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# Co-design of sectoral climate services based on seasonal prediction information in the Mediterranean

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A R T I C L E I N F O

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A B S T R A C T

We present in this contribution the varied experiences gathered in the co-design of a sectoral climate services collection, developed in the framework of the MEDSCOPE project, which have in common the application of seasonal predictions for the Mediterranean geographical and climatic region. Although the region is affected by low seasonal predictability limiting the skill of seasonal forecasting systems, which historically has hindered the development of downstream services, the project was originally conceived to exploit windows of opportunity with enhanced skill for developing and evaluating climate services in various sectors with high societal impact in the region: renewable energy, hydrology, and agriculture and forestry. The project also served as the scientific branch of the WMO-led Mediterranean Climate Outlook Forum (MedCOF) that had as objective -among others- partnership strengthening on climate services between providers and users within the Mediterranean region. The diversity of the MEDSCOPE experiences in co-designing shows the wide range of involvement and engagement of users in this process across the Mediterranean region, which benefits from the existing solid and organized MedCOF community of climate services providers and users. A common issue among the services described here -and also among other prototypes developed in the project- was related with the communication of forecasts uncertainty and skill for efficiently informing decision-making in practice. All MEDSCOPE project prototypes make use of an internally developed software package containing process-based methods for synthesising seasonal forecast data, as well as basic and advanced tools for obtaining tailored products. Another challenge assumed by the project refers to the demonstration of the economic, social, and environmental value of predictions provided by these MEDSCOPE prototypes.

**Practical implications**

Most sectoral seasonal prediction-based climate services developed during the MEDSCOPE project (https://www.medscope-project.eu) share a suite of steps starting from seasonal forecasting systems outputs and synthesising/correcting/downscaling forecasts, then using application models driven by seasonal forecasts to translate climatic variables into user variables and ending up with probabilistic forecasts for user defined variables or indicators. The role and contribution of users to each step is highly dependent on the nature of each step and on the particular service. Furthermore, the role of users can vary widely among different services during the cooperation process, ranging from a general collection of points of view to a more specific and structured co-design and co-development. All services were evaluated in a sufficiently long reforecast period computing deterministic and probabilistic skill scores to check the quality and usefulness of the service.

Our limited knowledge of the processes and feedbacks responsible for predictability and model systematic errors has restricted our

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capability to simulate and predict seasonal-to-decadal climate variability, especially over the Euro–Mediterranean area. The primary and underpinning goal of the MEDSCOPE project was to meet the needs of a wide community of seasonal forecast users grouped around the Mediterranean Climate Outlook Forum (MedCOF, http://medcof.aemet.es). MedCOF is a World Meteorological Organization (WMO)-endorsed initiative in the Mediterranean region that tries to respond to the strong demand for climate information by users and the need for improved services. The main idea behind Regional Climate Outlook Forums (RCOFs) was bringing together national, regional, and international climate experts, on an operational basis, to produce regional consensus climate forecasts from a variety of sources analysing individual model performance and their ability to simulate relevant variability modes (WMO, 2016). MedCOF is currently involved in a process of transition from a consensus procedure for generating seasonal forecasts to a new objective, traceable and reproducible approach (WMO, 2017; WMO, 2020) that will allow the exploitation of seasonal forecasts with a wide variety of downstream climate services.

The MEDSCOPE project was originally designed to contribute from a research perspective to the enhancement of seasonal forecast-based climate services underpinning the efforts of the existing MedCOF community and other initiatives in the Mediterranean region. The MEDSCOPE project has focused on the assessment and provision of climate services for various sectors with high societal impact: renewable energy, hydrology, and agriculture/ forestry. The project also had, as additional objectives, a better understanding of the mechanisms and processes driving the climate variability in the Mediterranean region and the development of a collection of tools aimed at improving the development and implementation of climate services based on climate forecasts.

The relationship between developers and users along the MEDSCOPE project has contributed to overcome some barriers in the development and implementation of climate services. Such barriers were in part related with the insufficient knowledge from users of the state-of-the-art seasonal forecasting capabilities/limitations and from the developers' side of the specific user needs for addressing decision-making. Discussion sessions, workshops, and questionnaires involving developers and users' communities have facilitated a better knowledge of the essence of climate services development which should mainly rely on an optimal exploitation of scientific knowledge addressing specific decision-making problems. The core arguments of all discussions between developers and users were mainly the following: usage of user-relevant indicators instead of climatic variables to help in decision-making, probabilistic instead of deterministic forecasts to express and accommodate uncertainty, and identification of objective scores to determine the skill of the forecasts.

It is important to underline that the co-design process for most prototypes developed within the MEDSCOPE project has been far from linear evolution. In fact, the main feature of this process has been iteration. Most prototypes have reached a mature state after several iterations involving different starting data, use of different tools to combine/correct/transform model outputs and different ways to display final results in a satisfactory and understandable format, adequate for final users.

Finally, it should be mentioned that the collaboration between developers and users established for the purpose of the project has in many cases resulted in a long-term collaboration beyond the project lifetime, including some form of institutional partnership or agreement. In other cases, especially when National Meteorological and Hydrological Services were involved and had since long collaborated with certain private or institutional users, the MEDSCOPE project has served to expand their existing collaboration for co-designing and co-developing new services. These long-term collaboration cases have been very fruitful and included frequent dialogue, capacity building, and a good understanding of user needs by developers as well as current limitations of climate science by users.

**Data availability**

The authors do not have permission to share data.

## Introduction

The recognition of the advantages of using climate information in decision-making processes for sectors sensitive to climate conditions has noticeably increased over the last years. Two main reasons are behind this growth. On the one hand, the increase of the awareness of the potentiality of climate services by decision-makers themselves. On the other hand, the fact that researchers and providers of climate data and information are becoming more conscious of the societal applications of their information and knowledge (Buontempo and Hewitt, 2018).

A climate service is commonly understood as the provision of climate information to assist decision-making. The service must respond to user needs, must be based on scientifically credible information and expertise, and should require appropriate engagement between the users and providers. Although there are many definitions of climate services, they frequently have in common the generation of tailored climate information to meet user needs and support their decision-making process through mobile phone apps, websites, and other customized products (see e.g., Vaughan and Dessai, 2014; Lucio and Grasso, 2016).

The transformation of climate data into specific products that can help in the decision-making process for those sectors affected by climate conditions consist of a suite of steps based on the Global Framework for Climate Services (GFCS) components (Lucio and Grasso, 2016). Climate variability at different timescales plays a relevant role in many climate-sensitive sectors (Doblas-Reyes et al. 2013). The most straightforward approach for estimating future climate variability is to assume climatological variability, i.e. variability derived from past conditions (Goddard et al., 2010). However, at seasonal time scales future conditions may not simply behave like climatology and some conditions might have more probability than others. Therefore, the climatology approach could lead to incorrect decisions (Calì Quaglia et al., 2021) and even more under the current climate change. Especially in those cases where some future evolution could be more favoured than others, the application of seasonal forecasts -providing a probabilistic estimation of how climate variables may develop in the coming seasons- can help to improve decision-making processes (Soares and Dessai, 2016; Torralba, 2019).

Climate predictions are estimates of future climate conditions covering monthly, annual to decadal timescales, and are crucially dependent on accurate data describing the initial state of the Earth system. Advances in climate prediction have taken place at major operational centres across the world meeting user needs for predictive information on seasonal timescales for decision-making purposes in different climate sensitive sectors. Although dynamical models for seasonal forecasting have noticeably improved during the last decades, they still show low skill over extratropical latitudes (Kim et al., 2012) and over Europe in particular (Doblas-Reyes, 2010). As a result of this limited skill over extratropical latitudes, seasonal forecasts tend to show a lack of consistency among different seasonal forecasting systems, hindering the automatic usage of model outputs. Consequently, from an operational perspective, progress on seasonal forecasting has been historically constrained in many regions of the globe. The surroundings of the Mediterranean Sea are specially affected by this low skill, due either to lack of predictability or to deficiencies in forecasting systems exacerbated by its complex orography and land–ocean distribution (Weisheimer et al., 2011; Doblas-Reyes et al., 2013). Calì Quaglia et al. (2021) have recently evaluated over the Mediterranean five systems contributing to the Copernicus Climate Change Service (C3S) and concluded that although these systems have limited correlation skill with respect to simple persistence, they do improve resolution and discrimination for most of the Mediterranean region, with better performance for the higher and lower terciles, versus the middle tercile.

