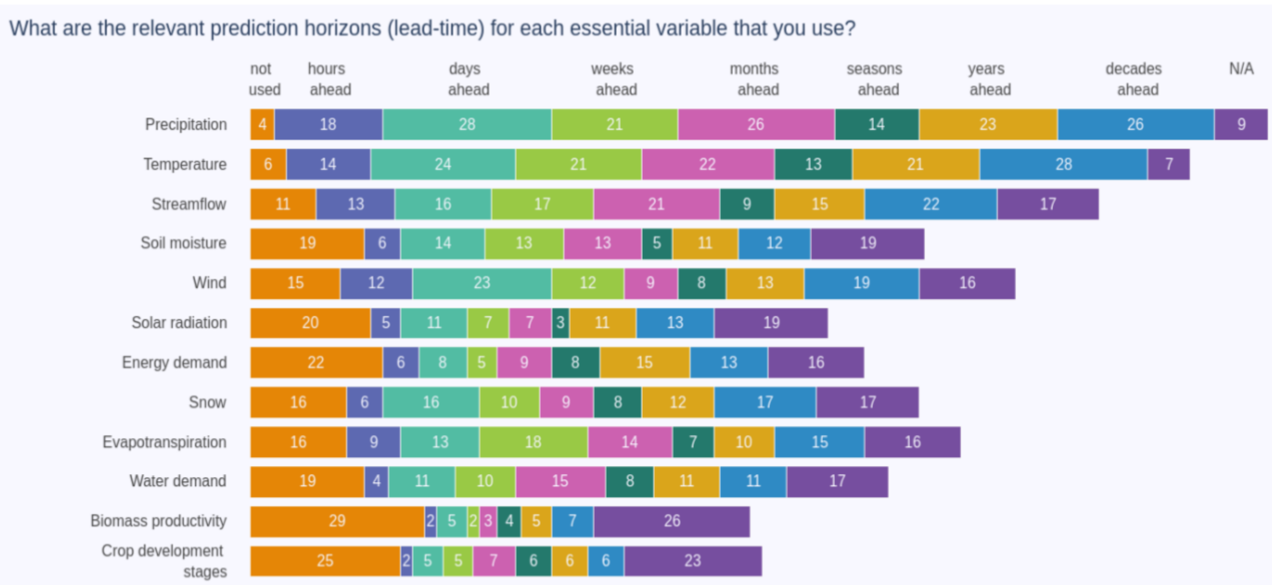


Figure 4.6 Results indicating the lead times of interest for different variables.

When the participants were asked what lead time they deemed ideal, they responded with daily, weekly and monthly. When they were asked how and how often they use prediction, the most replies were reported at least once per month to visually inspect what the future situation might be or qualitatively as additional knowledge to make decisions (Figure 4.7). Survey participants also indicated seeing hourly, daily and weekly update frequencies of climate/hydro-meteorological predictions as most ideal.

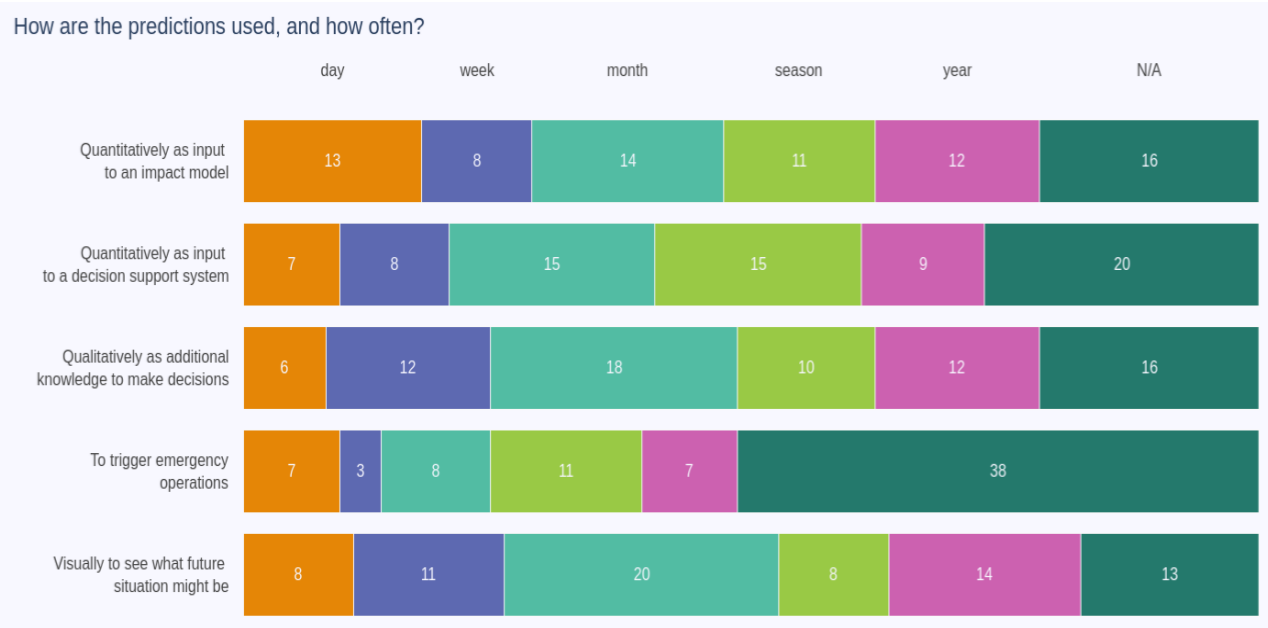


Figure 4.7 Results indicating the usability of the predictions.

4.6 Improved predicted information and uncertainty

The survey also aimed to understand ways for further improving the predicted information. When the participants were asked about their interest level for improved predicted information, better prediction of weather extremes was the option deemed by most (57%) as extremely important (Figure 4.8). Also seen as very important by more than 30% of the respondents were:

1. improved weather forecasts for longer lead times (sub-seasonal to seasonal scales),
2. a higher spatial resolution of the predictions, and
3. higher temporal resolution of the predictions.

