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EDITED BY
Veysel Turan,
Bingöl University, Türkiye

REVIEWED BY
Susan Kay,
Plymouth Marine Laboratory, United Kingdom
Charles Galdies,
University of Malta, Malta
Goran Trbic,
University of Banjaluka,
Bosnia and Herzegovina

*CORRESPONDENCE
Alba de la Vara
✉ adelavara@kveloce.com

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Co-creation of a scalable, climate service tool for the sustainable management of key blue economy sectors in the Spanish Mediterranean coast

Alba de la Vara[1]*, William Cabos[2,3], Mireia Ferri[1] and Maite Ferrando[1]

[1]Kveloce (Senior Europa S.L.), Valencia, Spain, [2]Resources and Environment, Henan Polytechnic University, Jiaozuo, China, [3]Department of Physics and Mathematics, University of Alcala, Alcala de Henares, Spain

The Mediterranean region is experiencing rapid warming, outpacing the global average, and is frequently impacted by extreme weather events like heatwaves and heavy precipitation. Climate models project an increase in the frequency and/or intensity of these events, which pose a significant risk of negative socio-economic impacts—particularly in the Western Mediterranean regions, such as the Spanish Mediterranean coast. Negative socio-economic impacts affect to a greater extent climate-exposed sectors such as the blue economy, which is defined as the economic activities associated with seas and oceans. Therefore, the development of climate service tools tailored to the needs and expectations of potential end-users from these sectors is crucial. This manuscript details the hybrid methodology adopted for the creation of the ECOAZUL-MED climate service tool, as well as its interface and main functionalities. The tool offers stakeholders from aquaculture, fisheries and coastal tourism along the Spanish Mediterranean coasts, for the first time, climate information from air-sea coupled simulations from the Med-CORDEX initiative to promote evidence-based decision-making regarding adaptation. Our work highlights the relevance of using bottom-up and participatory approaches combining quantitative and qualitative methodologies to generate tailored climate service tools adapted to the local context. Stakeholders' feedback, compiled through focus groups, workshops and questionnaires presented in this manuscript, was key to setting the contents of the tool and its final interface. Insights that emerge from this work allow us to highlight the importance of using participatory approaches to reinforce the long-lasting use of climate tools as they are designed based on stakeholders' inputs, and to propose this methodology to be applied in other contexts to build sustainable climate tools.

KEYWORDS

climate service tool, climate modeling, co-creation, climate change, future projections, climate adaptation, Spanish Mediterranean coast

1 Introduction

Human activities have influenced the Earth's climate in a continuous and unequivocal way since the industrial revolution (IPCC, 2021). The increasing volume of greenhouse gasses emitted into the atmosphere, together with changes in land-use (e.g., deforestation), have driven a significant increase in the global surface temperature, as well as changes in other

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meteorological parameters such as precipitation. The effects of climate change are particularly evident in the Mediterranean region, which is regarded by the scientific community as a climate change hotspot (Tuel and Eltahir, 2020) because it warms faster than the global mean and is frequently affected by extreme weather events, e.g., heatwaves, heavy precipitation (Scoccimarro et al., 2016; Rainaud et al., 2017; Darmaraki et al., 2019; Khodayar et al., 2021). Currently, climate models—the main tool available to date to study the future climate signal—project an increase in the frequency and/or intensity of these extreme events (Darmaraki et al., 2019; IPCC, 2019; Molina et al., 2020; Gutiérrez-Fernández et al., 2021; Miró et al., 2021).

Therefore, climate change can potentially pose negative impacts on a wide range of socio-economic activities, particularly in climate-exposed sectors (IPCC, 2023). This is well exemplified in the heavily populated Spanish Mediterranean coasts, in which the blue economy, defined as those economic activities associated with seas, oceans and coasts, represents an essential source of wealth and prosperity, as it provides opportunities for growth, employment and investment (Ruiz-Chico et al., 2020; Garza-Gil et al., 2021; Mejjad et al., 2022). Aquaculture, fisheries and coastal tourism are relevant sectors of the blue economy due to their contribution to social and economic development along the Spanish Mediterranean coast. According to the Spanish Aquaculture Business Association (APROMAR), the aquaculture production in Spain was 326,520 tons and had a first-sale value of 760.7 million euros in 2022.[1] Also, Spain was the European Union Member State with the largest aquaculture production in 2021 (271,060 tons), with 23% of the total, according to the Food and Agriculture Organization of the United Nations (FAO). The Spanish fishing fleet represents 24.4% of the total capacity of the European fleet and was made up of 8,657 vessels in 2022, based on data from the Spanish Ministry of Agriculture, Fisheries and Food.[2] According to the Spanish National Statistical Institute (INE), tourism activity reached in 2023 the 12.3% of the gross domestic product (GDP)—a contribution comparable to that of pre-pandemic times—which was, in turn, 0.9 points higher than in 2022.[3] In this context, the implementation of adaptation measures to potential negative socio-economic impacts of climate change is key to promote the sustainable development of these three key sectors of the Spanish blue economy. The possibilities for adaptation are many, ranging from technological innovations to changes in protocols and early warning systems for extreme events, the improvement of risk management, insurance options or the conservation of biological diversity, among others (Toimil et al., 2020).

Adaptation strategies must be built upon solid scientific knowledge regarding the future climate signal, enabling effective policies and practices by public administrations and entities that operate in implied sectors. In this context, climate service tools constitute an excellent way to bring coherent, solid, scientific-based climate information to stakeholders, promoting an efficient adaptation (Matsaba et al., 2020). Several key initiatives offering future climate information in the Mediterranean region include, for instance, the OCLE project (de la Hoz et al., 2018). This Open Access Database on Climate Change Effects on Littoral and Oceanic Ecosystems is an open access observatory for all the regional European seas that merges meteo-oceanographic data and presences of marine species, with the objective of facilitating the scientific community's assessment of the past, present and future distribution of coastal communities and ecosystems. Information offered derives from global climate simulations from the 5th phase of the Coupled Model Intercomparison Project CMIP5 (Taylor et al., 2012), which are quality controlled and statistically downscaled and include, e.g., sea-surface temperature, significant wave height, nitrate, salinity, wind speed etc. Projection data include both the near-term (2040–2069) and the long term (2070–2099) for the RCP (representative concentration pathways) 4.5 and RCP8.5 with a seasonal and monthly time frequency. Another example is the ATLAS-PRO, which compiles present and future of ocean aquaculture in Spanish sovereign waters. To that end, this repository provides information regarding the opportunity of cultivation of commercial species (fish and algae) by jointly considering the biological suitability of the species, the structural suitability of the cage and the operational suitability for operation and maintenance activities. Analyzed variables derive from global climate simulations from CMIP5, which are quality controlled and statistically downscaled as in de la Hoz et al. (2018). Variables studied include the sea-surface temperature, sea-surface salinity and photosynthetically active radiation. Projections cover the 2070–2,100 time period and the RCP8.5 scenario. Another interesting source is the scenario viewer from AdapteCCa, which offers atmospheric data (temperature and precipitation, as well as derived indexes) over land from EUROCORDEX simulations (Jacob et al., 2014) nested in climate projections from CMIP5. The offered domain covers Spanish territories: mainland Spain, the Balearic Islands, Ceuta and Melilla. Projection data include the near (2011–2040), medium (2041–2070) and long (2071–2,100) term future for the RCP4.5 and RCP 8.5 with a seasonal and monthly time frequency.

