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Developing a cloud-based service offering actionable coastal climate risk and adaptation data across Europe

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HIGHLIGHTS

- Integrated Coastal Climate Services platform for European coasts.
- Co-designed user stories aligned with operational adaptation decisions.
- Cloud-based framework combining web viewer and coding environment.
- Integrated into EDITO for sustainable long-term operational uptake.

ARTICLE INFO

Dataset link: EDITO: https://coclico.lab.dive.edito.eu

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ABSTRACT

Coastal zones face increasing climate-driven hazards such as sea-level rise, storm surges, flooding and erosion, threatening infrastructure and ecosystems. Addressing the need for actionable climate information in adaptation planning, we developed an integrated Coastal Climate Core Services platform for Europe that consolidates sea-level projections, flood and erosion maps, exposure data, damage estimates, and adaptation options into a unified, cloud-based service. Co-designed with national authorities, municipal planners, and infrastructure owners, the platform offers an interactive web viewer for non-experts and a collaborative coding environment for advanced users. It delivers localized, FAIR(Findable, Accessible, Interoperable, Reusable)-compliant data supporting evidence-based adaptation planning and compliance with European frameworks. By bridging scientific data and operational climate services, this platform (https://platform.coclicoservices.eu) enhances climate resilience and informs strategic coastal risk management across Europe and shows how a broad-scale coastal climate service can be delivered.

1. Practical implications

Coastal areas across Europe are increasingly exposed to climate-driven hazards such as sea-level rise (SLR), storm surges, and coastal flooding. Despite substantial scientific advances, actionable risk information often remains inaccessible, scattered across various disciplines or overly complex for key decision-makers. The Coastal Climate Core Services platform addresses this gap by offering an open-access,

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user-oriented digital service that transforms scientific data into usable knowledge for adaptation planning at various spatial (national to local) scales.

The platform integrates state-of-the-art datasets – covering SLR projections, flood hazards, exposure, damage costs, and adaptation effectiveness – into six "user stories" designed around real-world decision-making needs. An intense iterative co-design process provided qualitative evidence that the platform architecture and functionalities aligned well with the operational needs of the intended end users. It offers two main interfaces: (1) a web viewer to explore interactive flood maps, risk indicators, and scenario comparisons, and (2) a cloud-based coding environment for advanced users to perform custom analyses using the full data catalog.

All data are served in open, cloud-native formats and follow the FAIR principles, ensuring interoperability and long-term usability.

National Authorities: Strategic Adaptation Planning National policy-makers require consistent, scenario-based data to develop long-term adaptation strategies. The platform allows users to compare flooding and damage estimates across future time horizons, under both unprotected and adapted conditions.

To illustrate, the Adaptation Cost-Benefit story helps quantify avoided damages and supports investment prioritization. These insights are particularly relevant for national climate adaptation plans and EU resilience reporting.

Cities and Towns: Local Risk Management Urban planners in coastal municipalities benefit from local-scale data that are often difficult to compile independently. Through the web viewer, users can identify vulnerable districts, infrastructure, and populations, as well as explore SLR and storm surge impacts for mid- and late-century scenarios. In addition, they can assess the benefits of local adaptation options.

For example, a planner may assess how a 100-year flood in 2050 could impact specific urban zones, then use that information to prioritize investments or communicate risks to stakeholders. The platform's maps and statistics help translate climate data into public-facing material for planning consultations and resilience strategies.

Infrastructure Owners: Risk identification Private owners of critical infrastructure (e.g. ports, energy facilities) are increasingly required to assess climate-related risks and disclose them in financial and regulatory frameworks. The platform allows asset managers to quantify exposure to flooding under various climate scenarios, estimate potential damages in monetary terms, as well as evaluate adaptation options based on cost-effectiveness and return periods.

For instance, a port authority might use the Damage Costs user story along with the critical infrastructure and flood map layers to assess whether to relocate port infrastructure (buildings) in the future, given projected storm surge and sea-level rise.

Flexible Access for Technical and Non-Technical Users

The platform was designed to serve a diverse audience. Non-expert users can access pre-processed risk layers via a visual, intuitive interface. Meanwhile, technical users can query and analyze the underlying datasets – delivered in formats such as GeoTIFF, Zarr, and Parquet – through a Jupyter-based coding environment. Tutorials and documentation are provided to lower the barrier to entry and support reproducible workflows.

Scalability and Integration

Developed using open standards and a cloud-native architecture, the platform has been adopted into the European Digital Twin of the Ocean (EDITO) framework. This ensures alignment with broader EU digital infrastructure and enables long-term scalability, sustainability, and cross-sectoral integration.

Conclusion

The CoCliCo platform provides a practical, scalable solution for making climate risk information accessible and actionable at multiple decision levels. By combining visual tools, socio-economic metrics, and co-designed user stories, it enables more informed coastal adaptation planning across Europe — from national strategies to local interventions. As climate pressures intensify, a climate service like this are essential to support evidence-based resilience investments and policy decisions.

2. Introduction

Coastal areas are among the most climate-vulnerable regions globally, facing increasing hazards including sea-level rise (SLR), storm surges, erosion, and coastal flooding. In Europe, more than 50 million people live in low-lying coastal zones (below 10 m elevation), with approximately 670,000 currently exposed to a 1-in-100 year flood event (IPCC, 2023).

Projections indicate that global mean sea level could rise by up to a meter or more by 2100 under high-emissions scenarios (IPCC, 2021). In combination with potential changes in storm characteristics, this implies that coastal flood events currently considered rare (e.g. 1-in-100 year events) are expected to occur more frequently in the future, highlighting the urgent need for robust adaptation strategies. Consequently, decision-makers at national, regional, and local levels require timely, tailored, and actionable climate information to effectively manage these coastal risks (Le Cozannet et al., 2017; Oppenheimer et al., 2019).

The concept of climate services has evolved significantly over the past decades. It has roots in meteorological services dating back to the early 20th century, traditionally providing weather forecasts to support agriculture and transportation (WMO, 2014). From the 1990s onward, rising awareness of climate variability and climate change motivated initiatives to deliver seasonal climate predictions, initially aimed at climate-sensitive sectors such as water resources, agriculture, and disaster risk management (Hewitt et al., 2012). This period also saw the formalization of climate services as a framework for providing science-based, user-oriented climate information, culminating in the establishment of the Global Framework for Climate Services (GFCS) under the World Meteorological Organization in 2009 (WMO, 2014; Vaughan and Dessai, 2014). Since then, climate services have progressively expanded in scope to include multi-decadal climate change projections and sector-specific impact information, with a strong emphasis on co-production and stakeholder engagement to ensure relevance and usability (Street et al., 2015; Bruno Soares et al., 2018; Lavoie et al., 2024).

Despite these advances, relatively few climate services have addressed coastal climate risks specifically (Le Cozannet et al., 2017; Haasnoot et al., 2020), even though these pose substantial challenges to societal and economic resilience (Nicholls et al., 2021). Existing coastal climate information is often fragmented across scientific studies, engineering assessments, policy documents, and technical datasets (Ballinger and Dodds, 2020), making it challenging for practitioners to synthesize this knowledge into consistent, actionable guidance. This gap is particularly urgent at the local to regional scales, where urban planners, infrastructure managers, and national authorities must make investment and land-use planning decisions grounded in reliable, spatially explicit data (de Ruig et al., 2019; Hinkel et al., 2018).

Coastal climate services aim to address this gap by providing customized coastal hazard and adaptation information to key stakeholders. However, the effectiveness of these services depends greatly on how the information is delivered. Both custom-developed open-source geo-information systems and commercial web-based tools are currently the most established technologies in this field. Since the late 1990s, the development of the Extensible Markup Language (XML) has enabled the integration of spatial and non-spatial data for visualization and querying on the internet (Skoulikaris and Ganoulis, 2014). As a result, georeferenced web-based information systems have become the standard for data sharing, integrating a range of advanced computing technologies

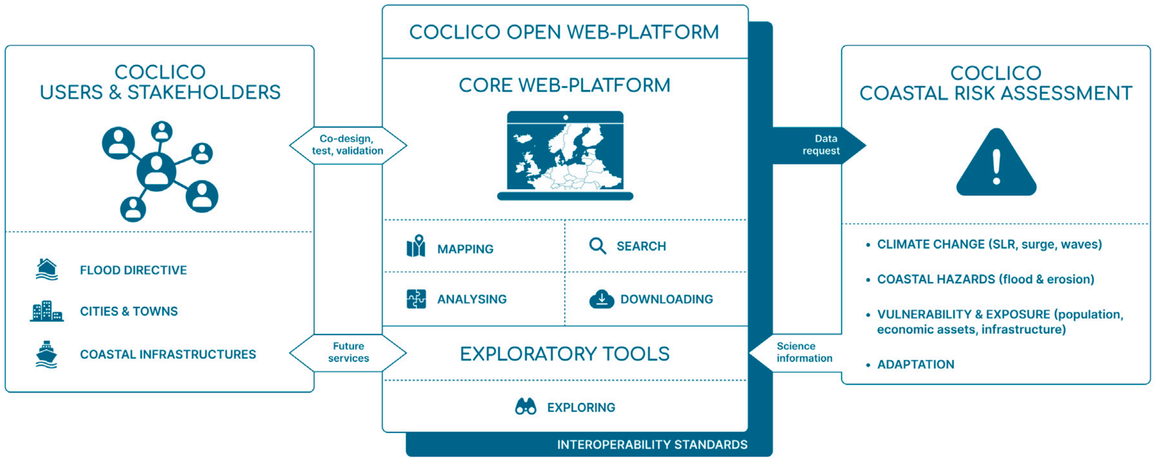

Fig. 1. The coastal climate service concept of linking users and stakeholder to coastal risk assessments through the web platform.

and programming languages across both terrestrial (Sermet et al., 2025) and coastal environments (Paranunzio et al., 2024).