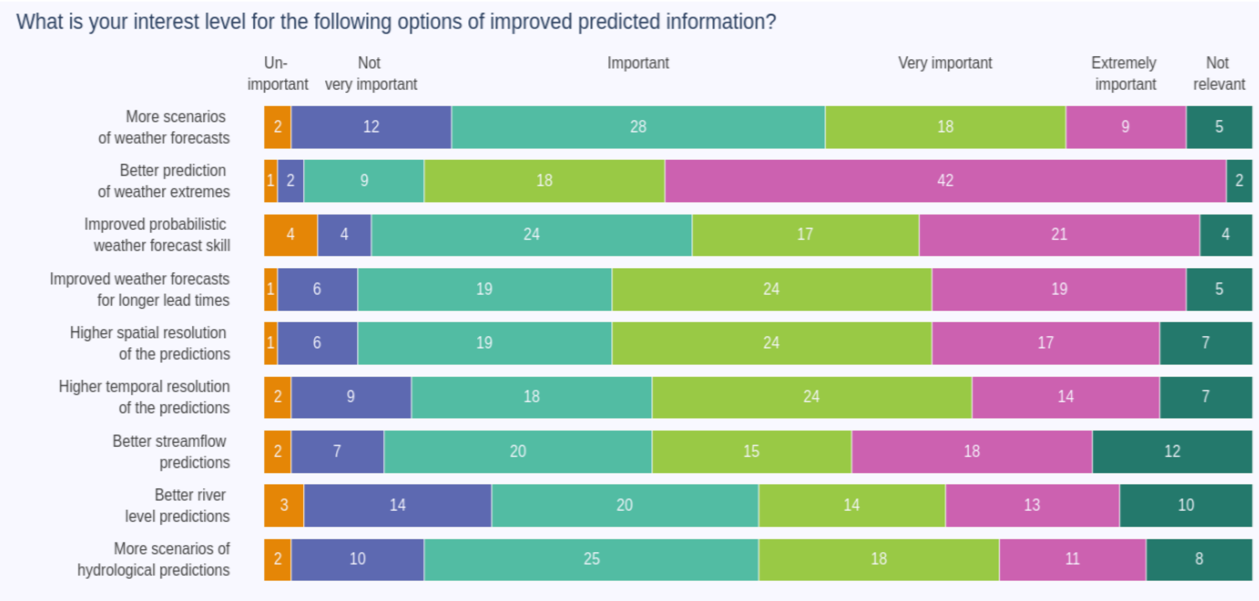


Figure 4.8 Responses indicating different methods for improving the predicted information.

More scenarios of hydrological predictions and of weather forecasts were also seen by many as important. Better streamflow and river level predictions were seen as least relevant, while improved probabilistic weather forecast skills were evaluated as least important. When making decisions, 87% consider the information on uncertainty/probability provided with the predictions by using scenario-based modelling or sensitivity analysis. Some of the remaining participants, who indicated neglecting uncertainty/probability state that uncertainty is simply not considered or is irrelevant because the predictions, do not have an immediate impact on their work.

4.7 Data sources, access and visualisation

Finally, when the participants were asked which sources they use to access climate data, they mainly stated sources such as Copernicus, NOAA (National Oceanic and Atmospheric Administration), national weather services and national organisations (such as SMHI). Some participants stated that they access data from Climate Services as NetCDF files using API services. Other forms of access seem to be Google, mobile apps, published papers and other web services. When they were asked which data visualisation from Climate Services users prefer, they primarily indicated maps, graphs, downloadable time series and key messages.

5 CONCLUSIONS

Climate Services are being recognized as valuable assets for supporting adaptation, mitigation, and disaster risk management today and under future climate change scenarios when Extreme Events are expected to increase in both frequency and intensity. Recent advances in Artificial Intelligence (AI) offer a unique opportunity for making the most of the available data with the aim of providing easily accessible, timely, and decision-relevant information to policy-makers and end-users, and of contributing to sustainable development strategies across different socio-economic sectors that need timely and effective climate actions.

This document provides a thorough introduction to Climate Services and reviews the identified barriers for the Climate Services uptake together with a SWOT (strength - weakness - opportunity - threat) analysis for the European applications. In addition, the document provides terminologies (glossary) lured in two large communities, i.e. Climate Services and artificial intelligence, in order to set the ground for common understanding when AI-enhanced Climate Services are developed. Moreover, a review of the state-of-the-art Climate Services for the pan-European domain is provided for the water, energy, and food sectors, with a particular focus on the lead times of interest and impact indicators available.

A major pillar of this document is the effort put into adding value to the understanding of the needs of users/stakeholders affected by climate variability. This is achieved through an online survey, which was co-designed within the CLINT project consortium to contribute to the large efforts to bridge the knowledge gap between climate service providers and users. The answers helped us to better understand the regional, national and continental contexts and user needs, and, finally, improve the basis upon which long-term decisions are made.

In summary, we note that for the European climate service providers to advance, innovation needs to happen along all four sources of innovation, which include institutional arrangements, users, suppliers, and inputs. The result of the SWOT analysis further indicated that the EU should try to gain an exporting market from the US, as well as seek to develop Climate Services in global regions of high demand. These conclusions were further complemented by the insights derived from the user survey. Some key messages are:

- Users currently base their long-term decisions mostly on information extracted from climatology (51%) and forecasting (47%). This sets the benchmark for long-term decision-making and indicates room for improvement of the existing services.
- The data types that are most collected are model-based (96%) and in-situ data (79%). These results were expected and indicate that earth observations have not been fully up-taken by the sectors. In addition, it pushes toward the need for improvements in the models, i.e. structure and setups.
- Forecasting is done primarily on a seasonal (77%) and sub-seasonal scale (66%). This conclusion highlights that, on a more operational mode, sub-seasonal to seasonal forecasts

have a higher weight than decadal and/or centennial projections, which are driving policy-making. With the sub-seasonal to seasonal model currently being developed, the conclusions here support these ongoing efforts.

- Most users need information at a spatial resolution of 2-10 km (28%) and at a daily temporal resolution (27%). This is a key message which can be a reason that existing Climate Services, which provide information at coarser spatial-temporal resolution, did not meet their potential with regard to their uptake. Efforts on climate service evolution should be put towards increasing the spatiotemporal resolution of the provided climate information.
- Decades ahead for temperature and days ahead for precipitation are the most relevant variables and lead times (both 38%). Moreover, better prediction of weather extremes is considered the most important information (57%). These results justify the efforts in the CLINT project to better detect extreme events and attribute them to climate change.
- Predictions are mostly used at least once per month or season in a qualitative way as input to a decision support system (20%) or once per month to assess future situations (27%). With the scientific results showing that the frequent initialization brings higher skill in the predictions and the need from the users' side, a direction towards evolving the climate model systems to account for frequent initialization can be justified.
- Finally, the majority of survey participants (87%) take uncertainty/probability into account for decision-making. This is a key conclusion which highlights that uncertainty (quantified by the large ensemble size in the predictions) is a characteristic of the predictions, which is increasingly understood and is being integrated into the decision-making process.