The EU funded project EUPORIAS (Hewitt et al., 2013) focussed specifically on the benefits of using seasonal predictions for the development and evaluation of services at this timescale. The mentioned project demonstrated the value of using seasonal forecasts in five climate service prototypes (Buontempo et al., 2015; Buontempo and Hewitt 2018) and paved the way for later initiatives aiming to develop, evaluate and implement the usage of climate predictions, particularly at seasonal timescale, for climate services, The Climateurope initiative sought to enable and facilitate a better integration and coordination of European modelling and climate service activities (Hewitt et al., 2017). The European Research Area for Climate Services (ERA4CS, https://www.jpi-climate.eu/ERA4CS) has been one of the leading funding lines in Europe in the field of climate services, and some of the projects developed under this initiative pointed to make use and demonstrate the benefits of using seasonal forecasts in the development of climate services. The Copernicus programme and its climate change services (C3S) has substantially contributed with the development of specialised services based on seasonal predictions (Thépaut et al., 2018).

Given the limitations of operational seasonal forecasting systems, the World Meteorological Organization promoted the development of a consensus-based approach to consolidate forecast information and products from multiple sources (WMO, 2018; 2020). To operationalize this approach, Regional Climate Outlook Forums (RCOFs) were first established by WMO in 1996. By assembling countries with common climatological characteristics, the RCOFs ensured consistency in the interpretation of climate information. In this vein, the Mediterranean Climate Outlook Forum (MedCOF) was established in 2013 to generate consensus seasonal forecasts for the Mediterranean region as part of WMO's drive to increase the availability of user-friendly climate services (see https://medcof.aemet.es).

The MEDSCOPE project (see https://www.medscope-project.eu), within the ERA4CS initiative (https://www.jpi-climate.eu/ERA4CS), was originally designed to support MedCOF and its strong and well-established link with users and stakeholders operating in the Mediterranean region. The MEDSCOPE project was originally designed as an extension of the MedCOF initiative for developing sectoral climate services. The project has focused on the assessment and provision of climate services for various sectors with high societal impact: renewable energy, hydrology, and agriculture/forestry. The MEDSCOPE project also had as additional objectives a better understanding of the mechanisms driving the climate predictability in the Mediterranean region and the development of a collection of tools aimed at improving the development and operational production of climate services based on climate forecasts.

However, the large amount of data arising from seasonal forecast systems, which is usually untailored and of difficult comprehension by non-experts, makes the exploitation of these forecasts difficult in decision-making processes. Hence, the reduction of vulnerability to seasonal climate-related risks in different contexts requires the adaptation and interpretation of the seasonal forecast data, including the development of tailored products and tools based on this source of climate information (Hewitt et al., 2013).

Recent efforts on seasonal forecast research and its application for climate services have focused on improvement of processes understanding and combination of sources of seasonal forecasting information. The remarkable improvement in predicting the inter-annual variability of the North Atlantic Oscillation (NAO) (e.g., Riddle et al., 2013; Scaife et al., 2014; Kang et al., 2014; Stockdale et al., 2015; Athanasiadis et al., 2017) is an example of the steady progress on the understanding of processes. The development of more advanced methods for an optimal combination or subsample of sources of forecasting information has additionally improved the skill of seasonal forecasts, e.g., Athanasiadis et al. (2017) obtained an enhanced skill through the combination of three different operational forecast systems, giving the same weight to each system. Riddle et al. (2013) obtained slightly improved Arctic Oscillation predictions with a single seasonal forecasting system when they use a weighted ensemble that rewards forecast runs that represent more accurately the Eurasian October snow cover extent. Dobrynin et al. (2018) enhanced prediction skill of surface temperature, precipitation, and sea level pressure over certain areas in the Northern Hemisphere by retaining only seasonal forecasting system ensemble members whose NAO state is close to a NAO empirical prediction. Alternatively, Sánchez-García et al. (2019) proposed a methodology for weighting of ensemble members in operational seasonal forecasting systems based on an enhanced prediction of a climate driver strongly affecting meteorological parameters over a certain region.

Co-creation of climate services is frequently based on iteration among seasonal forecasts providers, experts in sectoral applications and final users. This iterative cycle has proven to be essential for the successful generation of actionable science aiming at decision-making (e.g., Dilling and Lemos, 2011). Máñez Costa et al. (2021) have discussed good practice examples based on the review of the ERA4CS projects, identifying enablers and barriers for key elements in climate service co-production processes.

Benefits of climate forecasts certainly depends on their performance, but not necessarily in a direct way. Different actors contributing to climate services generation may have different expectations or assign different relevancy to different climate variables. Also, the extraction of useful information from seasonal forecasts may largely change depending on users' capabilities and expertise. A key outcome of the MEDSCOPE project has been the strong interaction between scientist and users (both end users and knowledge brokers) aiming at tailoring seasonal forecasts and services to user needs, including the estimation of final products quality to better meet users' expectations. Dialogue among forecast providers, experts in sectors and users to identify key variables and minimum level of required skill for different purposes was conducted in a limited set of demonstration cases. The involvement of many MEDSCOPE partners within the MedCOF initiative has additionally facilitated a close interaction between providers and users. Besides, the active participation of users and stakeholders operating in the Mediterranean within the MedCOF framework has guaranteed a continuous co-creating dialogue between them and the MEDSCOPE project.

The MEDSCOPE project has developed and evaluated several climate services prototypes specifically focused on the Mediterranean region and for the above-mentioned sectors (renewable energy, hydrology, and agriculture/forestry). The prototypes cover a wide variety of approaches and very different levels of user involvement. Many of them have been developed and evaluated for some particular country and/or region in collaboration with local users and their exportation to other regions or the whole Mediterranean domain may only require minor adjustments and access to specific climatic or non-climatic data bases. This work will describe the diversity of user roles in co-designing, co-developing and co-evaluating in sectoral climate services based on seasonal predictions within the MEDSCOPE project.

This text is structured as follows: in Section 2, we enumerate and briefly describe all services developed in the project; the typical steps leading to the development of sectoral climate services based on seasonal predictions are described in Section 3; Section 4 discusses the role of co-design in the three selected sectors; and conclusions are summarized in Section 5.

## Climate services based on seasonal predictions for the Mediterranean

The climate services developed and evaluated during the MEDSCOPE project focus on three relevant economic sectors in the Mediterranean: renewable energy, water management (hydrology), and agriculture and forestry (including fire risk). A detailed description of all services developed during the project -including users' role- and their evaluation is provided in deliverable D4.1 (see MEDSCOPE, 2021 and the attached annexes). For the purpose of this paper, we have selected a few prototypes among those developed in the project with the intention of showing the wide modalities of users' participation in service co-design and co-creation.

Three prototypes for the renewable energy sector were developed within the MEDSCOPE project. This paper exemplifies the role of users, describing one service providing wind power capacity factor to evaluate the relative performance of any generating power plant -with particular focus on extreme events relevant for the industry- in Spanish sites (Lledó et al., 2019).

Four prototypes were developed within the project for the hydrology and water management sector. This paper will show the role of users in co-designing for two of them: (1) extension of the S-ClimWaRe service originally developed in the frame of the EUPORIAS project for generating seasonal forecasts of water inflow into non-regulated dams in Spain (Sanchez et al., 2021); (2) service to forecast mountain snowpack evolution and response of selected Alpine glaciers to climatic forcing (MEDSCOPE, 2021).