The platform described in this paper is a new open-access Coastal Climate Services platform developed under the EU-supported H2020 CoCliCo project, to improve coastal risk management and adaptation across Europe. This paper presents the design, development, and initial implementation of a European Coastal Climate Services platform that delivers consistent, transparent, and user-oriented coastal hazard and adaptation information to decision-makers at multiple scales. The following sections describe the platform's data architecture, functionalities, and service components — including its cloud-native infrastructure, SpatioTemporal Asset Catalog (STAC)-based data catalog, and hybrid user interfaces. We also demonstrate how the platform addresses diverse user needs through co-defined user stories with Champion Users representing different stakeholder groups, and evaluate the potential of this approach to enhance evidence-based coastal climate adaptation by providing standardized, accessible, and actionable climate risk information across Europe.

3. Platform overview and user-centered design

The Coastal Climate Services (CoCliCo) platform (hereafter the platform) provides consistent data and tools on present and future coastal risks, helping to bridge the gap between climate science and decision-making. It is designed to support coastal adaptation planning at multiple scales – from national policymaking to local urban planning and infrastructure management – by integrating state-of-the-art datasets and models into user-friendly services. Ultimately, the platform's mission is to transform scientific data into 'understandable, actionable knowledge', enabling a broad spectrum of users to identify risk hotspots, explore plausible future scenarios, and develop evidence-based adaptation strategies for Europe's coastal zones.

The platform combines novel data and knowledge on coastal risks and adaptation, geospatial data management and user-oriented decision analytics (Penning-Rowsell et al., 2023; Hinkel et al., 2019). In doing so, it recognizes that a successful climate service is intended to improve climate-sensitive decisions by making climate information 'useful, usable and used'. Effective co-design is a pre-requisite to achieving this goal and setting out a common understanding (between provider and user) of 'what it is that is being designed' and for what purpose, with an explicit focus on providing a coastal information web-platform (Fig. 1) to inform coastal adaptation to SLR. The platform was co-developed with end-users to ensure it meets real-world decision-making needs. During development, we engaged "Champion Users" from three target groups — national policymakers, municipal coastal planners, and infrastructure operators. Through close collaboration and progressive reviews we worked with the Champion Users to co-define six representative user stories to maximize the utility of the platform. Each user story captures a common task or challenge faced by coastal stakeholders, guiding the platform's features and data outputs. These user stories (detailed later) include, for example, assessing SLR projections, mapping flood extents for extreme storm events, estimating exposed assets/populations, and evaluating cost-beneficial adaptation measures. A user story typically presents statistics per administrative unit: either municipalities (LAU, 2020: Local Administrative Units), regions (NUTS2, 2021: Nomenclature of territorial units for statistics) and countries (NUTS0, 2021). This is one of the outcomes resulting from the early involvement of end-users, confirming that the platform embraces a user-driven approach common in modern climate services.

The co-design process with Champion Users has shaped the platform's priorities and interface to be fit-for-purpose for each user category through a progressive process of initial co-design (to understand the main challenges and state-of-the-art used in practice), refinement (as the platform evolved to enable users to influence design choices), and a final stage of validation (to confirm suggestions had been acted upon and where future development priorities may lie). Recognizing that SLR is a significant challenge for all those with an interest in managing coastal risks, the co-design approach segmented the decision space into three distinct areas to capture the wide spectrum of coastal decision-makers, through three perspectives to enable core requirements to be distilled, namely:

- **National Authorities** (Policymakers and Regulatory Agencies): These users need broad-scale assessments to inform national policy (e.g. compliance with the EU Floods Directive, e.g. Le Cozannet and Cazenave, 2024) and identify coastal risk 'hotspots'. An ability to evaluate flood risks at national/regional scales, map flood hazard extents, and quantify exposed populations and assets, supporting the development of flood risk management plans is central requirement to appropriate national planning (e.g. Sayers et al., 2022). For instance, a ministry can use the platform to visualize projected flood zones under future SLR and storm scenarios, helping prioritize where to invest in adaptation, including defenses or updated land-use plans. This supports strategic planning and ensures policy decisions are grounded in up-to-date climate risk data.
- **Local Authorities** (Urban Planners in Coastal Cities and Towns): City and town planners require high-resolution, locally relevant information to design adaptation strategies and protect their communities (Jenkins et al., 2024). Tools that translate complex

climate data into planner-oriented, decision-relevant formats are critical for integrating climate risk into urban planning processes, as demonstrated in studies on urban climate services for collaborative adaptation planning (Giordano et al., 2020). The platform allows municipal users to perform city-scale coastal risk assessments, pinpointing vulnerable neighborhoods, critical infrastructure, and populations under various SLR and storm scenarios. By providing tools to explore local flood extent maps, erosion trends, and the benefits of nature-based solutions, it helps urban planners craft tailored resilience actions. For example, a coastal city can assess how a 100-year storm surge in 2050 might inundate certain districts, then use that insight to evaluate and compare potential adaptation responses, such as spatial planning measures, upgraded drainage systems, ecosystem-based approaches, or flood protection infrastructure — depending on local objectives and constraints. The platform's data-driven visuals and maps make it easier for local officials to communicate risks and engage the public and elected leaders on adaptation plans.

- **Infrastructure Owners and Managers**: Operators of ports, roads, industrial facilities, and other coastal infrastructure need to ensure the long-term continuity and safety of their assets (Jenkins et al., 2025; Koks et al., 2023). The platform helps these users analyze how coastal hazards (flooding and erosion) could impact specific infrastructure sites and what adaptation measures are cost-effective. For instance, a port authority can evaluate future flood depths across its terminals under different protection levels, or a rail network manager can identify stretches of track at risk from coastal erosion. By providing targeted hazard information and risk metrics, the platform informs operational decisions and investments in protective measures, enhancing the resilience of critical infrastructure.

Notably, the platform is also a valuable tool for broader communities, including climate scientists, consultants, academics, practitioners, and insurers, who can use the web-based map viewer, its data and analytical coding hub (Section 5.4) for more detailed studies. Besides, it can serve an educational role in postgraduate training. In summary, the platform was designed with a matrix of needs in mind, aiming to support high-capability users who need detailed analytics as well as high-level users who benefit from ready-made maps and simplified indicators (Fig. 2). By tailoring outputs to multiple end-user types, the service maximizes its relevance and uptake in the coastal adaptation domain.

4. Data products and climate information offered

A core strength of the platform is the breadth of coastal climate data that it consolidates and delivers in an integrated, consistent way. All datasets are organized in a structured SpatioTemporal Asset Catalog (STAC), which facilitates efficient search, retrieval, and standard metadata for the geospatial assets. STAC is a standardized metadata description that is used both by the high-level front-end (web-based map viewer) as well as the low-level API, and minimizes data duplication. It is a light layer around the heavy data that enables data usage at multiple levels. The catalog underpins the platform's data offerings, which span the following four thematic categories:

- **Sea-Level Rise Projections:** Regional and global SLR projections based on the latest Intergovernmental Panel on Climate Change (IPCC) scenarios (e.g. AR6 SSP pathways, plus high-end scenarios IPCC, 2023) that provide estimates of future mean sea level up to the year 2150. These projections incorporate the major components (thermal expansion, ice sheet and glacier melt, land water changes, see Melet et al., 2024) and apply regional adjustments (vertical land movement related to e.g. glacial isostatic adjustment Thiéblemont et al., 2024) for Europe. Users can explore multiple scenarios (from low-emission to high-emission and a high-impact low confidence scenario considering rapid changes and the collapse of melting ice sheets) and time horizons, viewing results as maps or graphs of sea-level change. In addition, it features future storm surge and extreme sea-level statistics, Total Water Levels (TWL) for various return periods, and drivers of the TWL. This informs long-term planning by indicating plausible ranges of SLR for specific coastal locations.
- **Coastal Hazards — Flooding and erosion:** This category includes data and model outputs characterizing extreme water levels, flood extents and erosion at the coast. It presents high-resolution (25 m) flood inundation maps for coastal flood events (Cotrim et al., 2026). The flood maps show the extent and depth of flooding for combinations of storm conditions (Cotrim et al., 2025a) and SLR, produced through large-scale 2D flood simulations. They account for tides, storm surges, wave setup, and even potential coastal defense overtopping or failure, to depict realistic flooding scenarios (Cotrim et al., 2025b). For example, a user can select a 100-year storm event in the year 2100 under a high emissions scenario and visualize which areas along the European coastline would be underwater (including depth), both with and without existing coastal defenses. Crucially, the platform provides flood statistics aggregated by administrative units (e.g. by municipality or province), such as the number of people or buildings exposed in each area. This helps policymakers quickly identify the hardest-hit localities and supports requirements under the EU Floods Directive to assess and map risks at various scales. Land use and coastal vulnerability information (such as an erosion susceptibility typology are also included based on (Hanson et al., 2026) to indicate how vulnerable locations are to hazards. The data on coastal change (Calkoen et al., 2025) informs the user whether erosion may jeopardize the first line of flood defense, making the area more vulnerable to flooding in case of no adaptation.
- **Exposure and Vulnerability Data:** To estimate impacts, the platform includes layers on the exposure of assets and populations in coastal zones. High-resolution datasets of buildings, infrastructure networks, and population distribution are integrated, for both present day and future projections. For instance, it uses building footprint data (e.g. OSM-derived or national data) and critical infrastructure locations to identify assets in harm's way (Ye et al., 2025). It also incorporates socio-demographic projections of population change in coastal areas, since future exposure depends on where people live and work. Combining the hazard maps with these exposure layers allows the platform to quantify, for any scenario, how many people, buildings, or infrastructure elements would be impacted. For example, a user story focuses on "Building Exposure" – enabling one to map all buildings within projected flood zones for a given event, highlighting at-risk infrastructure.
- **Risk and Adaptation:** Beyond identifying exposed assets, the platform estimates potential impacts and economic damages from coastal flooding. Using established impact models and vulnerability curves, it translates flood hazards into metrics like expected economic damage to buildings/infrastructure and affected population counts. One of the user story layers specifically provides damage cost assessments for exposed infrastructure under various flood scenarios. These datasets help stakeholders understand the scale of potential losses (e.g. in euros of damage) associated with a given coastal hazard scenario. By integrating exposure, depth-damage functions, and asset values, the platform can map where the highest losses would occur if, say, a 1-in-100 year storm surge strikes in 2050. Such information is vital for cost–benefit analysis of adaptation measures. Importantly, the platform not only maps hazard and risk information, it also informs coastal adaptation. A dedicated data layer category is for adaptation planning (Völz et al., 2025), which currently includes analyses of raising coastal

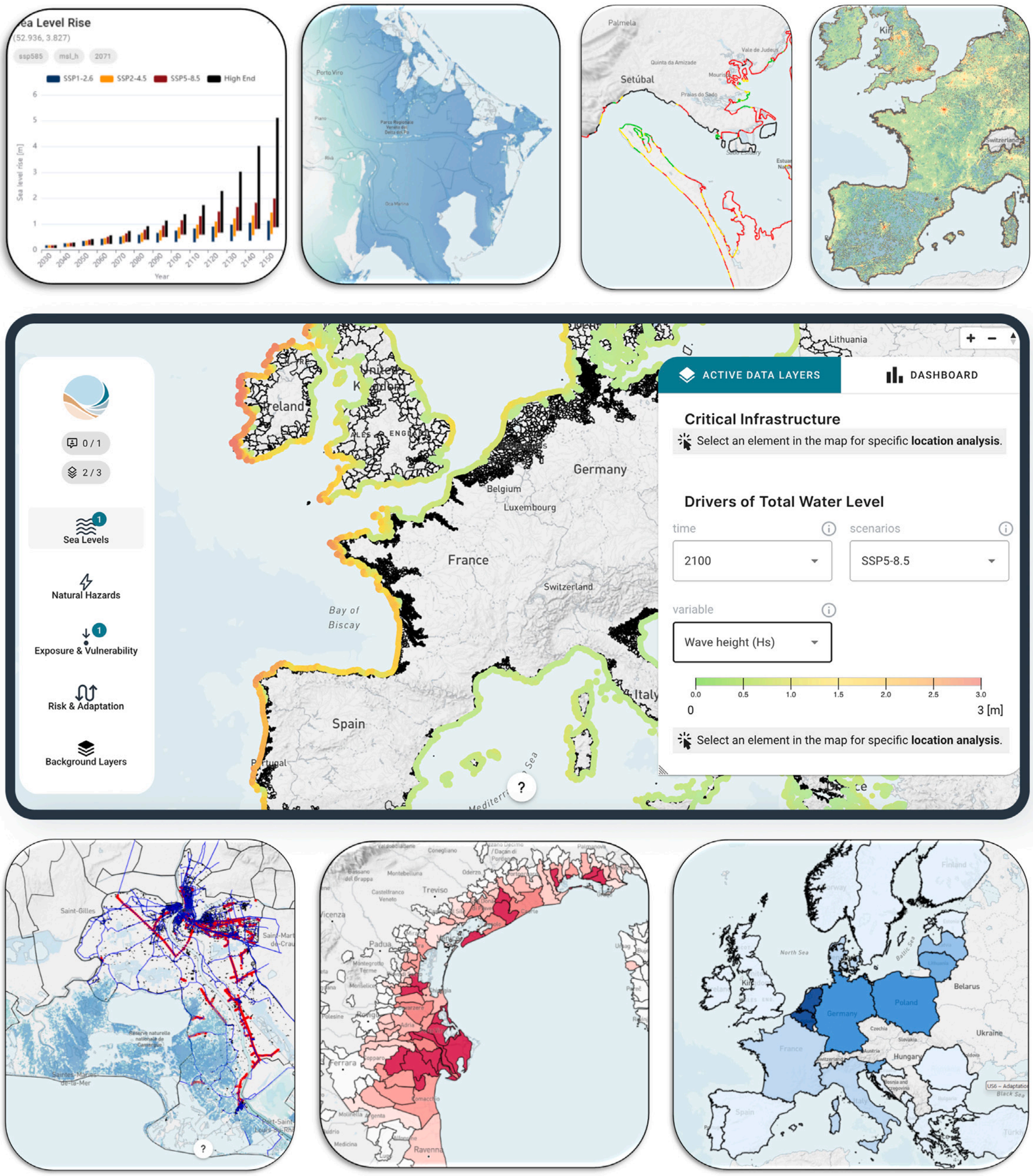

Fig. 2. Compilation of visuals of the Coastal Climate Services (CoCliCo) platform interface. The web-based map viewer (central panel) allows users to toggle between thematic categories (Sea Levels, Natural Hazards, Exposure & Vulnerability and Risk & Adaptation) and User Stories (e.g., SLR projections) or data layers. The interface supports interactive exploration, with options to adjust scenarios, time horizons, and view summary statistics as well as graphs or add layers to a dashboard. Such a design enables decision-makers to visualize complex climate data intuitively. The top row shows examples of the hazards (SLR, flood maps, coastal change) and population dynamics, while the lower row shows visuals of respectively infrastructure overlayed with a flood map, damage costs of exposed buildings aggregated to LAU level, and cost-benefit adaptation strategies at country level, respectively. The web platform can be found at: https://platform.coclicoservices.eu.

defenses and their cost-effectiveness. For example, at the scale of countries, a cost–benefit analysis dataset evaluates raising dike heights under different climate and socioeconomic scenarios. This helps identify where investing in higher protection yields economic benefits (avoided damages) that outweigh the costs. One of the six user stories is "Adaptation based on cost–benefit analysis", giving end-users a scenario of optimal protection levels: e.g. how a maximum protection standard in a given area would reduce expected damages by a certain amount. By visualizing side-by-side scenarios (e.g. no adaptation vs. improved defenses), the platform highlights the potential payoff of enhancing resilience measures. Decision-makers can thus use these tools to prioritize adaptation options that are most efficient in reducing risk.

In total, six User Story layers were derived to synthesize the above data into ready-made scenario maps. These user stories are:

- Sea-level rise (projections);
- Flood perspectives - inundation distribution during a flood event;
- Building exposure - projections of exposed buildings;