The conclusions above are key for the enhancement of current large-scale, i.e. pan-European, Climate Services. In particular, they identify the room for an added value through AI enhancement, which is the main objective of the CLINT project.

BIBLIOGRAPHY

Barsugli, J.J., Guentchev, G., Horton, R.M., Wood, A., Mearns, L.O., Liang, X.Z., Winkler, J.A., Dixon, K., Hayhoe, K., Rood, R.B., Goddard, L., Ray, A., Buja, L., Ammann, C. (2013). The Practitioner's Dilemma: How to Assess the Credibility of Downscaled Climate Projections, Eos Trans. AGU, 94, 424.

Blauhut, V., Stahl, K., Stagge, J.H., Tallaksen, L.M., De Stefano, L., Vogt, J. (2016). Estimating drought risk across Europe from reported drought impacts, hazard indicators and vulnerability factors, Hydrol. Earth Syst. Sci., 20, 2779–2800, doi:10.5194/hess-20-2779-2016.

Blöschl, G., et al. (2017). Changing climate shifts timing of European floods, Science, 357 (6351), 588-590, https://doi.org/10.1126/science.aan2506

Bruno Soares, M.B., Dessai, S. (2016). Barriers and enablers to the use of seasonal climate forecasts amongst organisations in Europe. Climatic change 137, 89-103.

Bruno Soares, M.B., Alexander, M., Dessai, S. (2018). Sectoral use of climate information in Europe: A synoptic overview. Climate Services, 9, 5-20, https://doi.org/10.1016/j.cliser.2017.06.001

Buontempo, C. et al. (2018). What have we learnt from EUPORIAS climate service prototypes?, Clim. Serv., 9, 21–32, doi:10.1016/j.cliser.2017.06.003.

Carleton, T.A., Hsiang, S.M. (2016). Social and economic impacts of climate, Science, 353, 6304, doi:10.1126/science.aad9837

Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jäger, J., Mitchell, R.B. (2003). Knowledge systems for sustainable development. Proc. Natl. Acad. Sci., 100, 8086-8091, 10.1073/pnas.1231332100.

Cash, D.W., Buizer, J. (2005). Knowledge-action systems for seasonal to interannual climate forecasting. In: Summary of a Workshop, Report to the Roundtable on Science and Technology for Sustainability, Policy and Global Affairs. The National Academies Press, Washington, DC.

Cortekar, J., Themessl, M., Lamich, K. (2020). Systematic analysis of EU-based climate service providers. Climate Services, 17, 100125.

Cronin, J., Anandarajah, G., Dessens, O. (2018). Climate change impacts on the energy system: a review of trends and gaps. Climatic Change 151, 79–93. https://doi.org/10.1007/s10584-018-2265-4

Demirel, M.C., Mai, J., Mendiguren, G., … Stisen, S. (2018). Combining satellite data and appropriate objective functions for improved spatial pattern performance of a distributed hydrologic model, Hydrol. Earth Syst. Sci., 22(2), 1299–1315, doi:10.5194/hess-22-1299-2018.

Dilling, L., Lemos, M.C. (2011). Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy, Global Environmental Change, 21, 680-689.

Dobrynin, M., Domeisen, D. I. V., Müller, W. A., Bell, L., Brune, S., Bunzel, F., … Baehr, J. (2018). Improved Teleconnection-Based Dynamical Seasonal Predictions of Boreal Winter. Geophysical Research Letters, 45(8), 3605–3614. https://doi.org/10.1002/2018GL077209

EU (2016). Study to examine the socio-economic impact of Copernicus in the EU: Report on the Copernicus Downstream Sector and User Benefits. European Union Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, Brussels, Belgium.

European Commission, Directorate-General for Research and Innovation, Jacob, D., Runge, T., Street, R., et al. (2015). A European research and innovation roadmap for Climate Services, Publications Office, https://data.europa.eu/doi/10.2777/702151

Feldman, D.L., Ingram, H.M. (2009). Making science useful to decision makers: climate forecasts, water management, and knowledge networks. Weather Clim Soc 1(1):9–21.

Forzieri, G., Bianchi, A., Silva, F. B. e., Marin Herrera, M. A., Leblois, A., Lavalle, C., Aerts, J. C. J. H., Feyen, L. (2018). Escalating impacts of climate extremes on critical infrastructures in Europe. Global Environmental Change, 48, 97–107. https://doi.org/10.1016/j.gloenvcha.2017.11.007

GEO (2015). GEO 2016-2025 Strategic Plan for Implementing Global Earth Observation System of Systems. Retrieved from https://www.earthobservations.org/geoss_wp.php

Hewitt, C., Buontempo, C., Newton, P., Doblas-Reyes, F., Jochumsen, K., Quadfasel, D. (2017). Climate observations, climate modeling, and Climate Services, Bull. Am. Meteorol. Soc., 98(7), 1503–1506, doi:10.1175/BAMS-D-17-0012.1

Kirchhoff, C.J., Lemos, M.C., Dessai, S. (2013). Actionable knowledge for environmental decision making: Broadening the usability of climate science. Annual Review of Environment and Resources, 38. 393 - 414. ISSN 1543-5938.

Kornhuber, K., Osprey, S., Coumou, D., Petri, S., Petoukhov, V., Rahmstorf, S., Gray, L. (2019). Extreme weather events in early summer 2018 connected by a current hemispheric wave-7 pattern. Environmental Research Letters 14.

Lemos, M.C., Morehouse, B.J. (2005). The co-production of science and policy in integrated climate assessments. Global Environmental Change, 15, 57-68. https://doi.org/10.1016/j.gloenvcha.2004.09.004.

Lemos, M.C. (2015). Usable climate knowledge for adaptive and co-managed water governance. Curr Opin Environ Sustain 12:48–52.

McDonnell, J.J., et al. (2018). Water sustainability and watershed storage, Nature Sustainability, 1, 378–379.

Meinke, H., Nelson, R., Kokic, P., Stone, R., Selvaraju, R., Baethgen, W. (2006). Actionable climate knowledge: from analysis to synthesis. Clim Res 33(1):101.

Mendoza, P. A., Wood, A.W., Clark, E., … Arnold, J.R. (2017). An intercomparison of approaches for improving operational seasonal streamflow forecasts. Hydrology and Earth System Sciences, 21(7), 3915–3935. https://doi.org/10.5194/hess-21-3915-2017

Meyer, R. (2011). The public values failures of climate science in the US. Minerva 49(1):47–70.