From the four services developed and evaluated during the project for the agriculture and forestry sector, two of them were selected to illustrate users' role in co-design: (1) estimation of winter cereal yield making use of the Aquacrop growth model driven with seasonal forecasts evaluated over a region in Spain (MEDSCOPE, 2021); (2) estimation of seasonal forecasts for a set of agro/eco-climatic impact indicators describing water availability, vegetation/forest water stress, and fire risk. These two services cover different types of outcomes. Whereas the first service is based on biophysical modelling at high-resolution (~5 km or less) for a selected pilot area in Spain, the second service provides, over the whole Mediterranean region on a one-degree resolution grid, the following three indicators: (i) Potential Evapotranspiration (PET, Hargreaves, 1994), Potential Soil Moisture Deficit (PSMD), Canadian Fire Weather Index (FWI, Van Wagner, 1987) (Costa-Saura et al., 2022).

## Steps in sectoral climate services based on seasonal predictions

Many sectoral climate services based on seasonal forecasts share a suite of steps starting from global model outputs and ending up with probabilistic forecasts for indicators defined by users. Fig. 1 depicts schematically the main steps in a typical prediction-based suite.

The Copernicus Climate Change Service (C3S) Climate Data Store (CDS) is the most used source of model outputs in the MEDSCOPE project, and all prototypes here described make use of such data. Of course, the final quality of sectoral prediction-based indicators will strongly depend on the skill of the selected seasonal forecasting system (s) (SFS).

Once selected adequate seasonal model outputs, the next steps consist in the application of a set of post-processing tools for synthetizing and correcting seasonal forecasts, such as bias adjustment (to correct systematic model errors), probability calibration (to make the forecasts reliable, i.e. match the issued probabilities with the observed frequencies), downscaling (to better represent unresolved spatial scales), combination and/or weighting of ensemble members (to deal with the different quality of systems and/or ensemble members) and mixed statistical-dynamical post-processing methods (to address problems of particular sectoral applications unmanageable by standard prediction approaches). All such tools were collected in a toolbox, named CSTools (Pérez-Zanón et al., 2021) that was publicly released at the end of the project. All functions in CSTools are documented in a standard reference manual on the CRAN website (https://CRAN.R-project.org/package=CSTools).

The next step is the use of application models driven by seasonal model outputs for translating climate data (e.g., precipitation, temperature, wind) into users' defined indicators (e.g., crop yield, dam inflow, wind energy capacity factor, etc.). Then probabilistic or deterministic relevant products (e.g., probability of exceeding a given threshold) are generated and displayed in a visual way.

Evaluation is conducted by computing objective verification skill scores for seasonal re-forecasts (between 20 and 30 years). Software for verification is also included in the developed toolbox. This evaluation is typically carried out for user indices computed from re-forecasts. Finally, selected indicators can be visualized, jointly with their uncertainty and skill, which is crucial for an effective support in the decision-making process.

## Collaboration and co-design in selected sectors. Description

This section shows a selection of prototypes developed by the MEDSCOPE project for which the role played by users is widely discussed. Besides their overall role in co-designing the whole service, special attention is paid to the specific roles in each of the steps in a typical service chain based on seasonal forecasts (see Fig. 1). Each selected prototype is described in an individual box having all the same structure and including the same sections: i) objective and motivation; ii) user needs; iii) prototype description; iv) role of users in the climate service co-design; v) concluding remarks.

To classify climate services according to their characteristics and functionalities different authors have proposed several schemes. Soares and Dessai (2016) describe barriers and enablers to the use of seasonal climate forecasts in Europe depending on the users' categories (classified as non-users, moderated, advanced, and operational). Most of the prototypes presented in this paper can be classified as moderated or advanced. The chosen categories are justified by the fact that the provided information is mainly qualitatively used, either to inform on how future conditions may affect the operations or activities in case of moderate users, or to help them to plan their operations (e.g. reservoirs water releases in winter time) in case of advanced users. However, no user automatically integrates this quantitative information in the organisational routine yet, although new normative framework aiming at the usage of seasonal forecasts for operations might boost this change in some cases (e.g., water reservoirs management). However, the main barrier for most users comes from the limited skill and high uncertainty of the state-of-the-art seasonal forecasting systems over Europe which frequently prevents their fully operational use. This limited skill also promotes a closer interaction between producers and users mainly focused on the analysis and interpretation of the provided products and

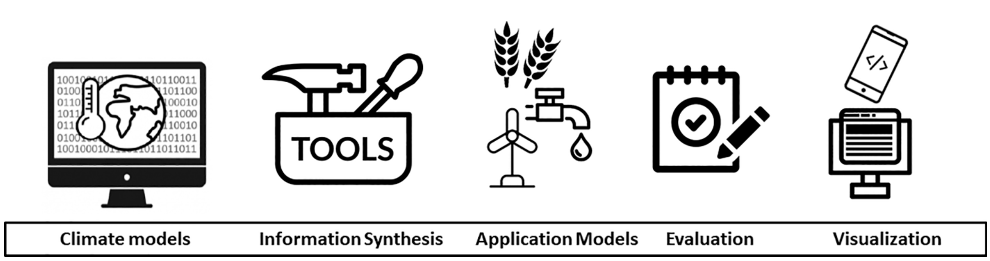


**Fig. 1.** Diagram with a simplified climate services chain based on seasonal forecasts.

services.

Visscher et al. (2020) proposed a classification of services considering two dimensions related to the way how services are offered to the market. One dimension differentiates between tailored and general services whereas the other one differentiates between individual climate services and climate services that are part of broader packages. The authors do not claim that all climate services can be univocally classified in one of the categories described. This is the case of some MEDSCOPE climate services, for which the commercial dimension is absent as they were developed to support the WMO-led Mediterranean Climate Outlook Forum. All MEDSCOPE prototypes described in this paper are focused on individual services and are not part of broader packages. Some of them fall more clearly into the type 'Maps & Apps' (as e.g., Box 5) as climate -and climate related- data are provided by meteorological and research institutes to large groups of users for their decision-making processes. The rest of the prototypes are tailored to specific decision-making, and then they would be categorized as 'Expert Analysis' type (see Visscher et al., 2020 for a more detailed definition of 'Maps & Apps' and 'Expert Analysis' types). However, some services corresponding to this last type (e.g., Boxes 2, 3, 4) are also publicly offered in the form of friendly web viewers, so they share characteristics of the two mentioned types.

**Box 1**

Seasonal predictions of wind capacity factor for Spain

*Objective and motivation*

Vast amounts of wind power generation are being installed in many countries to replace other polluting sources of energy and reduce CO2 emissions. But wind energy generation is affected by atmospheric variability at several timescales. With increasing shares of wind power in the electricity mix, anticipating wind power generation anomalies at seasonal timescales is becoming more important to many actors in the electricity system (Soret et al., 2019).

*User needs*

A continuous interaction with many stakeholders in the wind energy supply chain has revealed that the needs in terms of climate information are not the same for each type of user. Regarding monthly or seasonal mean anomalies, four types of users have been identified:

- Wind farm owners are primarily interested in wind farm revenues at monthly or quarterly scales, which depend mainly on total generation. This is useful, for instance, to ensure enough cash flow for loan payments. Precautionary actions can be taken in advance if generation shortages are anticipated.
- Energy traders can earn a lot of money if they successfully anticipate electricity prices at country level months in advance. Electricity prices depend largely on the total amount of wind and solar power generation in liberalized markets.
- Operations and maintenance teams need to work under safety conditions, so scheduling long maintenance tasks when wind speeds remain below a security threshold ensures more time available for repairing and leads to shorter downtime and important money savings.
- Grid operators oversee balancing energy supply and demand. If a shortage of renewable generation is anticipated, they can schedule reserve sources and reduce the risk of imbalance.

