MASTER THESIS

Provisions of Earth Observation data sources for use by a GIS content management system and online marketplace

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ABSTRACT

The objective of this investigation was to provide PIKSEL with EO data sources. Several steps were followed to achieve this goal.

The initial phase of the research involved the identification and compilation of EO data sources available. The selection process aimed to encompass a wide range of geospatial, environmental, and climatic data to cater to the diverse needs of the PIKSEL use cases and its users.

Subsequently, the EO data available was subjected to an evaluation to determine its relevance to the specific application and objectives of the PIKSEL platform. This assessment considered factors such as data accuracy, spatial and temporal resolution and data format.

Once the relevant EO data sources were identified, the next step involved a detailed analysis of the data downloading procedures associated with each source. Each provider often presents unique requirements, access protocols, and data delivery formats, necessitating a thorough understanding of the technical intricacies and obtaining the necessary credentials for data acquisition.

To streamline and automate the data retrieval process, a custom Python script was developed for the specific case of the evolution of the coastline.

Recognizing the importance of user experience, a user-friendly interface was designed to facilitate straightforward data management. The interface aims to simplify the process of accessing and querying, ensuring that users, irrespective of their technical expertise, can efficiently interact with the platform's resources.

However, various hurdles were encountered during the project, including diverse data access procedures, lack of standardization among data channels, and challenges in obtaining and understanding Copernicus data. Despite these challenges, this work presents a valuable resource for non-programming experts seeking to manage EO data with ease.

The work also explores future opportunities to expand the platform, integrate other Copernicus services, include diverse relevant sources, and implement the user interface on the PIKSEL website.

Dedication

I would like to thank my parents for the support, patience, and education they have given me. I also would like to thank Pere-Andreu Ubach de Fuentes, Laurence Sigler and Francisco Javier Mora Serrano for their guidance and supervision during the project. Finally, I would like to thank my friends and family for their moral support, particularly I would like to mention Sergio García Liviano for his friendship.

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List of acronyms

CAMS: Copernicus Atmosphere Monitoring Service
CEMS Copernicus Emergency Management Service
CHEOS: China High-resolution Earth Observation System
CIMNE (acronym in Catalan): International Center for Numerical Methods in Engineering
CLMS: Copernicus Land Monitoring Service
CMEMS: Copernicus Marine Service
CNES: French Space Agency
CSA: Canadian Space Agency
CSS: Copernicus Security Service
C3S: Copernicus Climate Change Service
DIAS: Data and Information Access Services
DTE: Digital Twin of Earth
EC: European Commission
ECMWF: European Centre for Medium-Range Weather Forecasts
EEA: European Environment Agency
EMSA: European Maritime Safety Agency
EO: Earth observation
ESA: European Space Agency
EU: European Union
EUMETSAT: European Organization for the Exploitation of Meteorological Satellites
GEE: Google Earth Engine
GIS: Geographic Information System
GUIs: Graphical User Interfaces
ICGC (acronym in Catalan): Cartographic and Geological Institute of Catalonia
IDE: Integrated Development Environment
JAXA: Japan Aerospace Exploration Agency
JEODPP: Joint Research Center Earth Observation Data and Processing Platform
JRC: Joint Research Centre
MFCs: Monitoring and Forecasting Centers
MWT: Sea surface wave period at variance spectral density maximum
NA: North Atlantic
NASA: National Aeronautics and Space Administration
ODC: Open Data Cube
ONDA: Open Network for Data Access
PIKSEL: Portal Integrative of Knowledge for the Sustainable management of the Ecosystems and Land
SEPAL: System for Earth Observation Data Access, Processing and Analysis for Land Monitoring
SH: Sentinel Hub
SWH: Sea surface wave significant height
TACs: Thematic Assembly Centers
USGS: United States Geological Survey
VMDR: Sea surface wave from direction
WEKEO: We knowledge Earth Observation
WMS: Web Map Service

CHAPTER 1
Introduction

The study and management of the territory houses profound significance across multiple domains and supports the foundations of sustainable development, environmental preservation, and prudent resource utilization. A thorough understanding of the territory's geographic characteristics, ecological complexities, and socio-economic dynamics provides invaluable insights for informed decision-making.

