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A New Approach towards a User-Driven Coastal Climate Service to Enhance Climate Resilience in European Cities

Roberta Paranunzio [1,*], Iulia Anton [2], Elisa Adirosi [3], Tasneem Ahmed [2], Luca Baldini [3], Carlo Brandini [4,5], Filippo Giannetti [6],, Cécil Meulenberg [7], Alberto Ortolani [4,8], Francesco Pilla [9], Gregorio Iglesias [10,11] and Salem Gharbia [2]

[1] Institute of Atmospheric Sciences and Climate, National Research Council of Italy (CNR-ISAC), 10133 Torino, Italy
[2] Department of Environmental Science, Atlantic Technological University, F91 YW50 Sligo, Ireland; iulia.anton@atu.ie (I.A.); tasneem.ahmed@mail.itsligo.ie (T.A.); salem.gharbia@atu.ie (S.G.)
[3] Institute of Atmospheric Sciences and Climate, National Research Council of Italy (CNR-ISAC), 00133 Rome, Italy; elisa.adirosi@artov.isac.cnr.it (E.A.); l.baldini@isac.cnr.it (L.B.)
[4] Consortium Laboratory of Environmental Monitoring and Modelling for the Sustainable Development (Consorzio LaMMA), Sesto Fiorentino, 50019 Florence, Italy; brandini@lamma.toscana.it (C.B.); ortolani@lamma.toscana.it (A.O.)
[5] Marine Science Institute, National Research Council of Italy (CNR-ISMAR), Sesto Fiorentino, 50019 Florence, Italy
[6] Department of Information Engineering, University of Pisa, 56122 Pisa, Italy; filippo.giannetti@unipi.it
[7] Mediterranean Institute for Environmental Studies, Science and Research Centre of Koper, 6000 Koper, Slovenia; cecil.meulenberg@zrs-kp.si
[8] Institute for the Bioeconomy, National Research Council of Italy (CNR-IBE), Sesto Fiorentino, 50019 Florence, Italy
[9] School of Architecture Planning and Environmental Policy, University College Dublin, Belfield, D04 V1W8 Dublin, Ireland; francesco.pilla@ucd.ie
[10] School of Engineering and Architecture & MaREI, Environmental Research Institute, University College Cork, College Road, T12 YN60 Cork, Ireland; gregorio.iglesias@ucc.ie
[11] School of Engineering, Marine Building, University of Plymouth, Drake Circus, Plymouth PL4 8AA, UK
* Correspondence: r.paranunzio@isac.cnr.it

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Abstract: Coastal climate services play a crucial role in developing customised climate information for diverse end-users and stakeholders. To build climate-resilient societies, decision-makers should be empowered through easy access to powerful tools that enable timely adaptation to future and ongoing hazards. For this reason, fit-for-purpose climate services are needed to conduct accurate historical characterisation and projections for interpretative studies on climate- and water-related risks at the local coastal scale. The EU-funded SCORE project (Smart Control of Climate Resilience in European Coastal Cities) utilises climate and marine services for the development of smart technologies that support nature-based solutions to address specific concerns, including rising sea levels, coastal erosion, and coastal flooding due to extreme weather events. As part of the SCORE project, decision-makers will be able to address climate change-related coastal effects in their own cities through novel participatory approaches (Coastal City Living Labs—CCLLs). As part of this framework, this work (i) discusses the main requirements for the identification of fit-for-purpose coastal climate services for local-scale impact studies in European coastal cities based on CCLL requests and prior knowledge and (ii) provides relevant parameters and features that fulfil the users' needs.

Keywords: coastal climate service; urban areas; coastal hazards; climate resilience

1. Introduction

The awareness of the challenges posed to the environmental and socioeconomic system by climate change is growing worldwide, together with the demand for customised climate information [1]. A climate service may be defined as "the timely production and delivery of useful climate data, information, and knowledge to decision-makers" [2]. Basically, a climate service is any type of service that transfers science-based climate data and information from researchers/experts to users to support different stakeholders or decision-makers in communicating the risks and opportunities of climate change and variability [3–6]. Actually, different definitions of climate services exist, and a unanimous description is still lacking. Nevertheless, most of these definitions share some common goals. Specifically, climate services are intended to (i) provide climate data and information for decision and policy making, i.e., to support climate change adaptation and mitigation and facilitate disaster risk management; (ii) provide users with need-based tailored products; and (iii) disseminate and communicate climate-related hazards, risks, and vulnerabilities to build more climate-resilient societies [7].

Given the ongoing digital transformation and in accordance with the Green Deal's adaptation goals [8], it is fundamental to foster the use of advanced digital technologies (e.g., digital twins, advanced climate and hydraulic/hydrological modelling) and reliable climate information to support decision making [9].

A range of national to European-scale services provides data and information about climate change for large end-user categories. In 2016, a review of lessons learnt and future perspectives for climate services by Brasseur and Gallardo [4] highlighted several shortcomings in this framework. Among others, they found a lack of a systematic overview. Most of the time, the perspective does not match the users' expectations, creating a disjunction between scientific outputs and stakeholders' needs. This is also reflected in terms of the temporal horizon, with which climate science tends to emphasise long-term predictions. The temporal horizon is crucial for various applications, including investment decisions and governance; however, it is of less interest for short-term planning purposes, e.g., from seasonal to interannual scale [10]. The mismatch between the time scales provided by scientists and those needed by the decision-makers is thus still a critical challenge [11].

The large availability of different climate services across Europe leads to many duplications or underutilisation, as well as difficulties for users in understanding what is best for their purpose due to a lack of clarity [7,12]. Climate services should be grouped based on a standard framework of different criteria and factors to avoid confusion for end-users [6,7]. These users include different actors, including local to national government agencies, civil protection and risk management officers, industry, service providers (e.g., transportation, tourism, food system, agriculture), and the public. Nevertheless, some initiatives across Europe have been carried out to support agreement on a standardised classification of climate services with diverse typologies [13]. Climate services are thus meant to transfer climate research into an operational delivery of services for users to support climate change mitigation and adaptation strategies [7].

In Europe, climate services focus on a range of diverse thematic areas; however, fewer efforts have been specifically devoted to coastal climate services (CCSs) [3]. The need for CCSs is becoming increasingly urgent since the risks of sea-level rise (SLR), coastal erosion, flooding, and saline intrusion are growing rapidly worldwide [3,14]. SLR has been approximately ~20 cm since 1990 [15], and projections range from 0.45 to 0.84 m by 2100, depending on the methodology and the emission scenarios considered [15]. In this framework, coastal urban areas are key targets with respect to climate change impacts [16], to which both methodology and emission scenarios contribute, and experience impacts of climate-related hazards such as urban heat stress [17–19] and pluvial and coastal flooding [20–25], which will most likely occur with increasing intensity and frequency in the future [16,26]. Throughout history, most of the world's cities expanded on the coast due to the uniqueness of their resources [27], with an increasing migration expected in the future [28]. In Europe alone, 30 million people live within the temporal horizon of a 100-year event flood coastal plain, while currently, more than 50 million live in the low-elevation coastal zone [27]. The coastal population potentially exposed to a 100-year coastal flood is expected to increase by approx. 20% for a 0.15 m SLR compared to 2020 levels in the mid to long term [29]. Thus, in the future, these areas of increasing urban expansion are expected to be particularly at risk [30].

Coastal risks are emerging due to a combination of climate-induced SLR hazards, exposures, and vulnerabilities [31]. Adaptation and mitigation measures can reduce the risks related to SLR [15] and should be supported by reliable and authoritative information and policies [32]. Understanding sea-level trends at a regional and local scale is thus crucial for the development of effective climate adaptation plans [33]. Coastal cities need to quickly adapt and react to such hazards with tailored strategies and policies [1]. In Europe, until 2010, the planning of local coastal risk and adaptation was lacking to a great extent, and the awareness of the utility of coastal adaptation was arguably more advanced in the UK and the Netherlands as compared to other European countries [34]. Recently, planning and coastal information have been increasingly demanded by various stakeholders, leading to an emergent market uptake in sectors like, e.g., flood risk, energy, agriculture, transport, and tourism [35]. Urban areas need to adapt, but actions and strategies differ from case to case according to already established actions and depending on different exposures and vulnerabilities to climate change impacts [36].

Cities thus need to be supported in their adaptation to climate change, although understanding the "hows" is challenging. Novel participatory approaches are needed to support cities' decision-makers in adapting to the expected local and regional changes in climatic conditions and related impacts [8]. Such new strategies to address climate change issues are based on the urban Living Lab (LL) participatory approach built upon an iterative feedback process which stimulates the co-creation of innovative solutions by linking different stakeholders. LLs are becoming an important component of smart cities across Europe [37,38]. Recently, a new approach that expands on the LL concept to coastal cities has been introduced [39], i.e., the Coastal City Living Labs (CCLLs). The SCORE project (https://score-eu-project.eu/, accessed on 17 November 2023) aims to address climate-related hazards in European coastal cities by adopting an integrated approach, with the ambitious goal of planning appropriate measures to minimise climate hazards, for which a deep knowledge of climatic parameters and changes for the historical characterisation and simulation of future scenarios is needed.