A prototype that could fulfil the varied needs of these four user profiles was co-designed with the stakeholders. The prototype provides forecasts of wind speed and wind power generation at site or regional level from one to three months ahead and was tested in the north-west of the Iberian Peninsula, where in March 2018 one of the users faced a situation of high winds that made electricity prices drop.

*Prototype discussion*

The wind capacity factor prototype follows the five steps depicted in Fig. 1. First, surface wind forecasts from ECMWF SEAS5 are bias adjusted with an empirical quantile mapping, then extrapolated with a power law to a typical hub height of 100m above ground. Turbine power curves are employed to convert 100m wind speed forecasts to power production forecasts, which are normalized by the installed capacity to produce capacity factor values (Lledó et al., 2019). After applying this transformation to each of the ensemble members, tercile probabilities (below normal/normal/above normal) and probabilities of exceeding the 90th percentile or not exceeding the 10th percentile are computed and plotted with the CSTools PlotForecastPDF function (Pérez-Zanón et al., 2021). The forecast quality is assessed in a hindcast by means of deterministic (ensemble mean correlation) and probabilistic metrics (ranked probability skill score, Brier skill score).

*Role of users in the climate service co-design*

The role of the users was crucial to shape the climate service in many aspects:

- Climate datasets: stakeholders repeatedly report that they want to use the best quality prediction systems, and with the highest possible spatial resolution. This emphasizes the need of providing a product-oriented verification along with the service. Timeliness is also important for some of these stakeholders, for example having the information before their competitors can provide a competitive advantage for trading energy. Copernicus Climate Change Service provides state-of-the-art predictions with only a slight delay of a few days, which allows testing the prototype in real-time conditions. Some users reported that consistency across different systems might be relevant for decision-making, but the developed prototype only uses information from a single system.
- Bias adjustment and pre-processing: users did not participate in the selection of bias adjustment methodologies. However, they identified a typical hub height of 100m for modern turbines, and wind speed was extrapolated to that height before bias adjusting and feeding the impact model.
- Impact model: the whole impact model was co-developed with one stakeholder, who pointed out the capacity factor indicator as a flexible solution that allows comparing the generation of wind farms of different sizes. With his help, a selection of three different power curves that are suitable for high, medium, and low wind speed conditions was made to represent different turbine types with contrasting efficiencies.
- Product definition and visualization: in view of the varied needs of the four user profiles presented above, a generic tercile probability product was proposed. Some stakeholders used to look at ensemble mean anomalies in the past, but they appreciated the richer information provided by the tercile probabilities in the prototype. This information was complemented with the probability of experiencing extreme conditions. A

graphical designer was involved in the selection of the colours for the visualization, and several interactions with users and climate scientists helped refine the final product.

- Verification: many actors in the energy industry are used to perform verification of weather forecasts. However, probabilistic forecast verification concepts and the usage of retrospective hindcasts can be challenging for some users. Therefore, some discussions with users were helpful to understand how forecast quality is perceived by them. In specific cases, the economic value of the forecasts was discussed.

**Box 2**

Seasonal forecast of snow and ice resources in the Italian Alps

*Objective and motivation*

Alpine snowpack and glaciers provide an essential water reservoir that can be exploited in the hot and dry season (summer), both locally and downstream. Due to the ongoing climate change and the growing anthropic pressure, water scarcity in summer is now a compelling issue and a potential source of conflict among end-users: in this context, an informed planning of the water resource based on seasonal forecasts is increasingly urgent.

*User needs*

All stakeholders involved in the use and management of Alpine water resources could benefit from seasonal forecasts of snowpack and glacier mass evolution. In order of priority:

- Drinking water suppliers are interested in seasonal forecasts in mountain areas to anticipate water shortages and organize water supply with alternative methods.
- Agricultural consortia are strongly affected by rivers summer stage: indications of a drier/wetter, warmer/colder than normal season with 2-3 months lead time would allow them to regulate farming activities and make agreements with reservoirs managers.
- Hydropower producers, beyond carrying on their economic activity, in summer must agree on irrigation needs with farmers and guarantee a minimum ecological river flow; in autumn, they have to decide if/how much to empty reservoirs, to be ready for autumn rainfall and filling from snow/ice melt in the season ahead. Forecasting snowpack and glacier evolution from winter to summer would allow them to manage water storage and release water effectively and conveniently.
- Public authorities decide water distribution among users when summer river flow drops below a certain threshold. Forecasts of meltwater contribution from the snowpack and glaciers would allow a timely planning of water distribution.
- Artificial snow makers supplement natural snow to extend the ski season. In November, they decide the amount of artificial snow to be produced in the entire ski season: it is a remarkable investment, so they would benefit from snow depth forecasts.

*Prototype description*

CNR developed two prototypes based on snow and glacier models, respectively, forced by the meteorological variables provided by the Copernicus seasonal forecast systems. The first prototype is based on the SNOWPACK model (Bartelt and Lehning, 2002), which is run at the beginning of November to simulate the evolution of snow depth and snow water equivalent over the 7 months ahead. The second prototype is based on a simple glacier model (Peano et al., 2016) and it is run at the beginning of May to simulate the variation of glacier length and mass over the summer season ahead. The prototypes have been evaluated in glacierized basins in the Western Italian Alps, providing observational data to calibrate models and evaluate their forecasts. The skills of the prototypes have been assessed in comparison to simpler forecasting methods based on climatology. Their performances strongly depend on the forcing and thus on the global seasonal forecast system employed (MEDSCOPE, 2021). Fig. S1 shows how seasonal snow depth forecasts are displayed.

*Role of users in the climate service co-design*

The co-design process can be summarized in the following steps:

- development and evaluation of the two preliminary prototypes for test areas;
- illustration of the prototypes and their performance to selected end-users; identification of their needs in terms of indicators to be forecasted, start and length of the forecast period, time resolution of the forecast (seasonal or monthly), lead-time;
- adaptation of prototypes to the needs expressed by end-users.

Contacted end-users and outcomes of the discussion were the following:

- IREN is one of the major Italian companies involved in hydropower production and management of water services. At present, planning is based on climatology and on the periodic follow up of the general conditions, which include water level in the reservoirs, but also energy price on the market, irrigation needs, etc. They may benefit from the outcomes of the prototypes: i) in November, to forecast snow depth evolution in the months ahead and estimate the water amount that will be available in the reservoirs; ii) every month, in spring and summer, for a reassessment of scenarios, aimed at the optimal management of the water resource.
- The Water Resources Department of the Metropolitan City of Turin (NW Italy) deals with the protection of surface and groundwater in its area of competence, which includes several glacierized alpine watersheds. It participates in working groups for the management of water resources that bring together public authorities and private bodies. In particular, for the critical summer months, the prototypes might help to foresee at least 2–3 months in advance any drought periods, allowing the distribution of water resources to be planned in time, avoiding conflicts between users.

- Monterosa Ski is an important and well-known ski area in NW Italy. The prototype for the seasonal forecast of snow depth can provide useful data in November to quantify the need for artificial snow for the entire ski season ahead.

*Concluding remarks*

End-users expressed a strong interest in the proposed prototypes, but also the need to see them "at work" for a certain period. As a first concrete result, a simple and intuitive visualization tool has been realized to display prototype outputs in the form of: i) ensemble mean/spread of the forecasts, and ii) tercile-based forecasts (conditions below normal/normal/above normal) and probability to have extreme events below the 10th and above the 90th percentile. The communication of uncertainty of the forecast has been the trickiest part and required particular care. End-users provided valuable suggestions regarding the webpage to disseminate the forecasts (http://wilma.to.isac.cnr.it/diss/snowpack/snowseas-eng.html), for example they asked to visualize and compare forecasts for all available previous seasons.

**Box 3**
Viewer of seasonal climate predictions supporting water reservoir management in Spain

*Objective and motivation*

Over 1 500 reservoirs, among other water infrastructure, allow to satisfy water demand not met by available natural resources in Spain (MITERD, 2021). River Basin Authorities, coordinated by the Spanish D. G. Water (Ministry for the Ecological Transition and the Demographic Challenge), oversee the largest strategic reservoirs management.