Importantly, for climate service tools to be effective, the local context must be considered all over the development of the tool to ensure that it is tailored to the expectations, needs and capacity of final users in understanding and using information (van der Horst et al., 2022). User knowledge and needs should set the basis of the climate service requirements to enable effective information uptake its use. The active participation of potential end users through co-creation strategies is key to developing tools that respond to their needs. The general objective of this manuscript is twofold. On the one hand, to describe the methodology adopted for the creation of the ECOAZUL-MED climate service tool, available at https://ecoazul-med.com/en/. On the other hand, to showcase its final interface and main functionalities. This public climate service tool provides relevant future atmospheric and oceanic information to increase stakeholder literacy and awareness, promoting an effective adaptation of the aquaculture, fisheries and coastal tourism sectors in the Spanish Mediterranean coasts. The methodology adopted for its development combines quantitative and qualitative research, which allows us to consider the needs and interests of regional stakeholders, ensuring that the co-created tool meets the expectations and needs of final users. The tool offers decadal information for the 2025–2064 period, assuming RCP4.5 and RCP8.5 climate scenarios, paying special attention to extreme weather events with the capacity to cause severe socio-economic damage such as heatwaves and heavy precipitation. The climate data contained in the tool derives, for the first time, from a set of high-resolution simulations from a regional air-sea coupled climate

1 https://apromar.es/wp-content/uploads/2023/10/Aquaculture_in_Spain_2023_APROMAR.pdf

2 https://www.mercasa.es/alimentacion-en-espana-2023-pesca-acuicultura/

3 https://www.ine.es/dyngs/INEbase/en/operacion.htm?c=estadistica_C&cid=1254736169169&menu=ultiDatos&idp=1254735576863

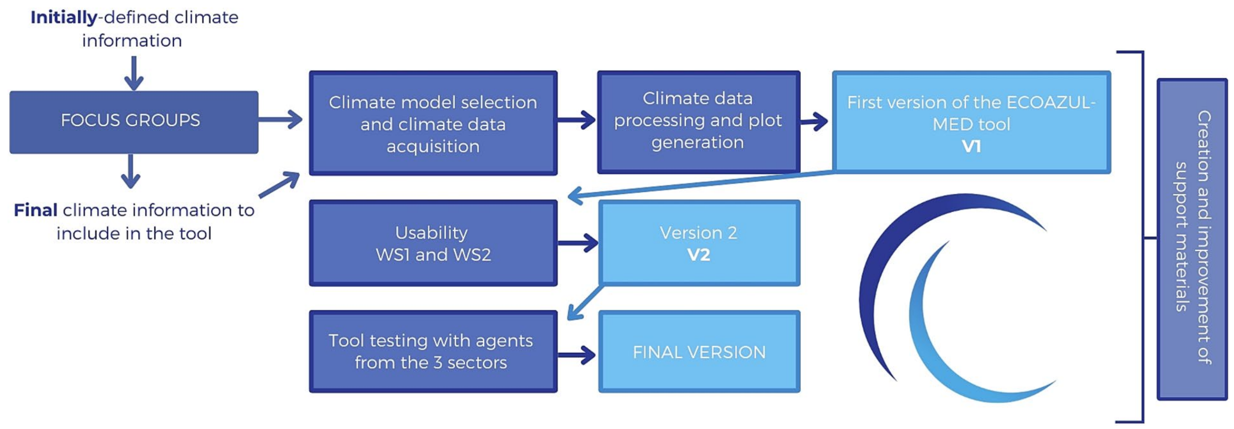

FIGURE 1
Steps for the creation of the ECOAZUL-MED climate service tool. Note that the creation and improvement of support materials was transversal and took place from the beginning until the end of the project. WS, workshop.

model ensemble from the MedCORDEX modeling initiative (Ruti et al., 2016).[4] The added value of the ECOAZUL-MED tool compared to presented services lies in three pillars: (i) Use of high-resolution, air-sea coupled, regional climate models, which makes downscaling dynamic and coherent from a physical point of view, which does not occur when global models are used and the downscaling is statistical, or when only regional atmospheric or oceanic models are used for downscaling. In the Mediterranean region, due to complex air-sea-topography interactions, the use of regional air-sea coupled simulations is key to dynamically downscale climate signal CMIP; (ii) Use of oceanic and atmospheric variables (over land); (iii) Consideration of extreme weather events, over land and the sea, with the capacity to cause severe socioeconomic damage such as heatwaves. The manuscript is structured as follows. In Section 2, the methodology used to generate the tool is presented. In Section 3, Results, the final interface and functionalities of the ECOAZUL-MED climate service tool are described. In Section 4, a Discussion and Conclusions are offered. This work has been produced in the context of the project ECOAZUL-MED (PTQ2020-011287) and is part of the Med-CORDEX initiative (see Footnote 4), supported by the HyMeX program.[5]

2 Methodology

The development of the ECOAZUL-MED climate service tool is based on the combination of quantitative and qualitative methodologies. The quantitative approach involved downloading and processing the climate data for the tool, as well as the creation of visual plots. The qualitative methodology required a strong participatory approach, involving stakeholders throughout the project's duration in activities such as focus groups, questionnaires and workshops, to ensure a tailor-made, and co-created tool that meets the expectations and needs of final users. The qualitative methodology was essential for the creation of the ECOAZUL-MED tool, particularly to integrate the relevant social, economic and contextual characteristics. This makes the final product more robust and will therefore facilitate more effective decision making (Colantonio, 2009). The co-design of the ECOAZUL-MED climate service involved the steps presented in Figure 1.

2.1 First version of the ECOAZUL-MED climate service tool

2.1.1 Literature review for an initial selection of information for the tool

As a preliminary step for the development of the ECOAZUL-MED climate service tool, an extensive literature review was conducted to assess the state of the different sectors in the current context of climate change and to provide a first approximation of the preliminary information to include in the climate service tool. Based on this review, we concluded that open-sea aquaculture production is highly determined by sea-surface temperature (SST). An increase in SST can affect the growth rates of commercial species or introduce changes in their diet (Poloczanska et al., 2009; Martínez-Cubillo et al., 2021). When the increase in SST is substantial and, in addition, sustained over time, as occurs during marine heatwaves (Perkins, 2015; Darmaraki et al., 2019), these effects are exacerbated, and species are subjected to greater thermal stress. In this context, it is important to highlight that climate projections indicate an increase in the frequency, duration, spatial extent and intensity of marine heatwaves in the future (IPCC, 2023). Furthermore, high temperatures favor, and will continue to do so in the future, the proliferation of bacteria and parasites capable of introducing diseases into commercial species, especially in the summer, when SST reaches the highest levels (Cascarano et al., 2021). This could lead to an increase in the use of antibiotics to prevent stock loss. Furthermore, high temperatures favor the development of algal blooms, which deteriorate both the quality of the water and the structures of the facility (biofouling), potentially making a greater use of biocides necessary (Fabri-Ruiz et al., 2024). In turn, alterations in the marine currents can have negative effects on the installation itself and the surrounding areas. On the one hand, an increase in hydrodynamics could favor the deterioration of the installation or even the breakage of cage nets, causing possible escapes

4 https://www.medcordex.eu/
5 www.hymex.org

and loss of stock. On the other hand, a reduction in hydrodynamics could lead to an increase in the accumulation of waste from cultivated living organisms, deteriorating the quality of the waters and the surrounding seabed. Also, changes in precipitation, whether due to excess or deficiency, will lead to fluctuations in salinity and water quality, which could have negative effects such as a reduction in the reproductive capacity of the cultivated species (Maulu et al., 2021).

Regarding fisheries, in the Mediterranean Sea, climate change has already caused evident changes in the distribution and abundance of commercial fish stocks (Darmaraki et al., 2019; IPCC, 2019; Ragheb, 2024). Changes in current systems or an increase in sea temperature could cause a displacement of commercial species to other areas where environmental conditions are more favorable (e.g., less thermal stress, especially during marine heatwave episodes). This could imply changes in the usual fishing areas of certain commercial species, changes in fuel consumption, fluctuations in total catches and variations in product prices. In more extreme cases, it has been observed that during heatwaves, anomalous SST values, together with toxic algal blooms, such as *C. coarctatus*, have led to mass mortality events of fish and other marine species, as occurred in Australia in 2013 (Roberts et al., 2019), which generated significant economic losses.

As to tourism, coastal areas are characterized by their great appeal to the "sun and beach" tourism industry, which represents a major part of the economy in coastal countries. Factors such as an increase in air temperature or environmental humidity have a direct impact on thermal stress and the emergence of new diseases in coastal areas induced by species with subtropical affinities (Neira et al., 2023). Both aspects have obvious health and economic impacts, as they are perceived as negative elements when choosing a holiday destination. In particular, an increase in temperature enhances the risk of cardiovascular, respiratory and cerebrovascular diseases, especially in children and people older than 65 (Basu, 2009; De Vita et al., 2024; Achebak et al., 2024).

Insights from this review allowed us to propose the preliminary information to be included at the tool, which could be of interest for the 3 sectors: (i) Ocean component: SST, ocean currents, marine heatwaves and (ii) Atmospheric component: daily maximum 2-m air temperature (T2MAX), relative humidity of the air and atmospheric heatwaves. This information was subsequently expanded taking into account stakeholders' feedback in the focus groups described in the following phase.