This article seeks to provide insights and discuss the following key research questions:

1. What is the current situation of climate services specific to coastal environments in Europe?
2. Building on the novel CCLL participatory approach, what are the main requirements to be considered while selecting climate services to meet users' needs and to address climate change impacts at a coastal local scale while delivering solutions?
3. What are the main challenges encountered by CCLL participants in the use of general climate data and services?

This paper is organised as follows. Section 2 is focused on the analysis of coastal users' needs and technical requirements to define tailored local-scale climate services for SCORE's coastal cities through a co-creative approach, considering the available products. Section 3 reports the results of the research: an identification search for existing CCSs in Europe; identification of user needs; indication of needed parameters, tools, and products; and definition of the technical features of the project data hub developed to optimise data collection and create the best user experience. Section 4 discusses challenges and gaps in the development of fit-for-purpose CCSs. Section 5 summarises the main conclusion of the current work, along with potential perspectives.

2. Materials and Methods

2.1. SCORE's General Framework

The SCORE project (https://score-eu-project.eu/, accessed on 17 November 2023) aims to address climate-related hazards in European coastal cities by adopting an integrated approach as outlined below and summarised in Figure 1. Thus, SCORE's ambitious goal is to plan appropriate measures to minimise climate hazards, for which a deep knowledge of climatic parameters and changes for the historical characterisation (impacts and hazards) and simulation of future scenarios (smart technologies and digital platforms) is needed.

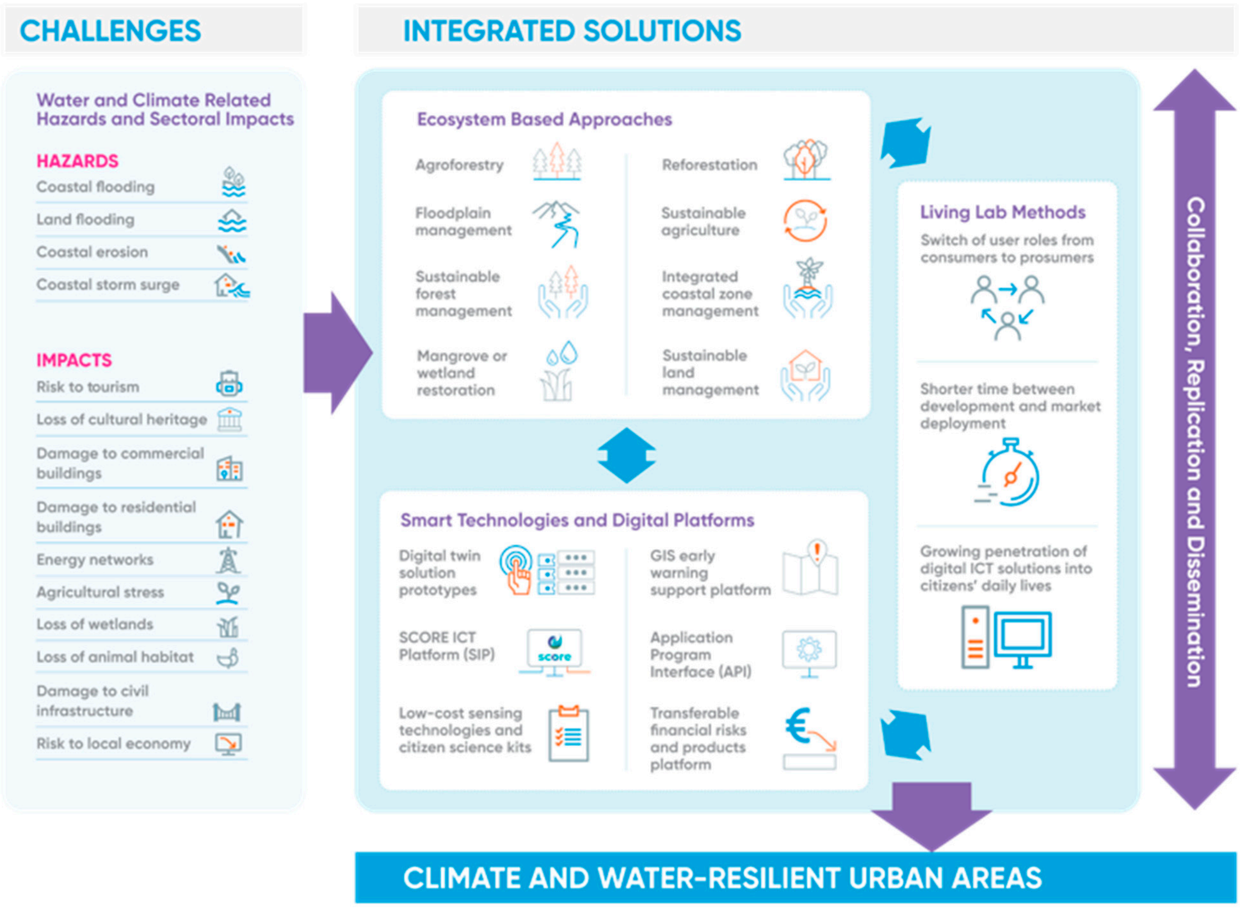

Figure 1. SCORE project concept.

Furthermore, as the SCORE project needs to build on previous initiatives across Europe to produce a reliable dataset of climate and marine data at high spatiotemporal resolution, the Living Lab methodology is applied through a network of 10 CCLLs by which each develops to enhance climate resilience through climate modelling and projections, smart technologies (digital twin), Ecosystem-based Approaches (EBA), and strengthening of financial sustainability and social acceptance. CCLLs in the SCORE project are spread around Europe and include Sligo and Dublin (Ireland), Massa (Italy), Oeiras (Portugal), Barcelona province (Vilanova I La Geltrù), Benidorm and Basque (Oarsoaldea) region (Spain), Gdansk (Poland), Piran (Slovenia), and Samsun (Turkey). For each CCLL, the availability and usability of free and reliable climate and marine data are crucial as they represent the basis for local climate impact assessment and for the delivery of solutions. These are key factors for cities and decision-makers that are united in climate services to plan and implement climate resilience measures, often under tight financial and social constraints [9].

Thus, as user, stakeholder, and services are confusing terms, in the context of this paper, the user is defined as someone who actively interacts with the climate services, while the stakeholder is impacted by the delivery of the service and, to an intermediate extent, is also passively interested. For the terms used in this article and their definitions, see Table 1.

Table 1. Terms used in this article and their definitions.

Term	Definition
Climate Service	A service that transfers science-based climate information and knowledge to customised products from experts to users to assist individuals and organisations in the decision-making process by enabling preparedness and actions [3–6].
Coastal Climate Service	Climate services in coastal areas [3].
User	Someone who actively interacts with the climate service.
Stakeholder	Someone who is impacted by the delivery of the service and, to an intermediate extent, is also passively interested.

According to the SCORE concept and its objectives, the methodological approach applied in this study is listed below and summarised in Figure 2 with each of these steps being explained further in the Materials and Methods section.

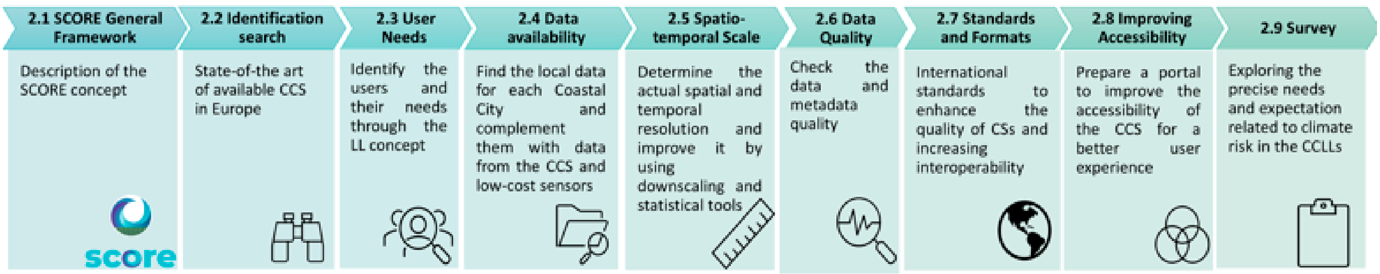

Figure 2. Methodological approach of this study.

2.2. Identification Search for the Available Coastal Climate Service in Europe

In order to define a preliminary state-of-the-art on CCSs in Europe, three databases have been selected: Science Direct, Web of Science, and Scopus. An initial search with the following keywords, limited to abstract, title, and authors' keywords, has been carried out: "climate service" AND (coast* OR marine) AND Europe*, "climate data" AND (coast* OR marine) AND Europe*, "climate service" AND "coast" AND "Europe", "climate service" AND marine AND Europe. The timeline 2010–2022 was selected since climate services have only been established in recent decades compared to, e.g., weather services [40]. The search was limited to Europe, the English language, and peer-review records. The application of this search string and requirements lead to more than 800 articles. In the second step, to achieve a result more focused on the topic of this paper, the search was limited to articles dealing with user needs, user engagement, stakeholders, coastal climate change, climate adaptation, climate resilience, coastal climate impacts, and climate information. Finally, around 85 papers have been selected and included to support the key research questions addressed in this work.

