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Seasonal Predictions and Their Applications in the Mediterranean Region: Part II—Prediction-Based Services

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ABSTRACT

This review paper examines the development and application of climate predictions, primarily at seasonal timescales, as actionable information for decision-making, with a specific focus on the Mediterranean region. It illustrates and analyses the steps required to transform climate model probabilistic forecasts into user-defined information, emphasising the iterative nature of climate service development. By leveraging tools such as bias adjustment, downscaling, probabilistic calibration and impact models, these services provide tailored solutions to key sectors including energy, water supply, transport and agriculture. The paper discusses the contributions of global initiatives, such as the Global Framework for Climate Services (GFCS), and EU-funded projects like EUPORIAS, MEDSCOPE and MED-GOLD, which have advanced sector-specific applications of climate predictions in the region. These initiatives illustrate how tailored climate services can address critical challenges ranging from renewable energy planning to drought risk mitigation and agricultural yield forecasting. The review highlights persistent challenges, including limited forecasting skill in the Mediterranean area, data accessibility issues and the need for robust impact-based verification. To enhance the uptake and effectiveness of climate services, the review recommends fostering interdisciplinary collaboration, promoting iterative co-production with users, improving the communication of uncertainty and forecast skill, and ensuring the sustainability of services beyond project lifetimes. This work underscores the potential of climate services to enhance resilience in the Mediterranean region, bridging the gap between scientific advances and practical applications.

1 | Introduction

The growing awareness of the profound impacts that climate variability, climate change and extremes can exert on all socioeconomic sectors has led to an increasing demand for reliable climate information to support decision-making processes. The need for such information is particularly acute in the Mediterranean region, a climate hotspot characterised by marked variability and sensitivity to global change, which strongly impacts human and natural systems. From agriculture and water management to renewable energy and disaster risk reduction, climate-sensitive sectors across the region require actionable insights to adapt to changing environmental conditions and enhance their resilience. Transforming climate predictions into usable and sector-specific information has become a cornerstone of climate services, with forecasts at seasonal to decadal timescales emerging as key components of any powerful adaptation tool.

Climate services aim to bridge the gap between complex climate science and practical applications. By leveraging outputs from climate prediction systems, these services provide tailored products, such as probabilistic forecasts and user-defined indicators, to guide critical decisions and actions. The World Meteorological Organization (WMO) and initiatives such as the Global Framework for Climate Services (GFCS) have been instrumental in promoting international collaboration, fostering user-provider engagement and standardising approaches to climate information delivery in regions like the Mediterranean. In particular, the early and ongoing engagement of potential users of climate services in effective, two-way dialogue with the providers of those services has proved to be a key factor for their success and for their actual, effective use, as shown by Vaughan and Dessai (2014) and Lúcio and Grasso (2016).

This paper is a review of the state of the art in climate services based on seasonal climate predictions, with a specific focus on their application in the Mediterranean region. It is a companion to a related study that delves into the drivers of climate variability and seasonal predictability in the Mediterranean region, assessing the predictive skill of various forecasting systems. Together, these papers present a comprehensive perspective: from understanding the mechanisms driving climate variability to translating predictions into actionable information tailored to the region's unique challenges.

Despite advancements, significant challenges persist. Seasonal prediction systems often lack sufficient skill in the mid-latitudes, including the Mediterranean area. Additionally, the integration of user-specific needs into the design, implementation and evaluation of climate services remains a significant hurdle.

This review highlights key initiatives, primarily represented by European projects such as EUPORIAS, MEDSCOPE, CLIM-RUN and MED-GOLD, which have demonstrated the potential of climate predictions to inform decisions in the Mediterranean region. By presenting successful examples and identifying gaps, this study aims to advance the understanding and practice of climate services, ultimately contributing to more resilient and sustainable systems in this climatically vulnerable region.

2 | Actionable Information: From Climate Forecast Model Outputs to Information for Decision-Making

Many applications of climate information, and in particular of climate predictions, are nowadays provided as climate services mainly designed to assist decision-making. The benefits of using climate information in decision-making for climate-sensitive sectors have received increasing attention in recent years. This growing interest reflects increased recognition by decision-makers and a rising awareness among researchers and providers of the need for societal applications (Buontempo and Hewitt 2018). These climate services frequently have in common the following features: (i) support of decision-making process through customised products based e.g., on mobile phone apps, web-services and other easy accessible platforms; (ii) sound basis in scientific information and expertise, including tools to improve forecast quality through post-processing of model data (e.g., Pérez-Zanón et al. 2021) and (iii) appropriate engagement between users and providers (see e.g., Vaughan and Dessai 2014; Lúcio and Grasso 2016).

Transforming climate predictions into actionable information for decision-making in climate-sensitive sectors often involves a series of steps, starting from global model outputs and leading to probabilistic forecasts of indicators jointly defined by service producers and users. Figure 1 schematically depicts the main steps in a typical prediction-based suite (Máñez Costa et al. 2021). Once adequate climate model outputs are selected, a set of post-processing tools for synthetising and correcting climate forecasts is applied. These are usually: bias adjustment (to correct systematic model errors and make forecasts reliable, i.e., match the issued probabilities with the observed frequencies; e.g., Manzanas et al. 2019, Perez-Zanon et al. 2024, Soret et al. 2025), downscaling (to better represent unresolved spatial scales; e.g., Manzanas et al. 2018; Manzanas et al. 2020; Vernon et al. 2025), combination and/or weighting of ensemble members (to deal with the different quality of systems and/or ensemble members; e.g., Hemri et al. 2020, Calì Quaglia et al. 2022, Torralba et al. 2024) and mixed statistical-dynamical post-processing methods (to address problems of particular sectoral applications unmanageable by standard prediction approaches;

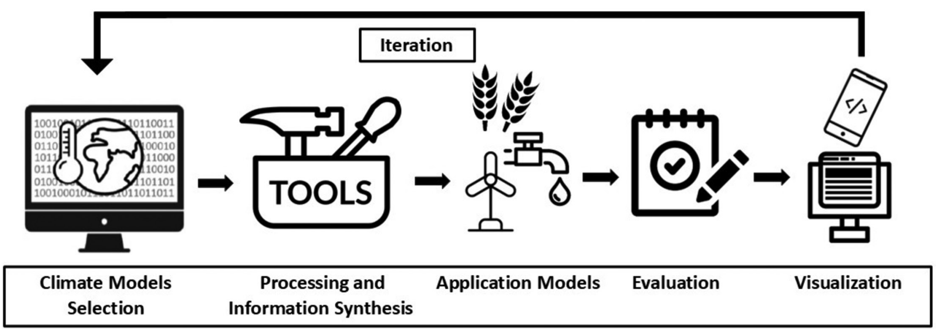

FIGURE 1 | Diagram with a simplified climate services chain based on climate forecasts.

e.g., Tsartsali et al. 2023). Such tools are frequently collected in general purpose software packages (e.g., the Climate Service Toolbox, CSTool, documented in Pérez-Zanón et al. 2021).

