# Innovative Coastal Management: Leveraging AI and Satellite Imagery for Monitoring Urban and Port Environments within the OCEANIDS Project

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## ABSTRACT

Coastal cities and ports play a crucial role in global trade, urban development, and environmental sustainability, but they are increasingly facing challenges related to climate change, urbanization, and complex operational demands. Within the framework of the OCEANIDS project, this study explores the integration of satellite imagery, climate data, meteorological and socioeconomic indicators, and artificial intelligence (AI) methodologies to improve the monitoring and management of coastal and port environments. By leveraging multi-source Earth Observation data and advanced machine learning techniques, a systematic approach is developed for environmental monitoring, operational assessments, and the detection of critical environmental changes. This integrated approach incorporates explainable AI techniques and data fusion methodologies to improve decision transparency, predictive accuracy, and operational planning. The implemented methodologies have resulted in actionable insights for managing urban growth, optimizing port operations, and mitigating environmental risks. End-user feedback from pilot sites in the Mediterranean, Boreal, and Atlantic regions highlights shared priorities, including wind forecasting, coastal changes, and sea level rise monitoring, as well as region-specific needs such as landslide risk assessments in the Azores and coastal changes monitoring in Malaga. The results underscore the importance of combining satellite data with forecasting models, predictive analytics, and GIS-based tools to support navigation safety, environmental monitoring, and climate risk management. A Decision Support System shall provide opportunities for scenario evaluation and policy development. This work establishes a scalable framework for sustainable coastal and port management, directly contributing to international sustainability objectives, including the European Green Deal and the United Nations Sustainable Development Goals.

**Keywords:** Coastal Monitoring; Ports Management; Satellite Imagery; Earth Observation; Environmental Sustainability; Data Fusion, Decision Support System;

## 1. INTRODUCTION

Coastal cities and ports are critical to the global economy, serving as hubs for trade, transportation, and cultural exchange. However, rapid urbanization and industrialization of these areas present significant environmental challenges. Globally, a high amount of geohazards and natural disasters threaten coastal zones[1], focusing not only on marine-induced ones, such as coastal erosion and sea level rise[2], but also on inland continental geohazards, like land subsidence[3], flash floods[4], and/or anthropogenic impacts.

Effective resource management and sustainability measures are crucial, especially as stakeholders endeavour to balance economic growth with environmental preservation[5]. Understanding the interconnection between ports and their surrounding urban areas is essential, emphasizing the need for integrated development and management strategies, aiming to foster sustainable growth that aligns with the broader goals of environmental preservation and societal well-being. Research by Smith et. al (2021)[6], indicates the utility of high-resolution satellite imagery for coastal wetland shoreline change monitoring, while highlighting the transformative impact of satellite monitoring in coastal science. Despite these advances, integrating diverse data sources and developing comprehensive analytical frameworks remains challenging.

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Recent advances in coastal monitoring have taken advantage of satellite remote sensing[7] and AI-driven analysis[8] to offer new insights into these continuously dynamic environments. Satellite-based coastal monitoring systems in combination with machine learning algorithms can offer an attractive solution for the observation, using relatively high-resolution data with frequent revisits, and prediction of coastal changes and risk, improving this way ports' management strategies. Despite the significant advancements in monitoring coastal dynamics, several challenges remain. While satellite imagery and AI-driven analysis have transformed coastal monitoring, limitations in spatial and temporal resolution, cost barriers, and data integration complexities hinder widespread adoption. For instance, real-time monitoring of coastal changes often requires integrating data from multiple sources, such as ground-based sensors and satellite observations, which can lead to discrepancies in data accuracy and consistency [9].

The OCEANIDS project[10] aims to address these challenges through an interdisciplinary approach. This project is a collaborative initiative aimed at addressing the challenges faced by coastal cities and ports through the integration of innovative monitoring technologies. The project is coordinated by a consortium comprising academic institutions, industrial partners, and research organizations, ensuring a multidisciplinary approach to tackling complex environmental and operational issues. The project is funded by a European Union initiative focused on fostering sustainable development and resilience in coastal regions. Its objectives align with broader governmental and non-governmental initiatives, such as the European Green Deal[11], which emphasizes climate resilience, digital transformation, and environmental sustainability. Moreover, the project contributes to the United Nations' Sustainable Development Goals (SDGs)[12], particularly SDG 13 (Climate Action)[13] and SDG 14 (Life Below Water)[14]. These synergies ensure that the project's outcomes have a tangible impact on global and regional policy frameworks.

By addressing critical challenges such as climate change, urbanization, and maritime safety, OCEANIDS aims to provide actionable insights and scalable solutions for coastal and port management, leveraging the latest advancements in EO data and AI. This alignment with international initiatives reinforces the project's relevance and its capacity to drive innovation in coastal resilience and sustainability. By leveraging advanced AI methodologies and satellite imagery, complemented by supporting data, the project focuses on monitoring and assessing coastal and port environments. AI techniques improve the analysis of these diverse data sources, allowing the detection of patterns and trends that might be overlooked by traditional methods. Fiorino et. al (2018)[15] underscores the need for a multidisciplinary strategic plan and integrated tools to effectively monitor urban transformations in coastal cities.

The project includes pilot sites in various geographical locations, incorporating ports from different climatic zones, such as the Mediterranean regions, such as in the Crete region (Greece), Greek islands, Malaga City and Port (Spain), Baltic regions (Coastal Finland), and Atlantic regions (Region of Bretagne, Azores and Bremen). These sites face various climate change risks and natural hazards, including landslide phenomena in Crete island[16], sea level rise and extreme weather events[17] in coastal Finland, for example, as well as more climatic hazards such as increased sea surface temperature, increased acidity, changes in phytoplankton communities, an increasing number of marine dead zones, the risk of biodiversity loss, and large increases in heat extremes. Addressing these challenges in these areas helps tackle some of the most pressing environmental issues coastal cities and ports face today. Building on the initiatives of the OCEANIDS project, this study presents an innovative approach to coastal monitoring.

Our research integrates satellite imagery with supporting data and applies state-of-the-art AI algorithms to provide precise and timely information. This approach not only improves the accuracy of environmental assessments but also contributes to the development of more resilient and sustainable coastal urban areas. The primary goal of this work is to demonstrate the value of this interdisciplinary collaboration and technological innovation in addressing the complex challenges faced by coastal cities and ports. In the upcoming sections, the materials and methods will be introduced as agreed among the project partners, followed by some preliminary results where the interconnection and flow of the data will be documented, and lastly, the discussions will be presented.