By comprehensively studying the territory, policymakers can devise tailored strategies that balance economic growth with environmental conservation, mitigating the adverse impacts caused by human development and safeguarding the planet's natural heritage for future generations. Through effective territorial management, governments can implement urban planning, disaster preparedness, and resource allocation, fostering resilient communities and fostering a harmonious coexistence between humanity and nature.

1.1 Motivation

My decision to undertake this project was driven by a combination of professional interest, a desire to contribute to the field of EO data management, and a passion for advancing technological solutions. As mentioned, Earth Observation plays a critical role in understanding and addressing various environmental challenges and shaping sustainable solutions.

Additionally, the opportunity to learn about a cutting-edge project like PIKSEL, integrate data sources into the platform, design a user-friendly interface, and overcome technical hurdles, was a personal motivating challenge.

Ultimately, the prospect of making a meaningful impact on the accessibility and usability of EO data and contributing to the advancement of a platform that benefits a wide range of users and applications was a driving force to develop this work.

1.2 Background: The PIKSEL project

Concerned citizens are deeply invested in a myriad of issues, spanning environmental, societal, and economic concerns that arise from human activities. In particular, they are keen to be informed about the concrete steps that administrations plan to take in addressing these pressing concerns.

Responding to this need, the Portal Integrative of Knowledge for the Sustainable management of the Ecosystems and Land (PIKSEL) [20] emerges as a collaborative, multidisciplinary initiative, uniting citizens, administrative bodies, the scientific community, and private enterprises in pursuit of a sustainable future for Catalonia. This union, known as Quintuple Helix framework [1] is an important manner of innovation.

At the core of this project lies the development of a sophisticated management and prediction tool, founded on computational models. Through these models, PIKSEL delves into the intricate interplay of environmental, economic, and social phenomena that profoundly impact the Catalan territory, giving rise to diverse use cases across thematic areas such as air quality, biodiversity, urban planning, coastal evolution, and natural disasters like earthquakes and floods.

PIKSEL seeks to facilitate the comprehension and communication of complex data. Commencing in January 2020, PIKSEL represents a collaboration between the Generalitat de Catalunya [21] and several research groups, coordinates by the International Center for Numerical Methods in Engineering (CIMNE, acronym in Catalan) [22]. By offering robust scientific evidence, PIKSEL empowers decision-makers to make well-informed choices when shaping public policies, paving the way for effective action plans.

PIKSEL models present a meticulously structured process, involving three distinctive phases.

The initial phase termed the diagnostic stage, revolves around comprehending the underlying reality or issue under scrutiny. This crucial step encompasses an in-depth analysis of the problem's manifestations, as well as an assessment of its far-reaching consequences and implications. Armed with a comprehensive understanding of the problem's multifaceted nature, the project gains a solid foundation for devising viable solutions.

In the subsequent phase, known as the prognostic stage, revolves around the meticulous estimation and contemplation of diverse scenarios, driven by rigorous scientific criteria. By employing this methodological approach, the project can anticipate potential outcomes, facilitating informed decision-making and strategic planning.

Lastly, the decision stage marks the final phase of the process. Herein, a range of actionable measures is carefully crafted, accounting for the economic, social, and environmental costs associated with each considered option. Through an intricately balanced evaluation, the project formulates a coherent strategy that optimally addresses the identified issues, aligning with the overarching goals of sustainability and enhanced well-being.