The next step is the use of application models driven by post-processed climate model outputs for converting climate data (e.g., precipitation, temperature, wind) into users' defined indicators (e.g., crop yield, dam inflow, wind energy capacity factor). Then, probabilistic or deterministic relevant products (e.g., probability of exceeding a given threshold) are generated and displayed. Specific packages are developed for computation of sectoral indicators, as in Ceglar et al. (2024) for agricultural services or Obolski et al. (2019) for health.

Evaluation is conducted by computing objective verification skill scores for a set of climate re-forecasts, typically covering 20–30 years, commonly referred to as hindcasts. As noted by Risbey et al. (2021), hindcasts represent more idealised conditions than real-time forecasts, and hindcast skill can therefore be slightly overestimated relative to that of operational forecasts. This difference arises from the availability of additional information, such as observations not available at forecast time, that may be used in post-processing procedures, including bias correction, tuning and calibration over events that are subsequently included in model evaluation, as well as in the preparation of forecast initial conditions (Risbey et al. 2021). Software for verification is usually included in the toolbox developed for the post-processing of climate predictions.

The evaluation step is typically carried out for user indicators computed from re-forecasts. An often-overlooked limitation of seasonal forecast evaluation is the assumption that the observational reference is perfectly reliable, when in reality these datasets may carry considerable uncertainty. Differences in coverage, assimilation strategies and bias adjustment mean that reanalyses and gridded products can disagree substantially, and these differences can directly influence the apparent skill of forecast systems (Ramon et al. 2024). This issue is particularly acute for variables such as precipitation and drought, where monitoring itself is highly uncertain. For example, Torres-Vázquez et al. (2024) show that predictions are more robust when multiple precipitation datasets are combined rather than relying on a single reference. These findings highlight that skill assessments which ignore observational uncertainty might risk overstating the performance of forecast systems and providing misleading information to users. Addressing this limitation by incorporating multiple references or explicitly representing observational uncertainty should therefore be a priority for the development of trustworthy seasonal climate services.

Finally, a friendly visualisation of the selected indicators, jointly with their uncertainty and skill, is crucial for effective support and guidance in the decision-making process.

Table 1 summarises the principal elements of the climate-service chain and offers illustrative (non-exhaustive) examples of post-processing tools, applications, evaluation approaches and visualisation/decision-support tools, including relative references.

It is important to underline that the whole process shown in the simplified climate services chain based on climate forecasts does not follow a linear path. In fact, the main feature of this process is iteration between climate scientists, climate service providers and users. Most services reach a mature state after a co-design procedure involving different starting data, use of different tools to combine/correct/transform model outputs and different ways to display final results in a format adequate for final users.

TABLE 1 | Summary of the climate-service chain in Figure 1, with illustrative (non-exhaustive) examples of post-processing, applications, evaluation and visualisation/decision-support tools.

Elements of the climate services chain	Objectives	References
Post-processing	Improving seasonal forecasting system outputs to make them usable for applications	E.g., bias adjustment (e.g., Perez-Zanon et al. 2024; Soret et al. 2025); downscaling (e.g., Manzanas et al. 2020; Sánchez-García, Abia, et al. 2022; Sánchez-García, Rodríguez-Camino, et al. 2022; Terzago et al. 2023; Vernon et al. 2025); combination ensemble members and subsampling (Hemri et al. 2020; Torralba et al. 2024; Famooss Paolini et al. 2025) and mixed statistical-dynamical methods (e.g., Vannitsem et al. 2021; Tsartsali et al. 2023)
Applications	Converting climate data into users' defined indicators for various sectors	E.g., crop yield (e.g., Ceglar et al. 2024, Dell'Aquila et al. 2023); water resources (Terzago et al. 2023; Silvestri et al. 2025; Brands et al. 2025); renewable energy (Torralba et al. 2017; Dubus et al. 2023) and health (Obolski et al. 2019; Khomsi et al. 2024)
Evaluation	Objective verification skill scores	E.g., Cammalleri et al. (2021), Ramon et al. (2024), Torres-Vázquez et al. (2024), Crochemore et al. (2024) and Khosravi et al. (2024)
Visualisation and decision supporting tools	Make climate data understandable and translate it into actionable guidance for sector-specific decisions.	E.g., Buontempo (2022, for an overview), Manrique-Suñén et al. (2023), Terrado et al. (2023) and Ceglar et al. (2024)

As a specific example of the user–provider iteration and co-production best practices, we can refer to the S-ClimWaRe service (see Section 3.2) providing seasonal forecasts of inflows, reservoir indicators and related variables to support water authorities in operational decision-making (Sánchez-García, Abia, et al. 2022; Sánchez-García, Rodríguez-Camino, et al. 2022). Its user–provider interaction was organised as a regular iterative cycle involving the Spanish Meteorological Agency (AEMET), basin authorities and technical agencies. Needs were first identified through surveys and workshops, then translated into prototypes that were jointly reviewed and refined. Users contributed data, operational requirements and feedback on usability, while providers ensured scientific feasibility and implementation. This co-production process and the subsequent iteration among users and providers allowed the service to evolve into a tool tailored to reservoir management, with functionalities and formats shaped directly by end-user input.