2.1.2 Focus groups: participatory selection of climate information to be shown in the tool

To test the relevance of the proposed climate information and detect any other information to be included in the ECOAZUL-MED tool, a series of focus groups were organized. We conducted four online focus groups with relevant stakeholders from the target sectors in the area of interest (aquaculture, fisheries, coastal tourism). The actors involved were found after a comprehensive mapping exercise, which included 16 or more stakeholders per sector. They were contacted by e-mail and phone, being phone calls more effective for a positive response. For the mapping, the following profiles were included: (i) practitioners, (ii) public administration, (iii) academia, (iv) NGOs, ensuring gender balance and spatial coverage. Finally, participating profiles included 10 males and 10 females from all regions covering the Spanish Mediterranean coast (Catalonia, Valencian Community, Murcia, Andalusia and Balearic Islands), as detailed in Figure 2. Focus groups, conducted between February and March 2022, had a duration of 1 h and 5 participants each. There was a specific focus group per sector—including practitioners, managers and other relevant stakeholders. An additional focus group brought together researchers from all three sectors. The objectives of the focus groups were: (i) to spot difficulties in the development of the activities in each sector; (ii) to identify barriers and opportunities derived from climate change for each sector; (iii) to comment on known adaptation measures to climate change for each sector; (iv) to discuss which additional information could be included in the climate tool. To that end, the following information was discussed, being 10 min dedicated for each question (Q): *Q1: What do you consider to be the greatest difficulties you face in developing your activity?; Q2: What barriers and "opportunities" could climate change pose to the development of your activity?; Q3: Do you think that initiatives for adaptation to climate conditions are important? Why? Are there any that you would like to highlight?; Q4: Do you know any initiatives to improve the environmental sustainability of your sector?; Q5: Are there any applications of the web tool that you consider relevant? Is there additional information that could be interesting to incorporate into the tool?* The inputs from stakeholders were analyzed following the thematic blocks, obtaining key insights to feed the multi-sectorial tool. While detailed responses obtained in the different focus groups can be found in the Supplementary material, regarding Q5, they mentioned, e.g., salinity, precipitation, heavy precipitation, nutrients etc. Suggestions from stakeholders were prioritized according to the resources available in the project and several additions were incorporated into the tool consistently. The final information included in the tool is shown in Table 1.

2.1.3 Climate model selection, climate data acquisition, processing and plot generation

Presently, climate models are the main tool available to perform future climate projections. Therefore, the analysis of variables derived from climate simulations allows us to get insight into the future climate signal and, in this case, to compile the information that will be shown through the climate service tool. In this sense, the first step before the acquisition of the climate variables derived from climate simulations for their subsequent analysis was to determine the model ensemble to be used. With regional purposes, such as this case, regional climate models are more adequate than global climate models due to their enhanced resolution, which is key to accurately reproduce the oceanic and atmospheric signal. Additionally, for Mediterranean coastal areas where air-sea interactions are known to play an important role, the use of air-sea coupled simulations, which are capable of providing a physically consistent signal in the oceanic and atmospheric component and better represent their interactions and feedback, is key. Therefore, in this study we used a model ensemble of regional atmosphere–ocean coupled climate model simulations from Med-CORDEX (Ruti et al., 2016), which has been used in Darmaraki et al. (2019). Particularly, from the 6 regional air-sea coupled models used in Darmaraki et al. (2019), 2 of them were not selected due to short or lack of a spin-up period (see details in Supplementary Table S1). Climate projections were conducted assuming the RCP8.5 and 4.5 IPCC radiative scenarios. These were chosen because (i) the RCP8.5 is the most radiative and thus extreme one, since this does not consider climate policies to limit carbon emissions, (ii) while the

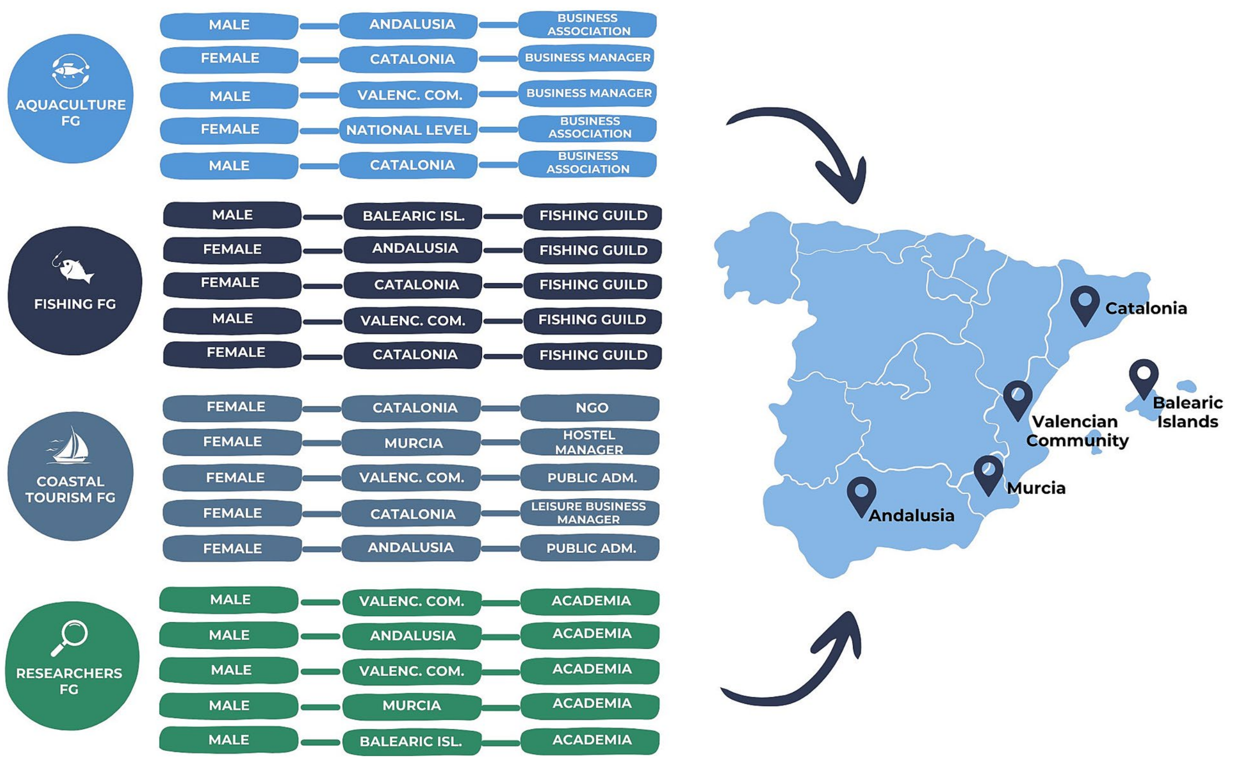

FIGURE 2
Profiles of participants of the different focus groups conducted in the ECOAZUL-MED project. FG, focus group.

RCP4.5 stabilizes radiative forcing at 4.5 W/m^2 due to the implementation of climate policies. It is worth noting that these scenarios do not diverge significantly until mid-century, so any differences seen in outputs for the first two decades could be due to internal model variability rather than the climate scenario. The other available scenario, RCP2.6, was not selected because it was only used in one of the ensemble models. All models use boundary conditions from CMIP5[6] given that, to date, an ensemble of regional air-sea coupled simulations using boundary data from CMIP6 is not available.

The subsequent acquisition of the climate variables was partly done through the Med-CORDEX server and partly via the corresponding research groups, depending on data availability. All the implied research groups agreed to provide the data with the purposes of the creation of the tool. Once all climate data were acquired, a thorough review of the data files was done to ensure that they were complete, they did not contain corrupted data, and that data structure was correct. Also, coherent units were given to the different climate variables, respectively. While the performance of the models has been individually validated in dedicated papers (see Darmaraki et al., 2019; Supplementary Table S1), we aimed to identify possible model outliers for the studied variables (maximum daily 2-m air temperature, precipitation, relative humidity, sea-surface temperature, sea-surface salinity and marine currents) within the models. Following de la Hoz et al. (2018), we use the mean square error (MSE) between the historical data and the reference period of the regional climate model simulations, as well as the standard deviation (std). In particular, the MSE between the historical model data and the same period for (i) the reanalysis ERA-5 (Hersbach et al., 2020) for atmospheric data and (ii) the reanalysis Glorys (Lellouche, 2021) for the oceanic data, was calculated for all variables. While for the atmospheric data we used 1976–2005, coinciding with our control time period, for the oceanic data we took the 1993–2005 interval, given that Glorys data is only available from 1993. An outlier is defined as the regional models for

TABLE 1 List of downloaded climate variables (left column), as well as climate information included in the ECOAZUL-MED (right column).

Downloaded variables	Information derived
Sea-surface temperature	Sea-surface temperature
	Marine heatwaves
Sea-surface salinity	Sea-surface salinity
u-component of the ocean currents	Module and direction of the ocean currents from the surface to 1,000 m depth
v-component of the ocean currents	
Relative humidity	Relative humidity
Maximum 2-m air temperature	Maximum 2-m air temperature
	Terrestrial heatwaves
	Number of days with summer conditions
Precipitation	Precipitation
	Heavy precipitation

White grid cells correspond to information planned to incorporate in the early stages of the project, while cells in gray to variables and derived information added in response to the stakeholder's suggestions in the focus groups.