Earth observation (EO) data plays a pivotal role in effectively managing and studying the territory, offering a wealth of valuable information that is otherwise challenging to acquire through traditional means. EO data gathered through remote sensing technologies and direct-contact sensors, provides comprehensive and real-time insights into various aspects of the territory, including land use, vegetation health, water resources, and environmental changes. This information is essential for evidence-based decision-making in territorial management, enabling policymakers to assess the impact of human activities, monitor environmental changes, and develop sustainable land-use plans. Additionally, EO data allows for the detection and prediction of natural hazards, such as floods and wildfires, enhancing disaster preparedness and response strategies.

EO data is crucial for PIKSEL as it offers reliable and up-to-date information. By incorporating EO data, PIKSEL can access more relevant and comprehensive data and verify computational models to make accurate predictions and assessments. This will help PIKSEL become a more robust platform for making well informed decisions and gaining a better understanding of the environment than any other tool available today.

Furthermore, by combining state of the art, computational models with high-detail EO data, PIKSEL can produce results far superior to any other tool available today.

The objective of this investigation is to provide PIKSEL with EO data sources. With this objective in mind, the following specific goals are proposed:

1. Identify EO data sources.
2. Decide if the data is relevant regarding the application
3. Understand the process of retrieving data from the source.
4. Implement a script to obtain the desired data.
5. Create a user-friendly interface to manage the retrieval.

As a consequence, this work has been organized into the following parts.

1.3 Overview of the document

In Chapter 3, the foundations of Earth Observation, the significance of the Copernicus program, and the initiative Destination Earth are introduced. The chapter also introduces key platforms for EO data management and analysis, such as Google Earth Engine (GEE), Sentinel Hub (SH), Open Data Cube (ODC), and ArcGIS.

Moving on, Chapter 3 is focused on Copernicus data, with a focus on the Copernicus Atmosphere Monitoring Service (CAMS) and the Copernicus Marine Service (CMEMS).

Then in Chapter 4, several PIKSEL case studies are presented with a focus on the evolution of the coastline case study. This chapter is followed by Chapter 5, focused on the tool development where practical methodologies are presented, including data retrieval processes using the Motu API and Web Map Service (WMS) API. The chapter culminates with a proposal for integrating the Copernicus Marine Service into the PIKSEL platform to enhance its capabilities.

Finally, conclusions are presented in Chapter 6.

This work provides a comprehensive journey through EO data analysis, presenting valuable insights into the significance of this research field and its practical applications within the PIKSEL project. Furthermore, this work also presents a methodology to retrieve EO data from Copernicus that is useful for numerical analysis in general, and for the PIKSEL project in particular.

CHAPTER 2
State of the art

2.1 Earth Observation (EO)

Earth observation (EO) offers a useful method for investigating the Earth's physical, chemical, and biological information by observing and evaluating natural and manmade environmental variables and changes, and for promoting the sustainable advancement of contemporary human civilization and the global environment [2].

Researchers and decision-makers can develop and put into practice effective strategies for environmental protection and sustainable management of natural resources based on information collected from EO data [3].

Herman Potočnik initially considered the concept of employing orbiting spacecraft to observe the Earth in his book from 1928, The Problem of Space Travel [4]. The first satellite created expressly for Earth observation to map the spread of cloud cover was the Vanguard 2 [5], and it was developed by the United States Naval Research Laboratory.

Nowadays, there are many satellites dedicated to EO such as Landsat satellites which are part of the Landsat program, a joint National Aeronautics and Space Administration (NASA) and the United States Geological Survey (USGS) [6]. China also has a program dedicated to EO known as China High-resolution Earth Observation System (CHEOS) [7]. In addition, Resurs-Prospective (Resurs-P) is an EO mission funded by Roscosmos under the Russian Federal Space Program. The Japan Aerospace Exploration Agency (JAXA) has a dedicated Program to EO that was consolidated in 2003.

Nanosatellites are also used for EO purposes. Despite their small size and limited resources, they have proven to be valuable platforms for conducting EO missions [8].