2.3. Identification of Users and Needs

It is fundamental to understand what type of climate information CCS users and CCLL participants are interested in before delivering adaptation solutions. User engagement is indeed the basis for performing a gap analysis of the data and information made available through the identified climate services. Discussion around the usefulness of climate services for a wide range of different users often points out their relevance for decision making specifically. Different public and private institutions, projects, and programmes have developed information portals and platform systems that provide access to a vast amount of climate data, information, and tools. Most of these systems state to adopt a user-need-oriented approach instead of a provider-driven approach, which is more devoted to building a better structure to deliver data rather than focusing on the better user experience to apply these data in practical applications [6,7,41].

According to Brasseur and Gallardo [4], end-users expect that climate services will advise them on how to use historical data and projections, how to deal with related uncertainties, and how to address the challenges they cope with. Thus, a climate service, through the eyes of end-users, is not seen as a mere data provision. Moreover, climate change is a complex issue involving many physical, economic, and social aspects; thus, the challenges addressed through a climate service should be taken by a broad spectrum of experts and integrated into the stakeholders' planning process. Long-term climate trends based on different emission scenarios are of interest for long-term projects dealing with investments and infrastructures but not for stakeholders who limit their plan of action to the next 5–10 years at the latest. Many sectors (e.g., tourism, agriculture, energy, water resources) cover situations from a few months (seasonal) to interannual scale, which is still very challenging to predict [10].

The provision of climate information affected by uncertainty is another major issue to be addressed by climate services. While scientists stress the need to communicate data and projections with their uncertainties, stakeholders ask for "perfect" information [42]. Uncertainties are related to the different scenarios assumed for the future greenhouse gas (GHG) emissions, the model spread (i.e., the climate response to the radiative forcing) and model approximations, the initial conditions to initialise the models, the natural variability of the climate system, and the time scale used [4]. This is hardly understood by decision-makers who, instead, need certainty to take action in the institutional framework in which they operate [12,33,43].

User engagement process is another challenging point [6]. Houtkamp et al. [44] proposed a four-step engagement process, namely, the following: i) stakeholder mapping and prioritisation, ii) user identification, iii) discussing and scoping the design situation, and iv) persona–scenario construction (use cases with fictional characters who represent typical user groups). In the framework of coastal adaptation decisions, Hinkel et al. [33] proposed a decision analysis perspective to identify the kind of SLR information the users need for local-scale impact assessment. The authors found that, to date, there has been little systematic exploration of users' needs, whether analysing the SLR information users employ [3] or asking them directly what kind of information they use [45]. However, asking users could sometimes bring misleading information due to lack of documentation or technical background. Hinkel et al. [33] followed a procedure based on characterisation and discussion of coastal adaptation decisions and SLR information given the state-of-the-art rather than using these information needs as entry points.

This framework is based on the Living Lab (LL) concept [46], which operates as intermediary among, e.g., citizens, scientists and decision-makers. LLs are real-life society environments based on an iterative feedback process focused on co-design and co-creation of innovative solutions and businesses of users to enhance climate resilience. The main pillars of this framework are (i) the orchestration, (ii) multi-stakeholder participation (quadruple helix model, academia, government, private and non-profit organisations), (iii) their active involvement, (iv) co-creation, (v) real-life setting, and (vi) the multi-method approach [47]. The CCLL is a new user-centric method that expands the LL concept to a broader vision for coastal cities and settlements to specifically address coastal climate change-related challenges [39].

2.4. Data Availability

The type of information that is needed differs depending on the purpose of use of the data and the user profile, e.g., climate scientists, impact researchers, or decision-makers. The former usually looks for historical and projected time series of temperature, precipitation, and climate variables requiring potential processing (like statistical analysis and downscaling). Decision-makers are instead more interested in customised products to support actions and best practices. All these specific pieces of end-user information need further processing, and thus, the number of intermediaries potentially increases to provide every end-user with the information they need [7].

Coastal cities are more particularly susceptible to climate change, which is also due to effects of SLR. This requires that the data of greatest interest include climate and marine data, alongside traditional meteorological and hydrological data, as they are needed to estimate, for example, the effects of extreme weather events, like rapid sea-level rises, storm surges, or coastal erosion.

Essential variables (EVs) are crucial for observing and monitoring the Earth. The requirements for EVs are constantly reviewed by expert panels in terms of spatiotemporal resolution and data quality. EVs include a wide range of different typologies [48]. In the context of coastal-scale impact studies like the SCORE project, essential climate variables (ECVs) and essential ocean variables (EOVs) are the most relevant. Concurrent time series across different force times are needed to better understand the concurrence of multiple hazard drivers like, e.g., compound flooding. Concurrent forcing data are available for typical marine variables, e.g., water levels and waves, while time series for the evaluation of dependencies between coastal and non-coastal forcing, like river flows and rainfall, are still limited [49]. ECVs provide crucial information to understand and predict the evolution of climate, support adaptation and mitigation actions, and underpin climate services [50]. ECVs, as identified by the Global Climate Observing System (GCOS), include a set of variables in the atmosphere, land, and ocean domains. EOVs refer to the ocean system, biology, ecosystems, and biogeochemistry as the ocean ECVs; the main EOVs focus on ocean circulation, transport, and distribution of salt, heat, and other water properties. Note that, as many variables are part of both ocean ECVs and EOVs, there is an overlap between the two categories. Hence, in the SCORE project, other key EVs will be considered to provide support throughout the process since they can be crucial to perform specific analysis on potential sectoral impacts experienced by the CCLLs, e.g., tourism, agriculture stress, local economy, animal habitats, loss of wetlands, etc. [51].

2.5. Spatial and Temporal Scale

For climate services and CCSs, spatiotemporal scales matter: a region or an area is usually impacted by multiple time scales. The importance of climate at different scales varies depending on the location, time of the year, and the variables considered [11].

Weather and climate services are often used interchangeably. Based on the WMO definition [52], the former covers timescales from days up to a month, while the latter from months to decades. Actually, the methods and data sources for (current, present, and future) climate projections and weather forecasts may differ a great deal and cannot be used equally [7]. The issue is thus to again tailor the information provided to the users' needs.

In this context, the uncertainty related to the climate information of interest should not be neglected. The main sources of uncertainties are due to, e.g., future GHG emission patterns and forcing conditions of the models, and vary widely depending on the timescale and variable under consideration. Climate projections are typically run until 2100 based on the Representative Concentration Pathway (RCP) scenarios for greenhouse gases, atmospheric constituents, and aerosol concentrations that will affect the radiative balance of the planet in the years to come. More recently, climate projections have often been based on the Shared Socioeconomic Pathways (SSPs), the novel climate change scenarios that are meant to improve upon and replace the RCPs [53]. As an example, in multidecadal projections, different forcing scenarios must be considered since policies and socio-economic factors will affect them significantly. Multimodel ensemble simulations are used to assess the uncertainty related to model spread, while the skill in seasonal forecasting is more limited due to the difficult predictability of the chaotic variations in climate variables [4].

In terms of spatial scales, global climate models (GCMs) provide climate information on global and wide regional scales, covering what could be a broad area with very different local extreme events and impacts. The horizontal resolution of such models limits the possibility to cover smaller scales, from regional to local. Regional climate models (RCMs) at relatively high resolution have been produced and made available to provide spatially detailed information to interested users [54]. RCMs are driven from the GCMs, which provide them with lateral boundary conditions and a more accurate representation of local phenomena (including extreme events). Nevertheless, estimating uncertainties in long-term climate projections and in their sources is not that straightforward, considering the internal variability of the systems. The degree of uncertainty is still very high for specific climate variables of interest for coastal areas like, e.g., precipitation and SLR. This is due to, e.g., fragmented and limited knowledge of some crucial physical processes controlling the response of extreme precipitation simulated by GCMs and RCMs, inter-model spread [55], lack or enhanced uncertainty in glaciers and ice-sheet representation in the climate models [56], and errors in the basin-scale ocean circulation features [57]. RCMs include uncertainties in the atmospheric circulation provided by global models, and thus, it is not always certain that they are more reliable than coarser-resolution models [58].

Large time scales, from decades to centuries, are used for evaluating response features of climate change and to detect its signals. Climate services at local and sectoral scales require finer spatial and temporal resolution for decision-making. This could be overcome by techniques like, e.g., downscaling methods and analogues. Obviously, downscaling from coarse to local scales comes with further uncertainty, which is also due to the methods selected for downscaling [59]. Local processes play a key role in global phenomena. As an example, SLR is related to a range of processes causing instability of large ice masses at the local scale, and the coarse resolution of GCMs cannot resolve them [60].

Some authors highlight the mismatch between the time scale used by climate modellers, who are interested in long-term simulations to detect climate change signals in a noisy system, and climate service programs, which instead focus on shorter time scales for local decision-making [59]. Areas are rarely impacted by only a single time scale. Analysis of different climate time scales guides resilience, and planning provides a historical characterisation of climate-related impacts, which can improve knowledge of future risks and help adaptation strategies [11,61].

In terms of temporal coverage provided by the main CCSs, climate data re-analysis datasets like ERA5 and ERA-5 Land go back in time up to 1950 and continue to nearly the present day. Climate projections are generally available up to 2100 at daily accuracy for both RCP 4.5 and 8.5 scenarios. Some datasets reach more accurate time scales (up to sub-daily) or provide long-term horizons, like in the emission scenario CORDEX, and also go beyond 2100, like in the case of CMIP5 and CMIP6.