6 https://wcrp-cmip.org/cmip5/

which the value of the MSE is out of the limits defined by the MSE ensemble mean ± the std. of the MSE of all models times 1.5, as shown in Equation 1 (see Chaudhary and Lee, 2016):

$$MSE\,model \leq MSEmean + MSEstd \times 1.5. \quad (1)$$

For all the ensemble members the criteria was met, which means that none of them is out of range for the selected variables (see Supplementary material). Model data were subsequently interpolated from their original grids, with a varying horizontal resolution (Supplementary Table S1), into a common regular grid of a slightly higher horizontal resolution (circa 10 km), as explained in de la Vara et al. (2024). This allows us to have a common grid and to operate with data from the ensemble, as well as to achieve an appropriate resolution to provide climate services (e.g., de la Hoz et al., 2018). Time resolution was set to 1 day for all variables, except for marine currents, in which values were monthly. The timing of the control, as mentioned above, covers the 30-year period before the start of the future projections in CMIP5. The future time period covers the next 40 years (near future), which is adequate for climate services purposes. Once all the climate data files were ready for subsequent analyses, the following calculations for the model ensemble were done using the Climate Data Operators[7] for the control (1976–2005) and future (2025–2064) time periods:

Estimation, for each climate variable and model simulation, decadal averages for the future time period. This thus involved the 4 decades included in the defined future time period (2025–2064: 2025–2034, 2035–2044, 2045–2054, 2055–2064).

- Calculation, for each climate variable and model simulation, time averages for the control time period (1976–2005).
- Estimation of the decadal changes in future climate with respect to the climate of the control time period. The decadal changes in future climate were calculated for each variable and model simulation, individually. To make the information more valuable for stakeholders, decadal future changes with respect to the control period were computed on a seasonal and monthly basis. The calculations were done considering all models (ensemble mean) to have a more robust climate signal.
- Assessment of the robustness of the results. To this end, the number of models from the ensemble that provided a future change of a positive sign was computed, since this provides us information regarding the consistency in the sign of the projection among climate models.

In the case of post-processed climate data, i.e., heavy precipitation, marine and oceanic heatwaves and summer days, the above-mentioned steps were followed after their initial calculation. The criteria to define them was:

- Atmospheric heatwaves were defined according to the Warm Spell Days Index, HWFI (Almazroui et al., 2021), defined as the number of days with at least 6 consecutive days in which the maximum daily 2-m air temperature (T2MAX) exceeds the 90th percentile of the T2MAX in a 5-days moving window during the control (1976–2005).
- Marine heatwaves were computed as the number of days with at least 5 consecutive days in which the sea-surface temperature (SST) exceeds the 90th percentile of the SST in a 5-days moving window during the control (1976–2005).
- Heavy precipitation conditions were defined as single daily events with a precipitation amount greater than the daily 90th percentile computed for the control (see, e.g., Kostopoulou and Jones, 2005).
- Summer days were defined as those days in which the daily maximum 2-m air temperature was equal or greater than 25°C (Indices | Climdex).

Afterwards, the corresponding plots—to be subsequently included in the ECOAZUL-MED climate service tool—were generated using The Generic Mapping Tools.[8]

2.1.4 Content creation

During the project, a series of support documents were created. These include the user's manual, dissemination and scientific materials, as well as other resources. Note that all materials were created in both Spanish and English, to foster the impact of the project. While the creation process of most of the materials was quite straightforward, the material used as a basis for the creation of two dissemination reports required to perform a stakeholder assessment of potential socio-economic impacts of climate conditions derived from our tool. Below we describe the methodology used to perform such an analysis, being the content of these two reports described in Section 3.3 (Results).

In this respect, once all calculations were done and figures to be embedded into the tool were ready, potential socio-economic impacts derived from the climate conditions from our tool were participatively assessed by stakeholders. In order to gather opinions of stakeholders from the 3 sectors in the Spanish Mediterranean coasts regarding potential socioeconomic impacts of future climate conditions derived from our tool, a series of online questionnaires were designed using the program Jotform.[9] To that end, the Delphi method was used—a projective technique that consists of questioning agents with the help of successive questionnaires in order to reveal convergences of opinions and deduce eventual consensus (Crisp et al., 1997). Questionnaires were sent by e-mail to all stakeholders involved in the focus groups, as well as others, until saturation in responses. The surveys included the participation of 13 agents, of which 4 were linked aquaculture, 4 to fisheries and 5 to coastal tourism. Of these, 10 completed the second-round survey, which was sufficient to understand the divergences in the results obtained (namely due to misunderstanding of questions) or to reach a consensus.

The first-round questionnaire, presented in the Supplementary material, was general and common to all sectors, although participants were asked to specify the sector to which they were linked in order to analyze the responses according to their profile. The questionnaire had two different blocks of questions: (i) First, a block where participants assigned scores to certain climatic

7 http://www.idris.fr/media/ada/cdo.pdf

8 https://www.generic-mapping-tools.org/

9 https://www.jotform.com

conditions based on their possible socioeconomic impacts (1: no negative impact expected, 5: expected to be significant). (ii) Second, an open answer block, in which participants explained the possible socioeconomic impacts associated with a series of future climatic conditions derived from our tool.

The questionnaires of the second round (one specific per sector) aimed to establish consensus on those issues for which there was discrepancy in the scores assigned in the quantitative block of the first questionnaire or, alternatively, to understand the reasons for such divergences. To do so, prior to the preparation of the second-round questionnaires, the answers given in the first-round questionnaires were analyzed in detail, considering that there was discrepancy in cases where the scores given to the impacts of a certain climatic condition presented a difference of 3 or more points. In the second round, only questions for which there was disagreement in the first round were taken into account for each of the sectors. Stakeholders were asked to score them again, explaining the reasons for their choice. In addition, an extra open question was added on the possible impact of climatic conditions on aspects such as employment and the gender gap.

2.2 Second version of the ECOAZUL-MED climate service tool

2.2.1 Usability assessment through participatory workshops

Once the initial interface of the ECOAZUL-MED tool was ready, two workshops with a general audience took place between February and March 2024. The aim of these workshops was to ensure that the tool is usable, i.e., the information included in the tool was presented in a friendly and useful way, considering aspects such as the interface, the content, the process of downloading climate information, and the structure of the information downloaded. The 1st workshop was physical (Sede Universitaria de la ciudad de Alicante, Alicante, Spain. February 2024) and conducted within a climate change dissemination event for all publics, organized by the University of Alicante. The diffusion of the event was done by the University of Alicante through social media,[10] local radio, press etc. and no pre-registration was required. The 2nd workshop was hybrid (Kveloce main office in Valencia, Spain, and online) and organized by the principal investigator of the ECOAZUL-MED project. It involved staff from Kveloce (the company where the tool has been developed), which includes a variety of academic backgrounds (e.g., communication, economics) and researchers in different fields (e.g., sustainability, soils, biomedicine). Most of the participants were from the Mediterranean region (Valencian Community, Murcia) and had higher education profiles, e.g., university level. Overall, the 1st workshop was aimed at potential general users of the tool, while the 2nd one at users with a higher education level—which is likely a profile closer to final users of the tool (e.g., technicians, researchers). The workshop agenda included the following blocks: (i) an initial presentation of the ECOAZUL-MED project; (ii) presentation of the ECOAZUL-MED website in which the climate tool is embedded;[11] and (iii) feedback session. In both workshops the same version of the website was shown, and the feedback session was launched using the program Mentimeter[12] which allows us to perform on-site surveys in real time. Attendants were anonymously asked to scan a QR code and use their smart phones/laptops to respond to the performed queries. While for the 1st workshop 12 people responded to the questionnaire, it is noteworthy that not all the attendants replied, likely due to the digital breach. Of them: 9% were related to tourism; 36% to climate and 55% to other sectors. All participants of the 2nd workshop, 15 in total, responded to the survey. Questions raised were: *Q1. Do you think it is easy to download data from the tool?; Q2. Do you consider that the climate information provided is relevant for the management of your sector?; Q3. Do you think the structure of the graphs is easy to understand?* Potential answers were closed and included: (a) yes; (b) yes, but it could be improved; (c) not much; (d) no; (e) no answer. Additionally, by the end of the workshop, participants were also invited to respond to the following open question: *Q4. Is there anything you would like to change in the structure or content of the website and the tool?* Responses to these questions entailed, for instance, higher resolution data to allow the visualization of coastal areas results, a connection between climate scenarios and impacts (indicators), more help in the selection menu, increase the font size to ensure accessibility, include a video-tutorial etc. This feedback allowed us to improve the tool and make it complete and more intuitive, e.g., more help buttons were added next to the selectors of the menu, other resources and links added, a video-tutorial was created and included to facilitate the downloading process, the font size of the text was increased to foster inclusiveness. Detailed responses to all questions can be found in the Supplementary material.