## 2. MATERIALS AND METHODS

The OCEANIDS project employs a holistic and adaptive methodology aimed at creating tools and collecting, harmonizing, and curating existing climate data services. This approach ensures that all data is accessible, reusable, and interoperable, facilitating the development of localized adaptation strategies to address the complex environmental challenges faced by coastal cities and ports. The methodology described below provides sufficient detail to enable replication and further exploration of its results. The OCEANIDS project employs a systematic workflow that integrates diverse data sources to generate accurate and actionable insights for coastal monitoring. Figure 1 illustrates the data processing framework used to harmonize satellite imagery, environmental datasets, and AI-driven analytics, which form the basis for regional analyses and decision-making.

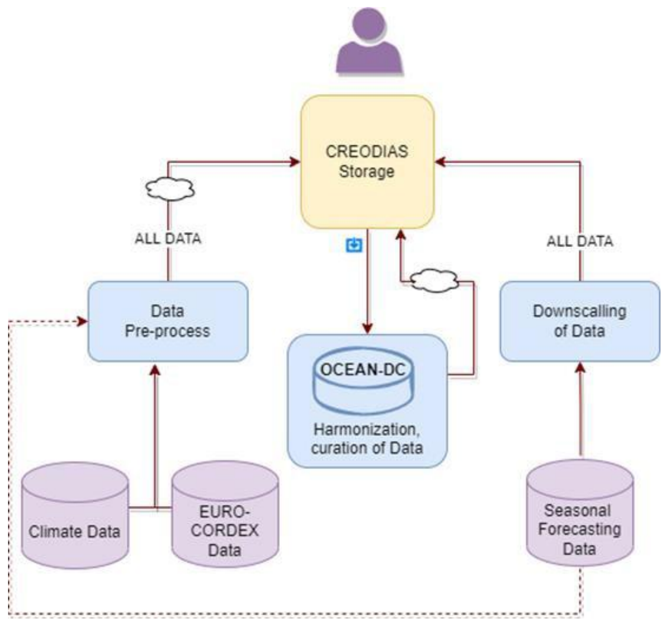


Figure 1. Architecture of the OCEANIDS data processing workflow, showcasing data collection from multiple sources, preprocessing workflows, harmonization through the OCEAN-DC framework, and storage in the CREODIAS infrastructure. The diagram highlights the integration of climate data, EUROCORDEX data, and seasonal forecasting data into a centralized processing system.

### 2.1. Data Collection and Sources

The study integrates data from multiple sources, as shown in Figure 1, to provide a detailed understanding of coastal and port dynamics. EO imagery, climate data on a regional scale, downscaled meteorological records, and operational datasets are gathered, offering detailed spatial and temporal insights into phenomena such as port operations, coastal erosion, and sea level changes. Complementing satellite data, meteorological data, including wind speed, temperature, precipitation, and humidity, are obtained from global and regional monitoring networks, providing essential inputs for climate risk assessments. Additionally, operational data, such as ship movements, air quality measures, and pipeline mapping, is provided through collaborations with local authorities and project partners. In addition, biological and chemical parameters, such as ocean acidity and changes in phytoplankton communities, are included to assess ecosystem health. The data sources underpinning these methodologies include Copernicus Sentinel missions, high-resolution commercial EO data, and climate projections from the EURO-CORDEX program. The latter datasets are further enriched with socio-economic indicators to ensure a holistic analysis. Feature engineering processes derive critical indices, such as coastal vulnerability assessments, heat stress indices, and infrastructure exposure models, which serve as essential inputs for AI-driven analyses. These bias-adjusted EURO-CORDEX datasets[18] provide high-resolution regional climate projections, including daily minimum, maximum, and average temperatures, precipitation flux, and daily maximum wind speed. These datasets are dynamically downscaled to improve local climate assessments and address variability across the studied regions. By collecting all this data, this project adopts a comprehensive approach, providing a holistic overview of decision-making.

### 2.2. Preprocessing and Integration

Collected data undergoes rigorous preprocessing to ensure accuracy, consistency, and harmonization for seamless integration. The Ocean-DC framework[19] has been implemented, providing harmonization and homogenization between the aforementioned datasets. Atmospheric corrections are applied to satellite imagery to eliminate distortions, while georeferencing will align datasets spatially. Normalization processes are used to harmonize data formats from different sources, facilitating seamless integration. A spatiotemporal alignment process synchronizes the data across spatial and temporal dimensions, ensuring compatibility between satellite imagery, climate data, and operational records. Quality control measures are also implemented throughout this stage to validate the datasets and maintain their integrity.

### 2.3. Downscaling of Data

High-resolution datasets were produced through a combination of statistical and dynamical downscaling methods to tailor global and regional climate model outputs to the spatial scales relevant for each pilot site. Statistical downscaling was applied using quantile mapping and bias correction techniques on EURO-CORDEX projections, reducing systematic errors and aligning outputs with in-situ observations. Dynamical downscaling leveraged regional climate models with finer spatial grids (~5–10 km resolution) to capture local topographic effects, such as orographic precipitation in Crete or wind channeling in coastal Finland. These enhanced datasets improve the granularity of seasonal forecasts and climate projections, enabling more accurate localized risk assessments for hazards including storm surges, extreme winds, ice formation, and coastal erosion. Validation was performed against historical records from meteorological stations, tide gauges, and EO-derived products to ensure representativeness of local climatic and oceanographic conditions.

### 2.4. CREODIAS Storage

All processed and curated datasets are stored in the CREODIAS cloud infrastructure[20], which provides scalable storage and high-performance computing capabilities for large Earth Observation datasets. Data ingestion follows FAIR principles (Findable, Accessible, Interoperable, Reusable) and adheres to ISO 19115 metadata standards for geospatial resources. The architecture supports automated ingestion pipelines, OGC-compliant services (WMS, WFS), and API-based access for integration with the OCEANIDS Decision Support Systems. By hosting the harmonized datasets within CREODIAS, the project ensures secure long-term storage, rapid retrieval, and computational scalability to support advanced analytics and near-real-time processing. The system's distributed nature enables multiple partners and end-users to query and process the same data without redundancy, supporting both operational use (e.g., daily forecasts) and research-oriented large-batch processing.