2.6. Data and Metadata Quality

Climate services should provide quality-controlled data along with associated metadata that are able to ensure compliance with procedures related to the FAIR (Findable, Accessible, Interoperable, Re-usable) data management approach [62] that forms the basis of the data management plan commonly requested from research and development projects. The push for adopting FAIR procedures is related to the machine-actionability of data, i.e., the possibility of analysing data from heterogeneous sources with minimal or null human support. The data quality aspect is indeed important. In this respect, some authors claim that the typical limitations to the use of available data are identified as the mere lack of interoperability, interactivity, and transparency [63]. Indeed, quality is also key for climate services [64], and metadata must include information about data quality and the processing followed to obtain such data. This is also related to the original data sources, and this information should be communicated in the portals. Users relate clear and adequate metadata with good-quality scientific data. Therefore, quality-assured information with an independent quality assessment of the past, current, and future climate trends should be guaranteed [6]. This is a prerequisite to making users trust data and accept the services' robustness, which are the main pillars considered when assessing the suitability of the selected datasets for their own applications and analysis [63]. Different sources of uncertainties have to be considered when dealing with climatology in particular, due to various processing methods adopted (e.g., downscaling methods to provide data at a spatiotemporal resolution suitable for local impact studies) and heterogeneity of data sources. For state-of-the-art long-term climate projections, the degree of uncertainty is still very high for specific climate variables of interest for coastal areas like, e.g., precipitation and SLR.

High standards of reliability are ensured by quality-controlled data and a metadata quality control procedure [65]. Most available climate services in Europe guarantee high-quality data and information provision through an operational framework of processes. As an example, the C3S provides a QA/QC in its "Evaluation and Quality Control" activities (https://climate.copernicus.eu/evaluation-and-quality-control-eqc, accessed on 17 November 2023) [6]. Thus, subsets stored in this platform guarantee additional metadata quality control, which is not trivial considering that, often, data could have inconsistencies, gaps, and metadata errors. Moreover, a continuous user-engagement process helps to identify gaps in the service.

2.7. Formats, Standards, and Conventions

Ensuring links and consistency between international and national sources of climate data and information is crucial. Since adaptation strategies will be implemented at a local level (e.g., the CCLL), consistency between the above-mentioned sources and local data is fundamental as well. Service-based interoperability is achieved through the implementation of interface protocols specified by international standards [63]. International standards help to enhance the quality of climate services and increase their interoperability by implementing interface protocols. File Transfer Protocol (FTP) and HTTP through web browsers or download pages are the most popular ways to send files and information across the network, although the use of web-based interactive computing platforms is increasing among the data scientist community [66].

2.8. Accessibility and Portal Design

According to [67], the structure of the portals providing climate services and CCSs is determined by data experts' preferences, i.e., by the way they present their work efficiently, but this is not necessarily the way users like to find (and use) information to address their questions. As a matter of fact, recent studies highlighted that many times, users often consider aspects like usability and accessibility rather than relevance because of the lack of technical background to interpret the outputs and access these data [64].

Different data require different visualisation techniques and standards (see Section 3.6). A survey among approx. 90 users [6] investigated the portals' main features to be considered, revealing that free open access and scientific correctness are fundamental. Information about the uncertainty of the results is particularly appreciated by impact researchers, while intermediate organisations (e.g., consultants or environmental agencies) pay more attention to guidance in the selection of climate data and impact indicators. Harmonisation of the data and tools is also considered important, along with the need to avoid redundancies among different sources. Moreover, the importance of taking the diversity of users, in terms of skills and needs, into consideration when designing the portals is also highlighted. Ease and comfort when browsing are thus key requirements for users since the website would act as a "shop window" with direct links to products and services [68].

An important aspect to consider is related to applicability and maturity of the datasets. As pointed out by Swart et al. [6], when interacting with climate service portals, users appreciate the availability of guided search functions, help desks, and, in particular, the presence of use cases as examples to follow. Use cases are examples of data and service deployment, i.e., tools to make users understand how they can use climate data retrieved by climate services in their daily work routine and how these data can be deployed in a range of different applications of impact assessment.

2.9. Survey

The surveys were conducted among each of the 10 CCLLs. As a first step for involving end-users, online questionnaire surveys were distributed to the project partners as follows:

the first was distributed during the proposal stage of the project, the second was distributed in October 2021, and the last was distributed in January 2022.

The responses were not specifically generated by a single person; instead, they were the collective of the living laboratory, usually a collected response from the core CCLL team with different positions: CCLL manager, project manager, pilot manager, communicator/panel manager, and/or researcher/human interaction specialist. While these positions within the CCLL can be filled by the same person, usually, a CCLL core team's composition is dynamic in time, having an average of three persons at any time. Still, the core CCLL team members have interacted and asked for advice on certain availability of data within their CCLL at specific stakeholders, making the responses to the surveys from this paper an early reflection of collaboration between project partners and CCLL stakeholders.

With approximately 180 questions in total, the questionnaire explored the precise needs and expectations related to climate risk in the ten coastal cities and, more specifically, (i) basic information about the environmental and geographical coastal area context, natural and climatic-related hazards, impacts, and vulnerable and exposed populations; (ii) objectives for creating and implementing the CCLL; (iii) expected outcomes; (iv) potential stakeholders; (v) technical and financial capacities; (vi) previous experience in relevant projects and level of expertise; and (vii) experience in different activities associated with each WP.

A numerical scoring was developed to assess the CCLLs based on their responses, which allowed for cross-comparison. These results were further investigated during the three-day workshops organised in 2022 in each CCLL, in which user stories for the digital twins and early warning support systems were fully defined (out of the scope of this paper). During the workshops, the participants could actively exchange opinions and knowledge, build consensus, and express disagreement to find common solutions to address coastal-related issues.

3. Results

3.1. Identification and Description of Coastal Climate Services in Europe

Across Europe, a vast number of institutes, agencies, and industries acquire expensive climate data, especially marine data, for specific purposes, thus generating large datasets that are often used only once or remain unused in data servers. Recently, international initiatives and programmes have started to centralise, standardise, and harmonise this information for a wide range of users. Interdisciplinary networks of climate information users, researchers, and providers complement the climate information at different scales [63]. Most of the ongoing climate services in Europe have been promoted through European research funding programs, such as Framework 6 and 7, Horizon 2020, or the Joint Programming Initiative for Climate "Connecting Climate Knowledge for Europe" (JPI Climate), which support a variety of projects within this field [69]. The results of the search for these projects and climate services, as described in Section 2.3, are shown in Table 2, and then consecutively, each service will be described in detail in the following sections.

The Copernicus programme is the European Union's Earth Observation Programme, driven by policies and by users' requirements, including coastal managers. Copernicus includes a dedicated Earth observation component (i.e., Sentinel mission), which is currently the largest world producer of openly and freely available Earth observation (EO) data [70]. Sentinel-1, -2, -3, and -6 provide information on sea level and other parameters (e.g., waves and surface winds) to monitor sea-level-related hazards and risks [71]. Copernicus offers information services based on satellite, in situ and integrated numerical models to produce quality-assessed datasets and information usable by different users. Copernicus data are provided through six different services. Of particular interest in relation to coastal hazard adaptation are the Copernicus Marine Environment Service (CMEMS), the Copernicus Climate Change Service (C3S), the Copernicus Emergency Management Service (CEMS), and the Copernicus Land Monitoring Service (CLMS).

Table 2. Search results of the identification of the available coastal climate service in Europe.

Full Name	Abbreviation	Website
Copernicus Climate Change Service	C3S	https://climate.copernicus.eu/, accessed on 20 November 2023
Copernicus Emergency Management Service	CEMS	https://emergency.copernicus.eu/, accessed on 11 November 2023
Copernicus Marine Environment Service	CMEMS	https://marine.copernicus.eu/, accessed on 17 November 2023
Copernicus Land Monitoring Service	CLMS	https://land.copernicus.eu/en, accessed on 4 November 2023
World Climate Research Program—Coordinated Downscaling Experiments Initiative	WCRP-CORDEX	https://cordex.org/, accessed on 21 October 2023
European Marine Observation and Data Network	EMODnet	https://emodnet.ec.europa.eu/en, accessed on 25 October 2023
European Research Area for Climate Services—Joint Programming Initiative	ERA4CS-JPI Climate	https://jpi-climate.eu/programme/era4cs/, accessed on 8 November 2023

C3S is one of the major contributors to climate data in Europe [9,71,72]. C3S has been designed around the Climate Data Store (CDS), which is a unified, freely available, and unrestricted access entry point to a variety of quality-checked and quality-controlled climate data. It provides information about past, present, and future climate, following a rigorous quality control procedure to guarantee usability in a standardised and reliable way. CDS datasets include observed historical climate data, reanalysis of past observations at global and regional scales, seasonal forecasts, and simulated past climate and future climate projections. An application programming interface (API) allows users to interact with and integrate the CDS.

CMEMS, implemented by Mercator Ocean International, provides information on the physical and biogeochemical state, dynamics, and variability of the ocean and sea ice for the global ocean and European seas over the past and present and the prediction of the situation 10 days ahead (forecast). CMEMS provides a response to European user needs, e.g., for marine and maritime safety, resources, coastal environment, weather, seasonal forecast, and climate. CMEMS responds to both public and private user needs by involving users in the service delivery process [73]. CMEMS products are freely available through a one-point access web interface (http://marine.copernicus.eu/ getting-started/, accessed on 17 November 2023).