As both skill and predictability vary considerably depending on the geographical area, the time of the year and the climate variable, 'windows of opportunity' (e.g., Mariotti et al. 2020) may enhance the usability of climate predictions for some users depending on the phenomenon, thresholds and decisions involved. These 'windows of opportunity' are related to the fact that at times certain influences/factors—if they are stronger and/or act in concert—may enhance predictability and skill. In such situations, signals in the forecast are likely to be stronger and the confidence in climate predictions may be greater than the average skill information would indicate (Bruno Soares and Dessai 2016; Acosta Navarro and Toreti 2023). Consequently, additionally to using models with higher levels of skill, many services should also focus on exploring how existing 'windows of opportunity' can be used to satisfy current users' needs and inform their decision-making (see e.g., McNie 2007, 2013).

2.1 | International Initiatives on Seasonal Forecasting

For various reasons, some of which are illustrated and discussed in Gualdi et al. (2026), the skill of seasonal forecasts is not particularly high in some regions of the globe, especially at mid-latitudes, and extracting the signal and the information they nevertheless provide requires careful interpretation of the results. This complexity may represent an obstacle to the widespread and effective use of these forecasts by users and stakeholders interested in their applications. In light of these potential limitations of seasonal forecast outputs, the WMO has promoted the development of a consensus-based approach as a means of consolidating forecast information and products from multiple sources (WMO 2018, 2020). In order to operationalise this approach, Regional Climate Outlook Fora (RCOFs) were first established by WMO in 1996. By assembling countries with common climatological characteristics, the Fora ensured consistency in the interpretation of climate information (raw model outputs, observed sea-surface temperature (SST), etc.). 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 http://medcof.aemet.es, accessed 30/10/2025). Other fora were established focused on specific subregions within the Mediterranean domain: the South East European Climate Outlook Forum, the Northern Africa Climate Outlook Forum and the Arab Climate Outlook Forum.

The Third World Climate Conference held in Geneva in 2009 marked the establishment of the GFCS aiming to improve and enhance the provision and use of climate information and services worldwide. All these directly benefit climate predictions and related services across the world. The GFCS components include: engagement between users and providers of climate services, climate services information system, observations and monitoring, research, modelling and prediction, capacity development as well as National Frameworks for Climate Services (NFCSs). The primary goal of the GFCS is to assist countries—particularly those in developing regions—in better understanding, predicting and adapting to climate variability and change; however, its principles and components are intended to benefit all countries and regions, regardless of their level of development. The GFCS recognises that climate-related challenges and the need for reliable climate information extend beyond national borders and affect both developed and developing nations. It promotes international cooperation and collaboration to enhance climate services, share knowledge and address climate-related issues collectively. In practice, the GFCS involves partnerships and activities at the global, regional and national levels, engaging governments, meteorological agencies, research institutions and various stakeholders from around the world. Its goal is to make climate information more accessible, understandable and actionable for all users, whether they are in developing or developed countries. By doing so, the GFCS contributes to building climate resilience and supporting informed decision-making on a global scale (Lúcio and Grasso 2016).

Prediction-based climate services must be underpinned by operational forecasting systems that guarantee the regular and reliable provision of seasonal predictions. For this reason, the WMO has, over successive years, completed the deployment of an infrastructure designed to support operational seasonal forecasting. A network of Global Producing Centres for Long-Range Forecasts (GPCs-LRF) was formally created in 2006 followed by the WMO Lead Centre for Long-Range Forecast Multi-Model Ensemble (LC-LRFMME) in 2009. At present, 14 designated GPCs-LRF provide seasonal forecasts on a monthly basis. Data from these forecasts are collected by the LC-LRFMME. The combination of GPCs-LRF and LC-LRFMME complemented with Regional Climate Centres (RCCs) producing objectives seasonal forecasts for RCOFs constitutes a solid foundation for the provision of seasonal forecasts on a global scale and is an authoritative resource for the formulation of specific seasonal forecasts for individual regions, countries and localities. Additionally, in recent years WMO recommended following a standardised strategic approach using global information provided by these entities to develop seasonal forecasts tailored to specific regions or countries (WMO 2020). This standardised strategic approach is summarised in a set of principles, recommendations and general technical guidance, all designed to facilitate the development of forecasts at the regional and national levels.

After two decades of successful implementation, WMO conducted a comprehensive review of the RCOF process in 2017.

The review concluded that the next generation of RCOFs should mainstream objective seasonal climate forecasting, expand the RCOF product portfolio and adopt standardised operational practices. This new generation of objective seasonal forecasting products paves the way for their exploitation as specific services for different sectors and users' profiles.

The EU funded EUPORIAS (EUropean Provision of Regional Impact Assessment on a Seasonal to decadal timescale) project (Hewitt et al. 2013) focused specifically on the benefits of using climate predictions for the development and evaluation of services, particularly at seasonal timescales. The EUPORIAS project was part of the broader effort within the EU to enhance climate services and improve climate resilience in the face of a changing climate. While the project itself has concluded, its work has contributed to ongoing efforts to provide valuable climate information and support decision-making in Europe and beyond. The project emphasised user engagement and collaboration with decision-makers, policymakers and other stakeholders to ensure that the developed climate services were relevant and useful for addressing real-world challenges. The project demonstrated the value of using seasonal forecasts in five climate service prototypes (Buontempo et al. 2018; Buontempo and Hewitt 2018). EUPORIAS left a legacy of research findings, tools and resources and paved the way for later initiatives mainly focused on Europe aiming to develop, evaluate and implement the usage of climate predictions for climate services (Buontempo et al. 2018). Three out of the five EUPORIAS prototypes (LEAP, RIFF, RESILIENCE) were led by institutions based in European Mediterranean countries and made use of climate predictions at seasonal timescales applied to food security, water management and renewable energy sectors, respectively. EUPORIAS was part of the broader effort within the EU to enhance climate services and improve climate resilience in the face of a changing climate.

The ERA-NET (European Research Area Network) Consortium 'European Research Area for Climate Services', so-called ERA4CS (https://jpi-climate.eu/programme/era4cs/, accessed 30/10/2025), was specifically designed to promote the development of climate services in Europe by supporting research for developing better tools, methods and standards on how to produce, transfer, communicate and use reliable climate information to cope with current and future climate variability. The ERA4CS initiative 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 climate forecasts and in particular at the seasonal timescale, in the development of climate services. The overall objective of ERA4CS was to enhance user adoption of and satisfaction with climate services, including adaptation services, and to connect that knowledge with decision-making. Two projects developed under the ERA4CS umbrella were specifically focused on the European Mediterranean region: MEDSCOPE and MED-GOLD. However, some prototypes within these last two projects were also extended to the whole Mediterranean region.