### 2.5. Feature Engineering

Following preprocessing, raw datasets are transformed into derived indices and thematic products tailored to coastal and port management needs. Examples include:

- Coastal dynamics indicators: shoreline change rates, erosion susceptibility indices, wave power indices.
- Port activity metrics**:** vessel density heatmaps, berth occupancy rates, emission hotspots derived from AIS and air quality sensor data.
- Climate stress indicators**:** extreme wind exceedance probabilities, heat stress indices, and flooding risk maps.
- Marine ecosystem health indicators**:** sea surface temperature anomalies, chlorophyll a concentration trends, and ocean acidity change rates.

Feature generation workflows are implemented in an automated, modular fashion using Python-based processing chains and containerized services to ensure reproducibility. These features feed directly into AI models for classification, forecasting, and change detection, allowing the system to detect emerging hazards, evaluate historical patterns, and support "what-if" scenario simulations for adaptation planning.

### 2.6. Data Analysis, AI Methods, and Machine Learning

Having prepared all the necessary tools and datasets, the remaining phase of the project will focus on analyzing the derived features using advanced data analytics and machine learning (ML) techniques to extract patterns, identify trends, and generate actionable recommendations. Methods such as regression analysis**,** time-series modeling, and clustering will be applied to reveal relationships and temporal variations within the data. ML models will be trained to detect significant temporal shifts in environmental parameters, thereby enhancing the user experience and supporting informed decision-making.

To address the complex environmental and operational challenges faced by coastal urban and port environments, the OCEANIDS project, as its main goal, applies advanced methodologies in combination with multi-source EO and climate data. These methodologies are aligned with the project's pilot site implementations across the Mediterranean, Atlantic, and Baltic regions, supporting both environmental monitoring and socio-economic risk assessments.

The AI techniques used within the project focus on classification and change detection to monitor urban expansion, port infrastructure development, and coastal land use transformations, providing critical insights for sustainable planning. In addition, time-series forecasting models are developed in parallel to assess seasonal risks, including air quality monitoring, extreme wind events, and potential flooding. These predictive models support operational decision-making by enabling ports to implement early warning systems, optimize maintenance scheduling, and mitigate economic disruptions.

Furthermore, AI models contribute to comprehensive socio-economic risk assessments by integrating environmental variables such as sea level rise and temperature anomalies with operational port data, including traffic flows and emission levels. This integration supports the OCEANIDS Decision Support Platform, enabling scenario-based evaluations and the development of adaptation strategies for climate resilience.

In support of stakeholder engagement and inclusive governance, the project also incorporates AI-powered natural language processing techniques through the development of interactive chatbots. These tools provide intuitive interfaces for querying climate-related risks and adaptation options, thereby fostering better communication between technical experts, policymakers, and local communities.

### 2.7. Risk Assessment and Recommendations

Moving forward, the analysis produces detailed recommendations and risk assessments tailored to the project's specific pilot sites. These recommendations will include the impact of high temperatures, air quality, and extreme wind events on coastal and port systems. Risk assessments quantify potential economic indirect and direct losses, identify vulnerable areas, and highlight measures required for critical infrastructure, providing actionable insights into the environmental and operational risks faced by ports and coastal regions.

### 2.8. Actionable Insights

The final stage of the methodology involves translating the previously conducted assessments into actionable recommendations. These recommendations include physical interventions, such as flood protection measures and infrastructure adjustments, as well as operational strategies, such as rescheduling port activities, implementing safety protocols, and raising awareness of potential hazards. By aligning recommendations with stakeholder feedback, the methodology shall ensure that outputs are practical and relevant to real-world needs.

### 2.9. Validation and Performance Metrics

The reliability of the methodology is validated through comparisons with ground-truth data and in situ observations. Cross-validation techniques, such as k-fold validation, will be used to ensure the robustness of the machine learning models and minimize overfitting. Key performance metrics will be taken into account to evaluate the accuracy of the models and identify opportunities for further refinement. This integrated approach of combining satellite imagery, supporting data, and AI techniques provides a robust framework for monitoring coastal cities and ports. The adaptability of this methodology will be evident in the pilot sites, spanning diverse climatic and geographic zones and thus highlighting its potential for broader applications.

## 3. RESULTS

As the OCEANIDS project is still ongoing, with a scheduled completion date of June 2026, the results presented here are preliminary. The collaboration among partners, as well as the integration of individual tasks, remains in the early stages. However, initial findings have already demonstrated the applicability and robustness of the OCEANIDS methodology in addressing the environmental challenges faced by coastal cities and ports. By integrating EO data, climate and meteorological data, supporting datasets, and advanced analytical techniques, the project will provide actionable insights into environmental dynamics, risk management, and adaptation strategies for diverse pilot sites. In this section, the overall progress and preliminary results will be presented, allowing the introduction of the progress of the project.

### 3.1. OCEANIDS Architecture and Data Flow

The seamless interconnection between the different tools of the OCEANIDS system will ensure the development of a robust single access window - the integrated EO and spatial data platform (EO-P) or the frontend application. The main Decision Support Systems (DSSs) comprising the main modules feeding the frontend component are: i) the Climate Change-Hazard and Risk-Decision-Support System (CC-HR-DSS) and ii) the OCEANIDS Decision Support Platform (O-DSP), each one contributing to the outcome. Figure 2 illustrates the architecture and data flow within the OCEANIDS system, showcasing how various data sources, user interactions, and DSS modules integrate to provide actionable insights.

The overall system is divided into several components:

- Backend of the EO-P: This layer processes user requests, integrates the data coming from various sources, including EO imagery, geospatial data, climate data, and hazard data, and communicates with other components of the system, such as the CC-HR-DSS, O-DSP, and the EO processes ecosystem.

- EO Data and Processing Ecosystem: Data from EO sources are harmonized and curated. This ecosystem could include processes like extracting built-up areas, port area identification, and ice coverage detection, which are critical for risk and impact assessments. The algorithms and outputs will be highly dependent on the assessment of current gaps between the stakeholders' needs and existing applications and services available
- CC-HR-DSS: This module provides pre-event, short-term, and post-event risk assessments based on EURO-CORDEX climate projections, seasonal forecasting, and EO data. The outcomes will be used by the O-DSP and contribute to decision-making processes regarding CC impacts. This module will accommodate different types of datasets (e.g., hazard, assets, fragilities) and risk analysis algorithms. The platform will be interconnected with the frontend of the EO-P and O-DSP, which will provide suitable user interface elements for scenario and data repository management, analysis workflows setup, intuitive result visualization, and reporting.
- Frontend of the EO-P: The user interface allows stakeholders and end-users to interact with the platform. Key functionalities include requesting EO data, a risk assessment module, a decision support module, visualizations, and initiating on-demand EO processes.