As part of the CEMS and of interest in the context of coastal flood risk, the European Commission has developed the European Flood Awareness System (EFAS), which provides operational flood predictions in major European rivers [74]. The project started in 2003 and was developed by the European Commission Joint Research Centre (JRC) in collaboration with national meteorological and hydrological services, research institutes and operational services. It was a pioneering project on probabilistic flood forecasting based on ensemble prediction systems in Europe.

The World Climate Research Program (WCRP) promoted the international Coordinated Downscaling Experiments Initiative (CORDEX, [75]), which carried out coordinated regional climate simulations for the 21st century for different regions of the world. For the European domain, CORDEX generates climate change simulations that are of large size and high resolution: one domain with two resolutions is used for the RCM simulations, at 0.44° and 0.11° grid resolution at a sub-daily to monthly scale [76]. Within the European region, the Mediterranean basin is a particularly vulnerable "hotspot" due to its complex morphology, interactions, and socioeconomic conditions. An additional CORDEX sub-domain, the Med-CORDEX initiative endorsed by Med-CLIVAR and HyMeX, has thus been promoted. Med-CORDEX [77] takes advantage of new high-resolution and fully coupled regional climate system models (RCSMs), coupling the various components of the regional climate. The C3S EURO-CORDEX fills the gaps between the GCMs' "driving models", RCMs, and RCPs to better depict uncertainty from models. C3S directly curated and quality-controlled part of the CORDEX simulations and funded further climate simulations on the European domain.

More focused on the provision of marine data is the European Marine Observation and Data Network (EMODnet), established in 2009, a European marine data and observation network of more than 150 organisations supported by the EU's Integrated Maritime Policy [78]. These organisations collaborate to gather and process marine and coastal data from different sources to provide an open access portal of data and metadata products. Currently, EMODnet provides seven sub-portals, including bathymetry, physics, chemistry, biology, seabed habitats, human activities, and geology. Recently, all EMODnet services have been centralised into one unified EMODnet data service.

At national and regional scales, a number of European projects supported by different EU programmes have furthermore contributed to increasing knowledge on coastal areas.

Copernicus data are increasingly exploited in a myriad of different sectors across Europe to address climate-related challenges in coastal areas [79]. Some examples are the MI-SAFE platform and the SHOC campaign. The former has been generated as a new approach to combine remote sensing and field data from foreshores to predict how these protect the shoreline; the latter uses SAR images to monitor the marine environment and track storms and hurricanes. Data from C3S have been used to improve local hydrology and coastal flooding models on the Irish east and west coasts, respectively, to address the impact of climate change on coastal inundation [80]. The Copernicus programme is in continuous evolution, with its progress driven by some ongoing and precursor projects like, e.g., CoCliCo (Core Climate Coastal Services) and H2020 ECFAS (European Coastal Flood Awareness System). The European Climate Adaptation Platform (CLIMATE-ADAPT, [63]) is a joint effort between the European Environment Agency (EEA) and the European Commission (EC) to foster climate change adaptation in Europe by providing users with access to and share information on expected impacts, adaptation strategies, and tools. Moreover, since the 1990s, a number of studies started to focus on downscaling GCMs or re-analysis over the European region (e.g., ENSEMBLES, Ref. [81]; RACCS, Ref. [82]; STARDEX, Ref. [83]; PRUDENCE, Ref. [84]; CIRCE, Ref. [85]; MERCURE, Ref. [86]).

In the framework of JPI Climate, the European Research Area for Climate Services [87] has been one of the leading funders in Europe in the field of climate services. Some of the projects developed under this initiative pointed to making use of coastal and marine data to deliver more efficient CCSs. Some examples are the INSeaPTION project (https://jpi-climate.eu/project/inseaption/, accessed on 8 November 2023), which aims to integrate SLR data and coastal and adaption science to co-develop and co-design with CCS users, and the ECLISEA project, which aims to develop climate coastal services through the development of innovative research of sea surface dynamics https://jpi-climate.eu/project/eclisea/, accessed on 8 November 2023.

At the national scale, some initiatives are being undertaken, and the concept of CCS is being adopted to support National Adaptation Plans (NAPs) [63] to identify adapation needs and develop strategies to address coastal flooding and related risks. A step-by-step guideline to establish national frameworks for climate services has been addressed by WMO [88].

3.2. Identification of User Needs and Engagement through Surveys

SCORE extended the Living Lab concept to coastal cities by creating the CCLL as an innovative ecosystem in a real-life environment that uses people as a pillar of the research base rather than limiting research to a mere science laboratory. Specifically, the CCLL approach aims to exchange and upgrade knowledge amongst end-users through feedback and reflection and to make the citizen evaluate and understand the context and solutions through informed approaches [39]. Through this, science data providers, different end-users, and stakeholders in each of the ten coastal cities work together in a synergic interaction to tackle specific challenges related to water and climate hazards in the area related to SLR, coastal erosion, and other extreme climate change and weather events through solutions comprising Ecosystem-based Approaches (EBA) and the use of smart technologies [39] to produce tailored coastal services and products employing the climate information available at coarser (regional) scale.

All actors are involved in the development process and regularly provide feedback to improve it [39,89]. The interaction is thus "user-centred" to fully comprehend what users really need. For this purpose, defining the type of users is crucial.

The main end-user groups have been identified based on the quadruple helix model [90], which recognises four major actors: science, policy, society, and industry. This allows more and more governments to prioritise greater public involvement in the innovation process. This open approach implies that anyone can participate in the process and helps to gather more varied feedback, which supports innovation in local governance.

During the workshops, users were asked what overall problem they would try to solve during the project life in their CCLL and specifically how they can benefit from climate services. Almost all CCLLs indicated coastal erosion, flooding, and SLR as the main hazards to be addressed by adaptation strategies. Multi-hazards are also seen as a major issue in the future. Based on survey results, the following have been identified as the main sectoral climate impacts: risks to tourism and the local economy; loss of cultural heritage, wetlands, and animal habitats; damage to commercial and residential buildings, civil infrastructure, and energy networks; and agriculture stress. The survey explored the experience of CCLLs with coastal climate data, i.e., the use of climate data to address climate-related natural hazard issues, the perceived applicability of such information and data, and the most appropriate way of knowledge transfer. Specifically, they were asked whether they have access to forecast systems, completed or ongoing activities regarding future projections, the availability of maps concerning hydrological and geological data, information about existing models for hydrological and marine monitoring, the availability of data, and whether or not their technical capacities need enhancing.

Results highlighted that 9 out of 10 CCLLs have access to forecast systems and probabilistic forecasts, while 3 out of 10 CCLLs have ongoing activities with regard to future projections. For many of them, there is a deficit of information when it comes to climate data usage for the protection and enhancement of adaptation and mitigation strategies. They argue that there is (i) a generalised lack of open climate and environmental information and local-scale data, (ii) a lack of access to local-scale data, and (iii) a lack of knowledge in tools for statistical analysis, modelling, or testing the probability of hazard occurrence. In general, all CCLLs need an enhancement of technical capacities. Nevertheless, some virtuous cities are already committed, with local governmental agencies collaborating and transferring local scientific knowledge for project purposes and beyond. Furthermore, we learned from end-users that participants mainly used this information and data for research activities, immediate or short-term planning, and operational activities, as well as for other purposes, such as strategic long-term decisions or to inform investment strategies.

3.3. Use of Historical Data and Projections

Climate data and projections are among the main sources of data production of the SCORE project as they are fundamental for (i) enhancing the understanding of past and future climate-related hazards and validating models to reproduce past situations; (ii) enabling downstream services/models and, in particular, the hydraulic and land–sea interaction models for urban-scale flooding and long-term evolution of the coast; (iii) designing Ecosystem-based Approaches (EBAs); (iv) producing risk estimations; (vi) driving models of digital twins; and (vii) supporting CCLLs activities. In the SCORE project, researchers are the main users handling the direct output of the models and analysing essential Earth observation and in situ parameters.

CCLL stakeholders often mention the combined interpretation of meteorological parameters, EOVs, and ECVs by multiple climate services as a strength in the accurate prediction of local risks for extreme events. Thus, as for coastal flooding events, on the one hand, often the astronomical gravitational pull (by the combined effect of the Moon and the Sun) is a standard periodic variable that is easily predictable, while more locally, the direction and intensity of the wind and the atmospheric pressure are additional key factors. Under certain circumstances, these variables will mutually combine to potentiate the risk of extreme events. Thus, normal high sea levels, in combination with storm surges, can lead to coastal flooding. It is for such variables that it is desirable to have precise predictions that are accurate in magnitude and spatiotemporal phasing. Timeliness in early warning is directly connected to the response capability and, thus, to the mitigation of risks for citizens and infrastructure. Thus, rather than having to extract meteorological data, EOVs, and ECVs from various climate services and RCMs, it is generally much more preferable to combine these variables in one particular local CCS. The challenge is to provide accurate variable predictions at the local level, while often, the general climate services and RCMs have too coarse resolutions (both temporal and spatial) of the key variables at the local scale.