Nijzink, R.C. et al. (2018). Constraining Conceptual Hydrological Models With Multiple Information Sources, Water Resour. Res., 54(10), 8332–8362, doi:10.1029/2017WR021895.

Panenko, A., George, E., Lutoff, C. (2021). Towards the development of climate adaptation knowledge-action systems in the European Union: An institutional approach to climate service analysis, Climate Services, 24, https://doi.org/10.1016/j.cliser.2021.100265.

Pappenberger, F., H. L. Cloke, … and J. Thielen (2015). The monetary benefit of early flood warnings in Europe, Environ. Sci. Policy, 51, 278–291, doi:10.1016/j.envsci.2015.04.016

Platts (2018). European Power Daily. S&P Global 20 (151).

Porter, J.J., Dessai, S., (2017). Mini-me: Why do climate scientists’ misunderstand users and their needs? Environmental Science & Policy, 77, 9-14.

Rivers, N., Blake S., (2020). Stretching the Duck: How rising temperatures will change the level and shape of future electricity consumption. The Energy Journal 41 (5):55-88.

Scaife, A. A., Arribas, A., Blockley, E., Brookshaw, A., Clark, R. T., Dunstone, N., ... & Hermanson, L. (2014). Skillful long-range prediction of European and North American winters. Geophysical Research Letters, 41(7), 2514-2519.

Tart, S., Kristensen, F.B., Hinsby, P., Howard, S., Howard, S. (2018). SWOT analysis of EU supply. EU H2020 project MARCO D3.5 (grant agreement No. 730272), MARCO_D3_5_SWOT_Analysis_of_EU_Supply.pdf (marco-h2020.eu)

UNFCCC (2015). The Paris Agreement. United Nations Framework Convention on Climate Change, https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

van den Hurk, B.J.J.M., Bouwer, L. M., Buontempo, C., Döscher, R., Ercin, E., Hananel, C., … Wijngaard, J. B. (2016). Improving predictions and management of hydrological extremes through Climate Services. Climate Services, 1–6. https://doi.org/10.1016/j.cliser.2016.01.001

van Loon A.F. et al. (2016). Drought in the Anthropocene, Nature Geoscience, 9, 89–91.

Wanders, N., Wood, E.F. (2016). Improved sub-seasonal meteorological forecast skill using weighted multi-model ensemble simulations. Environmental Research Letters, 11(9), 094007.

Ward, P. J., Jongman, B., Salamon, P., et al. (2015). Usefulness and limitations of global flood risk models. Nature Climate Change, 5(8), 712–715, https://doi.org/10.1038/nclimate2742

Weichselgartner, J., Arheimer, B. (2019). Evolving Climate Services into Knowledge–Action Systems, Weather, Climate, and Society, 11(2), 385-399, doi:https://doi.org/10.1175/WCAS-D-18-0087.1

Wetterhall, F., Di Giuseppe, F. (2018). The benefit of seamless forecasts for hydrological predictions over Europe, Hydrol. Earth Syst. Sci., 22, 3409–3420, doi:10.5194/hess-22-3409-2018.

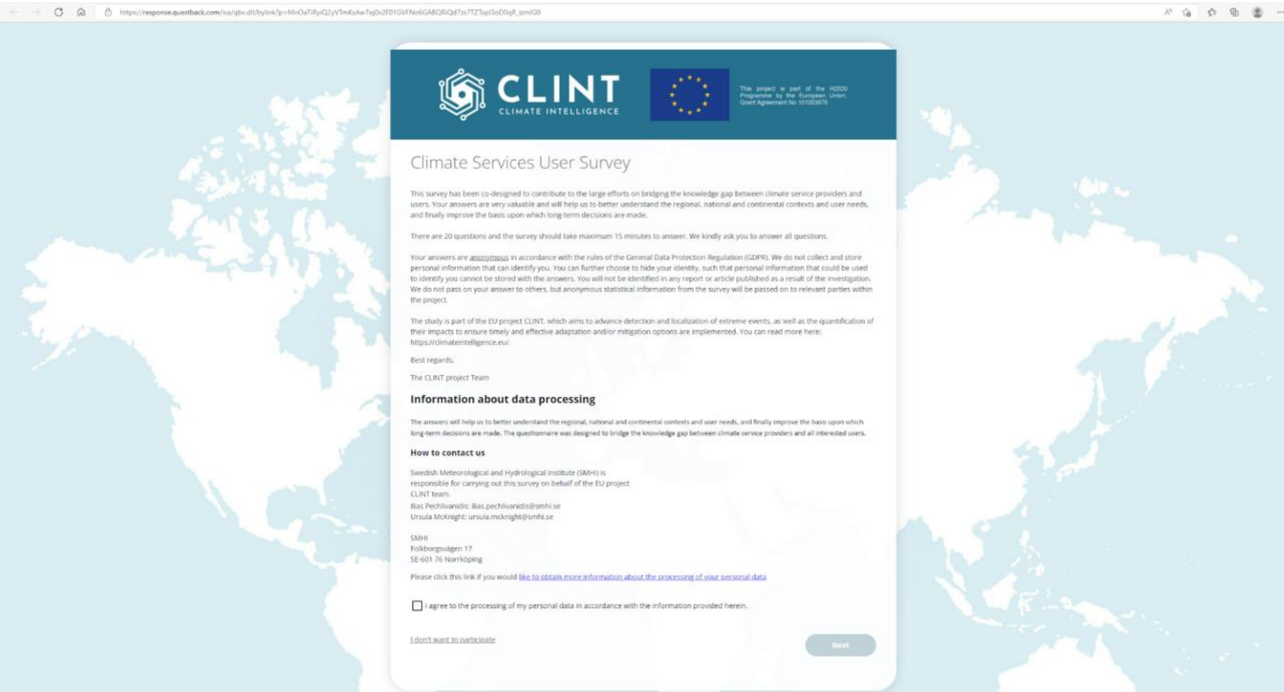
White, C.J., et al. (2017). Potential applications of subseasonal-to-seasonal (S2S) predictions, Meteorol. Appl., 24(3), 315–325, doi:10.1002/met.1654.

Zhou, G., et al. (2015). Global pattern for the effect of climate and land cover on water yield, Nature Communications, 6, 5918.

ANNEX

A.1 Survey introduction

In this section, survey questions prepared for the CLINT User Survey are shown as screenshots taken in Questback.