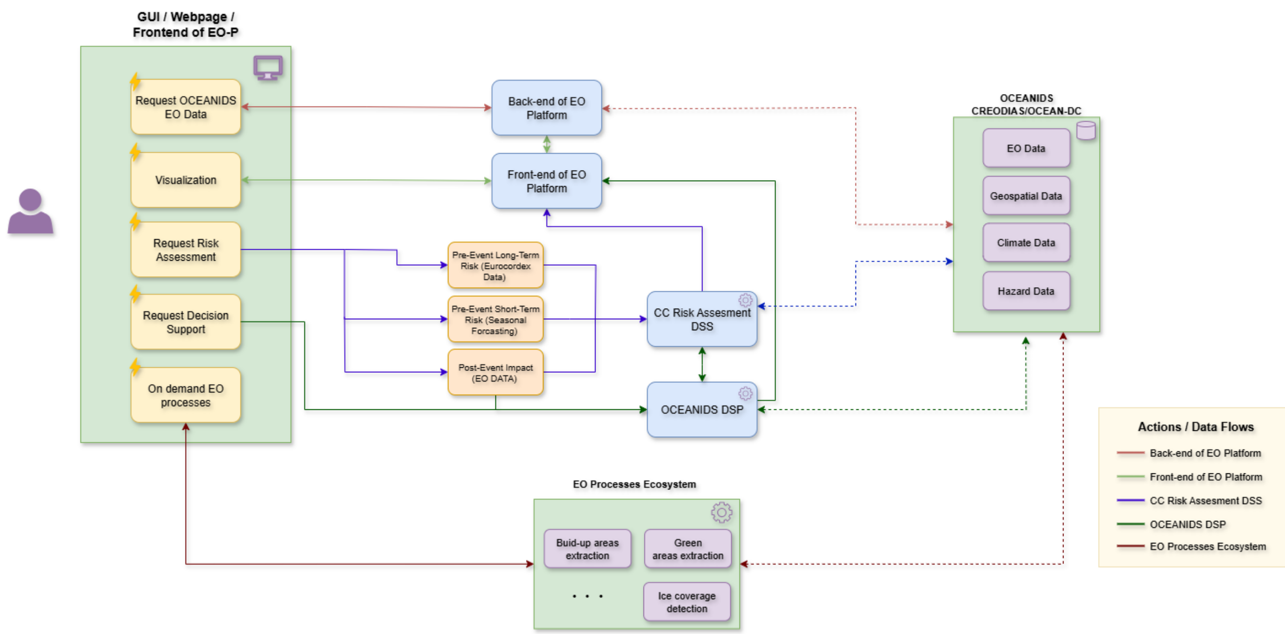


Figure 2. Workflow and data flow architecture of the OCEANIDS system, showcasing the integration of user interactions, data sources, and analytical processes. The platform includes a frontend for user requests and visualizations, a backend for data integration and processing, DSSs for climate risk assessments, and an EO processes ecosystem for extracting critical environmental insights. The architecture through the DSS risk assessment enables pre-event, short-term, and post-event risk assessments, facilitating effective decision-making and adaptive management for coastal cities and ports. Integrating these components ensures a seamless flow of data and enables the generation of timely, actionable insights for the stakeholders.

### 3.2. Visualization and Decision Support

The results of the analysis will be presented in user-friendly formats to facilitate decision-making. The single access window that will be developed shall provide interactive maps highlighting critical areas of concern, such as coastal erosion hotspots, biodiversity risks, etc., focusing on the results of the two decision support modules, and near-real-time dashboards and graphs will provide updates on air quality, wind conditions, and other key parameters. These visualizations will enable stakeholders to interpret complex data and make informed decisions to mitigate risks and improve sustainability. In Figure 3, the first mock-up of the platform is illustrated.

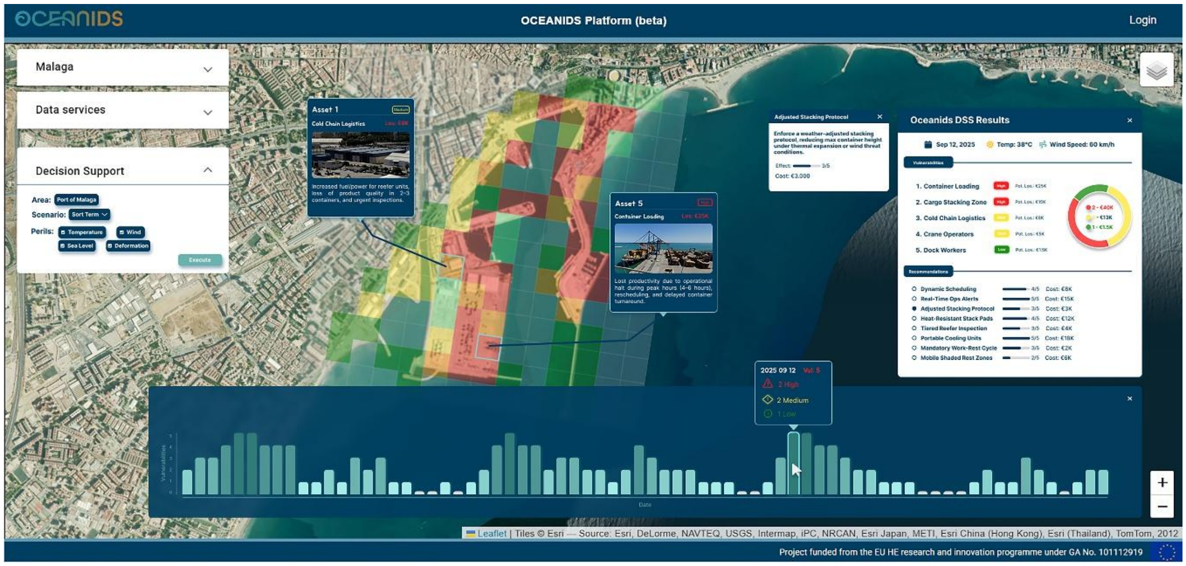


Figure 3. The OCEANIDS Decision Support System, integrated within the OCEANIDS Platform.