2.3 Final version of the ECOAZUL-MED climate service tool

2.3.1 Tool testing with agents from the 3 sectors

Once the collected suggestions were incorporated, the updated version of the tool was sent to agents from the 3 sectors to collect their feedback. The aim of this phase was to ensure usability for potential end users, and gather possible errors, improvements etc. for the final version of the tool. To that end, an online questionnaire, accompanied by the link of the ECOAZUL-MED website, was sent by e-mail to stakeholders identified during the project's life (the ones attending the focus groups and some additional ones until saturation in responses). A total of 14 anonymous agents from the 3 sectors (5 from aquaculture, 3 from fisheries and 6 from coastal tourism) participated in the online questionnaire. This was conducted with Jotform and had the same 3 first questions as the questionnaire performed in the two previous workshops (see *Q1, Q2* and *Q3* above). Additionally, the following open questions were raised, to get more insight regarding their view on the tool: *Q1: Is there anything you would like to change in the structure or content of the website and the tool?; Q2: In your day-to-day work, how could the climate tool help you and in what type of cases could it be useful?; Q3: In your day-to-day work, how could the climate tool help you and in what type of*

10 https://web.ua.es/es/actualidad-universitaria/2024/febrero2024/26-29/la-sede-ciudad-de-alicante-organiza-la-jornada-transformando-nuestro-futuro-desafios-y-soluciones-del-cambio-climatico.html

11 https://ecoazul-med.com/en/

12 https://www.mentimeter.com/

cases could it be useful? Stakeholder feedback, available in the Supplementary material, allowed us to improve, e.g., the "Documentation and other resources" section of the website, as well as to add captions to figures displayed in the tool. After this, the final version of the tool was ready (its interface and main functionalities are described in Section 3).

3 Results

In this Section we present the ECOAZUL-MED climate service tool, including its final interface and main features, as defined by the stakeholder inputs, as explained in Section 2.

3.1 The ECOAZUL-MED website

The ECOAZUL-MED website, in which the climate tool is embedded, can be accessed via https://ecoazul-med.com/en/. From this site, users have access to a general overview of the project, the climate service tool and accompanying documentation, as well as other related resources (Figure 3). Due to its open access nature, all users have access to all the functionalities of the tool, including downloading data and related documentation. From the main menu, users have access to 4 different tabs:

- **The project**: here, a general overview of the ECOAZUL-MED project is offered, including the objectives, involved sectors, study area, need of adaptation, methodology employed, added value of the project and the climate service tool.
- **The tool**: here users have access to the interface from which climate data can be downloaded in the form of plots. Detailed information about the tool will be given subsequently.
- **Documents and resources**: this section includes relevant documentation which has been created throughout the project and interesting resources for users. As to documentation, this has been organized in 3 distinct blocks: (i) user's manual, including an introduction to the project, an extensive description of the methodology, how to access the website, its content and a comprehensive description of the climate tool including how to download information, how to interpret the plots downloaded, relevant considerations and a glossary, among others; (ii) dissemination materials, including, e.g., a socio-economic impact report, a policy recommendations report, a case study to illustrate how to use the data from the tool in strategic planning of the Spanish tourist sector and a set of infographics; (iii) and scientific materials, with posters, papers etc. Regarding Resources, relevant links have been included for each of the sectors.
- **Contact**: here users can find a form and the details to contact the ECOAZUL-MED team.

3.2 The tool

Once users click on "the tool" button, the tool interface appears with 4 dropdown selectors to choose the desired criteria to download climate data (Figure 4):

- **Climate information**: this includes oceanic (SST, sea-surface salinity (SSS), ocean currents, marine heatwaves) and atmospheric (T2MAX, relative humidity, precipitation, heavy precipitation, atmospheric heatwaves, days with summer conditions) information.
- **Scenario**: users can select one of the 2 offered RCPs (RCP4.5, RCP8.5).
- **Time period**: it includes the time span 2025–2065, with 4 decades among which the user can choose (2025–2034; 2035–2044; 2045–2054; 2055–2064).

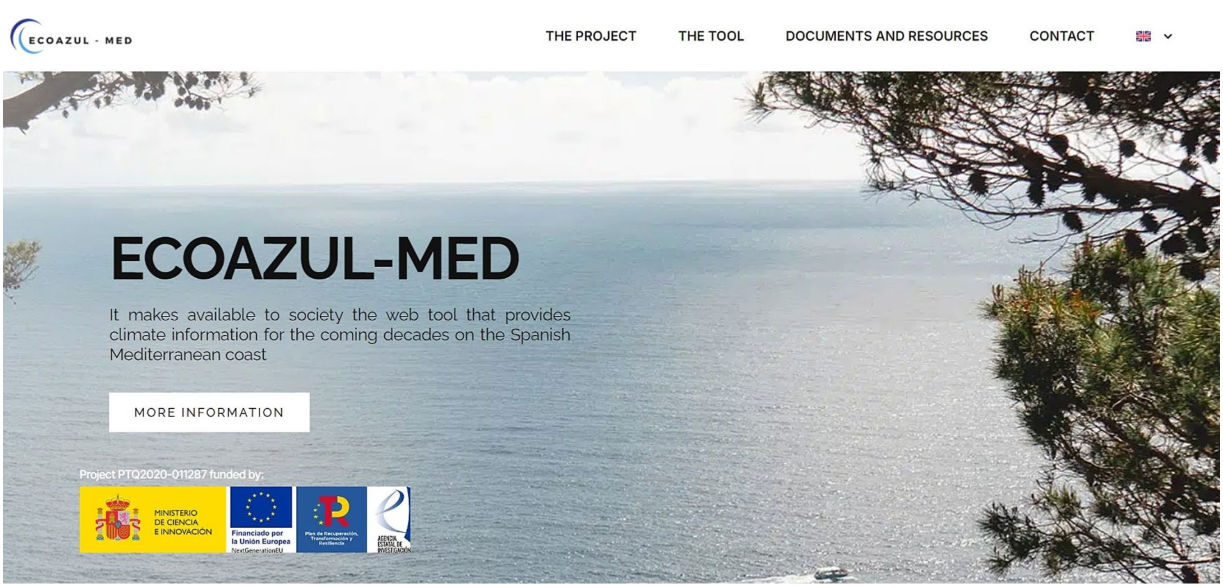

FIGURE 3
Interface of the ECOAZUL-MED project website.

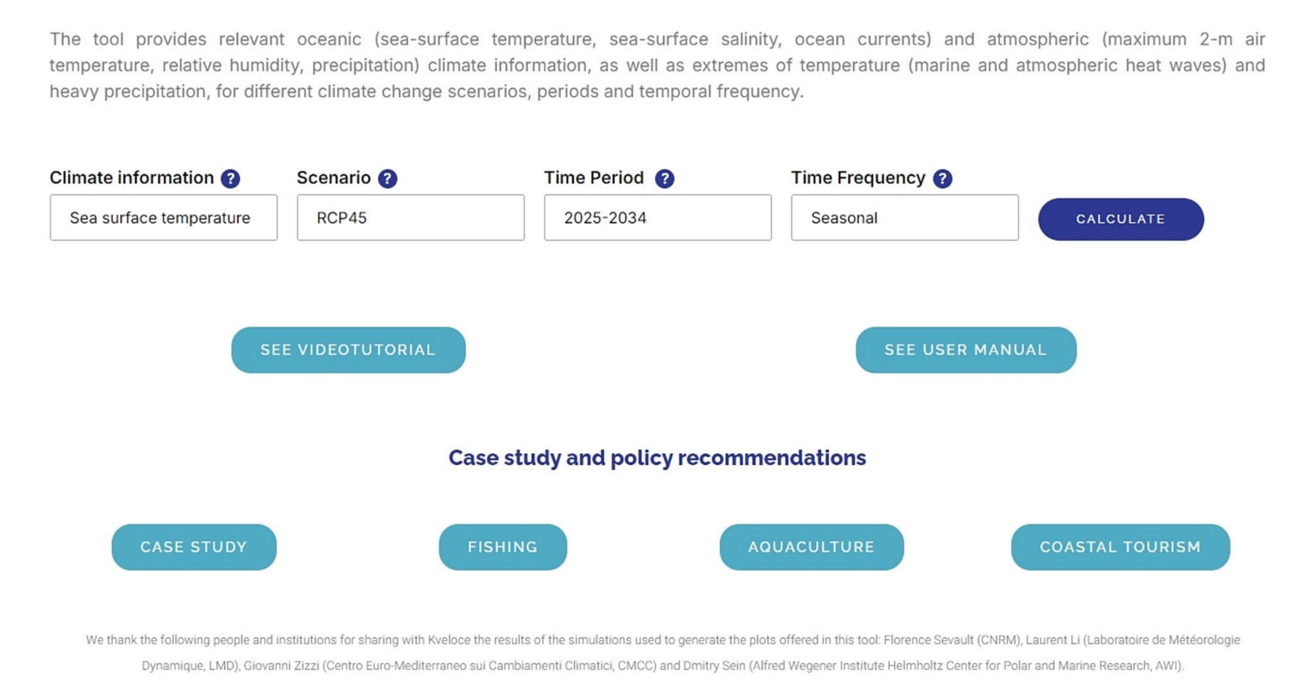

FIGURE 4
Menu of the ECOAZUL-MED climate service tool used to download data.