The MEDSCOPE project (see https://www.medscope-project.eu, accessed 30/10/2025) 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 also conceived as an extension of the MedCOF initiative for developing sectoral climate services. The MEDSCOPE project developed and evaluated a number of climate services prototypes specifically focused on the Mediterranean region and for the renewable energy, hydrology and agriculture/forestry sectors. The prototypes covered a wide variety of approaches and very different levels of user involvement (e.g., Sánchez-García, Abia, et al. 2022; Sánchez-García, Rodríguez-Camino, et al. 2022). Many of them were developed and evaluated in some particular countries and/or regions in collaboration with local users. However, their transferability to other regions or to the whole Mediterranean domain only requires minor adjustments and access to specific climatic or non-climatic data bases. The MEDSCOPE project also aimed at a better understanding of the mechanisms driving the climate predictability in the Mediterranean region and the development of a collection of tools improving the operational production of services based on climate forecasts.

The MED-GOLD project (https://www.med-gold.eu, accessed 30/10/2025) was a 54-month initiative supported by the Horizon 2020 programme under the European Union's Framework Programme for Research and Innovation. Its main objective was to create a tangible agricultural climate service concept co-designed with end-users, focusing on vital components of the Mediterranean food system: grapes, olives and durum wheat. The core concept behind MED-GOLD was to collaboratively design and develop prototypes for climate services, with active involvement and contributions from industrial partners in the wine, olive oil and pasta sectors (SOGRAPE, DCOOP and Barilla, respectively). These partners played a significant role within the consortium, recognised as the MED-GOLD sectoral 'champions' in the project's terminology. This structured methodology ensures that the climate-related data provided through MED-GOLD services is presented in a user-friendly format, aiding industrial decision-makers as well as farmers in their decision-making processes. The information is derived from a well-founded scientific basis across various timescales, offering authoritative and current insights, with room for further enhancement and refinement.

The Climateurope project (https://www.climateurope.eu, accessed 30/10/2025) was a collaboration network aimed at establishing a Europe-wide framework for Earth-system modelling and climate services, with a focus on identifying gaps, challenges and emerging needs (Hewitt et al. 2017). Its successor, Climateurope2 (https://www.climateurope2.eu, accessed 30/10/2025), specifically focuses on supporting and proposing standardisation procedures for equitable, quality-assured climate services that can inform decision-making across all sectors of society. It is envisaged to propose criteria for certification and labelling, as well as the user-driven criteria needed to support climate action. Co-production and stakeholder engagement in climate services are addressed in Climateurope2 through the creation of a network of different European climate services actors, including a large variety of interactive and innovative activities such as festivals, 'webstivals', art installations and roadshows.

An additional fundamental source of actionable information, derived directly from climate forecast model outputs to support climate service activities and inform decision-making, is provided by the Copernicus Climate Change Service (C3S, https://climate.copernicus.eu, accessed 30/10/2025). C3S is part of the European Union's Copernicus Earth Observation Programme, which aims to provide accurate and up-to-date information about the Earth's environment. The C3S specifically focuses on climate data and services. It is designed to support climate monitoring, climate change adaptation and mitigation efforts by providing a wide range of climate-related information and services to a variety of users, including policymakers, researchers, businesses and the general public. Numerous applications of seasonal forecasts in the Mediterranean region—for instance, the MedCOF, as well as research projects on the development of seasonal prediction-based services such as MedGOLD and MEDSCOPE—rely on the operational multi-model seasonal forecasts provided by C3S. Since 2018, C3S has been delivering seasonal predictions on a monthly basis, which are made available through its institutional website (https://climate.copernicus.eu/seasonal-forecasts, accessed the 30/10/2025).

To provide a concise overview of the evolution of forecasting systems over the past 30 years, Figure 2 synthesises key milestones in their development, highlights major international programmes dedicated to their advancement, and outlines the main projects that have focused on applying climate forecasts to support the development of climate services in the Euro-Mediterranean region. The figure, together with the milestones it highlights, is not intended as a complete and exhaustive catalogue of forecasting systems, initiatives, programmes and projects dedicated to seasonal prediction; rather, it aims to provide the reader with a clear and integrated understanding of the historical context and coordinated efforts that have shaped the field.

3 | Examples of Applications for Different Sectors and Timescales

Sectoral services based on climate predictions share, as mentioned before, a suite of steps from climate forecasting systems outputs to probabilistic forecasts of user defined variables or indicators. After development and evaluation, usually in the frame of research projects and initiatives (several of them described in Section 2), some of them have been operationally implemented in their respective sectors. We present here some selected examples covering different sectors, especially energy, the water sector and agriculture; three of the main GFCS pillars. Although most services have been implemented for the seasonal timescale, some of them can be extended to longer timescales, such as decadal. Special attention for the selection has been paid to novel aspects of the services such as synthesising information coming from different forecasting systems, Mediterranean regional and sectoral specificity.

3.1 | Energy

Energy generation and the planning of operations are strongly affected by meteorological and climate conditions. Particularly, renewable energy sources (i.e., hydro, solar and wind power) are strongly conditioned by climate variability at sub-seasonal, seasonal and multi-annual timescales (Soret et al. 2019; Lledó et al. 2019; Torralba et al. 2017; Troccoli et al. 2018; Manrique-Suñén et al. 2023). Energy systems could considerably improve their resilience to weather extremes, climate variability and change, as well as their full chain of operations during their entire life-cycle if they integrate climate information in their activities.

Several climate services initiatives have emerged in recent years to facilitate the integration of climate predictions at different timescales into the renewable energy industry and to reduce the dependency of the electricity system to atmospheric conditions. At the European level, the C3S Energy operational climate service assesses the impacts of climate variability and climate change on the energy sector in Europe (Dubus et al. 2023). This initiative is based on previous C3S proofs of concept targeted to the energy sector: CLIM4ENERGY and European Climatic Energy Mixes. Moreover, previous projects have also investigated the potential of the climate services for the renewable energy sector. Notably, the EUPORIAS project developed a semi-operational climate service to provide seasonal forecasts of essential climate variables relevant to energy applications (Buontempo et al. 2018). Furthermore, recent advancements in climate services for energy are evident in projects such as SECLI-FIRM (http://www.secli-firm.eu/, accessed 30/10/2025) and S2S4E (https://s2s4e.eu/, accessed 30/10/2025). SECLI-FIRM developed nine case studies (four of them in southern Europe) to demonstrate the economic added value of the seasonal forecasts for the decision making processes in both energy and water applications (Goodess et al. 2022; Troccoli et al. 2018). S2S4E co-designed a decision support tool (Manrique-Suñén et al. 2023) by the close collaboration of the climate research community and energy users to help increase the resilience of the solar, wind and hydropower energy sectors to climate variability and extreme events. This decision support tool provided sub-seasonal and seasonal predictions of essential climate variables and derived energy indicators such as wind and solar power, electricity demand or inflow anomalies at global scale.