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CLIMATE INTELLIGENCE

This project is part of the H2020 Programme by the European Union, Grant Agreement No 101003876

Climate Services User Survey

This survey has been co-designed to contribute to the large efforts on bridging the knowledge gap between climate service providers and users. Your answers are very valuable and will help us to better understand the regional, national and continental contexts and user needs, and finally improve the basis upon which long-term decisions are made.

There are 20 questions and the survey should take maximum 15 minutes to answer. We kindly ask you to answer all questions.

Your answers are anonymous in accordance with the rules of the General Data Protection Regulation (GDPR). We do not collect and store personal information that can identify you. You can further choose to hide your identity, such that personal information that could be used to identify you cannot be stored with the answers. You will not be identified in any report or article published as a result of the investigation. We do not pass on your answer to others, but anonymous statistical information from the survey will be passed on to relevant parties within the project.

The study is part of the EU project CLINT, which aims to advance detection and localization of extreme events, as well as the quantification of their impacts to ensure timely and effective adaptation and/or mitigation options are implemented. You can read more here: https://climateintelligence.eu/.

Best regards,

The CLINT project Team

Information about data processing

The answers will help us to better understand the regional, national and continental contexts and user needs, and finally improve the basis upon which long-term decisions are made. The questionnaire was designed to bridge the knowledge gap between climate service providers and all interested users.

How to contact us

Swedish Meteorological and Hydrological Institute (SMHI) is
responsible for carrying out this survey on behalf of the EU project
CLINT team.
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SMHI
Folkborgsvägen 17
SE-601 76 Norrköping

Please click this link if you would like to obtain more information about the processing of your personal data

☐ I agree to the processing of my personal data in accordance with the information provided herein.

I don't want to participate

Next

Figure A.1 Frontpage of CLINT Climate Services User Survey, ensuring GDPR requirements are met.

A.2 Questions related to background of survey participants

Figure A.2 Questions related to survey participants' characteristics, including in which country they work, their background, position and years of experience.

Figure A.3 Questions related to participants' primary sector they work in (top left), followed by more specific questions related to each of the WEF sectors, depending on the answer (top right, bottom left and right, corresponding to food, water and energy, respectively). Note that respondents could also choose "other", in which case a box opened into which they could add areas not presented.

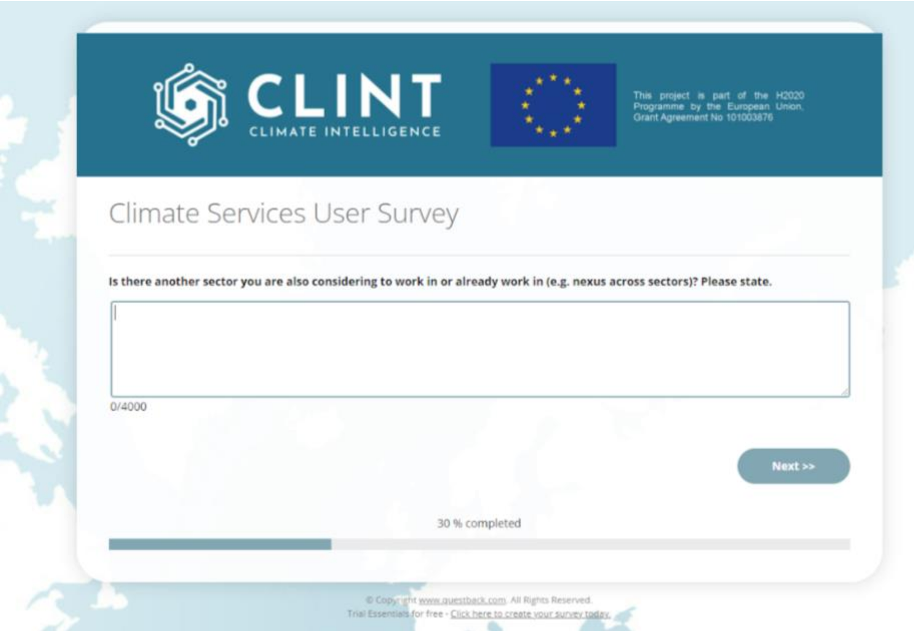

Figure A.4 Follow-up question to explore sector interests of the participants. The results of this question were explored as a word cloud (see Figure 4.3).

A.3 Questions related to benchmarking the use of climate information

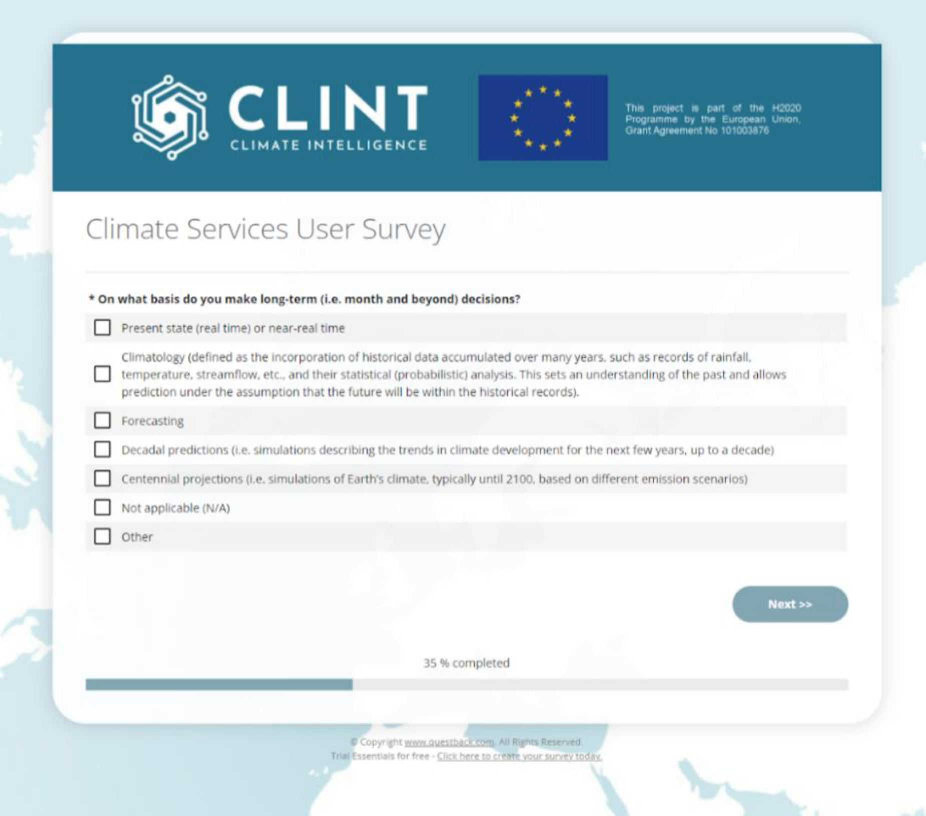

Figure A.5 Question to determine basis for decision-making. If either “present state” and/or “forecasting” were selected, additional questions were activated (see Figure 7.6).