- **Time frequency**: seasonal or monthly.

Before downloading data, users are recommended to watch the "video-tutorial" and read the "User's Manual," accessible through the "tool" interface. When the desired selection has been made, users should click on the "calculate" button. Then, they will visualize a caption explaining the structure of the figure, a short summary with the selected information and a miniature of the plot. When clicking on "download," the corresponding plot(s) in PDF format will appear. Once opened, they can be visualized on the screen or downloaded. As stated above, atmospheric and oceanic climate data is offered for 2 different climate scenarios, 4 decades, and seasonal or monthly time frequency. To facilitate the understanding of the plots, e.g., seasonal or monthly cases, some examples are given below.

3.2.1 Seasonal frequency

Figure 5 shows, for the RCP8.5 scenario, in the first row, the seasonal average T2MAX for the control time period (1976–2005), which is a 30-year time reference to evaluate future changes. In the second row, the future seasonal change of T2MAX for the 2055–2064 decade with respect to the control period is given. This is calculated as future minus control values. Therefore, a positive sign indicates a future increase in T2MAX. In the third row, the number of models from the ensemble that project a future positive change is presented. This has been done following previous projects (e.g., SOCLIMPACT H2020),[13] and gives an idea of the uncertainty associated with the presented results. It is important to keep in mind that all calculations have been carried out taking into account the model ensemble presented in de la Vara et al. (2024). This means that, in the RCP4.5 scenario the ensemble is composed of 3 models, while there are 4 models in the RCP8.5. In this case, therefore, the orange color extended throughout the area of interest indicates that the 4 models of the ensemble project an increase in T2MAX. This indicates that, regardless of the season, the projected increase in T2MAX is robust. In the event that there is a decrease in the future values of some climate variables, results will be more robust when the number of models that project an increase are 0 (or closer to it).

3.2.2 Monthly frequency

Figure 6 is equivalent to Figure 5 but has been computed for the monthly case. In particular, Figure 6 displays results for the winter months (December, January and February). The user can also download the data for spring (March, April and May), summer (June, July and August) and fall (September, October and November) months.

3.3 Documents and resources

The ECOAZUL-MED website also hosts the users´ manual for the climate tool, as well as dissemination materials (reports, infographics) and scientific documents (papers, posters). Dissemination materials are intended to raise awareness and increase literacy regarding climate change and blue economy in the region, and widespread insights derived from our project that are accessible to potential end users, as well as a wider audience. Below, the main content of the dissemination materials (2 reports and a set of infographics), many of them generated using stakeholders' inputs, are described. While reports offer a comprehensive description of the results obtained, here, for brevity, we only concentrate on the main findings presented. All documents

13 https://soclimpact.net/wp-content/uploads/2020/03/D4.3-Atlases-of-newly-developed-hazard-indexes-and-indicators-with-Appendixes-Compressed.pdf

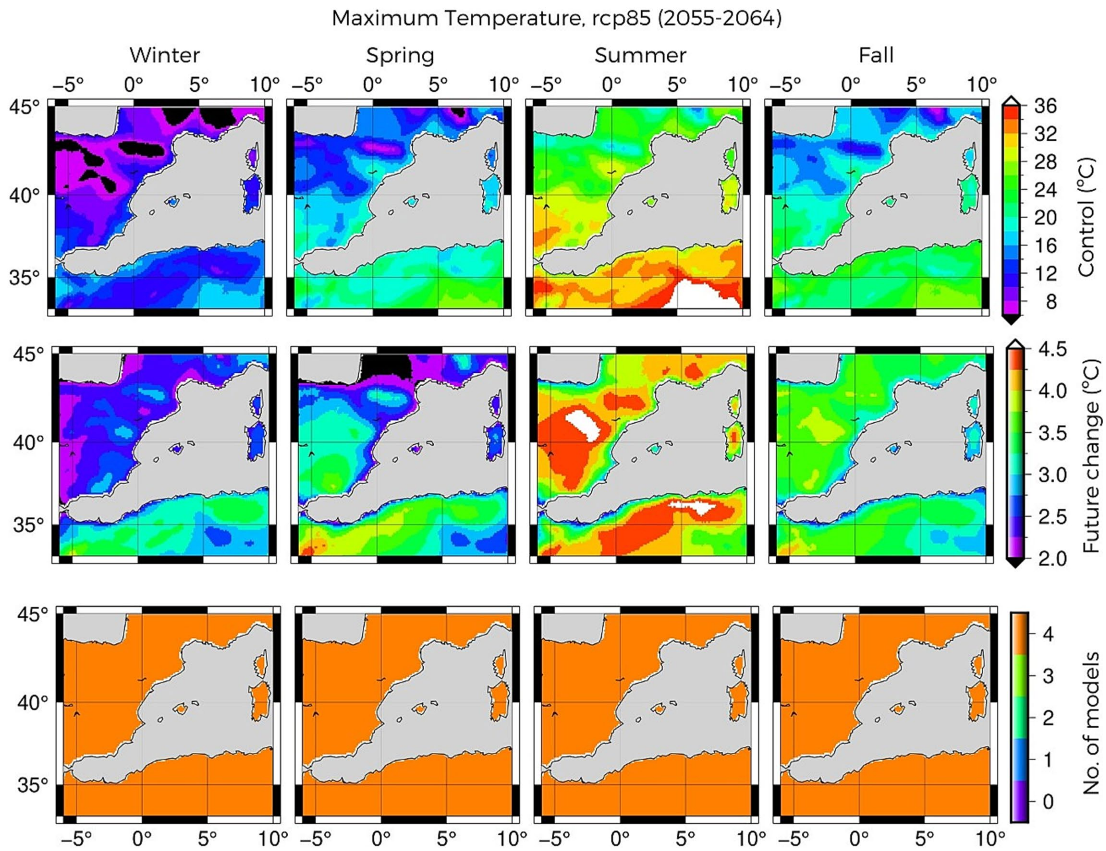

FIGURE 5
Example of a plot computed with a seasonal frequency derived from the ECOAZUL-MED tool. In this particular case, the figure shows seasonal information regarding the maximum 2-m air temperature (T2MAX) computed for the 2055–2064 decade. In our calculations, winter is defined by the months of December, January and February; Spring by March, April and May; Summer by June, July and August; Fall by September, October and November.

described below can be accessed through the Documents and Resources Section of the ECOAZUL-MED website.[14]

3.3.1 Report on socio-economic impacts derived from future climate conditions

This report compiles results from the stakeholder assessment on the impacts of climate conditions on their respective sectors performed using the Delphi method (see Section 2.1). Results from the analysis indicate that, for the **aquaculture** case, there are two factors with an average score equal to or greater than 4, which indicates that they are perceived as potentially harmful to the sector (see scores in the Supplementary material). These are the speed of marine currents and the increase in SST. For the **fisheries** sector, the change perceived as most detrimental is an increase of the SST. In addition to this factor, other changes perceived as potentially negative include (i) an increase of T2MAX—especially in summer; (ii) an SST rise; (iii) an increase in the number of days with heatwave conditions; (iv) an increase in the number of days with summer-like conditions in fall and spring; (v) changes in the SSS, and (vi) direction and speed of marine currents. For **coastal tourism**, an increase in summer T2MAX and in heatwave episodes, also during this season, are considered the climatic conditions that could have the greatest negative impact on the sector.