Open Constellation [9] is an example of a relevant program for EO. It is a global, shared satellite infrastructure that Open Cosmos [10] built and manages. The goal of this initiative is to provide open access to satellite data so that anyone can address issues related to the climate crisis, energy, natural resources, and other issues.

The Menut is the second nanosatellite that the Government of the Generalitat has put into orbit as part of the NewSpace Strategy of Catalonia. Promoted by the Generalitat and the Institut d'Estudis Espacials de Catalunya (IEEC) and developed by Open Cosmos. Its mission is the observation of the Earth to improve the management of the territory and help control and combat the effects of the climate crisis.

The Copernicus program, coordinated and managed by the European Commission (EC), is also devoted to EO [11]. In the next section, the details of the Copernicus program will be discussed.

2.2 Copernicus program

Copernicus [12] is the Earth observation component of the European Union Space Programme. It was launched in 1998 and it is managed by the EC and implemented in partnership with the European Union (EU) Member States, the European Space Agency (ESA) [13], the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) [14], the European Centre for Medium-Range Weather Forecasts (ECMWF) [15], the Joint Research Centre (JRC) [16], the European Environment Agency (EEA) [17], the European Maritime Safety Agency (EMSA) [18], Frontex [19], SatCen [20] and Mercator Océan [21].

Copernicus offers free access to near real-time data collected by specialized EO satellites, in-situ observations, and a set of core information services crucial to managing environmental and global security issues. Its ongoing observations for monitoring the atmosphere, oceans, and land have a significant positive impact on socioeconomic as well as smart and sustainable growth, encouraging the creation of novel solutions in many fields and assisting in the EU climate plan [22].

Copernicus offers six core services free of charge that convert Sentinel products for six different theme areas into information that is suitable for further use.

The Copernicus Land Monitoring Service (CLMS) [23] offers geospatial information on land cover and its changes, land use, vegetation and agriculture state, water cycle, cryosphere and incoming solar radiation. In addition to applications in areas like spatial and urban planning, water management, agriculture and food security, nature protection and restoration, rural development, ecosystem accounting, and climate change adaptation and mitigation, the service supports environmental and development policies [12].

The Copernicus Emergency Management Service (CEMS) [24] has a mapping component that offers map and geo-information resources for all forms of natural and man-made catastrophes, as well as an early warning component about risk assessments for floods and forest fires.

The Copernicus Atmosphere Monitoring Service (CAMS) [25], provides consistent and quality-controlled information related to air pollution and health, solar energy, greenhouse gases and climate forcing.

The Copernicus Marine Service (CMEMS) [26] provides consistent and systematic reference data on the state, variability, and dynamics of the ocean and marine ecosystems for both the global ocean and the European regional seas [12]. All marine applications are supported by the service's observations and forecasts, including:

- Coastal and marine environment.
- Sustainable use and conservation of marine resources.
- Weather, seasonal forecasting and climate.
- Marine safety.

CMEMS is the Copernicus service on which the focus of the work has been placed. The reason is the case study used for the elaboration of the tool is the PIKSEL model of the evolution of the coast. In other words, this service presents relevant variables of the coast and the marine environment for the evolution of the coastline model.

In particular, CMEMS provides historical information on the sea state and its prediction. Since the forecast goals of PIKSEL's Challenge 2 on the evolution of the coastline (several months) go far beyond the forecast scope of Copernicus (a few days), PIKSEL only uses the historical information from Copernicus.

The Copernicus Security Service (CSS) [27] is responsible for border surveillance, maritime surveillance, and assistance with EU External Action [28]. It focuses on crisis prevention, preparedness, and response in these three areas. It provides information in response to security challenges and is only accessible to authorized users, supporting EU policies.

The Copernicus Climate Change Service (C3S) [29] offers materials regarding the past, present, and future climate that are reliable and of high quality.