In the SCORE context, since many EOVs are also ECVs as defined by the GCOS, it was preferred to categorise the variables of interest in terms of the following categories related to four macro categories: climate and weather, sea and coast, pollutants, and radiations. Table 3 groups the most important variables identified. Climate- and weather-related variables, along with marine data (sea and coast), are the main parameters of interest for end-users and mainly on those on which the selection of the datasets has been based. Pollutant- and radiation-related variables are, instead, secondary parameters that can help additional and contingent analysis (beyond feeding other applications than the specific coastal ones addressed in SCORE).

Table 3. Survey-identified variables of interest in SCORE's CCLLs.

Climate and Weather	Sea and Coast	Pollutants	Radiations
Air temperature, dew point, heat index	Mean sea level	Atmospheric concentration (CO, CO_2, NO_2, SO_2, PM_{10}, $PM_{2.5}$) [1]	Solar irradiance
Humidity	Sea (lakes, rivers, channels) level	pH	Radiation in the ultraviolet
Atmospheric pressure	Storm surge residual	Mass concentration in the water	Radiation in the infrared bands
Cloud height and coverage	Total water depth		
Precipitation (rain, snow, hail) intensity and total precipitation	Sea temperature		
Lightning strikes	Tidal elevation		
Wind (speed and direction)	Sea wave motion		
Zero-degree isotherm height	Shoreline position		
Tropospheric features (melting-layer height, thickness)	Salinity		

[1] CO: carbon monoxide; CO_2: carbon dioxide; NO_2: nitrogen dioxide; SO_2: sulfur dioxide; PM_{10}: particulate matter with a diameter of 10 microns or less; $PM_{2.5}$: particulate matter with a diameter of 2.5 microns or less.

Besides the products provided by the climate services, the CCLLs provide useful digital information on local terrain models, coastal bathymetry, hydrological basins, and urban maps, as well as local data from existing (legacy) sensor networks that are currently used by municipalities, i.e., marine, meteo, and hydrological in situ measurements. To this aim, the cities have been asked to complete questionnaires with data requirements, guidelines, and indications (see Section 3.1). These data will complement the information provided by the CCSs by, e.g., filling eventual gaps and providing data for model initialisation/calibration/validation. In addition, planned citizen science activities will gather data from low-cost sensors (or citizen science sensor kits) that can contribute to reducing existing spatial/temporal gaps or guarantee some desirable redundancies to produce more solid coastal city early warning support systems.

3.4. Spatiotemporal Resolution, Downscaling, and Modelling

The conclusions suggested by coastal impact modelling (i.e., numerical) experiments should be sufficiently robust to quantify and address the uncertainties in the parameters and scenarios incorporated by the models and be in agreement with observations. Thus, models should be sufficiently accurate and have a spatiotemporal resolution that is suitable for local impact studies.

The time span is related, back in time, to the availability and occurrence of climate-related hazard events in the ten coastal cities of interest and, in the future, to the temporal horizon of the projections. From the spatial coverage point of view, since SCORE's CCLLs are distributed across Europe and on the Black Sea coast of Turkey, datasets covering at least this spatial domain have been considered (i.e., 27° N–72° N—southernmost–northernmost latitude—and 22° W–45° E—westernmost–easternmost longitude). These spatial domains are not always provided on homogeneous grids; thus, projections could vary depending on RCMs and domain.

Based on the occurrence of the main climate-related hazards identified across CCLLs, the temporal coverage has to guarantee sufficient extension back in time for the historical characterisation and for future scenarios. To investigate the historical time span, in situ data measurements, wherever available, and/or re-analysis products are used. Well-known climate data re-analysis datasets, e.g., ERA5 and ERA-5 Land, are exploited in this framework since they go back in time up to 1950 and continue to the present day, providing an accurate description of the climate of the past. Existing spatial and temporal gaps can be reduced by ancillary measurements from low-cost sensors, whose aim is to complement the available climate monitoring infrastructures. The temporal resolution needed to support early warning should be at least at daily or better sub-daily scale.

Data produced from GCM have a large gap with respect to the RCM. GCM resolutions are in the order of 0.25°–05° (25–50 km at the mid-latitudes) compared to the 0.125°–0.1° (10–12 km at the mid-latitudes) of the RCM. For local scale studies, RCMs are necessarily preferred over GCMs since they allow for reaching a higher spatial resolution and relatively fine detail over a limited area to support more detailed adaptation assessments. The availability of data at the European scale from various initiatives like the CORDEX (EURO and Med CORDEX) project is crucial to properly describe the atmospheric forcing that drives, e.g., wave, sea level, or hydrological local modelling. These climate projections generally cover a period up to 2100 at a daily scale under RCP 4.5 and 8.5, but some of them provide even 3 h resolution data.

To better simulate phenomena induced by processes predicted by large-scale climate models at the urban scale, downscaling techniques are used to infer information at the proper local scale. These underlie the provision of detailed models to enable the simulation of urban-scale scenarios.

The concept of downscaling that we use in SCORE is not only to produce local-scale data that may be of interest by themselves but also to enable the creation of new downstream models (urban-scale models) that are crucial, for example, for flood mapping and the study of adaptation solutions. In SCORE, downscaling was mainly focused on increasing the spatial resolution of projections. The reason for this choice was principally due to the availability of the physical variables and their accuracy in simulating wave climate, sea water level, and rainfall rate at a sufficient temporal resolution, which was identified as 3 h, for all ten coastal cities. Marine and hydrological variables were downscaled using physical models nested in the RCMs along the projection time range. Atmospheric spatial downscaling was instead assumed as less critical, and a statistical (neural-network-based) approach was thus experimentally used to produce some sensitivity estimations for the downstream models and the projection resolutions (in addition, note that an atmospheric physical downscaling would be particularly computationally demanding and out of the scope the project).

The RCMs related to the EUROCORDEX project are run on a geographical domain containing all the CCLLs of the project. In order to guarantee consistency, produced historical (1950–2005), evaluation (1979–2019), and scenario (2006–2100) runs of the same RCM have been used.

Coastal cities have specificities compared to the surrounding natural coastal territory: being located on the sea, they are the parts of the territory in which resident people are, perhaps, most susceptible to the effects of climate change, which is also due to the effects of SLR.

This requires that the data of greatest interest include marine data alongside traditional meteorological and hydrological data, as they are needed to estimate, for example, the effects of storm surges, extreme sea levels, or coastal erosion.

The main data of interest are therefore:

- Wave data, which are used for various applications, such as estimating run-up extremes or forcing coastal morphodynamics;
- Sea-level data, which are used for estimating storm surge effects and interactions with urban hydraulics;
- Hydrological data, such as flow rates and levels, which are needed for urban flooding models as well as to improve understanding of the potential effects of EBA solutions;
- Meteorological data, which are needed to force all the other models, for example, to provide a more correct distribution of the rainfall input to hydrological models.

Each of these datasets needs to be produced with tools, mainly models, that are different from each other.

In terms of modelling choices, another general preference was given to physical models that provide greater flexibility of use by avoiding the use of multi-nesting techniques. In particular, especially for marine models, the adoption of unstructured mesh models was preferred. This is because the aim of the project is not to build climate services on uniform grids or with a uniform level of output but to focus on specific coastal areas in order to build tools that guarantee the provision of highly detailed data for those areas and to possibly maintain a certain easiness to replicate/adapt procedures and to guarantee the exportability of the methods adopted in other contexts.

3.5. Data Quality and Standards

Conformity with the common data model and data format specifications is desirable to ensure both easy cooperative data analysis and automated machine readability of data. Most of the solutions adopted are finalised to implement the FAIR approach. The SCORE project will benefit from data consistent with the international data sharing principles and comply with agreed specifications and standards, such as ESGF, the International Organisation for Standardisation (ISO) specifications, Open Geospatial Consortium (OGC) Web Coverage Service, ESGF, OPeNDAP, or application programming interfaces such as REST API, acting like a mediator between the users and the resources they need. In this context, the INSPIRE Directive 2007/2/EC aims to establish an Infrastructure for Spatial Information in the European Community supported by legislation and technical guidelines on data models and network services. Most climate data are provided using the Network Common Data Format (NetCDF) model, following the climate and forecast (CF) convention for metadata formalisation. The known advantage of NetCDF is that it is self-describing, i.e., all of the metadata necessary to describe data can be contained in the same NetCDF file. The recent version of the CF convention allows the use of new NetCDF-4 data types along with the classical version as well. When NetCDF-4 cannot be used, earlier format versions are considered. Other common formats are CSV and ASCII files for plain text information and GeoTIFF to share geographic images with georeferencing metadata embedded in TIFF files themselves. Weather radar products or HF radars are instead made available in HDF5 or GRIB format. Data from local networks complementing the climate information from climate services are thus provided or converted in a common and unified format for the SCORE partners. All this information is being gathered into the SCORE ICT Platform (SIP), allowing interfacing between the SCORE database and existing databases.

3.6. Improving User Accessibility: The SCORE Project Data Portal

In the framework of the SCORE project, climate services are intended to help not only the scientific community but also the public in understanding the risks induced by climate change and to empower all the stakeholders to respond to them. The idea behind SCORE is that climate services should serve as public goods that any user can access and exploit [4]. Therefore, (i) climate (meta)data and information should be open and free of charge and available online to guarantee easier accessibility to services on websites and platforms through direct download or sub-setting service, and (ii) CCSs identified in the framework of SCORE should guarantee a strong user experience of the web portals.