For the hydropower sector there is a climate service prototype at decadal timescales which is still in an incipient stage. We mention it here because, although the service was originally developed in the context of decadal prediction, its underlying approach is sufficiently general to be easily transferred to applications based on seasonal forecasts. The service aimed at predicting precipitation in three drainage basins (Guadalquivir, Ebro and Po) for the next 10 years, and was developed in close collaboration with users (Tsartsali et al. 2023). The predictive skill for precipitation provided by a European multi-model ensemble was found to vary with calendar season, forecast range and the drainage basin considered, being in general low for the required climate service. Given the good predictive skill of the North Atlantic Oscillation (NAO) and the observed dominant influence of the latter on the decadal variability of precipitation in the areas of interest, a hybrid approach was developed combining the predictive information from the dynamical multi-model ensemble with statistical information from observations. This hybrid predictive system was able to significantly improve skill in the three basins studied during

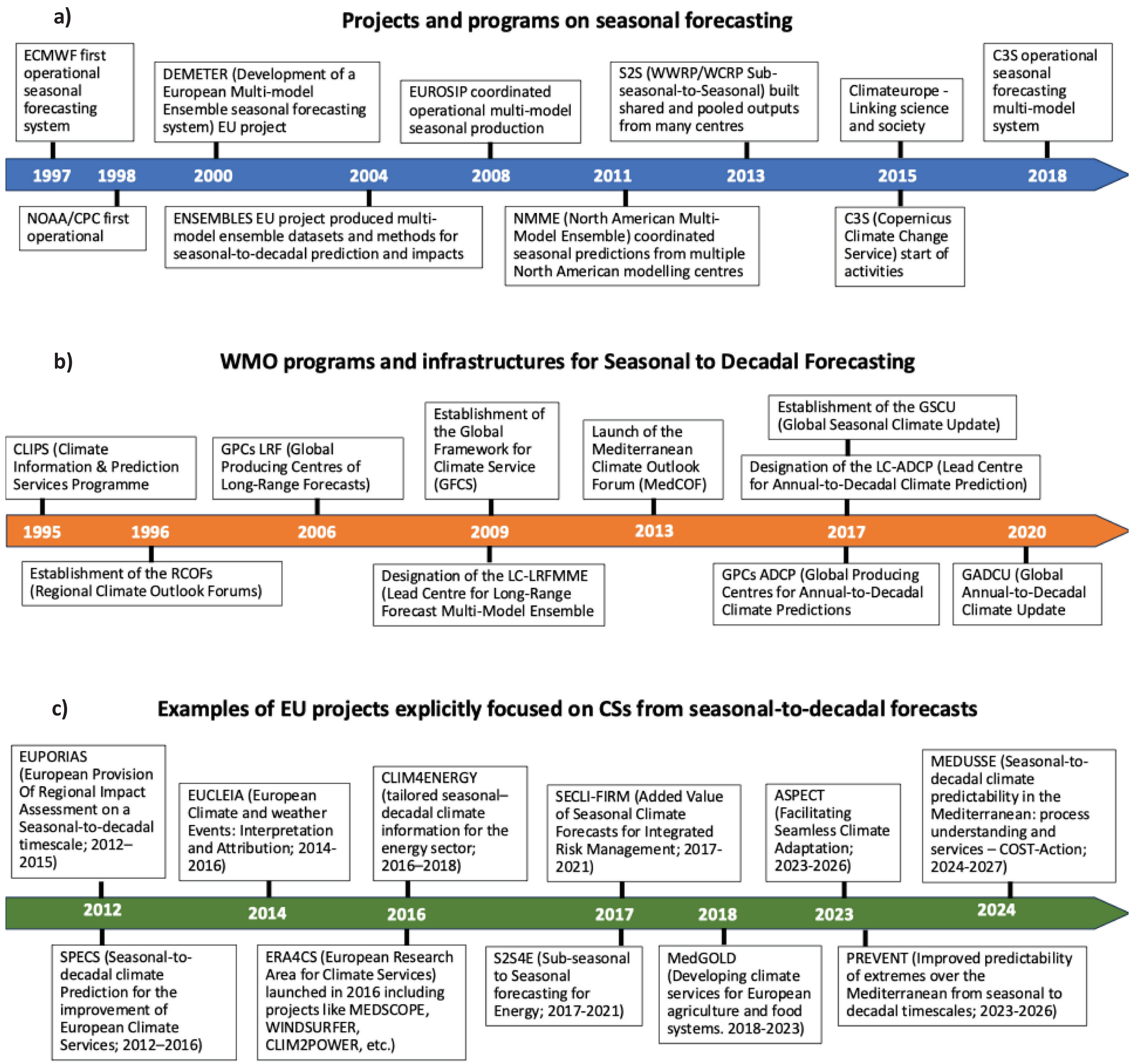

FIGURE 2 | Schematic synthesis of the evolution of some key international initiatives in seasonal forecasting (a), WMO programmes and infrastructure designed to foster climate predictions and their applications (b), examples of some of the main EU collaborative projects focused on developing prediction-based climate services (c). The reader should note that the scale along the time–axis is different in the three panels. [Colour figure can be viewed at wileyonlinelibrary.com]

the extended cold season (November–March) for the first 10 forecast years.

3.2 | Water Resources

Within the water resources sectors we have selected one example of service for the management of reservoirs in Spain at seasonal timescale and making use of a hybrid forecasting step based on an optimal combination of a dynamical model and an empirical algorithm. It was developed and improved within the lifetime of EUPORIAS and MEDSCOPE projects and it is now fully operational for the partition of available water resources among different categories of users, as, e.g., general population provision, irrigation and energy production.