Figure A.6 Follow-up questions, related to selections made previously, i.e. for “present state” (left) and “forecasting” (right) (see Figure 7.5).

Figure A.7 Questions to determine whether participants currently use CS data in their work (left), and if so, they were asked to state which CS they currently use (right).

A.4 Questions related to spatial and temporal resolutions of CS

Figure A.8 Questions to determine highest spatial and temporal resolutions currently in use.

A.5 Questions related to lead times of interest and use of predictions

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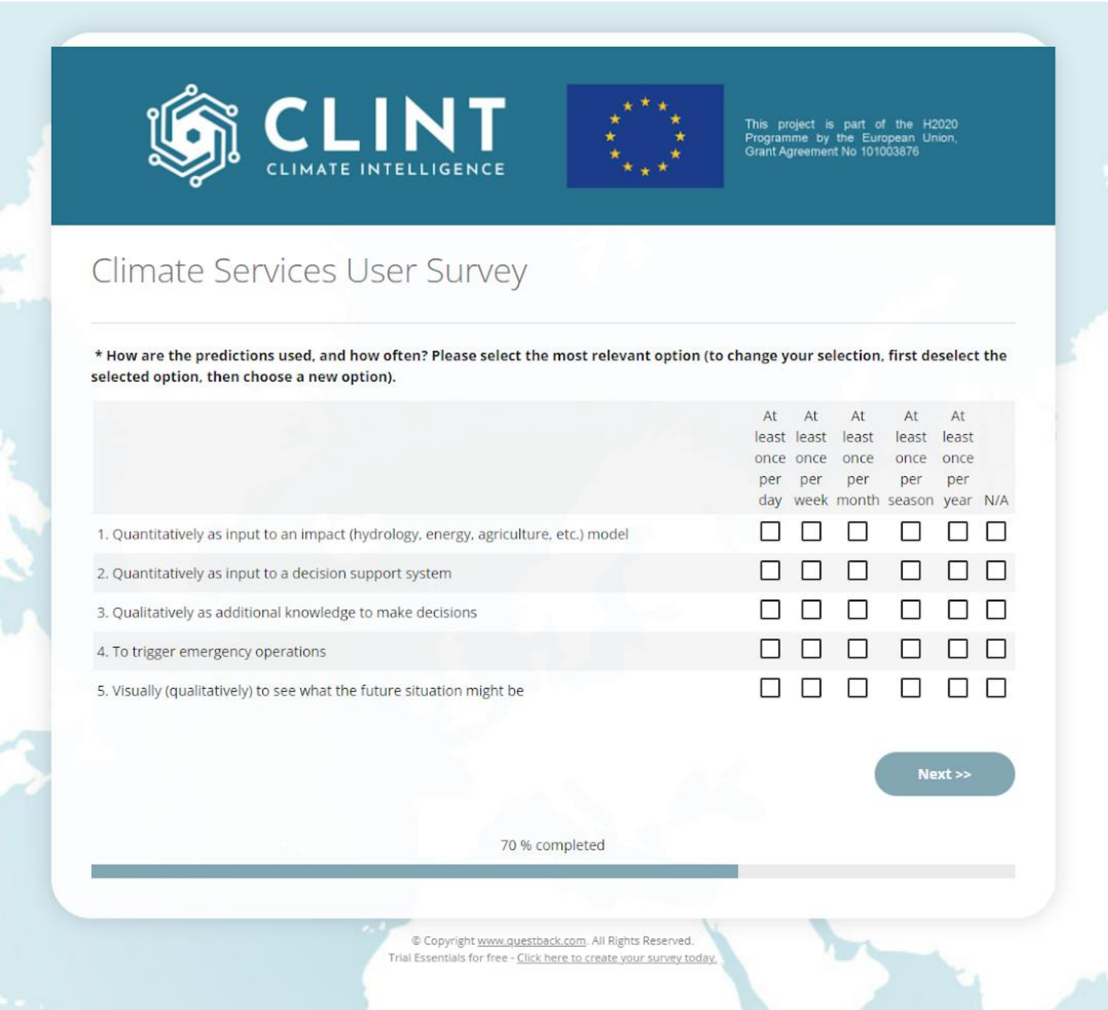
* Please select all relevant prediction horizons (lead-time) for each essential variable that you use.

	Not used	Some hours ahead	Some days ahead	Some weeks ahead	Some months ahead	Some seasons ahead	Some years ahead	Some decades ahead	N/A
1. Precipitation	☐	☐	☐	☐	☐	☐	☐	☐	☐
2. Temperature	☐	☐	☐	☐	☐	☐	☐	☐	☐
3. Streamflow	☐	☐	☐	☐	☐	☐	☐	☐	☐
4. Soil moisture	☐	☐	☐	☐	☐	☐	☐	☐	☐
5. Wind	☐	☐	☐	☐	☐	☐	☐	☐	☐
6. Solar radiation	☐	☐	☐	☐	☐	☐	☐	☐	☐
7. Energy demand	☐	☐	☐	☐	☐	☐	☐	☐	☐
8. Snow	☐	☐	☐	☐	☐	☐	☐	☐	☐
9. Evapotranspiration	☐	☐	☐	☐	☐	☐	☐	☐	☐
10. Water demand	☐	☐	☐	☐	☐	☐	☐	☐	☐
11. Biomass productivity	☐	☐	☐	☐	☐	☐	☐	☐	☐
12. Crop development stages	☐	☐	☐	☐	☐	☐	☐	☐	☐

Next >>

65 % completed

Figure A.9 Question to determine lead times of interest.



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*** How are the predictions used, and how often? Please select the most relevant option (to change your selection, first deselect the selected option, then choose a new option).**

	At least once per day	At least once per week	At least once per month	At least once per season	At least once per year	N/A
1. Quantitatively as input to an impact (hydrology, energy, agriculture, etc.) model	☐	☐	☐	☐	☐	☐
2. Quantitatively as input to a decision support system	☐	☐	☐	☐	☐	☐
3. Qualitatively as additional knowledge to make decisions	☐	☐	☐	☐	☐	☐
4. To trigger emergency operations	☐	☐	☐	☐	☐	☐
5. Visually (qualitatively) to see what the future situation might be	☐	☐	☐	☐	☐	☐

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70 % completed

Figure A.10 Question to determine whether CS are used in decision-making.