According to the above considerations, a dedicated SCORE ICT Platform (SIP) has been designed and developed to support all the data and models generated within the SCORE project. In this framework, to facilitate data retrieval for end-users, SIP also implements interfaces to collect, store and share all heterogeneous data acquired from relevant climate services for SCORE. This will allow access to raw data (consisting of both historical datasets and real-time sensor readings) that feed models that generate climate services.

The SCORE platform consists of the following two macro-subsystems, which run independent services, as shown in Figure 3.

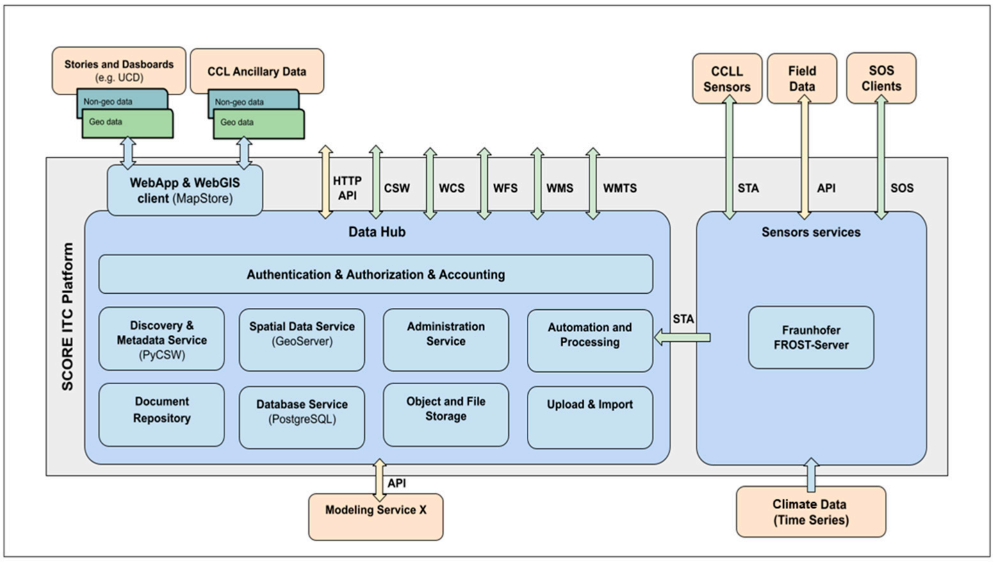

Figure 3. High-level architecture of the SCORE platform.

- The Data Hub—developed using GeoNode (https://geonode.org/, accessed on 17 September 2023) and GeoServer (https://geoserver.org/,accessed on 17 September 2023)—includes the SCORE database where all project data are stored, including the relevant services (spatial data, metadata, etc.) and interfaces (GUI, etc.). It also provides the data and metadata catalogue, the data management services, the APIs to access and manage the catalogue, and the client application;
- The Sensor Service—based on the FROST server (https://www.iosb.fraunhofer.de/en/projects-and-products/frost-server.html, accessed on 17 September 2023)—is dedicated to the collecting, cataloguing, and publishing of sensors and sensor data.

The Data Hub collects information from the sensor services and exposes the list of sensors inside the data catalogue, along with the other resources directly managed by the Data Hub itself.

The data portal of the SCORE project exhibits some remarkable features, which are outlined hereafter:

- It aggregates geospatial, documentary, and multimedia content from multiple channels;
- It enriches the data that feeds the platform with metadata according to standard formats (Dublin Core, ISO, etc.);
- It offers visual tools for creating maps, dashboards, and geostories based on the catalogue of data and documents (in addition to being published on the platform itself, these representations can be included in external portals and web pages);
- It is based on open-source software that can be used without license fees, is freely analysed for quality and safety checks, and can be extended and modified by anyone.
- It is accessible at the following URL: https://platform.score-eu-project.eu/, accessed on 17 November 2023. The relevant landing page is depicted in Figure 4.

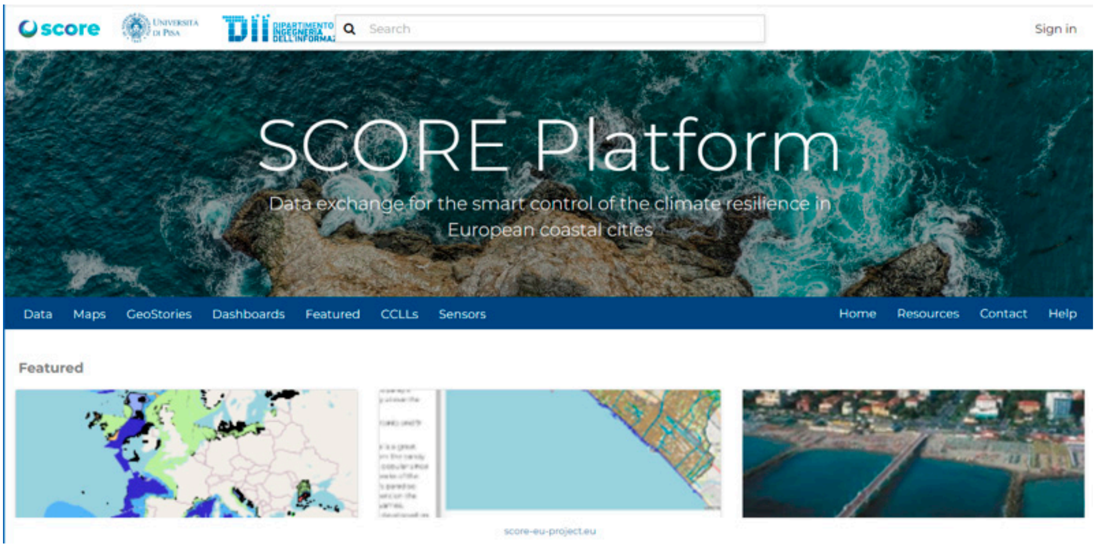

Figure 4. Landing page of the SCORE platform at URL https://platform.score-eu-project.eu/, accessed on 17 November 2023.

4. Discussion

4.1. Research versus Users' Needs

The interaction between users and providers of the climate service is one of the least developed aspects of climate services. The demand for user-driven climate information is growing in almost every impact sector. Nevertheless, there is a broad agreement that climate services tend to be more centred on the production of outputs that are not easy to handle due to, e.g., the lack of technical capacity to interpret the outputs, thus limiting their use for context-specific needs and decision making [64]. Good practices and strategies to achieve effective user engagement have been fostered by WMO [68]. There, recommendations are provided with examples of the use of climate information, showing who is involved in the engagement, how their engagement operates, and the goal to achieve. In this context, use cases are very serviceable and are part of the SCORE project strategy as examples of data and service deployment to guide the users through some relevant climate services.

The CCLL concept introduced in SCORE is a user-centric social system focusing on co-developing coastal city interventions to mitigate the impacts of climate change. It involves the co-creation and co-production concepts that have been proven to be a valuable form of collaborative governance between different actors playing critical roles in climate adaptation. As such, users are involved from the very beginning of the project. They collaborate in gathering and analysing data and information and share critical thoughts. Users and policy needs should drive the evolution of climate services in the coastal environments. Their involvement is crucial to better address questions related to spatial scale and resolution, time scenarios, and choice of variables and, thus, to develop products tailored to their expectations [57]. For instance, interactions between Copernicus and the European countries will be deepened in the future. National marine engagement plans are to be set up to allow specific discussions between the Entrusted Entity for the Marine Service and EU Member States. This will contribute to a better integration of the CMEMS with European countries' expectations, which is of particular relevance in the context of the co-design of services and products and for implementing actions with Member States in the coastal areas. A similar roadmap was recently delivered for other Copernicus services [91]. Such evolution will be crucial for the risk assessment of coastal zones. Precursor activities such as ongoing European projects will contribute to enhancing the exploitation of European climate services with regard to coastal areas [71].

4.2. Fragmented and Heterogeneous Knowledge and Data Sparse

Gaps in climate and weather information in data-sparse regions of the ocean and seas undermine climate services worldwide. Coastal and marine data specifically tends to be unfortunately gathered and stored in fragmented ways across Europe by different national agencies, industries, and institutions. This is also due to the prohibitive cost of acquiring data from the marine environment, often resulting in collecting data for specific purposes or user needs. Fragmented datasets prevent marine knowledge and interactions between land and sea, which are crucial to addressing climate resilience and the sustainable economic development of Europe's marine sector. Moreover, this makes access difficult for non-expert or ad hoc data users.

The issue in Europe has been partially addressed recently by international initiatives like the CMEMS or EMODnet. Nevertheless, some data (e.g., in situ wave data, buoys, or multidisciplinary parameters at depth) are still very sparse and concentrated in a few areas, thus limiting their application in local-scale models. Gaps in EOVs are partially filled through satellite observations, e.g., Sentinel missions or modelling techniques. Nonetheless, in situ measurements, including tide-gauge networks, are fundamental to validate and complement the information retrieved by satellite-based measurements and models [73].