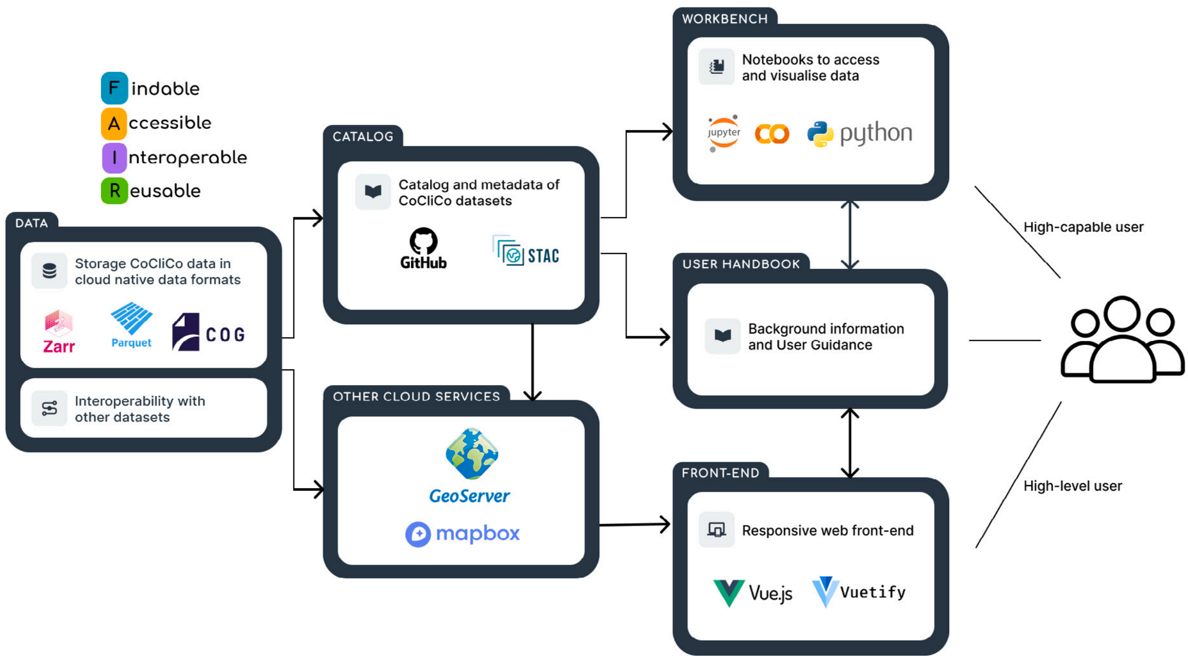

Fig. 3. Overview of the platform's architecture highlighting the different components and their connections as well as the links to different types of end-users.

- People exposure - projections of exposed people;
- Damage costs (of exposed buildings);
- Cost–benefit analysis (of coastal adaptation).

Each User Story represents a common question a user might ask. For example, "What are the expected flood extents and depths in my region for a 100-year storm in 2050?" would be answered by the inundation user story; or "How many people and assets would be affected, and what would the damages cost, under that scenario?" answered by the exposure and damage cost stories; and "How much risk reduction would a certain dike upgrade achieve by 2100?" answered by the adaptation story. By packaging complex analyses, overlaying multiple data layers, into these pre-cooked thematic stories, the platform makes it easier for non-experts to obtain insights quickly. Simultaneously, all underlying data and methods are transparent and accessible for experts who want to dive deeper. The next section describes the innovative infrastructure enabling this balance of interactive simplicity and analytical power.

An important aspect of the platform is the explicit consideration of uncertainty in future coastal risk assessments. The underlying datasets are generated using a consistent set of integrated scenarios that combine climate pathways (RCPs), socio-economic pathways (SSPs), time horizons, return periods, and adaptation assumptions, thereby spanning a broad range of plausible future conditions. Rather than presenting a single deterministic future, the platform enables users to explore how projected hazards, exposure, damages, and adaptation effectiveness vary across alternative scenarios. Within the web viewer, users can interactively compare combinations of scenario parameters through maps, statistics, and dashboards, while the Workbench provides advanced users with direct access to the underlying datasets for more detailed uncertainty analyses, including comparisons of uncertainty ranges in climate projections. In doing so, the platform supports exploratory adaptation planning under uncertain future climate and socio-economic conditions, helping users assess the robustness of decisions and reduce the risk of long-term lock-in.

5. Cloud infrastructure and innovative framework

Delivering the rich data described above in an accessible yet flexible manner required a novel, cloud-based architecture. The platform is built on a modern cloud infrastructure that hosts all data products and provides tools for on-demand analysis, aligning with Open Science and FAIR data principles. The modular approach of the platform architecture enables the independent scalability of both front- (web-based map viewer) and back-end (data & catalog), as well as the use of any with other infrastructures/services (interoperability). Fig. 3 below captures the platform's key components and 4 shows a visual of the outcome for the CoCliCo project. Each component is elaborated in the following sections.

5.1. *Catalog: SpatioTemporal asset catalog (STAC)*

At the core of the platform's architecture is a STAC that connects all components. The STAC is essentially a standardized metadata catalog for all data assets, including raster layers, vector layers, and time-series, enabling interoperability and efficient search. By adopting the STAC specification, the platform ensures that each dataset (each 'spatiotemporal asset') is described with consistent JSON metadata (including spatial/temporal extent, resolution, and license) and can be indexed and searched uniformly. This standardization is key to the FAIR data principles — making data findable and accessible to users via open APIs. Furthermore, the platform provides a RESTful STAC API that external applications or users can deploy to search and retrieve data programmatically (following Open Geospatial Consortium (OGC) API standards). By using STAC, the developers avoid the need to build a custom data API from scratch; instead they leverage a robust, widely-used framework (also employed by e.g. Google and NASA) that is highly scalable and interoperable. For example, data can be queried by area, time or property using standard STAC queries, and many existing tools can directly read STAC catalogs.

5.2. *Data: Cloud storage and data formats*

Equally important is the way the data are stored and served. The platform uses cloud-optimized data formats and cloud storage to handle large geospatial datasets efficiently. Many datasets (especially large gridded datasets like climate projections or flood maps) are stored as Cloud Optimized GeoTIFFs (COGs), in multi-dimensional Zarr format or tabular Parquet files on cloud object storage. These formats are cloud-native, meaning they can be accessed via HTTP range requests served

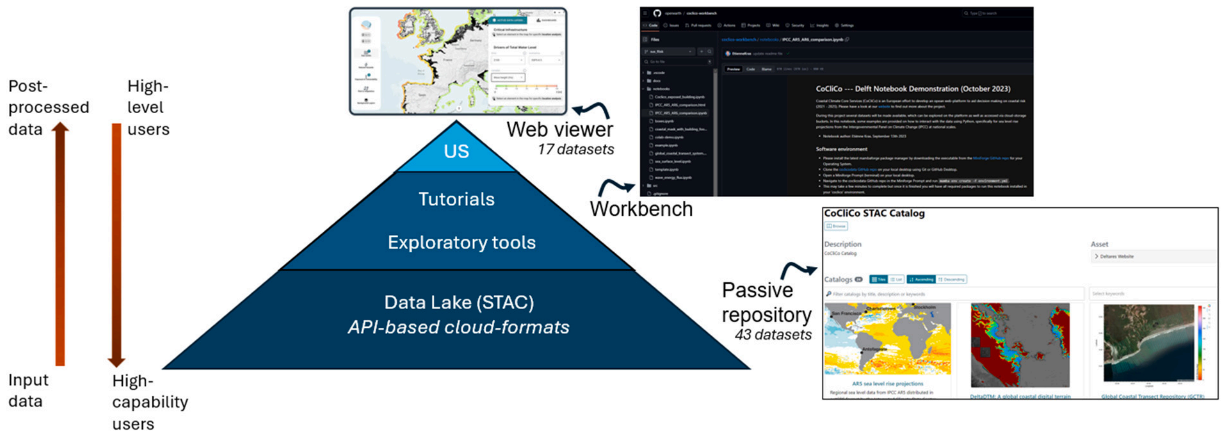

Fig. 4. Data pyramid and platform components (from top to bottom or high-level to high-capability users: front-end with User Stories, workbench with Tutorials and Exploratory Tools and data & catalog with API-based cloud-formats). The small insets represent screenshots of the components in this figure. The CoCliCo STAC catalog contains 43 datasets (input data) of which 17 datasets are post-processed to be web-viewer data layers or dedicated user stories.

by GeoServer and allow partial loading (so a user can retrieve just a small tile or a subset of a dataset without downloading it all). The use of cloud object stores (for example, Google Cloud Storage buckets for large arrays) and tiling services (e.g. MapBox for pre-rendered map tiles and Geoserver for OGC compliant services) means that even continental-scale datasets can be viewed quickly in the web interface without heavy local processing. For instance, national authorities can pan/zoom a map of Europe's flood zones seamlessly, because the flood data have been preprocessed into tiled layers at multiple zoom levels and served via a tile service for smooth visualization. Meanwhile, the full-resolution data remain accessible on the cloud for analysis. All data ingested are also made CF-compliant (Climate and Forecast metadata conventions) and follow standardized vocabularies, such as CMIP6 variable names, ensuring scientific compatibility.

5.2.1. Data fairness and standards

A brief but decisive point is that the platform was built following best practices in data management, in compliance with the FAIR principles. Each dataset has rich metadata, DOIs where applicable, and standardized formats like Parquet, GeoTIFF, or Zarr. Conversions are done to ensure consistency (e.g. many original NetCDF datasets were converted to Zarr for cloud efficiency, with checks on CF-compliance), as well as to create lighter data formats for visualization. As a characteristic example, NetCDF files of approximately 7.5 GB were converted to about 1.8 GB Zarr, corresponding to a compression of roughly 76%. At the same time, raster files in typical GeoTIFF formats of 5.1 GB were transformed into COG files of 0.6 GB, enabling rapid visualization, data overlaying, and spatial analysis requests by users. By doing so, the platform not only serves its own application, but effectively creates a coastal climate data repository that others can easily use. In the long term, this could feed into broader European climate data platforms (e.g., Copernicus Marine Service or a Copernicus Coastal Hub) or digital twin initiatives, illustrating how targeted climate services can complement larger data ecosystems. The platform is also part of a cluster of EU projects (e.g. collaborating with projects like SCORE, PROTECT, and others) aiming to build an "ecosystem" of coastal adaptation services — sharing knowledge and ensuring interoperability across efforts.