*User needs*

Water planning in general aims at reaching good status of water bodies, managing, and protecting the public water domain, satisfying water demands (domestic uses, environmental flows, agriculture, hydropower, industry, leisure activities…), increasing water resources availability (specially under drought conditions) and coping with flood risk. Dams planning has traditionally relied on the usage of past observations to make estimations of hydrological variability at seasonal scale.

*Prototype description*

The S-ClimWaRe (Seasonal Climate predictions in support of Water Reservoir management) web tool (see http://www.aemet.es/es/serviciosclimaticos/apoyo_gestion_embalses) has been developed and implemented to inform decision-making during the November to March filling reservoirs period in Spain. The very first idea of this climate service emerged in a workshop, organised in the framework of the national implementation of the GFCS and the EU FP7 EUPORIAS Project, to promote the usage of seasonal climate predictions in the water sector. The S-ClimWare web tool provides information at 388 water reservoirs (covering 95% of the total storage capacity), or any other location in Spain, by means of two main displaying panels. The first "diagnostic" panel, based on the usage of time series of hydrological and meteorological observations, displays a set of indicators of the existing hydrological variability and risk over the extended winter (NDJFM), and its linkage with the main climate driver for this area and season: the North Atlantic Oscillation (NAO). The second main "forecasting" panel provides seasonal climate predictions for the expected NAO index, water reservoir inflow, accumulated precipitation and snowfall and mean temperature. Information about the forecast's uncertainty and skill is also displayed. A detailed description of the climate service can be found in Voces et al. (2019) and Sánchez et al. (2021).

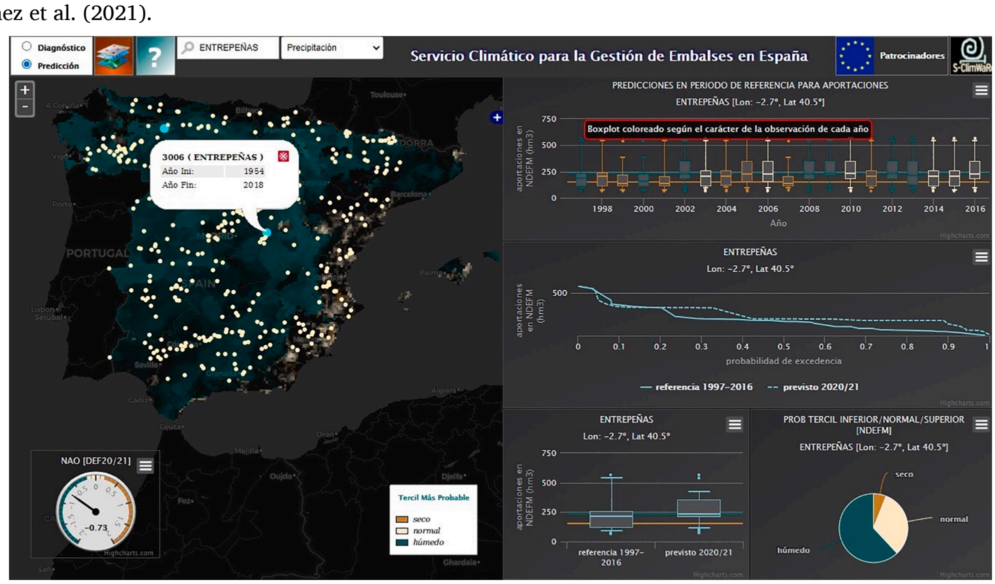


**Fig. 2.** Forecasting panel of S-ClimWaRe web viewer showing accumulated water inflow seasonal forecast (November to March) for Entrepeñas reservoir.

*Role of users in the climate service co-design*

S-ClimWaRe has been fully user-driven since its beginning and it is characterised by a fluent dialogue and interaction between developers and users/stakeholders. The joint leadership and engagement of the Spanish D.G. Water and AEMET (the State Meteorological Agency of Spain) have enabled a continuous development and upgrade of this climate service. Since 2014, there have been several cycles of interaction starting with surveys and workshops where the River Basin Authorities' requirements were collected. Joint examination of these user needs and scientific advances that may meet them was then performed. The following step was the co-design and planning of the prototype by users and providers, including selection of indicators and impact model to be used, needed (climate, meteorological and hydrological) data, visualization platform to be developed, and climate service public dissemination. Both D.G. Water and AEMET have closely monitored the progress of new developments, and all stakeholders participated in a cooperative assessment of successive versions of this climate service. The cyclic interaction was complemented with the needed training sessions on the upgraded climate service and their underlying scientific keys. Behind this cyclic relationship, a reciprocal learning process and exchange of data are organized to enrich and strengthen user and provider relationships in benefit of the climate service continuous improvement.

*Concluding remarks*

Among the main difficulties encountered we can mention an easily understandable and friendly communication of seasonal forecasts skill and uncertainty. The co-design of the web tool and its functionalities has enabled and facilitated its usability by end users, mostly dam managers. However, the reliability of state-of-the-art forecasts and their lack of sharpness at some places and/or seasons are still important hurdles preventing user confidence in this climate service that will still need further scientific progress in the field of seasonal climate prediction. Although the usage of this climate service is still emerging within water reservoirs management in Spain, a progressive uptake of the information provided by the viewer is being enabled by regular meetings organized between users/stakeholders and developers, increasing exchange of experiences and discussions on practical cases of usage. In any case, funding of R+D+i projects will still be needed to promote and improve both scientific basis of this type of climate services and innovation in the decision-making process.

**Box 4**

Estimation of seasonal cereal crop yield for Castile and Leon region (Spain)

*Objective and motivation*

Castile and León (CyL) is the largest region in Spain mainly comprising the northern half of the Iberian Peninsula's Inner Plateau and covering an area of over 94,000 km2. Within the region, agriculture plays a relatively important role for a developed country as it provides around 5% of gross added value and employs around 5.5% of registered workers. Most of its production is concentrated on winter and spring cereals, legumes, and forage obtained in rain fed farms and therefore very much affected by precipitation variability. CyL is the main national producing region of winter cereals in Spain. The objective of this climate service is to provide some estimation of winter cereals yield at the harvest time (end of June) with 3 months of anticipation. Yield forecasting is an important service for providing information to markets and easing the trade of products based on stocks (coming from past yields and imports), consumption and new production expectations. This climate service, as most yield forecasting systems, is mainly oriented to provide data for policy makers and markets as they are the only source of aggregated data. The utility of yield forecasts for farmers is a controversial issue. At farm level there is a very detailed information gathered by farmers themselves about the status of their fields and their respective yield forecasting based on the fertilization level, tillage and some other practices conducted. This information is in principle only known by themselves. Soil water availability is still the main uncertainty for the farmer. Farmers must decide at the start of the season -8 months before the harvest time- the variety and the base fertilization level. It is important to consider that seeds and fertilizers represent 50 % of the costs for a farm according to the national farm accountancy survey. Those decisions are made based on past seasons experience considering all the limiting factors for each parcel.

*User needs*

Farmers must make some other decisions in spring about the usage of more fertilizers (top-dressing), plant protection products and possibly irrigation. Those decisions are based on an updated farmer yield expectancy that at that time is in the range of 3–4 months to harvest. The service here described is specifically focused on those decisions that could comprise about 30% of the costs depending on the crop. In this case yield forecasting could give a good projection and bias the farmer towards a more optimistic or pessimistic frame. With a low yield forecast farmers could decide to reduce top-dressing fertilization and not to apply some plant protection products obtaining some savings. From the environmental perspective, especially on the nitrogen crop nutrition aspects, it is important to accommodate the fertilizers applications with yield extractions. Low productive agriculture represents a big issue related to the proper crop nutrition practices if rainfall variability impacts of nutrients uptake. Even in cases of low applied fertilizers doses, the crop may not uptake all nutrients producing some months after harvest nitrate leaching to groundwater.