Data assimilation is an objective method to fill in the gaps in observations and combine these data with model information to provide an estimate of the likely state (and uncertainty) of the Earth system [92]. Additional sources of data are retrieved by citizen science low-cost sensors and local data provided by local environmental agencies, weather services, and consortia. These provide an opportunity to extend the range of observational networks available to society and, in particular, at spatiotemporal scales that are highly relevant to local-scale impact studies. Nevertheless, merging these data with traditional sources (in situ and satellite) is not trivial, as they need to satisfy essential standards and requirements to be assimilated [92]. In this framework, standards facilitate interoperability, usage, and facility to integrate with other data. Standards also enhanced the reusability and integrity of data underlying climate research.

Data should be available at a suitable scale to address a particular question. Observational marine datasets often provide insufficient spatial and temporal coverage to provide reliable statistics and the data needed for local coastal impact studies. To partially fill this gap, reanalysis and hindcasts are used as an alternative. These, along with historical time series, are needed for operational purposes on shorter time ranges (e.g., seasonal to multi-annual), such as those required for urban planning for data-sparse regions. Long-term projections are instead mandatory for longer-term erosion, e.g., to model coastal erosion and related protection or for adaptation plans and policies [93]. Moreover, in this context, for sea-level scenarios, there is a generalised lack of information on the temporal dynamics of sea-level changes [3]. Sources of temporal variability in sea-level projections, like mesoscale processes (El Niño) or interactions between tides and SLR [94], are often assumed to be stable in the future or considered as additional uncertainty [3,95].

4.3. Computational Challenges and Interoperability

The management of massive datasets and the algorithms involved in impact modelling and downscaling are complex and computationally demanding. Actually, this is part of the challenges of Big Data. Storage volume, process rate to transform data, data access, as well as visualisation are the main issues to be addressed [63].

Creating the conditions to combine climate and marine data with other sources to support the development of effective tools and models for climate change adaptation is fundamental. This allows interoperability to be achieved, using common conventions and standards to facilitate data use and accessibility [63,69]. In the SCORE project, interfacing between the SCORE database and other relevant multiple sources following an Open Science approach is foreseen through an ICT Platform. This will ensure data storage and single-point access to any relevant information for project users, which will constitute an efficient tool for sharing knowledge on climate and marine-related hazards in the CCLLs.

Another major challenge in this framework is the incorporation of continuously updated climate data into the system. In the SCORE project, the integration and representation of spatially distributed and real-time data derived from both institutional and cost-effective sensors will be simplified by the use of smart GIS-based tools such as digital twins and early warning support systems (currently in development). These data will be utilised to visualise CCLLs in both present and future scenarios, thus making the integration of low-cost citizen science sensors with weather forecasts and climate projections possible. The collected sensor data will be utilised in the tools within the digital twins and early warning support systems until the next maintenance cycle. These tools will measure specific parameters in various CCLLs, incorporating citizen science activities and diverse hydrodynamic models. The weather forecast acts as a dynamic input for the DT system, while the digital terrain model (DTM) used by models remains a static input. If, on the one hand, this can be seen as a potential shortcoming of the system, on the other hand, this offline mode enables environmental monitoring in a back-test scenario, evaluating model reliability and environmental resilience under varying weather conditions and modifications to urban infrastructures with a limited computational effort.

4.4. Fostering Interdisciplinarity

Data from climate services should be integrated with other information to improve transnational, national, and local (urban) climate change risk and vulnerability assessments. Adaptation services providing complementary information to climate services for different sectors (e.g., on cost loss–benefits assessments, tools, and policies) are crucial. Climate impact analysis requires an integrated interdisciplinary collaboration [12,96]. Intermediaries with knowledge of different disciplines could help in these cases. Intermediaries such as citizens, professionals, and scientists operating within the same sector might have different views on how to adapt to the sector's climate vulnerability, especially because they perceive the sector's ecosystem services differently (see [89] for the particular example of Adriatic food production through marine aquacultures). Acknowledging and including social and human sciences within climate action will strengthen climate resilience by empowering citizens and creating an integrated and focused network throughout society (see [89]). A framework for such participatory co-creation was recently developed by [97], while practical examples of co-created early warning adaptation pathways were recently published that included Living Lab and citizen science approaches [98,99].

Consequently, the interaction with other non-scientific disciplines will also advance climate services towards transdisciplinarity, facilitate mutual learning, and be of great help in translating knowledge into usable information [7]. Despite the call for the inclusion of social sciences in climate services over the past few years, the research mainstream is still strongly oriented towards natural sciences. Insights from social and human sciences may lead to achieving a smoother interface between data producers and users and to a more robust knowledge of climate service co-production [100]. Social sciences can contribute to the co-production, co-design, governance, and innovation of climate services by improving the accessibility of such services [69]. The CCLL concept in the SCORE project works towards this direction since it involves ongoing research, knowledge, and tools from different stakeholders dealing with interlinked environmental and socioeconomic issues [101].

4.5. User Engagement and Impact on Decision Making

A meaningful decision-making support service would demand an active role of scientists in understanding the governance and the context in which stakeholders and end-users operate. Researchers can help support decision making under uncertainties or lack of climate data availability. On the other hand, information has to be clear, and uncertainty must be communicated in a proper way to increase the effectiveness of actions [102]. Engaging different users to identify improvements to CCSs through co-design and co-production is crucial. Actually, user engagement goes beyond service distribution, rather aiming to improve the quality of climate services through the co-production of usable knowledge [69,100].

In this context, the role of the CCLLs is crucial as a "real-test" laboratory to develop alternative solutions to climate change adaptation. The Living Lab framework ensures enhanced end-user ownership of solutions through an integrative process. In the CCLL framework, there is a continuous exchange among the CCLL core team and involved end-users. The core team participates in the training and provides contact persons with technical backgrounds, and the users become co-designers and co-developers of smart solutions based on their own experience. By doing this, the possibility of success and acceptance of the developed solutions greatly increases.

4.6. Methodology Evaluation

As the CCLLs are supposed to be a through-time evolving collaborative of stakeholders, the metrics to assess the CCSs' effectiveness through the co-creative CCLL approach are acquired by analysing the number of non-project users and stakeholder identities linked to the CCSs, both during the remaining SCORE period and beyond, along with whether newly developed early warning support systems will be adopted, upscaled, upgraded, and used within the CCLL. Since these metrics are not yet available, the methodology can currently not be assessed as being useful or effective, but the current paper is trying to integrate CCLL input in the CCSs in development. Thus, the current paper should be considered more of a methodology proposal than a research paper.

5. Conclusions

This paper presents a framework for the preparation of a fit-for-purpose user-driven climate service to address coastal climate-related risks in urban areas. Building on previous experience in Europe and on the CCLL approach of the SCORE project, key user needs and requirements are delineated. As outlined in the previous paragraph, some important conclusions and answers to the initial research questions can be drawn from this work, as listed hereinafter.

The climate information available to date on coastal environments in Europe was gathered and provided to the CCLLs. The application and needs are geographically distributed across Europe, which renders the approach and underlying considerations transferable throughout urban coastal areas facing similar challenges, such as SLR, coastal floods, storms, and erosion.

This work showcased the requirements for the baseline characterisation of the historical period and for the climate projections of interest for the activities of the SCORE project by embracing the involvement of a large audience of different users.

Data selected and produced should be user-oriented, i.e., fit-for-purpose for specific applications at the local coastal scale, following appropriate specifications and standards. At the same time, the processing should be sustainable in terms of computational costs, timing of the activities and dedicated budget. The active involvement of the users in the engagement process through co-development and co-designing is crucial to better delineate their needs and specific actions at the coastal urban scale. The creation of a dedicated project data portal fulfils the need for a climate and marine data repository from relevant CCSs across Europe, thus facilitating consultation and use within the project to deliver project activities and, in particular, modelling.

One of the main challenges to be addressed in this context is reducing the gap between science data providers and end-users in terms of needs. This can also be achieved by enhancing the synergies between different research sectors, which can facilitate the translation of information to non-academic users and stakeholders. The research is supposed to guide users towards coastal models and products that are sufficiently accurate and spatiotemporally resolved to incorporate scenarios or projections of, e.g., SLR, coastal erosion, and flooding, and to respond to their needs. Another major gap is related to the sparseness and insufficient coverage of observational marine data. Nevertheless, CCSs and initiatives across Europe are trying to fill the gap.

In terms of the future perspective of SCORE's CCLL local climate services, while all of the previously mentioned issues will be addressed by establishing the CCSs for each of the 10 CCLLs within the next phase of the SCORE project, they will upgrade the current situation of CCSs in Europe, with the feedback of the collected experience of the SCORE project and in the light of ongoing experience of similar projects. The current work provides new insights about relevant users' requirements through the mediation of CCLL, which is a novel approach bridging the gap between data providers and end-users in coastal cities and creates challenges of providing tailored climate information to address climate change in different coastal contexts, like the 10 SCORE CCLLs, and across Europe. The analysis of coastal users' needs and technical requirements will, in time, define the tailored local-scale climate services for SCORE's coastal cities through a co-creative approach, but it depends largely on the further development of each CCLL and can only be finally assessed after the finalisation of the project. Thus, the project data hub developed as an approach here will identify user needs and indicate the needed parameters, tools, and products, as well as define the technical features, optimise data collection, and provide the best user experience for its CCSs, but the specific criteria and assessment details should be more readily available within some two years from now, and it is anticipated that fit-for-purpose CCSs will emerge, along with potential perspectives.

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