5.3. Front-end: Map viewer

The platform front-end is a web-based map viewer that any user can access through a browser. It provides interactive maps, layer selection menus, scenario sliders, and simple analytics (charts, summaries). Users can overlay multiple layers (e.g. viewing flood depth with population density) and obtain statistics at specific locations or administrative units. The viewer highlights the results of the six user stories at the appropriate spatial scale. For example, a city planner can click on their municipality (the Local Administrative Unit, LAU) and see summary statistics like number of buildings in flood-prone areas or expected annual damage cost in that area — derived from the underlying data. The latter ability to get statistics per administrative unit could be valuable for local decision-making and reporting. The web interface is designed to be intuitive for non-experts, with informative tooltips, a tour and "story" narratives that guide the interpretation of each layer. Hence, not all data present in the data catalog is present on the map viewer (see Fig. 4). The users can also access the Handbook (Section 5.6) to be guided through a detailed overview of the functionalities of the platform and how to use them. A key feature is the interactive dashboard capability, where users can add multiple layers or indicators and create a custom dashboard for their region of interest, facilitating comparisons between scenarios or over time.

5.4. Workbench: Collaborative coding hub

For more advanced users, such as researchers and technical staff, the platform offers a collaborative cloud-based coding hub, referred to as the 'Workbench'. This is essentially a collection of notebooks, under git version control, hosted on an open server (Github) pre-configured with access to all the platform's data via the STAC API. Expert users can launch interactive notebooks (for instance via Binder or Google Colab integration) that come with the necessary Python libraries and example scripts to query and manipulate the datasets. Through the Workbench, users can write custom code to perform analyses beyond the canned user stories, i.e. Exploratory Tools. For example, running a tailored flood frequency analysis for a specific subregion, or cross-comparing platform data with their own local datasets. The STAC catalog can be accessed directly from these notebooks, allowing users to browse available datasets without downloading them in full. They can pull in only the required portion of data (benefit of cloud-optimized formats) and apply their analysis. This approach brings the computation to the data, avoiding the need for users to handle large files on their own machines. Moreover, the workbench environment is integrated with version-controlled repositories (GitHub), so users can share their notebooks, reproduce each other's analyses, and collectively improve the code base. This encourages a collaborative community around the platform and ensures analysis workflows are transparent and reproducible (a key aspect of FAIR services). Notably, by providing both a friendly web GUI and a programming interface, the platform caters to a wide audience — from decision-makers who just want a quick answer, to data scientists who want to deeply engage with the data.

5.5. Cloud services for efficient visualization

To support efficient visualization on the web, the platform leverages additional cloud services. Map tile layers are generated and hosted through services like Mapbox and Geoserver, which provides standardized visualization templates and high-performance map delivery. The flood and hazard maps, for example, are pre-rendered into tile sets (with styling for depth ranges) and served via Geoserver tiling, so that when a user toggles on a layer, the map loads quickly. The base maps and background layers (e.g., administrative boundaries, satellite imagery) are also integrated via these services. The architecture is modular and scalable — new data layers can be added to the STAC catalog and immediately become available through the same framework, and the cloud infrastructure can scale to accommodate increased user uptake or data volumes. The entire platform is being developed as open-source software, which means the code for the front-end and the analytical tools are openly available, encouraging community contributions and transparency (see on Code Availability).

5.6. User handbook

To assist the platform user to navigate through the viewer and how to use the information, a digital User Handbook was developed and is easily accessible via the platform. This handbook shares background information related to the datasets and links to resources and associated documentation to assist in understanding the data. Also a direct link to the Data Catalog (STAC) is embedded to enable a direct access to the underlying datasets. Furthermore, an explanation on the use of the Workbench and its Exploratory Tools is included. This involves details on running Python Notebooks through either online coding environments or through an offline (local) setup.

6. Outputs of the climate service

In the subsections below we detail the outputs of the climate service, starting from high-level (user story highlights) to high-capability (exploratory tools) user output.

6.1. User story highlights

To illustrate how the platform brings together data for end-users, we present an example of a coastal flood risk user story output. In Fig. 5, the platform's flood mapping capability is demonstrated for a location in Normandy, France under different adaptation scenarios.

This example underscores the platform's utility in translating complex model outputs into decision-relevant visuals. A policymaker could, for instance, use such maps to argue for higher investment in coastal defenses in certain provinces, by showing the reduction in flood extent (and by extension, reduced exposure of communities) between the unprotected and protected scenarios. Similarly, an infrastructure manager might focus on the left panel to see worst-case flood extent and ensure critical facilities outside the protected zone have contingency plans.

Other user stories provide analogous insights: the 'Sea-level rise projections' story offers graphs and maps of how sea levels rise under each climate scenario, often informing questions about planning for different time horizons (e.g., what does 0.5 m of SLR mean for our city's port by 2070?). The 'Building exposure' and 'Population exposure' stories produce choropleth maps indicating the number of buildings or people in flood-prone zones, enabling quick identification of the most exposed municipalities or city districts – valuable for emergency preparedness and adaptation resource allocation. The 'Damage costs' story assigns monetary values to those exposures, translating hazard scenarios into estimated economic impact (which can support cost-benefit evaluations and raise awareness of the potential 'cost of inaction'). Finally, the 'Adaptation cost-benefit' story goes one step further to compare the damage avoided vs. cost incurred by specific adaptation investments, helping users quantitatively assess the costs, benefits, and timing of different adaptation options under varying future risk scenarios.

All these functionalities are accessible within a single platform, providing consistency (e.g. the same SLR scenario feeds both the hazard and impact analyses) and ease of use. This integrated approach is a marked improvement over the fragmented tools often used in the past, where practitioners might have had to manually gather data from disparate sources and run their own analyses. By co-designing the user stories with stakeholders, the platform ensures that these outputs align with practice – for example, informing EU Flood Directive reporting, municipal climate adaptation plans, or infrastructure risk assessments in the private sector.

6.2. Tutorials

The Workbench includes a dedicated set of tutorials that guide high-capability users in accessing and analyzing the platform's coastal climate data using programmatic tools. These tutorial notebooks provide short, practical examples on how to configure and interact with the CoCliCo STAC data repository, illustrating workflows for different data types such as Cloud Optimized GeoTIFFs (CoGs) rasters, Zarr multi-dimensional arrays, and Parquet tabular datasets. The tutorials are designed to support both online coding environments (e.g., Google Colab or Binder) and offline local installations, enabling users to explore platform datasets, query the STAC catalog, visualize results, and build customized analyses beyond both the predefined user stories in the web-based map viewer as well as developed Exploratory Tools. By offering step-by-step instructional notebooks, the workbench tutorials lower the barrier (also for interested high-level users) to enter advanced data exploration and support reproducible research using the platform's FAIR-compliant data assets.

6.3. Exploratory tools

Some user needs identified through the course of the project have been defined as Exploratory Tools within the Workbench, as these services were too specific to be implemented in the web-based map viewer but could potentially support future services. The Exploratory Tools typically consist of fully developed Jupyter notebooks designed to allow users to interact with the data through STAC APIs for their own needs. The Exploratory Tools that are currently implemented include for example code to aggregate population, buildings or networks exposure to coastal flood scenarios at various spatial levels (i.e. from LAU to NUTS-0), or to explore the details of the cost-benefit analyses (user story 6) at finer temporal and spatial scales. Exploratory Tools are also conceived to allow users to interact with the core platform using their own input data. As an example, we designed an exploratory tool that enables users to use their own high-resolution (1-m instead of 25-m) coastal flooding simulation results (as geospatial layer) to estimate potential damage costs to buildings following the CoCliCo risk analysis approach. In the area of coastal adaptation, this type of interlinkages between high-resolution locally-owned datasets and stakeholder tools alongside broad scale data is considered critical for the success of coastal climate services because using higher resolution digital elevation models and more precise information on coastal defenses usually improves flood modeling results significantly (Chaumillon et al., 2017). In addition, broad scale data can also be used as boundary conditions for high resolution adaptation exploration tools (e.g. Future Flood Explorer (Sayers et al., 2020), applied with the Fens case study (Jenkins et al., 2024)). Exploratory Tools also include a notebook to visualize and compare sea-level projections from IPCC's (Intergovernmental Panel on Climate Change) AR5 (Church et al., 2013) and AR6 (Fox-Kemper et al., 2021), allowing users to determine to what extent the scientific understanding on projected sea-level changes has evolved over the last decade in their region of interest (Fig. 6).