A.6 Questions related to user needs for improving predicted information and uncertainty

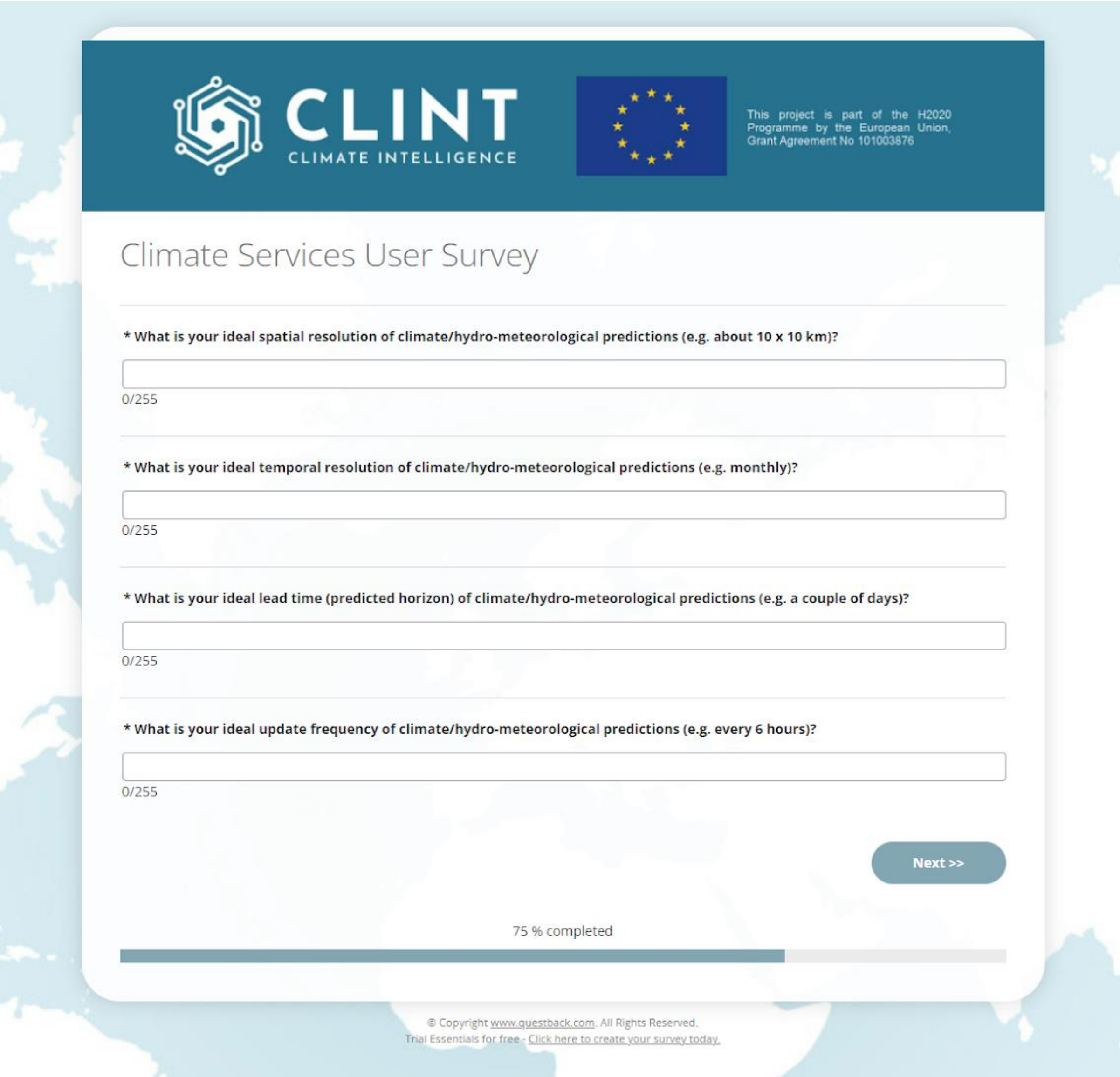

Figure A.11 Questions to identify user needs, which could form the basis for improving existing or adding new CS.

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*** Please state your interest level for the following options of improved predicted information (select only one; to change your selection, first deselect the selected option, then choose a new option):**

	Not important	Not very important	Important	Very important	Extremely important	Not relevant
1. Better prediction of weather extremes	☐	☐	☐	☐	☐	☐
2. Improved probabilistic weather forecast skill	☐	☐	☐	☐	☐	☐
3. More scenarios (ensembles) of weather forecasts	☐	☐	☐	☐	☐	☐
4. Improved weather forecasts for longer lead times (sub-seasonal to seasonal scales)	☐	☐	☐	☐	☐	☐
5. Higher spatial resolution of the predictions	☐	☐	☐	☐	☐	☐
6. Higher temporal resolution of the predictions	☐	☐	☐	☐	☐	☐
7. Better streamflow predictions	☐	☐	☐	☐	☐	☐
8. Better river level predictions	☐	☐	☐	☐	☐	☐
9. More scenarios of hydrological predictions	☐	☐	☐	☐	☐	☐

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80 % completed

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Figure A.12 Question to determine participants' interest level for various CS.

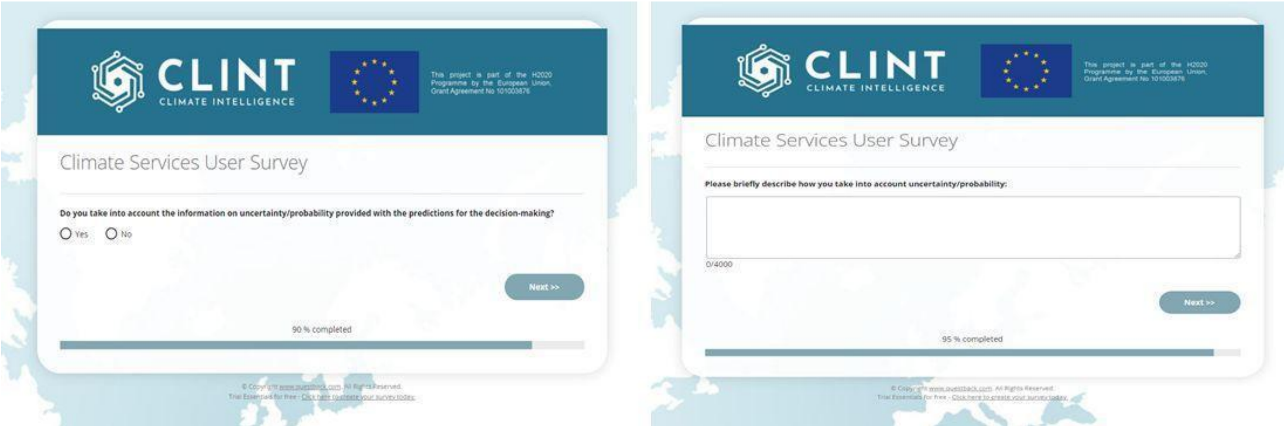

Figure A.13 For participants choosing to continue, it was determined whether uncertainty is currently taken into account (left), and then the respondent was asked to briefly describe how (right) or why not (not shown).