*Prototype description*

This operational climate service produces expected cereal yield for the CyL region based on the crop growth model Aquacrop developed by FAO (http://www.fao.org/land-water/databases-and-software/aquacrop/en/) that simulates every agricultural year from September to June. From 25th September until 1st April, Aquacrop is driven by meteorological forcing coming from observational grids. After 1st April simulations are fed by short and medium range weather forecasts and after- until the end of June- by seasonal forecasts (SF) based either on climatological data or on outputs from the ECMWF SF System (SFS) version 5. Therefore, predictability and skill of this service come partly from the memory of past meteorological data carried by the AquaCrop model and partly from the skill associated with short, medium range and seasonal forecasts. The current operational version of this climate service – developed by the Agricultural Technology Institute of Castile and León (ITACyL) and the State Meteorological Agency of Spain (AEMET) and run routinely by AEMET – makes use of seasonal forecasts based on climatology, relying on the skill coming from memory carried by Aquacrop in the observational driven period (25th Sept - 1st Apr) and from short and medium range forecasts (from 1st Apr onwards). Beyond medium range, an ensemble replicating climatology is used as seasonal forecast. This system has been delivering yield predictions since the 2015 campaign (http://cosechas.itacyl.es/). The upgrade of the existing climate service developed within the MEDSCOPE project makes use of the ECMWF Seasonal Forecast System (SFS) version 5, to estimate future spring climatological forcing beyond weather forecasts, and of tools and methods developed during the project, in particular of a downscaling based on analogues.

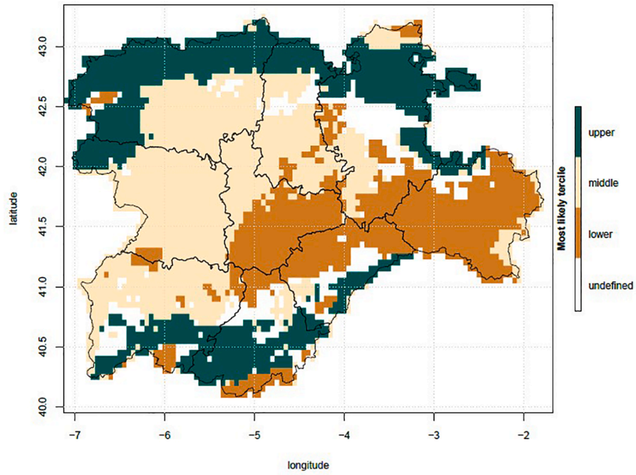


**Fig. 3.** Cereal yield expected in June 2021 for Castille and León region according to the MEDSCOPE prototype based on the Aquacrop model driven by ECMWF SEAS5 seasonal forecasts started on 1st April 2021. The most likely tercile of wheat yield at each grid point is shown (upper/middle/lower tercile in green/cream/brown). Borders of the different Castille and León provinces are also displayed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

*Role of users in the climate service co-design*

Both AEMET and ITACyL have contributed to the co-design of the current and upgraded prototype. They have also conducted a series of experiments leading to co-evaluate and unveil the origin of predictability and skill of this service. Periodic meetings and workshops have facilitated the exchange of information and views leading to the final design of this service. ITACyL has mainly contributed with the definition of an appropriate setup for the Aquacrop model and evaluation and interpretation of results. ITACyL has also liaised with end users like policy makers (frequently institutional ones), cereal brokers and individual farmers. Final presentation in the form of maps of forecasted yield expressed as variation percentage of the average yield over a reference period was jointly co-designed with ITACyL collecting views from end users.

*Concluding remarks*

Although the new prototype making use of seasonal forecasts to drive Aquacrop model has produced promising results, it is felt that more training is still needed for improving the correct interpretation and limitations of this service among end users, especially those concerning uncertainty and skill.

**Box 5**
Seasonal forecasts of climatic indicators for ecosystem management

*Objective and motivation*

Several types of decisions in the agro-forestry sector, from operational to strategic, need to be taken several months in advance of any water scarcity period (Bedia et al., 2018; Klemm and Mcpherson, 2017). These management decisions have been traditionally based on observed seasonal climate patterns, which are currently altered because of climate change. Thus, accurate climate predictions clearly communicated to the end-users and stakeholders, without mismatching concepts, greatly benefit land managers and practitioners for adaptation and planning.

*User needs*

Based on results from previous projects (such as Orientgate[1], Secteur[2]) and further informal discussion with Regional either Agrometeorological Departments or Agencies for the Environment Protection, involved in agricultural, fire and forest research and management, agroclimatic indicators were recognized as useful tools for assessing potential climate effects on agriculture and forests and to guide broad choices to better adapt and cope with climate risks. Users from the agricultural and forestry sectors primarily require information regarding trends or anomalies on water availability, vegetation water stress, and fire risk for guiding tactical and operational decisions. Intermediate stakeholders such as Agrometeorological Departments issue bulletins informing on water availability and drought occurrence, as well as supporting irrigation plans addressing farmers' needs. Forest managers also benefit from agroclimatic information -e.g., on water cycle components as potential evapotranspiration and soil moisture- to envisage possible vegetation stress and thus plan fire prevention activities. Finally, regional, and national agencies require accurate spatial and temporal predictions of fire danger anomalies for strategic planning and risk management (such as design of prevention actions and suppression resources allocation). This type of strategic and tactical decisions could be also conveyed to other stakeholders for field operations in agriculture (e.g., crop selection, planting, tillage, irrigation, and fertilization) and forestry (e.g., pest scouting, spatial allocation of fire suppression resources), and largely depend on optimal forecast timing. An improved knowledge concerning forecast skill and accuracy can increase appreciation from land managers and adaptation practitioners.

*Prototype description*

The AgroForInForecast prototype provides intermediate stakeholders with a tool for decision making at regional level regarding forecasts of out-of-normal events with high anticipation (approx. 6 months) (Costa-Saura et al., 2022). The prototype focuses on three agroclimatic indicators related with water deficit and fire risk: Potential Evapotranspiration (PET), Potential Soil Moisture Deficit (PSMD), and Canadian Fire Weather Index (FWI). Data are provided on a regular grid jointly with climate parameters forecasts, skill of previous forecasts and distribution of past events. Two seasonal prediction systems (SPSs) releasing data through the Copernicus Climate Change Service (C3S), the CMCC Seasonal Prediction System (SPS) v3 and the ECMWF Seasonal Forecast system (SEAS) 5, were used. Post-processing correction techniques based on the R package CSTools were applied to forecasted climatic indicators. The forecast quality is assessed in a hindcast by means of deterministic (anomaly correlation coefficient) and probabilistic metrics (Brier skill score).

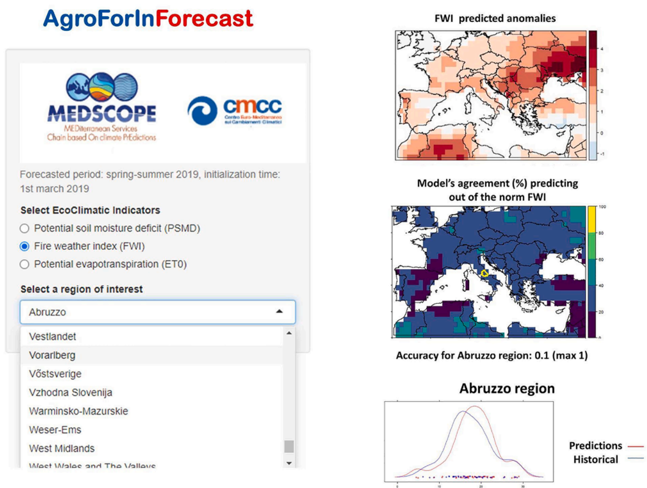


**Fig. 4.** Prototype display for the agricultural and forestry sectors. On the left, the user can select the provided indicators and the region (NUT2) of interest. On the right, the panels show: on the top, the predicted anomalies; on the middle, the models' agreement in predicting out of the norm event (in percentage); on the bottom, the frequency distribution (across members) of both forecast and hincasts for the selected region and indicator.