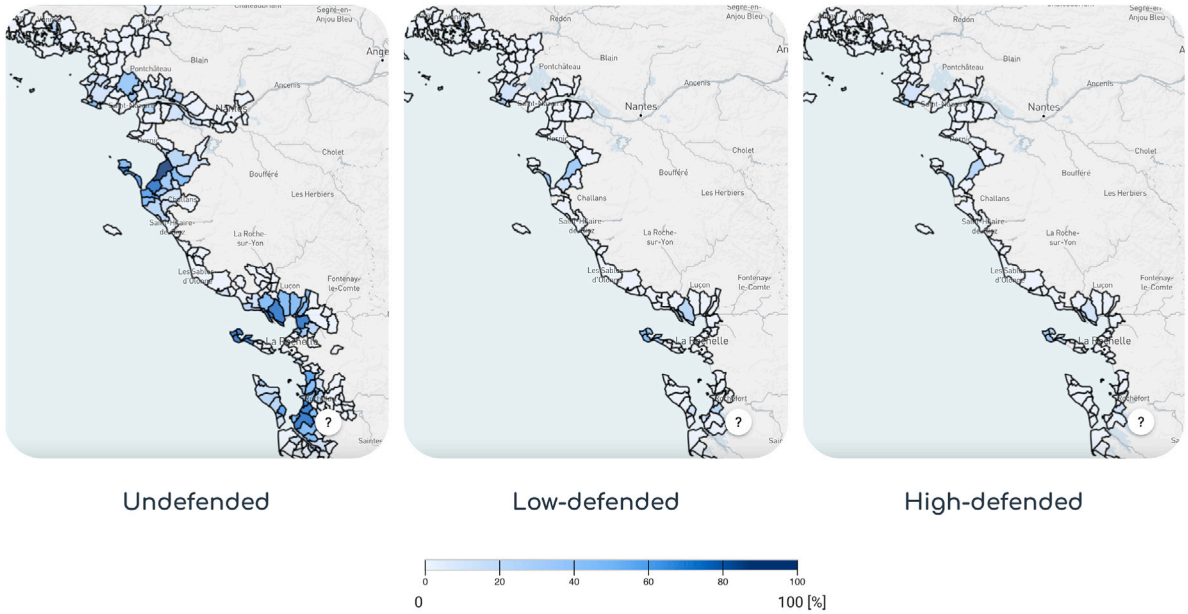

Fig. 5. Example output from the "Flood perspectives" user story, showing modeled inundation distribution in a coastal region (around the Vendee, France) for a 1000-year extreme event of total water level (TWL) around year 2100 under various coastal defense assumptions. Left: Unprotected flood map — the inundation distribution (blue shading) if no coastal defenses are present or functional. Center: Flood distribution with a minimum standard of protection (e.g., existing defenses of lower quality or height). Right: Flood distribution with a maximum standard of protection (e.g., upgraded dikes or robust natural barriers). The comparison vividly shows how stronger coastal defenses significantly reduce the inland reach of flooding. Such scenario maps help users evaluate the benefits of adaptation measures. For instance, national authorities can gauge how policy-driven improvements in defense standards might limit damages, and local planners can identify areas where even maximum protection would still be overtopped, indicating hotspots for additional measures. These maps were generated by combining high-resolution terrain data, extreme sea level statistics, and known defense data, using a fast inundation model (RFSM: Rapid Flood Spreading Model) to simulate water flow inland. The platform displays these outputs interactively, allowing users to toggle defense levels, choose return periods (e.g., 100-year vs 1000-year event), and select timeframes (present-day vs future) to see how flood risk evolves.

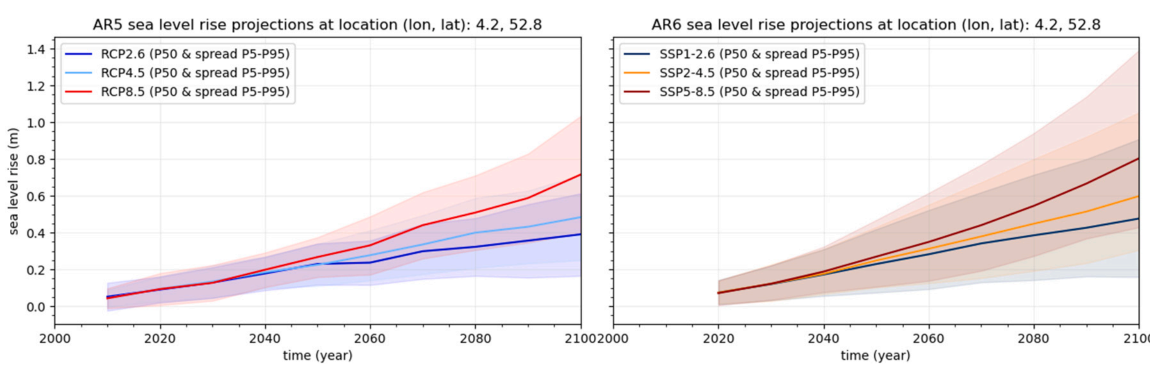

Fig. 6. Mean SLR projections in the Netherlands according to the AR5 (left) and the AR6 (right).

7. Integration into EDITO infrastructure

The demonstrated prototype of the Coastal Climate Services platform is designed for long-term sustainability and integration within broader European digital infrastructures. In this context, the platform has been taken up by the European Digital Twin of the Ocean (EDITO), an initiative of the European Commission that aims to provide high-resolution, data-driven digital replicas of the ocean and coastal systems to support science-based policy and sustainable ocean governance. Integration into EDITO ensures that the platform and its underlying coastal hazard and adaptation datasets – covering SLR, floods and erosion, exposure, and cost-benefit adaptation analyses – become accessible through a federated, continued and interoperable digital twin ecosystem. This alignment enables enhanced cross-sectoral applications, including support for the EU Missions on Adaptation to Climate Change and on Ocean and Waters, as well as the EU Climate Law. Moreover, the platform's adherence to FAIR data principles, cloud-native architecture, and use of STAC standards made it technically well compatible with EDITO's core infrastructure. Through this exploitation pathway, the platform will serve not only as a standalone decision-support service but also as a foundational component of Europe's next-generation coastal and marine digital services for the years to come, contributing to climate resilience, coastal planning, and the operational delivery of digital public goods.

8. Discussion

This section reflects on key design and development decisions made during the creation of the Coastal Climate Services platform, highlighting both technical and user-oriented considerations that shaped the final framework.

8.1. Technical considerations

The platform's data catalog and web-based viewer were built around the STAC standard, enabling a flat architecture with minimal reliance on additional servers. This design choice facilitated a lightweight and modular system architecture. However, the reliance on a static STAC configuration introduced scalability limitations, particularly when handling large volumes of JSON metadata — such as asset queries in notebook environments, which resulted in noticeable performance bottlenecks.

Although a dynamic STAC implementation would have resolved these issues, an interim solution was found by introducing GeoParquet-based STAC items at the collection level during the platform's final development phase. At the project outset, STAC technology was still maturing, and several functionalities were implemented through a project-specific extension. These were gradually replaced by standardized extensions as the ecosystem evolved. The subsequent adoption of dynamic STAC by EDITO enabled smoother integration of the platform into Europe's digital ecosystem, supporting long-term sustainability and interoperability.

To support visualization in the map-based viewer, data duplication could not be avoided – particularly for vector (Zarr), raster (GeoTIFF) and tabular (Parquet) formats – across platforms such as MapBox and GeoServer. This necessitated the careful design of data pipelines to ensure that updates were propagated consistently. As the platform operates on preprocessed data layers rather than dynamic computations, each user story had to be developed as a distinct STAC collection. This significantly increased post-processing effort, limiting the number of user stories that could feasibly be included during the initial development phase.

Regarding data format transformation, the conversion of conventional formats (e.g. NetCDF) into cloud-native formats (e.g. Zarr, GeoTIFF) proved advantageous in terms of storage efficiency and processing performance. Nevertheless, this process remains highly case-specific and lacks generalizability, particularly due to the heterogeneity in input data structures, dimensions, variables, and metadata. The harmonization of variable names and metadata, especially for CF-compliant vocabularies, was a major challenge in a multidisciplinary environment with many partner institutions. This underscores a broader need for improved vocabulary governance and semantic standardization in future coastal climate services initiatives.

Similar climate service platforms are increasingly emerging in other regions and sectors, often focusing on specific hazards, urban adaptation, or national-scale climate information portals (e.g. Lavoie et al., 2024; Paranunzio et al., 2024). Compared to these initiatives, the CoCliCo platform emphasizes the integration of coastal hazards, exposure, risk, and adaptation within a single interoperable framework. Importantly, the platform architecture was intentionally developed using open-source components, FAIR principles, and cloud-native standards (e.g. STAC, Zarr, COGs), allowing components to be adapted or simplified for use in regions with more limited technical or financial resources. The modular structure also enables lightweight implementations that can operate with fewer datasets, reduced computational demands, or locally hosted services.

Finally, an important consideration in interpreting future coastal flood scenarios is the non-stationary nature of coastal flood hazards under climate change. The return periods referenced in this study are based on present-day statistical estimates of extreme water levels. However, progressive sea-level rise alters these probabilities over time. As mean sea levels rise, flood events currently associated with rare return periods (e.g. present-day 1-in-100 year events) are expected to occur more frequently during the 21st century. This highlights the importance of interpreting future flood risk dynamically rather than assuming stationary present-day probabilities.