### 3.3. Validation and Accuracy

Ground-truth data and field observations validated model predictions. Cross-validation techniques, such as k-fold cross-validation, will ensure robustness. This rigorous validation process will demonstrate the accuracy and applicability of the methodology across diverse environmental contexts. Model outputs were validated using **ground-truth datasets** and **field observations** collected at multiple pilot sites, representing diverse climatic zones. Validation data sources include:

- **Tide gauge and buoy records** for sea level, wave height, and wave period (e.g., Azores).
- **Meteorological station measurements** for wind speed/direction, temperature, and precipitation (e.g., Coastal Finland, Malaga).
- **In-situ air and water quality sensors** deployed in ports and coastal areas (e.g., Heraklion Port, Crete, and Malaga, Spain).

Statistical validation methods included **k-fold cross-validation** for machine learning models, **root mean square error (RMSE)** and **mean absolute error (MAE)** for continuous predictions, and **confusion matrices** for classification tasks. These comparisons will demonstrate the alignment between model predictions and measured data for parameters such as coastline change, wind speed forecasting, and flood risk mapping. Performance metrics will be further refined in upcoming project phases as additional ground-based measurements are collected, ensuring continued calibration and reliability across diverse environmental contexts.

### 3.4. Site-Specific Findings

The tailored methodologies implemented at each pilot site highlight the diverse environmental and operational challenges faced by the coastal regions and ports. For each Climatic zone, a chart is displayed, representing a stacked bar graph that visualizes the total scores of importance for various solutions as rated by OCEANIDS end-users in each zone. Each bar represents a specific solution (e.g., "Forecast and map winds"), with the total height of the bar indicating its overall importance score across the regions. The bars are divided into several colored segments -the number varies for each zone- each representing the contributions from one of the regions. Additionally, monochromatic colors differentiate the regions while maintaining a cohesive visual design. The x-axis lists the solutions provided by OCEANIDS (e.g., "Detect and monitor ice risk at sea"), while the y-axis quantifies their total scores of importance based on interviews. The key findings for each climatic zone are summarized below.

- Mediterranean Climatic Zone - Regions: Crete Island, Heraklion port, Greek islands (Greece), and Malaga (Spain)

The results for the Mediterranean region, specifically focusing on Crete Island in Greece (abbreviation: CRETE), Heraklion port on Crete Island (abbreviation: HPA), Greek islands and Malaga (Spain) (abbreviation: MLG), provide a comprehensive understanding of the environmental and operational challenges of the region, as illustrated in the diagram in Figure 4. The prioritization of solutions by the end-users reflects the varying needs and vulnerabilities of these areas, shaped by their geographical, climatic, and socioeconomic contexts.

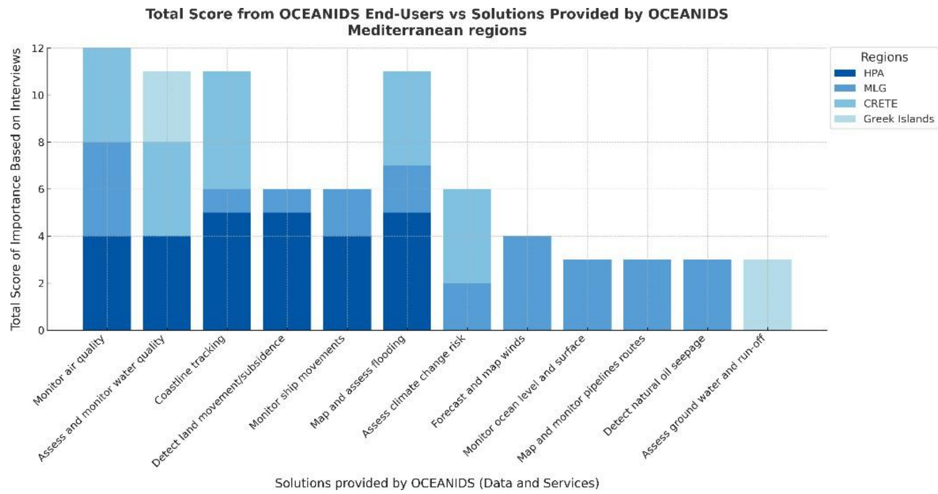


Figure 4. Regional Prioritization of OCEANIDS Solutions Based on End-User Interviews - Mediterranean regions

The diagram illustrates the total scores of importance assigned to various solutions provided by OCEANIDS across (4) four Mediterranean regions: Heraklion (Crete Island), Malaga (Spain), Crete (Greece), and the Greek islands. Each bar represents the cumulative score for a solution, with individual contributions from regions depicted using shades of blue. High-priority solutions, such as Monitor Air Quality, Coastline Tracking, and Map and Assess Flooding, exhibit significant regional alignment, while others show variability in importance based on localized needs. This visualization underscores the diverse regional demands for ocean and environmental monitoring services.

Air quality monitoring emerged as a high-priority solution across Crete (Greece), Heraklion (Crete Island), and Malaga (Spain), with stakeholders assigning equal importance. This reflects the growing concerns over air pollution caused by industrial activities, urbanization, and maritime operations in these densely populated and economically critical zones. For instance, studies have documented the adverse effects of port emissions on urban air quality, emphasizing the need for real-time monitoring systems to mitigate health and environmental impacts, focusing on Mediterranean regions[21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31].

Water quality monitoring received significant attention in Crete and the Greek Islands (Greece), scoring highly due to the importance of preserving coastal ecosystems and supporting tourism. The Mediterranean's sensitivity to eutrophication, pollution, and overfishing makes this a critical area for intervention. Although Malaga (Spain) assigned slightly less importance, the ongoing pressures of urban expansion and industrial activities highlight the need for robust monitoring frameworks[32, 33].

Coastline tracking emerged as a top priority for Crete (Greece) and HPA (Crete Island), where stakeholders highlighted the risks of coastal erosion and sea-level rise. These areas are particularly vulnerable to the impacts of climate change, including increased storm intensity and flooding. The use of satellite imagery and machine learning to track and predict coastal changes has been well-documented as a critical tool for managing these risks[34, 35, 36]. Conversely, Malaga (Spain) rated this solution lower, suggesting regional differences in exposure or existing mitigation strategies.