*Role of users in the climate service co-design*

As mentioned, previous users' engagement in past funded projects and further informal discussion (including a questionnaire submitted to Regional Agencies and practitioners dealing with environment protection and with agricultural, fire and forest research and management) were used to collect users' point of view on a series of elements supporting the prototype co-design.

Agroclimatic indicators were defined considering the stakeholder needs in the field of ecosystem (agriculture, forest, fire) management and they met our aim to assess varying levels of complexity (i.e., by combining variables) on the forecasts performance. Although the bias adjustment methodologies were not discussed with stakeholders due to their limited familiarity with such a complex topic, forecast outputs were bias corrected to allow the decisions implementation based on established hazard scales.

On the other hand, the accuracy of seasonal forecasts (at spatial and temporal level as well as in terms of overestimation vs. underestimation) is one of the most important elements and concerns for stakeholders. Furthermore, stakeholders express the necessity of knowing summer predictions in advance at different moments of the year, i.e., late winter (1st March) and mid-spring (1st May). As they also expressed their concern about predictions reliability and skill at different initialization times, two different lead times were included during the second phase of prototype upgrade.

In terms of product quality assessment, stakeholders appreciated the classical evaluation scores. Furthermore, this information was complemented with analysis of percentiles to discriminate out-of-the-norm and extreme events. Some intermediate users also suggested providing forecasted maps of some devastating extreme events versus observation maps for evaluating the model performance for predicting the occurrence of extreme or abnormal events.

[1]ORIENTGATE – A structured network for integration of climate knowledge into policy and territorial planning (2012–2014). Funded by South East Europe Transnational Cooperation Programme

[2]SECTEUR - Sector Engagement for Copernicus Climate Change Service; Translating European User Requirements (2016–2017). Funded by ECMWF for the European Commission

## Models of collaboration

Although Máñez Costa et al. (2021) have identified different models of collaboration in 16 out of the 26 projects developed under the ERA4CS programme, the MEDSCOPE prototypes here described allow us to identify some coincidences and differences in the collaboration mode between users and providers. In some cases here described the initiative for developing a particular service comes from the provider/research community. Typically, a research group notices that some product, e.g., a seasonal forecast for some relevant indicator, has not been fully applied or exploited for certain sectors and addresses to the corresponding relevant institutions/persons of such sectors. A preliminary prototype potentially able to help in their sectoral operational/strategic decisions is initially presented with the intention to be further developed and tailored based on the user needs (e.g., Boxes 2 and 5).

Another model of collaboration experienced in the MEDSCOPE project is based on long-term strategic collaboration among institutions and/or private companies. In this case providers and users that had previously collaborated in other projects, services or applications decide by mutual agreement to expand their work to some neighbouring application area. A typical case is the extension to the seasonal time scale of weather forecasts helping with short-term operational decisions. This case usually takes advantage of the relatively good previous knowledge of user needs by providers. In the case of some National Meteorological and Hydrological Services, that had since long collaborated with certain private or institutional users in developing sectoral climate services, the MEDSCOPE project has served to expand their existing cooperation for co-designing and co-developing new or improved services through the establishment of additional collaborative actions within the periodic interaction between both institutions. These examples of long-term collaboration have been in some cases very fruitful as they include frequent dialogue, capacity building and a good understanding both of user needs by developers and current limitations of climate science by users. This is the case, for example, of the National Meteorological Agency of Spain (AEMET) and its long collaboration with Spanish DG Water and River Basin Authorities for the co-design and co-creation of different hydrological services (Box 3). Also, AEMET and ITACyL have since long collaborated in the co-design of several services for the agricultural sector (Box 4). Besides, ITACyL has in turn liaised with additional end users as e.g., Agriculture Department officers and/or farmers. The long-term collaboration between the Barcelona Supercomputing Centre (BSC) and several relevant private companies in the wind energy sector (Box 1) is another example of this model of collaboration.

In a third model of collaboration, the initiative for starting the design and development of some service may come from the user's side. This less frequent case –and not represented by the prototypes here shown-may arise when some sector sensitive to climate variability clearly identifies how decisions could benefit from the knowledge of climatic features with seasonal anticipation. Knowledge brokers are usually in a good position to take initiative and propose the development of some specific service. They are well familiarized with end-user needs and at the same time they frequently know the potential of application of state-of-the-art seasonal predictions.

In many prototypes, the collaboration between developers and users established for the purpose of the project has resulted in attempts to extend such collaboration beyond the project life with some form of institutional partnership or seeking other projects serving as an umbrella for further joint work. The MEDSCOPE project has served in some cases to start collaborations that seem to have good perspectives for a long-term partnership.

In all modes of collaboration here described, and usually after some iterative process, end-users may have a more or less active role in the co-design of an improved version of the prototype (see section 4.2) with higher involvement in some specific aspects in the value chain such as visualisation, evaluation, interpretation of results, provision of specific-sectoral data, etc.

**Role of users in the service co-design**

The co-creation dialogue between users and providers is organised in two different steps. The first step corresponds to the routinely (twice a year) convened MedCOF sessions that usually book one full day for the interaction between providers and users/stakeholders. Regional Climate Outlook Forums (RCOFs) are meetings that bring together scientific experts and stakeholders with the aim of producing regional-scale climate information products (generally seasonal climate forecasts) that are relevant for societal decision-making (WMO, 2016). RCOFs in general, and MedCOF in particular, represent some of the earliest attempts to develop formal mechanisms for sustained interaction between producers and users of seasonal climate forecasts. MedCOF sessions usually involve representatives of users, and then they transfer the information down the chain until it finally gets to the final user. In MedCOF, the "representative" users come largely from national-level organisations. Daly and Dessai (2018a, 2018b) have described the whole RCOF interaction process focusing on user engagement and showing that approaches vary significantly from region to region.

The second step in the co-creation dialogue is a MEDSCOPE internally organised process with an independent structure and protocol for each developed prototype, according to the selected mode of collaboration.

The MEDSCOPE project has provided a general umbrella and tools (see *Sec* 2) for the development of a number of climate services prototypes. Different metrics and criteria for evaluating the quality of developed climate services were proposed as a result of discussions and one internal workshop. A wide range of indicators covering most of the decision–making needs in different application sectors, but especially in agriculture and forestry, were put forward (MEDSCOPE, 2021). These indicators are either direct climate variables, a combination of climate variables, or variables calculated by application models (e.g., a crop model, hydrological model). To implement climate service prototypes, partners identified a few basic, specific requirements that ensemble predictions should meet: i) seasonal forecast data should be calibrated and debiased, as long term trends are not sufficient to characterise the future; ii) seasonal forecasts should have high spatial resolution, e.g., few kilometres for the prototypes considered; iii) ensemble forecasts should provide a variety of meteo–climatic variables needed to compute relevant sectoral indicators, and not only precipitation and air temperature.

The modularization of the development of a typical seasonal prediction-based suite (see Fig. 1) facilitated the co-design and co-creation by users. Besides the core steps appearing in Fig. 1 mainly describing the service operationalisation, other elements relevant for the co-design should be considered and discussed, as e.g., identification of user needs, scheme for organising user feedback, training, etc.

The identification of user needs usually implies a detailed description of the whole production process and decision-making including an identification of critical steps where climate conditions play a predominant role. As an example, the prototype for estimating seasonal cereal crop yield for Castile and Leon region (Box 4) identifies critical decisions with the corresponding translation in terms of costs. Focusing tservices on such critical steps will enhance the service saliency. The procedure mostly followed for the identification of user needs were surveys and face-to-face meetings. The election of one or another alternative depended on the number of final users. In case of one or few users, face-to-face meetings and workshops were the preferred way to identify and collect users (as e.g., Box 3 and 4). In other cases (e.g., Box 1 and 2) the continuous interaction with stakeholders and users has allowed to grasp a clear idea of the supply chain and to identify the specific needs for each user profile. Finally, information and knowledge from previous projects and meetings with a few selected users (e.g., Box 5) allow to estimate user needs for some restricted geographical area and extrapolate to a larger domain.