8.2. User-centric development process

From a user-engagement perspective, the adoption of a fast-track version of the platform early in the project proved highly effective. It catalyzed more focused discussions with end-users, clarified expectations, and significantly enhanced user commitment throughout the development process. Although working closely with Champion Users demanded considerable effort, this investment paid off through well-defined user story requirements and early-stage mock-ups that guided front-end development.

Although a formal quantitative usability assessment was beyond the scope of the present study, the platform underwent iterative validation through repeated interactions with Champion Users representing the three target user groups. Feedback collected during workshops, demonstrations, and progressive prototype reviews directly informed the refinement of user stories, visualization choices, administrative aggregation levels, and scenario selection. This iterative co-design process provided qualitative evidence that the platform architecture and functionalities aligned well with the operational needs of the intended end users.

However, releasing an initial prototype in the first year posed certain (budgetary) risks, notably the potential obsolescence of underlying software components. Indeed, a mid-project upgrade to VUE3 became necessary to support continued development and deployment of the final platform version.

A defining feature of the platform is the consistent application of integrated scenarios across all data products. These scenarios, informed by stakeholder needs, specified emissions (RCPs: 2.6, 4.5 and 8.5), socio-economic (SSP: 1, 2 and 5) pathways, time horizons (2010, 2030, 2050 and 2100), storm return periods (1, 100 and 1000 years) and adaptation choices. All in all, this resulted in 192 scenarios to be calculated, of which specific combinations were selected to span the solution space (envelope of possibilities). This alignment ensured coherence in the boundary conditions applied across CoCliCo's technical work packages focused on SLR, hazards, exposure & vulnerability, and risk & adaptation.

Defining these scenarios required intense coordination early in the project — often before model configurations were even finalized by the respective teams. Nevertheless, this early alignment exposed interdependencies across the modeling cascade and laid the foundation for the following integration and harmonization of data layers in the final platform. In doing so, the project demonstrated a successful approach to scenario-driven co-design, enabling traceability and consistency throughout the platform's components.

9. Conclusions and outlook

The development of this European Coastal Climate Services platform demonstrates a novel approach to climate data delivery for adaptation. It combines cutting-edge climate science (e.g. IPCC AR6 sea-level scenarios, high-resolution flood modeling) with user-centric design and modern cloud technology to bridge the gap between data producers and decision-makers.

By providing an open, authoritative source of coastal risk information, the platform helps planners and policymakers access up-to-date evidence on which to base climate resilience strategies. Users can identify at-risk areas, explore future scenarios, and even test adaptation options in a virtual setting — fulfilling key needs such as prioritizing investments, observing trends, exploring alternatives, and future planning.

A particular innovation is the two-tier publicly accessible interface: a simple interactive web-based map viewer for rapid insights, and a dedicated cloud workbench for detailed analysis. This lowers the entry barrier for less-resourced users (maps and statistics acquisition with a few clicks), while still empowering experts to perform advanced tasks (scripting against the data for custom analysis). An intense iterative co-design process provided qualitative evidence that the platform architecture and functionalities aligned well with the operational needs of the end users. The use of cloud infrastructure and open standards (STAC, cloud-optimized formats) means the service is scalable and interoperable; it can easily integrate new datasets (e.g. updated climate projections or observed data) and link with other platforms. The commitment to FAIR data and open-source development also ensures transparency and reproducibility, which builds trust in the information provided – a crucial factor for an ''authoritative platform'' that practitioners can rely on.

This coastal climate service can serve as a template for similar tools in other global regions or for other sectors. It exemplifies how leveraging advanced digital technologies – from cloud computing to interactive geo-visualization – can enhance climate resilience by putting 'powerful tools into the hands of decision-makers'. By enabling stakeholders to easily access and interpret complex coastal risk information and allowing them to combine the broad scale datasets with their own local data (see Section 6.3), the platform can support evidence-based planning and help coastal communities across Europe better understand today's risk and prepare for the challenges of rising seas and climate change. The platform should therefore be viewed as a decision-support environment that enables users to evaluate alternative adaptation strategies under consistent scenarios, rather than as a prescriptive tool for selecting preferred interventions.

Ultimately, climate services like this aim to contribute to building more climate-resilient societies by connecting science, data, and policy in a usable form. The Coastal Climate Services platform described here aims to do exactly that for Europe's coasts — turning detailed climate-risk data into actionable knowledge for those on the front lines of adaptation. As coastal hazards continue to grow in the coming decades, these tools will be indispensable in guiding effective responses and safeguarding coastal livelihoods and assets.

CRediT authorship contribution statement

Arjen Luijendijk: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Etiënne Kras:** Writing – original draft, Validation, Methodology, Conceptualization. **Luis Rodriguez Galvez:** Visualization, Software, Methodology. **Floris Calkoen:** Methodology, Conceptualization. **Charalampos Skoulikaris:** Formal analysis, Data curation. **Eva Loukogeorgaki:** Formal analysis, Data curation. **Rémi Thiéblemont:** Validation, Investigation, Data curation. **Vincent Bascoul:** Validation, Investigation, Formal analysis, Data curation. **Susana Romao:** Visualization, Validation. **Jacinta Hamley:** Visualization, Validation. **Paul Sayers:** Writing – review & editing, Validation, Methodology, Conceptualization. **Robert J. Nicholls:** Writing – review & editing, Supervision. **Angélique Melet:** Writing – review & editing, Supervision. **Gonéri Le Cozannet:** Writing – review & editing, Supervision, Funding acquisition.

Code data availability

All produced data products, being the core of the Coastal Climate Service, can be found in the digital User Handbook accessed through the web platform: https://platform.coclicoservices.eu/. An identical copy of the platform can also be found on EDITO (https://coclico.lab.dive.edito.eu). Background information regarding the User Stories as well as the Tutorials and Exploratory Tools with their corresponding Jupyter Notebooks as part of the Workbench can also be found in the Handbook. The User Handbook can also be accessed on Zenodo: https://doi.org/10.5281/zenodo.18327718. All CoCliCo technical reports and materials can be found here: https://doi.org/10.3030/101003598.

Declaration of competing interest

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

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During the preparation of this work the authors used ChatGPT in order to assist with phrasing, editing, and clarity. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Data availability

Link Provided

EDITO: https://coclico.lab.dive.edito.eu (CoCliCo (Original data))

References

Ballinger, R., Dodds, W., 2020. A coastal climate services approach to climate change adaptation. Clim. Serv. 18 (100166).

Bruno Soares, M., Daly, M., Dessai, S., 2018. Renewable energy and climate services: Taking stock and looking forward. Clim. Serv. 10, 42–55. http://dx.doi.org/10.1016/j.cliser.2018.03.003.

Calkoen, F.R., Luijendijk, A.P., Vos, K., Kras, E., Baart, F., 2025. Enabling coastal analytics at planetary scale. Environ. Model. Softw. 186, 106257. http://dx.doi.org/10.1016/j.envsoft.2024.106257.

Chaumillon, E., Bertin, X., Fortunato, A.B., Bajo, M., Schneider, J.-L., Dezileau, L., Walsh, J.P., Michelot, A., Chauveau, E., Créach, A., Hénaff, A., Sauzeau, T., Waeles, B., Gervais, B., Jan, G., Baumann, J., Breilh, J.-F., Pedreros, R., 2017. Storm-induced marine flooding: Lessons from a multidisciplinary approach. Earth-Sci. Rev. 165, 151–184. http://dx.doi.org/10.1016/j.earscirev.2016.12.005.

Church, J., Clark, P., Cazenave, A., Gregory, J., Jevrejeva, S., Levermann, A., Merrifield, M., Milne, G., Nerem, G., Nunn, P., Payne, A., Pfeffer, W., Stammer, D., Unnikrishnan, A., 2013. Sea level change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Cotrim, C., Toimil, A., Losada, I.J., Lobeto, H., Menéndez, M., 2025a. A framework for storm classification and hydrograph generation from total water level in europe. Earth's Futur. http://dx.doi.org/10.1029/2025EF006545.

Cotrim, C., Toimil, A., Losada, I.J., Menéndez, M., Lobeto, H., 2025b. Assessing extreme total water levels across europe for large-scale coastal flood analysis. EGUsphere http://dx.doi.org/10.5194/egusphere-2025-2998, Preprint under review.

Cotrim, C., Toimil, A., Losada, I.J., Novo, S., Suárez, I., 2026. Pan-European assessment of coastal flood hazards. Nat. Hazards Earth Syst. Sci. 26, 1859–1881. http://dx.doi.org/10.5194/nhess-26-1859-2026.

de Ruig, L.T., Haer, T., Wagemaker, J., Aerts, J.C.J.H., 2019. Adaptive infrastructure planning for flood risk reduction under climate change uncertainty. Mitig. Adapt. Strat. Glob. Chang. 24 (6), 1009–1028. http://dx.doi.org/10.1007/s11027-018-9836-2.

Fox-Kemper, B., Hewitt, H.T., Xiao, C., Drijfhout, S.S., Edwards, T.L., Golledge, N.R., Hemer, M., Kopp, R.E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I.S., Ruiz, L., Sallée, J.-B., Slangen, A.B.A., Yu, Y., 2021. Ocean, cryosphere and sea level change. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelek¸ci, O., Yu, R., Zhou, B. (Eds.), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I To the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362. http://dx.doi.org/10.1017/9781009157896.011.