Detecting land movement and subsidence was also a key concern for Heraklion (Crete Island), scoring the highest priority in this category. The region's susceptibility to geohazards[37, 38], including tectonic activity[39] and soil instability[40], necessitates advanced monitoring solutions to prevent infrastructure damage and economic losses. Previous studies have highlighted the widespread occurrence of these issues in Crete (Greece) and surrounding areas[41, 42].

Flood risk assessment was another area of strong interest in Crete (Greece) and HPA (Crete Island). The region's topography, characterized by steep slopes and urban areas close to rivers and coastlines, makes it prone to flash flooding during intense rainfall events[43]. The emphasis on mapping and assessing flood risks underscores the need for predictive tools and adaptation measures to reduce the socioeconomic impacts of such hazards. These findings are consistent with prior research that identified Mediterranean coastal zones as hotspots for climate-related disasters [44, 45].

Climate change risk assessment was particularly emphasized in Crete (Greece), where end-users prioritized the integration of long-term climate projections into planning frameworks. The impacts of rising sea levels, biodiversity loss, and extreme heat events are increasingly evident in the Mediterranean, making this a critical area of focus. This finding aligns with international frameworks such as the Paris Agreement[45] and the Sendai Framework for Disaster Risk Reduction[46], which stress the importance of adaptive strategies to address climate risks. Wind forecasting was a unique focus for Malaga (Spain), reflecting its reliance on maritime activities and port operations. Accurate wind predictions are essential for navigation safety, port management, and renewable energy projects like offshore wind farms[47], which are gaining traction in the Mediterranean region[48]. Lastly, water-related challenges such as groundwater and runoff assessment were highlighted as a priority for the Greek Islands. With limited freshwater resources and increasing demands from tourism and agriculture[49, 50, 51] the need for localized data and adaptive management is evident. These concerns are documented in studies addressing water scarcity[52] and sustainability in the Mediterranean.

- Boreal Climatic Zone: Coastal Finland

The Boreal Climatic zone encompasses critical maritime and coastal zones such as the Port of Rauma, Port of Raahe, and Coastal Finland, each with distinct priorities shaped by their geographic, climatic, and operational contexts. The data derived from OCEANIDS end-user feedback illustrates a thorough understanding of the environmental and operational concerns in these areas, as demonstrated in the chart in Figure 5.

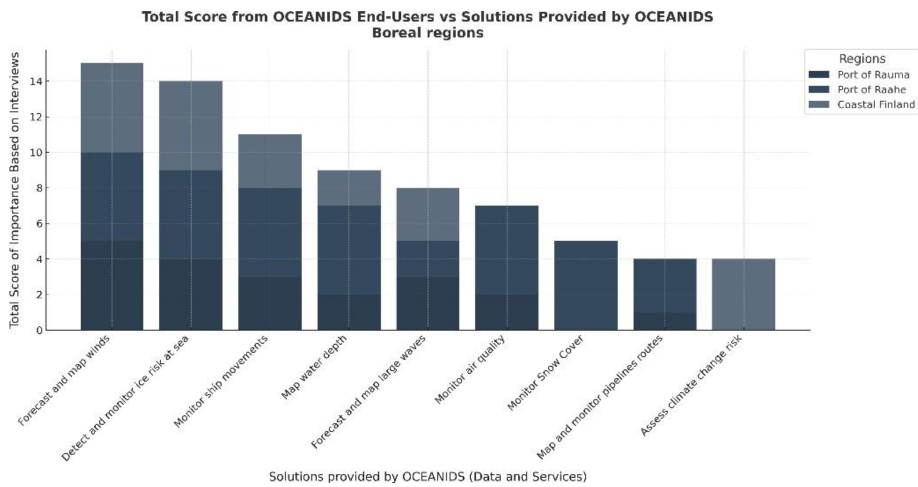


Figure 5. The chart illustrates the total scores of importance assigned by OCEANIDS end-users for various solutions provided in the Boreal regions. Data reflects specific contributions of the Port of Rauma, Port of Raahe, and Coastal Finland, highlighting regional variations in priority solutions.

Forecasting and mapping winds emerged as the highest-priority solution across all three regions, with scores of 5. This uniform importance underscores its critical role in ensuring safe navigation, especially given the challenging wind conditions common in the Boreal seas[53, 54, 55]. Accurate wind predictions are essential for vessel route optimization, operational safety, and mitigating delays caused by adverse weather. Research has shown that advanced meteorological models, coupled with satellite data, have significantly enhanced wind forecasting accuracy, benefiting maritime operations in regions like the Baltic Sea [56].

Detecting and monitoring ice risks at sea received equally high scores, particularly for the Port of Raahe and Coastal Finland, where scores of 5 reflect the criticality of this solution in Arctic-like conditions. Ice poses significant threats to vessel safety, infrastructure integrity, and port operations in these regions[57]. While the Port of Rauma scored slightly lower (4), this still highlights its relevance in mitigating risks during the winter months. Ice monitoring technologies, including radar and satellite imaging, have become indispensable in these regions, enabling predictive assessments of ice formation and movement[57].

Monitoring ship movements was especially important for the Port of Raahe, with a score of 5. This likely reflects its role as a hub for industrial exports and its high traffic of cargo vessels. Ports like Rauma and Coastal Finland rated this solution moderately (3), possibly due to differences in traffic density and operational focus. Studies have demonstrated the effectiveness of AIS (Automatic Identification Systems)[58] and satellite tracking in improving ship movement monitoring, reducing collision risks, and optimizing port logistics[59,60].

Mapping water depth[61,62] was highly prioritized at the Port of Raahe, with a score of 5, reflecting its critical importance for ensuring safe navigation in shallow or sediment-prone areas. In contrast, both the Port of Rauma and Coastal Finland, assigned lower scores (2 each), indicating that services might already exist and are operational. Accurate bathymetric mapping, supported by advancements in GIS-based technologies, plays a pivotal role in maintaining navigational safety, especially in areas affected by sediment deposition and ice-related seabed changes[63,64].

Forecasting and mapping large waves showed moderate importance at the Port of Rauma and Coastal Finland (scores of 3), whereas the Port of Raahe showed less interest with a score of 2. The variation reflects the existence of already advanced operational services. Wave forecasting systems, such as spectral wave models[65], are essential for ports facing significant open sea influences.

Air quality monitoring was particularly important for the Port of Raahe (score: 5), emphasizing its industrial activity and the associated need for emission control. The Port of Rauma showed lower interest (score: 2), reflecting its smaller industrial footprint[66]. Continuous air quality monitoring is vital for mitigating health and environmental risks in industrialized areas, as shown by research linking emissions in port regions to significant environmental impacts. Monitoring snow cover was a unique priority for the Port of Raahe, which rated it at 5.