User feedback to identify user needs either at the starting point or during the development phase or even during the operational implementation is an essential element in the whole lifetime of the service. Although continuous feedback is an option (as in Box 1 or Box 4) other ways based on cycles of interaction (as in Box 2 and 3) -comprising the phases of: collection of requirements, co-design and planning, co-supply of the needed data, co-monitoring of work progress, co-assessment of the prototype, operationalisation and training- have demonstrated to be very efficient and provide a good characterization of the initial and evolving needs of climate information.

Training and knowledge transfer in both directions -providers to users and users to providers- is critical to generate a common body of knowledge including concepts, terminology, etc. for all agents intervening in the design, development, and application of the service. Some of the described prototypes (as Box 3) have conducted a very comprehensive plan of workshops mainly aiming to convey to users the benefits and limitations of the science behind seasonal forecasts. In the opposite direction, a clear picture of relevant decisions and schedules of water managers has permitted the service to focus on the right magnitudes, time, and visualisation tools for maximising its utility.

The steps shown in Fig. 1 describing the main tasks in a typical seasonal prediction-based suite have facilitated the identification of user role in service co-design and co-creation. In most prototypes, users have mainly intervened in some specific steps as e.g., selection of the impact model to be used, visualisation, display, evaluation, etc. For example, the viewer described in Box 3 incorporated most of the suggestions proposed by dam managers to facilitate a friendly access to relevant information during their decision-making process. Also, the presentation of snow depth forecasts in the form of probability density distributions in Box 2 has been included with users' intervention to convey a clear idea of the probabilistic nature of such forecasts. From our experience in all prototypes shown, we have learnt that user participation is more relevant during design or development phases mainly in the pointed-out steps. These steps do not usually require high expertise on model outputs and their manipulation to extract some useful signal for its exploitation in some sectoral application. Finally, it should be underlined that the presented prototypes show very different participation in the co-design phase depending on each specific step.

## Barriers to the development and use of services

Some common barriers to the co-development of all services here described were related to the low seasonal predictability limiting the skill of seasonal forecasting systems, to the need of an adequate training on the tools for synthesising seasonal forecast data and to the insufficient knowledge from users of the state-of-the-art seasonal forecasting capabilities/limitations -including the full understanding of the probabilistic nature of seasonal forecasts- and of the downstream services.

Specific barriers were also identified during the development of individual prototypes. For example, it was found that users, and probably due to the lack of a proper understanding of probabilistic forecasts, were more willing to take actions when a particular forecast shows a distribution differing significantly from the climatology (as in Box 1 prototype). Sometimes, users did not have a deep knowledge of the application models translating climate variables into user variables making their involvement in the co-design and co-development of the full-service chain more limited (as in Box 2 prototype).

In some prototypes, usage of alternative sources of data have challenged the final consistency of output (e.g., hydrological variables in Box 3 prototype). Calibration and regionalisation of global climate models output, and their combination with other information sources is currently an active field of research in the service provider side. Also the lack of standardised observations of user variables adds difficulties to the prototypes assessment (like cereal yield observations in Box 4). This last issue is frequently palliated using synthetic observations derived from an application model driven by perfect atmospheric conditions (coming e.g., from a reanalysis).

Clements et al. (2013) pointed to several factors affecting the value of climate services beyond forecast properties such as accuracy, lead time, probabilistic nature, specificity, or spatial resolution. In particular, decision-maker characteristics like risk aversion, prior knowledge, or the relationship to the asset also influence the value of climate services. The environment in which a decision-maker is immersed is also a key element. Credibility of forecasts and/or forecasting institutions, different level of vulnerability to climate impacts, government programs and policies, and community norms and rules have consequences for the use of forecast information. Many of these barriers are also pertinent for MEDSCOPE prototypes. On the other hand, when users are relevant actors in the institutional sphere of a certain sector, the continuous interaction towards the development of useful and usable climate services can also induce changes on the existing normative, and in this way help to reduce some of these barriers. This is the case of the collaboration between AEMET and D.G. Water in Spain. Indeed, the development of the climate service in support of water reservoirs (Box 3) has recently boosted a modification to the Water Bodies Law aiming at the usage of seasonal forecasts for water reservoir operations (https://www.boe.es/eli/es/rdl/2021/09/14/17).

## Conclusions

The overview of selected MEDSCOPE prototypes provided by boxes allows us to draw the following general conclusions on the role of users, specifically on co-design.

The most straightforward conclusion is the high diversity of users, user needs, and user roles in the co-design step. Some prototypes are very much user-driven and were initially conceived after developers were approached by users with some climate related specific problem or need. This modality in its pure form was hardly represented by the prototypes here shown. Other prototypes were developed in the framework of long-term strategic collaboration among institutions and/or private companies. This was the case of Box 3 and Box 4 prototypes, where water authorities responsible for dam management and the Agricultural Technology Institute of Castile and Leon, respectively, addressed AEMET for meeting their needs on specific forecast information and data on seasonal time scale. Box 3 and 4 prototypes may also be partially interpreted as user driven services. Others, finally, had their origin in developments that arose within the research community and then were presented in a final format to users. This was the case of the Box 5 prototype, where the initial idea derived from the results obtained in previous project initiatives and informal discussion with regional end-users.

Additionally to these three modalities of collaboration, a wide variety of user roles appear. Besides, the fact that the MEDSCOPE project had from its inception a strong link with the MedCOF community -and through it with users and stakeholders operating in the Mediterranean region- has guaranteed continuous feedback between potential users and the project. Moreover, whereas some prototypes were initially developed and evaluated during the MEDSCOPE project for some region or country, after being presented to the MedCOF community many potential users manifested their interest in expanding or applying such prototypes in their respective regions or countries. Therefore, MEDSCOPE prototypes evaluated over a particular geographical zone may have a transfer and broader application to other regions within the Mediterranean.

Users have substantially intervened during the life of the project in: i) identification of their needs in terms of variables or indicators to be forecasted; ii) identification of their needs in terms of start and length of the forecast period, time resolution of the forecast (seasonal or monthly), lead-time; iii) suggestion and/or supply of the impact models used; iv) introduction of additional stakeholders; v) provision of data either for evaluation or for running application models; vi) selection of demonstration cases; vii) analysis, interpretation and evaluation of results; viii) suggestion of format for displaying results; ix) outreach of the climate service.

The interaction maintained between users and providers of these prototypes has also revealed that undertaking certain challenges would enable a greater and faster uptake of these climate services in the future. A common issue is related to how to convey forecasts uncertainty and skill for efficiently informing decision-making in practice. The way of communicating both forecast properties –uncertainty and skill- is key. Another challenge concerns the demonstration of the economic, social, and environmental value of predictions provided by these MEDSCOPE prototypes. Evaluation studies should ideally express benefits in terms easily understandable by decision-makers. Research is needed to determine the value of forecasts for a range of design and operating settings of those environments where the climate service is used for decision-making. For example, Turner et al. (2017) conclude that in order to complement water reservoir operations without imposing downside risks, forecast skill has to be consistently available additionally to forecasts. In any case, tackling the challenges, beyond forecast properties mentioned by Clements et al. (2013), in MEDSCOPE prototypes would require a still stronger involvement of users and the participation of experts from different fields may be also needed.

Finally, it should be mentioned the fact that the operational prototypes developed during the MEDSCOPE project are a valuable legacy that need to be maintained and supported also beyond the lifetime of the project to guarantee the long-term sustainability of the climate services, their enhancement, exportability, and application to a larger scale.

## CRediT authorship contribution statement

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## Declaration of Competing Interest

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

## Data availability

The authors do not have permission to share data.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cliser.2022.100337.

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