General insights that emerge from the surveys indicate that, for the **aquaculture** sector, the SST increase could, on the one hand, promote the growth of fish. However, on the other hand, it could alter the physico-chemical conditions of the water, affecting the ability of fish to metabolize and assimilate food. Additionally, the SST rise could increase pathogen populations, favoring infectious and parasitic diseases. Although it is difficult to assess the overall net effect, SST changes will impact aquaculture. Furthermore, changes in marine currents' velocity are perceived as a factor that could have negative socio-economic consequences. The impacts of climate on marine aquaculture are both direct (e.g., increase in sea temperature, hydrodynamics) and indirect (e.g., global impact on plant productions used in feed manufacturing, such as soybeans, corn, etc.). Therefore, an effort is needed to adapt the sector to the new climate conditions and make it sustainable over time.

As to **fisheries**, an SST increase could alter the distribution of species, enhancing or decreasing the abundance of populations, therefore complicating the proper management of resources. This would affect, e.g., species of bluefish that move in the surface layer of the sea, exerting a key control on the presence or absence of species such as mackerel, sardines, anchovies, and tunas. Other factors

14 https://ecoazul-med.com/en/documents-and-resources/

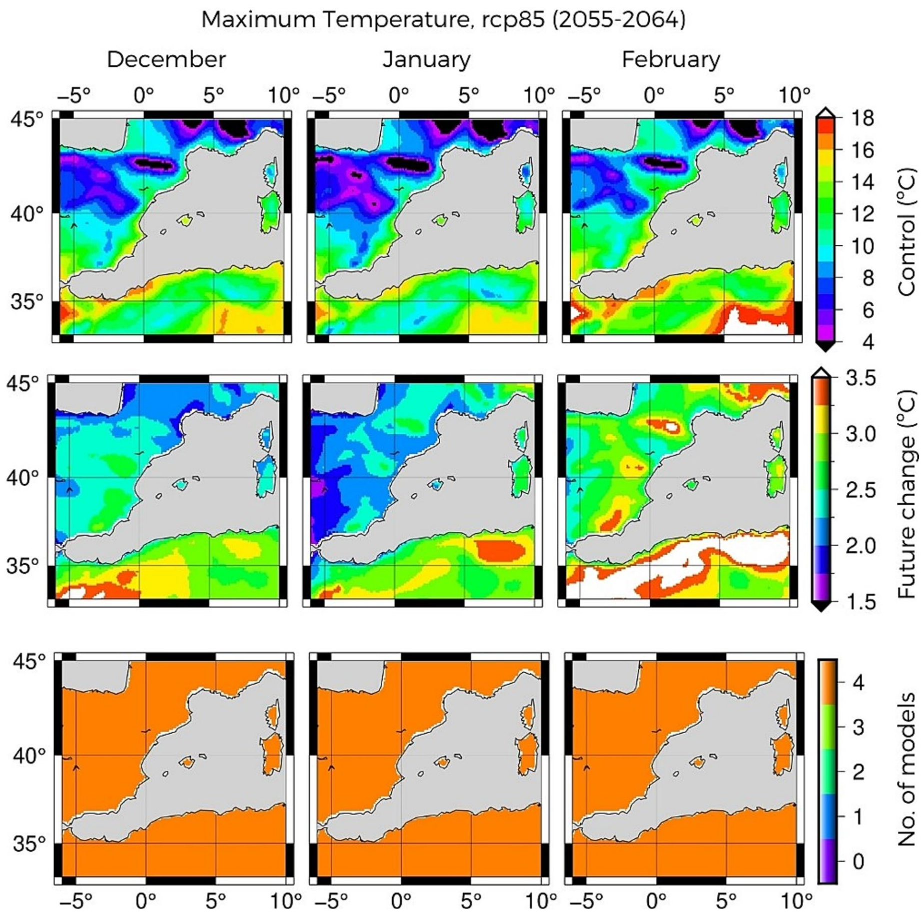

FIGURE 6
Equivalent to Figure 5, but created for the monthly case (December, January, February).

perceived as particularly negative are changes in marine currents' direction, velocity, or SSS. Although fishing depends on numerous factors (e.g., energy costs, consumption habits, competition, lack of generational turnover, or overfishing), climate change is affecting the species caught. This has favored, or disadvantaged (and will continue to do so in the future), fisheries depending on changes of species, having a direct impact on Mediterranean fisheries.

Regarding **coastal tourism**, T2MAX increase is perceived as negative since it could reduce thermal comfort, which, in turn, could decrease tourist influx in destinations affected by frequent and intense heatwaves. Under these circumstances, the use of air conditioning would increase, resulting in higher expenses, which is negative for the sector. Therefore, destinations should try to minimize negative climate impacts and "take advantage" of those aspects that could be "positive," such as the extension of the tourist season beyond summer. It is key that tourist destinations implement efficient adaptation measures to maintain the sustainability of the coastal tourism sector.

3.3.2 Report on policy recommendations

The main objective of this report is to provide local and regional agents scientific-based recommendations regarding adaptation of the aquaculture, fisheries and coastal tourism sectors to promote informed decisions and thus sustainable development. The report offers a summary of the main future climate conditions derived from our tool, as well as the possible socio-economic impacts of future climate conditions that emerged from the Delphi analysis (see previous sub-section). Based on a literature review and knowledge gained during the project, a series of sector-specific adaptation measures are proposed to avoid/minimize the potentially negative socio-economic impacts expected based on the Delphi analysis, taking into account the Quadruple Helix of Innovation (practitioners—professionals working on the sector, public administration, academia, citizenship; see Carayannis and Campbell, 2009). This allows us to adapt to the readers' profiles, enhancing the usability of the report.

While all details can be found in the corresponding report, some examples of adaptation measures proposed for the different sectors are provided:

- **Aquaculture**: (i) Practitioners: Selection of suitable locations from an environmental (including climatic aspects), technical, legal, and socio-economic perspective to enhance the success of cultivation; Utilization of cages and other infrastructures that are safer, more sustainable, and more resistant to strong hydrodynamics resulting from extreme weather conditions, e.g., heavy precipitation. (ii) Public administration: Promotion of responsible consumption, labeling, and new commercially viable species with greater tolerance to climate conditions; Intensification of phytosanitary monitoring of cultivated species to prevent diseases (iii) Academia: Intensification of efforts to generate tools enabling optimal site selection for cultivated species considering climatic and meteorological criteria; Enhancement of research aimed at closing the life cycle and cultivation of resilient species against climate conditions (iv) Citizenship: Flexibility in introducing new species into the diet that are more resilient to climate conditions; Responsible consumption of aquaculture products.

- **Fisheries**: (i) Practitioners: Adjustment of fishing efforts based on the biomass of stocks, which, in turn, may be influenced by climate conditions; Utilization of climate services tools or alert systems to anticipate future climatic or weather conditions, including extreme events to enhance activity planning; (ii) Public administration: Promotion of research and development to improve understanding of the causes of population changes, their new routes, etc., to properly manage stocks; Protection of key species from a socioeconomic perspective, such as *Posidonia oceanica*, which mitigates hydrodynamics, is a reproduction and breeding area, and acts as a CO_2 sink, among other services; (iii) Academia: Promotion of research and development to enhance understanding of the causes of population changes to properly manage stocks; Promotion of research to increase the selectivity of fishing gear and techniques; (iv) Citizenship: Flexibility in introducing new species into the diet that are more resilient to climate conditions; Responsible consumption of sea products.
- **Coastal tourism**: (i) Practitioners: Monitoring carbon and water footprint to reduce resource usage; Developing a well-planned tourist calendar and effectively communicating tourist events, promoting the activity during seasons other than summer. (ii) Public administration: Promotion of spatial planning in tourist destinations through sustainable and healthy urban planning that fosters energy rehabilitation, the design of public spaces with efficiency and sustainability parameters, the expansion of green spaces, the design of an efficient public mobility and the reduction of greenhouse gas emissions to mitigate climate change; Development of local and regional climate change adaptation plans to reduce potential negative socio-economic impacts derived from climate conditions. (iii) Academia: Development of climate service tools or alert systems that allow to anticipate extreme weather events; Development of Nature-Based Solutions—"actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits" (UNEA-5, 2022). (iv) Citizenship: Responsible consumption of resources in tourist destinations, such as energy and water; Preference for sustainable destinations.