This highlights the operational challenges posed by heavy snow accumulation in northern Finland, where snow can disrupt port logistics and infrastructure. Satellite-based snow cover models have proven effective in managing such risks by providing real-time data for resource allocation and safety planning[67].

Assessing climate change risks was specifically emphasized by Coastal Finland, with a score of 4, reflecting its exposure to sea-level rise[68], storm surges[69], and shifting ecosystems. The focus on climate risk underscores a commitment to long-term sustainability and adaptive planning. Recent advances in climate modeling and the use of satellite data have enhanced regional resilience strategies, making them increasingly actionable.

- Atlantic Climatic zone - Regions: Bretagne (France), Azores (autonomous region of Portugal), and Bremen (Germany)

The analysis of OCEANIDS end-user scores for the Atlantic regions, encompassing the Azores, Bretagne, and Bremen, reveals a broad landscape of environmental and operational priorities shaped by distinct regional challenges and characteristics. The following insights expand upon the results to provide a comprehensive understanding of the region-specific priorities.

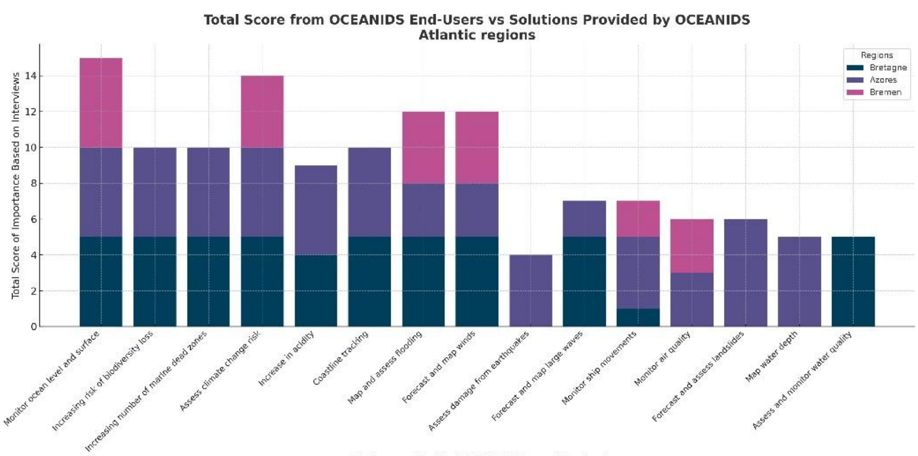


Figure 6. This chart depicts the total importance scores derived from OCEANIDS end-user interviews across the Atlantic regions (Bretagne, Azores, Bremen). It highlights regional priorities in ocean monitoring and assessment solutions, such as tracking sea levels, forecasting winds, and mapping water quality. The scores reflect a comparative analysis of user needs across diverse maritime challenges.

Certain priorities emerged as consistent across all three Atlantic regions, reflecting shared concerns related to maritime and environmental challenges. The most notable of these was monitoring ocean levels and surface, which received a unified score of 5 across all regions. This highlights a broad consensus on the need to address sea-level rise, coastal erosion, and the impacts of extreme weather events. These concerns align with ongoing research emphasizing the importance of satellite altimetry and oceanographic models in providing real-time data for coastal resilience.

Similarly, assessing climate change risk was ranked as a high priority across the Atlantic regions, with a slight variation in Bremen, which assigned a score of 4. This reflects the pervasive impact of climate change on ocean dynamics, fisheries, and coastal infrastructure. Advanced climate modeling tools are being increasingly employed to evaluate these risks, providing actionable data for regional adaptation strategies.

The Azores demonstrated a distinct set of priorities shaped by its geographic and geophysical context. The highest-rated task, forecasting and assessing landslides, with a score of 6, underscores the region's susceptibility to landslide events due to its volcanic terrain and steep coastal slopes. Landslide forecasting technologies, such as GIS-based models and remote sensing, have proven invaluable in similar environments, enabling early warning systems and mitigation strategies in addition to landslide risks. The Azores assigned consistent importance to coastline tracking and air quality monitoring, reflecting its need to balance environmental protection with increasing tourism and maritime activities. Research highlights the value of satellite imagery and high-resolution topographic mapping for monitoring coastline changes and addressing air quality issues in small island settings. Bretagne prioritized monitoring ocean levels and surface and forecasting, and mapping large waves, both receiving scores of 5. This reflects the region's exposure to powerful Atlantic storm systems, which pose significant risks to coastal infrastructure, shipping, and fishing activities. Advanced wave modeling systems, coupled with local observation networks, play a critical role in predicting storm surges and mitigating their impacts.

In contrast, tasks such as monitoring ship movements were assigned lower scores (~1), indicating that maritime traffic management may not be a primary concern for the region. This aligns with Bretagne's emphasis on environmental monitoring over logistical challenges, suggesting a focus on sustainable maritime practices rather than high-volume port operations.

Bremen exhibited a more balanced but less intensive prioritization across tasks, with scores slightly lower than those of the Azores and Bretagne. Monitoring air quality and ship movements received moderate scores of 3 and 2, respectively. These priorities reflect Bremen's industrial and urban context, where air quality monitoring is critical for managing emissions from shipping and nearby industrial activities. The city's moderate concern for ship movement monitoring could stem from its established logistics infrastructure, which already integrates AIS and satellite tracking technologies to optimize port operations. Bremen's emphasis on monitoring ocean levels and surface and assessing climate change risk is slightly lower than in other regions, highlighting a regional awareness of the broader impacts of climate change on urban infrastructure and maritime activities. Research indicates that adaptive planning in urbanized port areas, such as Bremen, is crucial to mitigating long-term risks from rising sea levels and changing weather patterns.

The Azores stand out for their unique emphasis on landslide forecasting, driven by the region's volcanic terrain and vulnerability to slope instability. In contrast, Bretagne's high prioritization of wave forecasting and ocean monitoring reflects its exposure to powerful Atlantic storms. Bremen demonstrates a more moderate approach, balancing concerns about industrial emissions and the broader impacts of climate change on maritime and urban systems.