The service is thoroughly described by Sánchez-García et al. (2019), Voces-Aboy et al. (2019), Sánchez-García, Abia, et al. (2022) and Sánchez-García, Rodríguez-Camino, et al. (2022). The so-called S-ClimWaRe (Seasonal Climate predictions in support of Water Reservoir management) web tool (see http://www.aemet.es/es/serviciosclimaticos/apoyo_gestion_embalses, accessed 30/10/2025) was developed and implemented to inform decision-making during the November to March filling reservoirs period in Spain. This service makes use of two postprocessing steps developed for the MEDSCOPE

CSTools package. The first one, named the best estimate index (BEI), optimally combines climate indices from two forecast systems and provides weights for members of an ensemble forecasting system. The second is an analog-based downscaling method bridging the gap between coarse seasonal model outputs and local hydrological applications, enabling tailored forecasts for reservoirs (Pérez-Zanón et al. 2021; Sánchez-García et al. 2019; Sánchez-García, Abia, et al. 2022; Sánchez-García, Rodríguez-Camino, et al. 2022). The S-ClimWare web tool provides information at 388 water reservoirs (covering 95% of the total storage capacity), or any other location in Spain, displaying diagnostic and forecasting information for the extended boreal winter (NDJFM). The '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 and its linkage with the main climate driver for this area and season: the NAO. The 'forecasting' panel provides seasonal climate predictions for the expected NAO index, water reservoir inflow, accumulated precipitation and snowfall and mean temperature. The forecasting part of the service optimally combines information from two seasonal forecasting systems: the ECMWF SEAS5 (Johnson et al. 2019) and one empirical system.

Seasonal forecasting of snow resources is of paramount importance for water management, hydropower production, river transport and mountain ski tourism. Mountain snowpack provides an essential water reservoir that can be also exploited in the hot and dry season (summer), both locally and downstream. Terzago et al. (2023) have developed a prototype to generate seasonal forecasts of snow variables for Alpine sites. The modelling chain is based on outputs from two seasonal forecasting systems (ECMWF SEAS5 and MF SFS v6) including bias adjustment and downscaling to three sites in the Western Italian Alps. Finally, the physically based multilayer, one-dimensional snow model SNOWPACK (Lehning et al. 2002) is applied to generate integrated, slow-varying and more predictable variables, such as snow depth and snow water equivalent. Perhaps the most relevant feature of this service is the enhanced predictability of the snowpack acting as a natural 'integrator' of the climatic conditions at a monthly/seasonal timescale, so even if the forecasts of the drivers (air temperature, precipitation, etc.) do not exactly match the observations at daily timescales, the differences may compensate over longer timescales and provide reasonable monthly/seasonal snowpack forecasts. A complementary service based on ice resources from glaciers is also described by Sánchez-García, Abia, et al. (2022) and Sánchez-García, Rodríguez-Camino, et al. (2022).

3.3 | Agriculture Sector

The reduced maize yields in France and Italy by 30%–35% as a result of the increased heat and drought stress consequence of the 2003 heat wave in Europe (Ciais et al. 2005), made the agricultural sector aware of the significant potential of climate forecasts to support and inform both shorter-term agricultural decisions as well as longer-term climate adaptation plans. The variability in weather and climate during the upcoming crop growing season significantly impacts the decisions of farmers and market strategies, particularly in climate hotspots like the Mediterranean. Despite the evolving landscape of crop management due to new technologies, obstacles such as training deficiencies and the absence of relevant and actionable information pose significant challenges, especially for small agricultural enterprises. Most yield forecasting systems are oriented to provide data at seasonal and annual timescales for policy makers and markets as they are often the only source of aggregated data. At farm level there is also interest in shorter timescales covering the sub-seasonal-to-seasonal timescale to get support in their agro-management practices related to, e.g., sowing and fertilisation. At this level there is a need for very detailed information to be gathered by the farmer about the current status of their fields and their respective yield forecasting based on the fertilisation level, tillage and some other agro-management practices.

Furthermore, along the growing season, soil available water and heat stress represent the main uncertainty and risks for the farmer. Farmers must decide at the start of the season (covering 6–8 months) the crop to be sown, the variety and the base fertilisation level. Those decisions are made based on past seasons' experience and more recently on decision supporting systems powered by climate information considering all the limiting factors for each parcel. Rainfall is the major limiting factor for rainfed crops. At the end of winter and during spring farmers make some other strategic decisions about the usage of more fertilisers (top-dressing), plant protection products and irrigation, if possible and needed. Those decisions are based on an updated farmer yield expectancy at 3–4 months to harvest. Yield forecasting may bias the farmer towards a more optimistic or pessimistic frame. With a low yield forecast farmers could decide to reduce top-dressing fertilisation and not to apply some plant protection products obtaining some economic savings. Decadal timescales are also of interest for long-term investments, e.g., in irrigation infrastructures. Similar interest on decadal predictions is shared by breeders to get support in programmes related to the development and testing of new crop varieties.

Concerning the seasonal timescale, different approaches have been proposed, developed and applied over the Mediterranean region. Climate prediction can be used to assess climate risk in specific critical phenological phases by using a set of tailored indicators (e.g., Ceglar et al. 2024). They can be also integrated in operational services producing expected yield (e.g., for cereal in Castile and Leon, Spain) making use of a crop growth model (Sánchez-García, Abia, et al. 2022; Sánchez-García, Rodríguez-Camino, et al. 2022). From sowing to harvest, the crop model can be driven by meteorological forcing coming from observations (or near-real time reanalysis) combined with forecasts to cover the period still to be observed. Predictability and skill of such a service come partly from the memory of past meteorological data carried by the crop model and partly from the skill associated with short, medium range and seasonal forecasts. The system for cereal in Castile and Leon has been delivering yield predictions since the 2015 campaign (http://cosechas.itacyl.es/, accessed 30/10/2025). This service makes use of an analog-based downscaling method bridging the gap between the coarse seasonal model output and the local crop growth model (Pérez-Zanón et al. 2021; box 4 in Sánchez-García, Abia, et al. 2022; Sánchez-García, Rodríguez-Camino, et al. 2022). At the European scale, the MARS Crop Yield Forecasting System was established by the European Commission's Joint Research Centre in 1993 and provides crop yield forecasts by using a hybrid approach based on crop growth models, analogs and seasonal forecasts (Van der Velde et al. 2019).