A.7 Optional questions related to data sources, access and visualisation

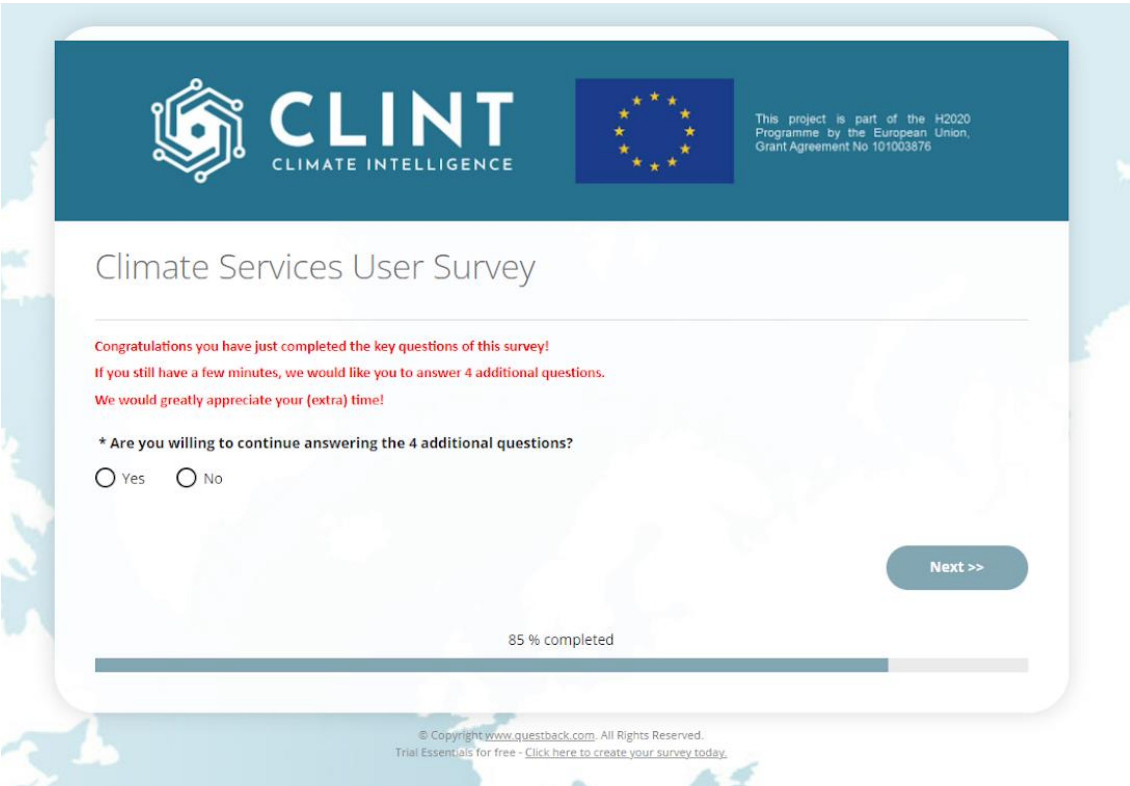

Figure A.14 Question allowing participant to opt out of additional questions.

Figure A.15 Questions to identify data sources used to access climate data, as well as file types and preference for visualisation.

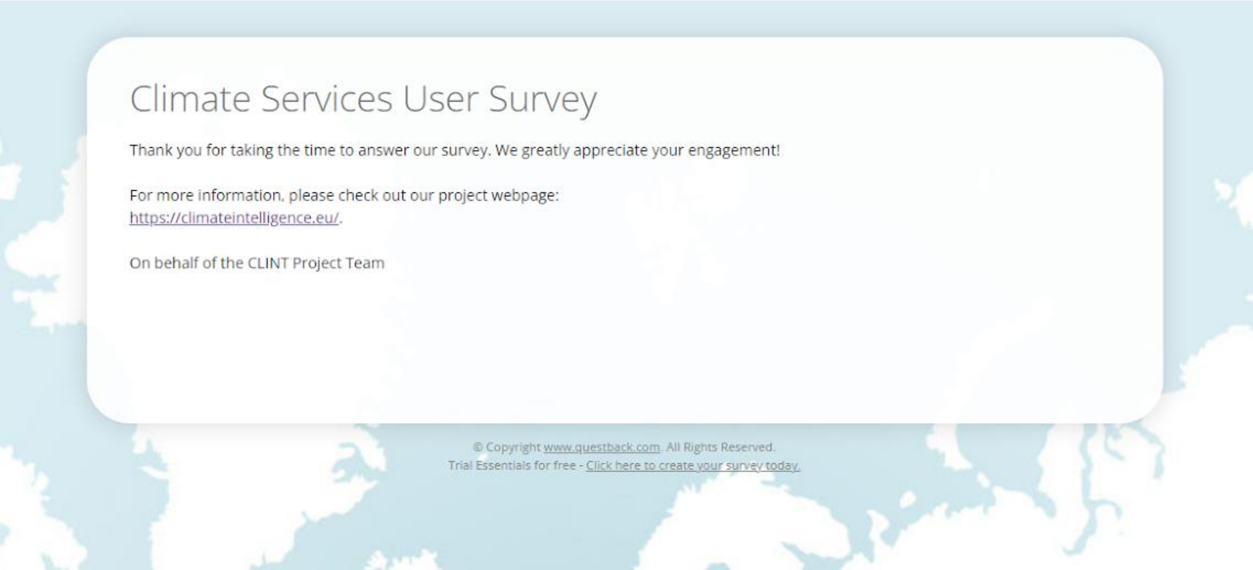

Figure A.16 Back-end of the survey.

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