Giordano, R., Pagano, A., Pluchinotta, I., del Amo, R.A., Hernández, S.M., Lafuente, E.M., Pagano, A., 2020. Climate services for urban planning: The case of Barcelona. Clim. Serv. 17, 100151. http://dx.doi.org/10.1016/j.cliser.2019.100151.

Haasnoot, M., Kwadijk, J.C.J., Van Alphen, J., Le Bars, D., van den Hurk, B., Diermanse, F., Katsman, C., 2020. Adaptation to uncertain sea-level rise: How uncertainty in antarctic mass loss impacts coastal adaptation pathways. Environ. Res. Commun. 2 (11), 115008. http://dx.doi.org/10.1088/2515-7620/abb9ba.

Hanson, S.E., Nicholls, R.J., Calkoen, F.R., Le Cozannet, G., Luijendijk, A.P., 2026. A geospatial database of coastal characteristics for erosion assessment of europe's coastal floodplains. Nat. Hazards Earth Syst. Sci. 26, 1685–1703. http://dx.doi.org/10.5194/nhess-26-1685-2026.

Hewitt, C., Mason, S., Walland, D., 2012. The global framework for climate services. Nat. Clim. Chang. 2, 831–832. http://dx.doi.org/10.1038/nclimate1745.

Hinkel, J., Church, J.A., Gregory, J.M., Lambert, E., Le Cozannet, G., Lowe, J., McInnes, K.L., Nicholls, R.J., van der Pol, T.D., van de Wal, R., 2019. Meeting user needs for sea level rise information: A decision analysis perspective. Earth's Futur. 7 (3), 320–337. http://dx.doi.org/10.1029/2018EF001071.

Hinkel, J., Lincke, D., Vafeidis, A.T., Perrette, M., Nicholls, R.J., Tol, R.S.J., Marzeion, B., Fettweis, X., Ionescu, C., Levermann, A., 2018. The ability of societies to adapt to twenty-first-century sea-level rise. Nat. Clim. Chang. 8 (7), 570–578. http://dx.doi.org/10.1038/s41558-018-0176-z.

IPCC, 2021. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, URL https://www.ipcc.ch/report/ar6/wg1/.

IPCC, 2023. Climate change 2023: Synthesis report. In: Core Writing Team, Lee, H., Romero, J. (Eds.), Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, http://dx.doi.org/10.59327/IPCC/AR6-9789291691647.

Jenkins, K., Nicholls, R., Sayers, P., 2025. Climate Change Adaptation in the Port Industry: Evaluating Evidence of Implemented Adaptation using a National Adaptation Inventory. Climate Change Adaptation in the Port Industry: Evaluating Evidence of Implemented Adaptation using a National Adaptation Inventory. Tech. Rep..

Jenkins, K., Nicholls, R., Sayers, P., Redhead, J., Price, J., Pywell, R., He, Y., Tozer, N., Carr, S., 2024. The UK fens climate change risk assessment: Big challenges and strategic solutions. Tyndall Cent. Clim. Chang. Res..

Koks, E., Le Bars, D., Essenfelder, A., Nirandjan, S., Sayers, P., 2023. The impacts of coastal flooding and sea level rise on critical infrastructure: a novel storyline approach. Sustain. Resilient Infrastruct. 8 (Sup1), 237–261.

Lavoie, J., Caron, L.-P., Logan, T., Barrow, E., 2024. Canadian climate data portals: A comparative analysis from a user perspective. Clim. Serv. 34, 100471. http://dx.doi.org/10.1016/j.cliser.2024.100471.

Le Cozannet, G., Cazenave, A., 2024. Adaptation to sea level rise in France. Sci. Fis. E Nat..

Le Cozannet, G., Rohmer, J., Cazenave, A., Idier, D., Van de Wal, R., De Winter, R., Pedreros, R., Balouin, Y., Vinchon, C., Oliveros, C., 2017. Evaluating uncertainties of future marine flooding occurrence as sea-level rises. Environ. Model. Softw. 95, 176–185. http://dx.doi.org/10.1016/j.envsoft.2017.06.015.

Melet, A., van de Wal, R., Amores, A., Arns, A., Chaigneau, A.A., Dinu, I., Haigh, I.D., Hermans, T.H.J., Lionello, P., Marcos, M., Meier, H.E.M., Meyssignac, B., Palmer, M.D., Reese, R., Simpson, M.J.R., Slangen, A.B.A., 2024. Sea level rise in europe: Observations and projections. State the Planet 3-slre1, 4. http://dx.doi.org/10.5194/sp-3-slre1-4-2024.

Nicholls, R., Hanson, S., Lowe, J., Slangen, A., Wahl, T., Hinkel, J., Long, A., 2021. Integrating new sea-level scenarios into coastal risk and adaptation assessments: An ongoing process. Wiley Interdiscip. Rev.: Clim. Chang. 12 (3), 289–302. http://dx.doi.org/10.1002/wcc.706.

Oppenheimer, M., Glavovic, B., Hinkel, J., van de Wal, R., Magnan, A., Abd-Elgawad, A., Cai, R., Cifuentes-Jara, M., DeConto, R., Ghosh, T., Hay, J., Isla, F., Marzeion, B., Meyssignac, B., Sebesvari, Z., 2019. Sea level rise and implications for low-lying islands, coasts and communities. In: Pörtner, H.-O., Roberts, D., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., Weyer, N. (Eds.), IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 321–445. http://dx.doi.org/10.1017/9781009157964.006.

Paranunzio, R., Anton, I., Adirosi, E., Ahmed, T., Baldini, L., Brandini, C., Giannetti, F., Meulenberg, C., Ortolani, A., Pilla, F., Iglesias, G., Gharbia, S., 2024. A new approach towards a user-Driven Coastal climate service to enhance climate resilience in European cities. Sustainability 16 (1), 335. http://dx.doi.org/10.3390/su16010335.

Penning-Rowsell, E., P.B., S., Carr, S., Derval, C., Machí Castañer, C., Lutzu, J., 2023. Co-Design of Climate Services Decision Mapping, User Requirements and Development Priorities. Tech. Rep., Deliverable 1.2 Report CoCliCO Project.

Sayers, P., Horritt, M., Carr, S., Kay, A., Mauz, J., 2020. Third UK Climate Change Risk Assessment (CCRA3): Future flood risk. Research undertaken by Sayers and Partners for the Committee on Climate Change (using the Future Flood Explorer). Published by Sayers and Partners and the Committee on Climate Change, London.

Sayers, P., Moss, C., Carr, S., Payo, A., 2022. Responding to climate change around England's coast - the scale of the transformational challenge. J. Ocean. Coast. Manag. Vol. 225 http://dx.doi.org/10.1016/j.ocecoaman.2022.106187.

Sermet, Y., Liang, C.-Y., Dey, S., Muste, M., Merwade, V., Cox, A.L., Minear, J.T., Demir, I., 2025. River morphology information system: A web cyberinfrastructure for advancing river morphology research. Environ. Model. Softw. 183, http://dx.doi.org/10.1016/j.envsoft.2024.106222.

Skoulikaris, C., Ganoulis, J., 2014. Cooperative webgis interactive information systems for water resources data management. In: Hydrology – Changing World: Environmental and Human Dimensions (IAHS Publ. 363). International Association of Hydrological Sciences (IAHS), pp. 342–347.

Street, R., Buontempo, C., Harjanne, A., Hewitt, C., Masson-Delmotte, V., 2015. A European Research and Innovation Roadmap for Climate Services. Tech. Rep., European Commission, http://dx.doi.org/10.13140/RG.2.1.5110.7682.

Thiéblemont, R., Le Cozannet, G., Nicholls, R.J., Rohmer, J., Wöppelmann, G., Raucoules, D., de Michele, M., Toimil, A., Lincke, D., 2024. Assessing current coastal subsidence at continental scale: Insights from europe using the European ground motion service. Earth's Futur. http://dx.doi.org/10.1029/2024EF004523.

Vaughan, C., Dessai, S., 2014. Climate services for society: Origins, institutional arrangements, and design elements for an evaluation framework. Wiley Interdiscip. Rev.: Clim. Chang. 5 (5), 587–603. http://dx.doi.org/10.1002/wcc.290.

Völz, V., Hinkel, J., Lincke, D., Honsel, L., Nicholls, R.J., Thiéblemont, R., Le Cozannet, G., Sayers, P., 2025. The economically optimal mix and timing of coastal adaptation in europe to 2150. Res. Sq. http://dx.doi.org/10.21203/rs.3.rs-6314787/v1, Preprint.

WMO, 2014. Implementation Plan of the Global Framework for Climate Services (GFCS). Tech. Rep., WMO, Geneva, Switzerland, URL https://gfcs.wmo.int/.

Ye, M., Ward, P.J., De Plaen, J.J., Koks, E.E., 2025. A deep learning pipeline to power infrastructure detection in high-resolution satellite images. Big Earth Data 9 (3), 525–546. http://dx.doi.org/10.1080/20964471.2025.2490408.