In the same vein, the Moroccan National System for crop monitoring and cereal yield prediction was developed and operationalised in 2011. This Crop Grow Monitoring System (CGMS-MOROCCO) (http://www.cgms-maroc.ma, accessed 30/10/2025) was initiated by the National Institute of Agronomic Research (INRA) as part of the E-AGRI project and it is managed by a national consortium (INRA, DGM and DSS). It allows for monitoring the agricultural season and prediction of cereal harvests. Predictions are provided based on a combined approach using parametric and non-parametric statistical analysis of meteorological data, crop growth simulations (using several agrometeorological data) and satellite data. Forecasting the production of crop yields early before harvest (up to 3 months in advance) allows decision makers to be prepared in advance for potential consequences of anomalous climate conditions (such as drought), in particular for cereals that are important commodity crops. Dainelli et al. (2022) provide another illustrative instance of an open-access, innovative climate service aimed at forecasting durum wheat yields in the Mediterranean at seasonal timescale. This service was specially focused on diminishing barriers, especially for small agricultural enterprises, such as training deficiencies and absence of relevant and actionable information. In this work, a simulation model architecture is developed to effectively manage the critical risks associated with durum wheat production. The objective is to support the reduction of agricultural return volatility and to facilitate the planning of storage and distribution strategies in Italy (http://www.agrosat.it, accessed 30/10/2025).

4 | Services for Water Cycle and Extremes for Risk Management

The updated Atlas of Mortality and Economic Losses from Weather, Climate and Water-related Hazards by the WMO, covering the years 1970 to 2021, reveals that the most devastating events during this period were droughts, resulting in 650,000 deaths globally (WMO 2022). Notably, in Africa, droughts were responsible for a staggering 95% of reported fatalities. Furthermore, droughts proved to be a significant financial burden, emerging as the primary cause of economic losses in both 2020 and 2021.

A recent estimation reveals that during the 1981–2010 period, annual economic losses due to droughts in Europe reached approximately 9 billion euros per year, affecting key sectors such as agriculture (livestock included), energy, public water supply, river navigation and infrastructure. Remarkably, nearly 1.4 billion euros per year of these losses were concentrated in a single country, namely Italy. Predictably, agriculture and forestry bore the most significant pressure, constituting 60% of the losses in the Mediterranean region (Naumann et al. 2021). Very recently, the European central bank estimated that extreme (plausible) droughts make at risk 15% of the economic output (ECB Blog 23 May 2025).

Climate change is expected to worsen climate extremes by, e.g., increasing their frequency, intensity and persistence (IPCC 2021). Concerning drought, it is expected to become worse in the Mediterranean region as a result of climate change regardless of the emissions scenario; but, the magnitude of change increases under higher emissions (FAQ 8.3, figure 1 in IPCC 2021: Chapter 8). It has been shown that in a high-end emission scenario (RCP 8.5), extreme events (such as the one of 2018) may become a common occurrence (Toreti et al. 2019). The recently published European Drought Risk Atlas (Rossi et al. 2023) also pointed to the remarkable increase of risks for all analysed sectors and ecosystems in most of Europe under 2 and 3 degrees warming scenarios and highlighted the Mediterranean region as a hot-spot for drought risk. Therefore, it is crucial to take action to mitigate and adapt to the impacts of climate change to reduce the severity of these droughts and their associated risks. Indeed, it is important to highlight that proactive measures have the potential to mitigate drought risks and enhance the resilience of ecosystems and communities facing precipitation deficits. As shown by Toreti et al. (2022) for the durum wheat sector, the integration of sectoral adaptation strategies based on tailored climate service can alleviate and even (in some cases) offset the negative impacts of climate change (mostly related to heatwaves and drought), especially if coupled with dedicated economic stabilisation mechanisms.

To this end, the Integrated Drought Management Programme (IDMP) has been developed as a joint initiative of the Global Water Partnership (GWP) and WMO. The IDMP strategy builds on three pillars: (i) monitoring and early warning; (ii) risk and impact assessment and (iii) risk mitigation, preparedness and response. The primary pillar, centred on monitoring and the provision of early warning, emphasises the development of robust early warning systems that generate valuable information to enhance both monitoring activities and the effectiveness of sub-seasonal and seasonal forecasting. This constitutes a critical foundation for proactive disaster risk reduction, highlighting the importance of continuously monitoring conditions and developing a dynamic early warning system. Such a system is intended to deliver timely and accurate information, which is pivotal for mitigating the impacts of a wide range of hazards, including, but not limited to, droughts. This collective effort is designed to reinforce early warning capabilities, especially in the context of dealing with multiple hazards, with a specific focus on addressing the challenges posed by droughts to establish a comprehensive framework for disaster risk management that prioritises preparedness, responsiveness and resilience in the face of various threats and challenges. An example of a regional early warning system is the European Drought Observatory of the Copernicus Emergency Management Service (https://emergency.copernicus.eu, accessed 30/10/2025), which is also moving from a hazard-based service to a multi-sectoral risk-oriented one.

Several studies conducted an extensive examination of literature pertaining to drought forecasting systems and methodologies, with a specific emphasis on their application at global and regional scale for the Mediterranean region. A common categorisation clustered these approaches into three main groups: statistical models, dynamic models and hybrid statistical-dynamic models (Hao et al. 2018; Torres-Vázquez et al. 2023; Zellou et al. 2023). The comparative analysis revealed that each of these strategies possesses its own strengths and weaknesses. Notably, hybrid methods generally exhibit higher predictive accuracy than other approaches, even for longer-term forecasts. However, these hybrid models come with significant computational demands and often grapple with the challenge of limited access to reliable and sufficiently extensive observed data series for robust statistical calibration. For a more comprehensive and comparative evaluation of the underlying methodological aspects of these different approaches it is possible to refer to Prodhan et al. (2022).

Most of the methodologies primarily focus on estimating the Standardised Precipitation Index (SPI) for agrometeorological drought, with only around a third of the examined studies delving into multifactorial indices. These multifactorial indices are primarily employed to project drought patterns in the forthcoming decades, particularly in response to global warming. Agrometeorological drought garners substantial scientific attention, while a smaller proportion of research addresses the complexities of long-term hydrological droughts (Zellou et al. 2023).