Despite these regional differences, the uniform emphasis on monitoring ocean levels and surface and assessing climate change risk underscores a shared commitment to addressing global environmental challenges. These priorities highlight the importance of integrated solutions that combine advanced satellite technology, predictive modeling, and localized risk assessments to ensure sustainability across the Atlantic regions.

### 3.5. Broader Implications

These preliminary results underscore the importance of integrating EO data and machine learning techniques for the sustainable management of coastal and urban environments. The adaptability of the methodology in various climatic and geographic zones highlights its potential for broader applications, providing a scalable framework to address climate risks and improve resilience in coastal regions.

Expanding the focus from regional to broader outcomes provides an opportunity to evaluate the overall implications of the OCEANIDS end-user scores, emphasizing cross-regional patterns and their relevance for global environmental and operational challenges. This detailed examination reveals shared priorities and highlights overarching trends that transcend regional differences.

Across all regions, the consistent emphasis on monitoring ocean levels and surface underscores its critical importance. This task is universally recognized as essential for managing the impacts of sea-level rise, storm surges, and oceanic circulation changes. High scores across Boreal, Atlantic, and Mediterranean regions reflect the global reliance on accurate and real-time ocean monitoring for safeguarding coastal communities and maritime infrastructure. Research demonstrates the effectiveness of satellite altimetry, coupled with oceanographic models, in providing actionable data for policymakers and industry stakeholders. The strong prioritization of assessing climate change risk highlights a universal awareness of the growing threats posed by climate change. Across regions, climate risk assessment serves as a cornerstone for developing adaptive strategies, from mitigating the effects of extreme weather events in the Atlantic to addressing long-term ecological shifts in the Mediterranean and Boreal regions. The integration of predictive climate models and localized risk assessments has been shown to enhance resilience against climate-related disasters on a global scale.

Certain tasks, such as forecasting landslides in the Azores or monitoring ice risk in the Boreal regions, are tied to specific regional vulnerabilities. However, their broader relevance becomes evident when considering similar challenges in other parts of the world. For instance, landslide forecasting technologies developed for volcanic islands can be adapted for use in mountainous coastal regions elsewhere. Similarly, ice risk monitoring systems in the Boreal regions offer valuable insights for managing Arctic shipping routes and mitigating risks in polar regions experiencing increasing maritime activity.

The prioritization of advanced forecasting and monitoring solutions across all regions points to the increasing reliance on technology to address complex challenges. Satellite data, GIS-based models, and AI-driven analytics are emerging as pivotal tools for achieving both regional and global sustainability goals. These technologies not only enhance accuracy and efficiency but also enable cross-regional collaboration by providing standardized datasets and tools applicable to diverse contexts.

The OCEANIDS end-user scores reveal a global consensus on the critical role of monitoring and forecasting in addressing environmental and operational challenges. While specific priorities vary across regions, the overarching trends reflect a shared commitment to sustainability, safety, and resilience. By focusing on solutions that address both localized and universal concerns, the findings underscore the interconnected nature of maritime and environmental challenges in a rapidly changing world.

## 4. DISCUSSION

The preliminary findings underscore the pressing need for integrated and scalable solutions to manage climate risks in coastal cities and ports. Coastal zones are increasingly recognized as critical hotspots for climate change impacts, facing challenges such as sea level rise, biodiversity loss, and extreme weather events. The OCEANIDS methodology proposes a practical framework for addressing these challenges by combining EO data with advanced analytical tools to generate actionable insights for stakeholders. These findings align with previous studies that emphasize the critical role of EO data and AI techniques in assessing environmental risks and supporting decision-making for climate adaptation strategies. For instance, the identification of flood-prone zones in Bretagne and Bremen justifies existing research highlighting the vulnerability of low-lying coastal regions to sea level rise and extreme weather events. Similarly, the requirement outlined by the end-users for air quality monitoring and urban growth assessments in Malaga (Spain) aligns with studies emphasizing the environmental pressures posed by industrialized port operations.

The methodological framework of the OCEANIDS project adds value to the existing literature by addressing data integration challenges through spatiotemporal alignment and harmonization processes. The incorporation of bias-adjusted EURO-CORDEX datasets for long-term climate projections ensures that risk assessments are grounded in reliable data, bridging gaps identified in earlier studies or addressed as needed by the end-users of the project.

From a broader perspective, the project's emphasis on user-friendly visualizations and decision support systems aligns with global efforts to enhance climate resilience through accessible and transparent data platforms. The ability to provide pre-event, short-term, and post-event risk assessments ensures that stakeholders can adopt proactive and adaptive strategies, reducing the socioeconomic impacts of climate-related hazards. These contributions are particularly relevant in the context of international frameworks such as the Paris Agreement [48] and the Sendai Framework for Disaster Risk Reduction [49], which prioritize data-driven and participatory approaches to climate adaptation.

The findings from this study demonstrate the effectiveness of integrating satellite imagery, AI-driven analytics, and EO data in addressing diverse challenges faced by coastal and port environments. By tailoring solutions to specific regional needs, the study highlights significant advancements in environmental monitoring and operational efficiency.

In the Boreal regions, the prioritization of ice risk monitoring and snow cover analysis underscores the importance of climate-specific tools to mitigate hazards that disrupt navigation and port operations. The Port of Raahe, in particular, benefited from enhanced bathymetric mapping, reflecting the critical need for precise seabed data in sediment-prone and ice-affected areas. Similarly, in the Mediterranean region, air quality monitoring emerged as a key focus, particularly for industrialized ports, where emissions significantly impact local environments. Advanced satellite monitoring and predictive modeling were shown to effectively address these concerns, supporting both environmental and public health objectives.

The Atlantic regions revealed unique priorities, such as landslide risk forecasting in the Azores and wave forecasting in Bretagne, demonstrating the importance of region-specific strategies. The high prioritization of ocean level monitoring across all regions highlights the universal relevance of this solution for mitigating risks from sea-level rise and extreme weather events.

The results also validate the role of AI and EO technologies in enabling cross-regional scalability while addressing localized challenges. By combining real-time data analytics and tailored decision-making frameworks, the study provides actionable insights for policymakers and stakeholders, advancing the sustainable management of coastal and port systems. The results presented in this study are constrained by the ongoing nature of the project. Further integration of datasets and refinement of analytical models are anticipated as the project progresses. Future directions include incorporating additional datasets, enhancing model performance, and expanding the analysis to explore long-term climate scenarios. The insights generated thus far provide a solid foundation for continued development and application of the OCEANIDS methodology.

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