3.3.3 Infographics

A series of infographics were created with communication purposes to illustrate key insights from the project regarding climate change, in general, and its potential effects on the 3 target sectors, in particular:

- One infographic, which offers a summary of the responses given in the 4 focus groups conducted at the beginning of the project.
- Three general infographics, one per sector, including: (i) the objective of the ECOAZUL-MED project, (ii) the justification of our area of study, (iii) some examples of how climate conditions could affect the sector, based on literature review and stakeholder responses from the focus groups, and (iv) how the tool can be of help.
- Three infographics with policy recommendations, one per sector, based on the insights presented in the Socio-economic impact assessment and Policy recommendations reports. These include: (i) the objective of the ECOAZUL-MED project, (ii) a summary of future climate conditions derived from our tool, (iii) a list of possible socio-economic impacts, (iv) adaptation measures for the Quadruple Helix of Innovation and (v) how the tool can help the sector.
- Three infographics, one per sector, regarding the implications of climate conditions on blue and green jobs. These compile: (i) a summary of future climate conditions derived from our tool, (ii) adaptation measures (the ones provided in the previous set of infographics), and (iii) implications of climate conditions for blue and green jobs, being green jobs defined by the International Labor Organization as "Decent jobs that contribute to preserve or restore the environment, be they in traditional sectors such as manufacturing and construction, or in new, emerging green sectors such as renewable energy and energy efficiency."
- One infographic showing a case study on strategic planning of the touristic sector created from results derived from our tool, based on de la Vara et al. (2024). This includes (i) the general objective of this project, (ii) future climate conditions derived from our tool for coastal tourism (text and figures), (iii) examination of the possibility of extending the high tourist season toward late spring-early fall, based on our results, (iv) adaptation and mitigation recommendations for stakeholders.

To maximize impact, fostering the sense of belonging of results and engagement, key documents in which stakeholder inputs were embedded, e.g., socio-economic impact report, focus groups infographics etc. were shared with implied stakeholders. In addition, some of these infographics were widespread in social media with communication purposes, e.g., LinkedIn and X/Twitter.

4 Discussion and conclusions

4.1 Lessons learnt

Our work highlights the relevance of using bottom-up, participatory approaches which combine quantitative and qualitative methodologies to generate tailored, usable climate service tools which are adapted to the local context and needs. Through the project's duration, stakeholders participated in different activities, providing valuable information to help build up the climate service tool. Co-creation processes entail (a) additional effort, involving stakeholder mapping and engagement, planification of activities, analysis of results of participatory activities, implementation of changes etc. and (b) require flexibility in the working process, which typically involves refining work iteratively taking into account stakeholders' feedback. However, the benefits of adopting co-creation approaches in the development of the ECOAZUL-MED climate tool are many.

For instance, the focus groups conducted at the beginning of the project were essential to complement insights from the literature review and understand the regional context in which the tool would operate. These allowed us to gather information from the 3 target sectors from the inside and understand the challenges faced in the development of their day-to-day activities, particularly, in terms of climate. In this respect, the information compiled was consistent with findings from our initial literature review (Section 2.1). For instance, in **aquaculture** there was a concern regarding an increasing mortality and pathogens due to higher SST, in fisheries the divergence between administration requirements and sector capacities was highlighted, and for coastal tourism the difficulty in enhancing the natural value of some "sun and beach" destinations was stated. An insight that emerged from the focus groups is that climate change, aligned with literature (Bădîrcea et al., 2021), is generally perceived as a threat imposing barriers to their activity, with few potential opportunities such as the development of new aquaculture production methods, e.g., offshore (Mengual et al., 2021), appearance of fishing species with high commercial value (Farahmand et al., 2023) or increase in the number of tourists in other seasons different to summer (de la Vara et al., 2024). While adaptation measures were known for aquaculture and fisheries sectors, no measures were known for the fisheries sector. Additionally, focus groups allowed us to present stakeholders with the preliminary information to be included in the tool and collect their feedback regarding potential information that could be added. Stakeholders' suggestions were prioritized and some of them considered for its incorporation in our tool based on the project's resources. Although this increased the computational workload, this set the pathway toward a more tailor-made tool, taking into account end user's needs.

Also, stakeholder feedback was key to assessing potential socio-economic impacts derived from the future climate conditions from our tool on the 3 target sectors. According to our results (sub-section 3.3), for **aquaculture**, the most detrimental factors are an increase of SST and changes in the speed of marine currents. This is in agreement with recent studies which indicate that water temperature is a key factor influencing the physiology and ecology of fish (Neubauer and Andersen, 2019) and shellfish (Bayne, 2017) and that changes hydrodynamics, e.g., due to storms, could increase damage to farm infrastructure and escapes (Reid et al., 2019). For **fisheries**, the conditions perceived as most negative were many: an increase of T2MAX; an SST rise, an increase in the number of days with heatwaves, an increase in the number of days with summer conditions in spring and fall, changes in SSS and direction and speed of marine currents. This is not surprising given the traditional nature of Mediterranean fisheries, typically with daily landings, which leaves the sector widely exposed to climate conditions. Thus, a departure from historical conditions leading to a well-known seasonality of water masses, and thus commercial fish species distribution (Woźniacka et al., 2024), is usually perceived as negative, since this will affect the location of fishing areas and catches. For **coastal tourism**, an increase in summer T2MAX and heatwave episodes are depicted as the conditions that could have the greatest negative impact. This is consistent with Agulles et al. (2022), in which heat stress and the loss of beach availability have been identified as the climate change hazards that will affect to a larger extent the attractiveness of the Mediterranean region.

Also, stakeholders were essential for a participative assessment of the usability of the tool, through workshops and online questionnaires, considering their feedback for the creation of the final version of the tool. These activities allowed us to understand that, in terms of content, potential users demanded mainly more information regarding the data downloading process and the interpretation of maps, e.g., help buttons in the tool menu, a video-tutorial, figure captions. The iterative process followed for the generation of the tool not only allowed us to collect information from the stakeholders, but also to prepare reports and infographics that were used to give them feedback regarding the activities in which they participated, providing them the opportunity to get a greater overview regarding the discussed topics (e.g., the opinion from stakeholders belonging to other sectors), fostering engagement for subsequent activities. In turn, these materials have also been included at the "Documents and resources" section of the ECOAZUL-MED website to increase awareness and literacy of the general public.

5 Conclusion, limitations and future outlook

The Mediterranean region, located between the arid and warm northern African climate and the humid and mild European climate (Cramer et al., 2018), is considered a climate change hotspot. This is because it experiences an enhanced warming trend and frequent extreme weather events, e.g., heatwaves or intense precipitation (Scoccimarro et al., 2016; Rainaud et al., 2017; Khodayar et al., 2021), and climate models project an increase in the frequency and/or intensity of these events in the area (Darmaraki et al., 2019; IPCC, 2019; Molina et al., 2020; Gutiérrez-Fernández et al., 2021; Miró et al., 2021). The ECOAZUL-MED climate service tool arises from the imperative need of climate projection data to promote an effective adaptation of climate-exposed sectors of the blue economy in the Mediterranean region, fostering their long-term sustainability. This includes, for the first time, oceanic and atmospheric information for the Spanish Mediterranean coast for the coming decades derived from regional, high-resolution, air-sea coupled simulations performed under the RCP4.5 and RCP8.5 scenarios in the context of the Med-CORDEX initiative. Its generation entailed the combination of quantitative and qualitative research and highlighted the added value of co-creation processes and stakeholder engagement in the design of tailor-made climate services, adapted to the regional needs of the 3 target sectors. Stakeholder feedback was useful for the design of the tool (in terms of the climate information to be included and its final interface), as well as for the generation of supporting documents offered in the ECOAZUL-MED website and allow us to promote awareness and literacy regarding climate change in the region. While this work represents an excellent starting point, future developments of the tool would be directed to overcome potential limitations detected, e.g., reduced amount of climate data, use of CMIP5 boundary conditions etc. Being aware of potential room for improvements, one of the main challenges at this stage is to ensure usage of ECOAZUL-MED tool after the project. In order to foster the continuous update of the tool and make it even more usable, future actions lines would:

- Expand climate information presented in the ECOAZUL-MED tool targeted to the aquaculture, fisheries and coastal tourism

sectors, considering suggestions made by stakeholders, e.g., droughts, temperature and salinity over the entire water column, radiation etc.
- Perform a similar analysis with a regional coupled model ensemble from Med-CORDEX using boundary conditions from CMIP6, once this is available.
- Process new climate variables to include information relevant for the management of other blue economy sectors, such as offshore renewable energy productivity (photovoltaic and wind).

Insights that emerge from this work allow us to propose that our methodology can be applied to other areas where the blue economy is relevant, including not only the Mediterranean region. Therefore, the methodology presented here can be transferred and/or scaled up to other regions to develop other climate service tools adapted to the respective local contexts.

Data availability statement

All climate data can be downloaded in the form of a map from here: https://ecoazul-med.com/en/tool/.

Author contributions

AV: Writing – original draft, Writing – review & editing. WC: Writing – original draft, Writing – review & editing. MiF: Writing – original draft, Writing – review & editing. MaF: Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2025.1512707/full#supplementary-material

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