Additionally, the review analysis underscores that a majority of the studies concentrate on a local spatial scale as opposed to a national or regional perspective. This tendency can likely be attributed to the geographical diversity that introduces a wide array of physical mechanisms governing drought onset and evolution, rendering the identification of pertinent factors more challenging. Concerning temporal scales, the short term, specifically the monthly scale, receives comparatively less attention compared to the longer-term climatic perspective. Lastly, the quantification of uncertainty remains an aspect that has been largely disregarded (AghaKouchak et al. 2022).

5 | Gaps and Needs

The Mediterranean region is not characterised by high predictability at the seasonal timescale and beyond. Most climate forecasting systems lack sufficient skill for their application across many sectors except for certain 'windows of opportunity' associated with specific seasons, regions or climate states. In order to maximise these windows of opportunity for practical use, the scientific and climate forecasting communities have made significant efforts to combine or integrate different seasonal forecasting systems to enhance the robustness and accuracy of predictions. These efforts recognise that individual seasonal forecasting models have inherent strengths and weaknesses, and that combining multiple models can yield more reliable and skilful forecasts.

Early prototypes of climate services for specific sectors were generally based on individual forecasting systems, either based on dynamical or empirical models, supported by post-processing tools (for correcting and downscaling climate forecasts) and application models (for converting climate data into users' defined variables). In some cases, these approaches were able to enhance the limited skill of available forecasts (Sánchez-García, Abia, et al. 2022; Sánchez-García, Rodríguez-Camino, et al. 2022). Soon afterwards objective procedures started to be developed combining different forecasting systems (Sánchez-García et al. 2019) based either on dynamical, empirical or hybrid methods (WMO 2020). Because model skill varies spatially, one might hypothesise that they should be weighted differently when combined into a single forecast. However, several authors have shown that, given the short hindcast periods (typically less than 50 years), unequal weighting schemes rarely outperform equal-weighted schemes (e.g., Mishra et al. 2019). For larger sample sizes, unequal weighting can be estimated more robustly and may lead to more skilful forecasts (Siegert and Stephenson 2019). Overall, there remains substantial scope for improving multi-model combination strategies to maximise the skill of climate forecasts.

The development and evaluation of climate services—particularly those related to prediction—often require more than just climate data. Additional data, such as hydrological (including river flow, groundwater levels and water quality information), agricultural (including yields), ecosystemic, health-related or in general socioeconomic, may be needed for a comprehensive evaluation of a climate service. Such non-climate data are often only available at the national (or even subnational) level, limiting the scalability of services beyond national borders. In some cases, these datasets are not accessible even to the research community. A more holistic approach to climate services, integrating these diverse datasets, would enable a better understanding of the interconnectedness of climate and various societal and environmental factors and facilitate the expansion of services, initially developed for some country or region, to the whole Mediterranean. Interdisciplinary collaboration and availability of comprehensive databases are thus crucial to enhancing the quality, reach and usability of climate services.

Verification of climate services involves assessing the accuracy and reliability of not only climate variables (e.g., temperature and precipitation) but also user-relevant variables or impacts. Such impact-based verification, still frequently lacking, should evaluate the performance of climate services in predicting real-world impacts. This approach connects climate information to the outcomes that matter to users, such as crop yields, water availability or energy demand. Also, climate services should utilise metrics that are meaningful and relevant to end-users and decision-makers. This may involve the development of new verification scores or the adaptation of existing ones to capture the accuracy of predictions for user-specific variables. As different user sectors have distinct requirements, and verification should be tailored to address these specific needs (Sánchez-García, Abia, et al. 2022; Sánchez-García, Rodríguez-Camino, et al. 2022), engaging stakeholders and end-users in the development of climate services is crucial. Understanding their priorities, concerns and the variables that impact their decision-making informs the selection of appropriate verification metrics. Analogously to climate variable forecasting, many climate services provide probabilistic forecasts for user-relevant variables and therefore their verification in terms of probabilistic scores should also be pursued. Also, indicators based on economic value—such as cost–benefit analysis, return on investment, avoided costs and damages—play a crucial role in assessing the impact of climate services on various economic sectors. These indicators help quantify the benefits and costs associated with using climate information and services, providing valuable insights for decision-makers, policymakers and stakeholders. In addition to the objective verification skill scores and user engagement mentioned above, other metrics of climate services evaluation should be further developed, as for example the degree of climate service implementation and service lifespan (Máñez Costa et al. 2021).

Perhaps the main barrier to wider and faster uptake of climate prediction-based services lies in the insufficient interaction between users and providers throughout the entire process—from design, development, implementation, evaluation and visualisation. The establishment of a common language and shared concepts between users and providers, including the organisation of training events for users to address and clarify current limits of science, is still not developed enough to enhance the interaction between both parties. Climate prediction has its own limits that should be well perceived and understood by users. Many users are relatively well familiarised with weather concepts, and they frequently request a similar level of accuracy or skill for climate products, in particular for climate prediction products. The organisation of workshops mainly aiming to convey information from the research side to users on the current limits of climate science is essential to bridge the gap between what science can provide and what users can reasonably expect. Communicating forecast properties, uncertainty and skill to support decision-making remains another major challenge. Finally, it should be emphasised that many climate prediction-related services are frequently developed in the framework of research projects. Ensuring their long-term sustainability, enhancement, scalability and operational continuity beyond project lifetimes is vital to realising their full potential and long-term impact.

Author Contributions

Silvio Gualdi: supervision, conceptualisation, writing – review and editing. **Ernesto Rodriguez Camino:** conceptualisation, writing – review and editing. **Esteban Rodriguez Guisado:** conceptualisation, writing – review and editing. **Andrea Toreti:** conceptualisation, writing – review and editing. **Massimiliano Pasqui:** conceptualisation, writing – review and editing. **Constantin Ardilouze:** writing – review and editing. **Wafae Badi:** writing – review and editing. **Lauriane Batté:** writing – review and editing. **Fatima Driouech:** writing – review and editing. **Kristina Fröhlich:** writing – review and editing. **Javier García-Serrano:** conceptualisation, writing – review and editing. **Silvia Terzago:** writing – review and editing. **Veronica Torralba:** writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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