2.3 Destination Earth

The EC launched in January 2021 an initiative called Destination Earth [30], often known as DestinE with a goal to construct a Digital Twin of the Earth (DTE) by 2027. This simulation will be utilized to better comprehend the effects of climate change and environmental catastrophes. It will provide interoperability while integrating numerous models and simulations of various phenomena (such as weather, social, and marine) onto a single platform.

DestinE will enable users to interactively explore the various elements of the Earth system and natural and human-induced change using an unprecedented quantity of data, creative Earth system models, and cutting-edge computers. They will be able to examine the history, the present, and design and test many scenarios for the future.

ESA, ECMWF and EUMETSAT are leading the development.

2.4 Platforms for EO data management and analysis

Due to technology advancements and open data policies set by governments and space organizations, the amount of EO data that is publicly available for society and researchers has significantly expanded in recent years. The following platforms were investigated due to their similarity with the objective of the PIKSEL project.

Google Earth Engine (GEE) [31], Sentinel Hub (SH) [32], Open Data Cube (ODC) [33], System for Earth Observation Data Access, Processing and Analysis for Land Monitoring (SEPAL) [34], openEO [35], JEODPP (Joint Research Center Earth Observation Data and Processing Platform) [36], and pipsCloud [37] are some of the available platforms for EO data management and analysis [3].

2.4.1 Google Earth Engine (GEE)

Large-scale scientific analysis and visualization of geospatial datasets are made possible by the cloud-based Google Earth Engine (GEE) platform. Google introduced GEE as a closed system in 2010.

For the management and analysis of data, GEE offers JavaScript and Python APIs. A web Integrated Development Environment (IDE) is also made available for the JavaScript version, giving the user quick access to the data, programs, and real-time visualization of the processing results. The JavaScript version of the Python API's structure is also accessible through a module.

This platform offers a data catalog that houses a sizable collection of geospatial data, including optical imagery from different satellites and air systems, environmental factors, weather and climate forecasts, land cover, socioeconomic and topographic datasets, and environmental variables. These data sets are preprocessed before being made available, facilitating effective access, and removing many obstacles related to data management [31].

In Figure 2.1 the architecture diagram of GEE is presented.

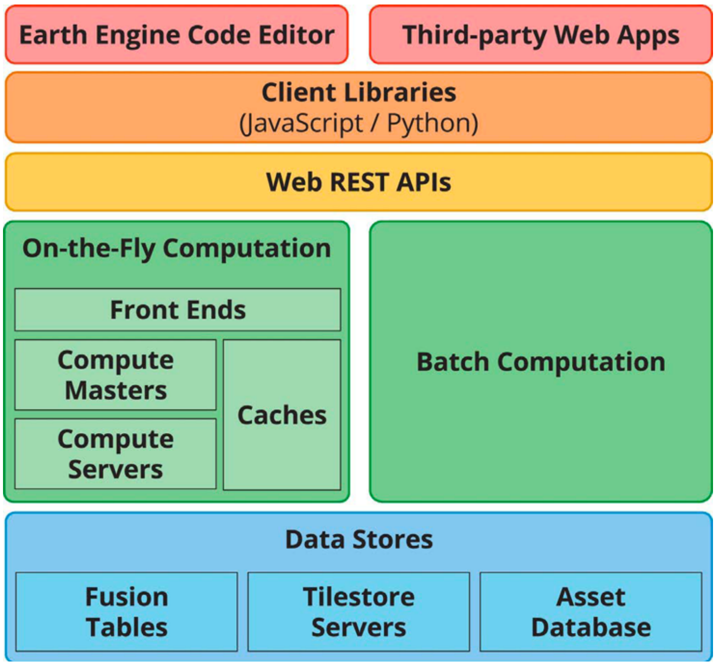

Figure 2.1: Google Earth Engine (GEE) system architecture diagram [31].

When looking at Figure 2.1 we would expect the Asset Database to contain the tool that will be developed in this work.

2.4.2 Sentinel Hub (SH)

Sentinel Hub (SH) is a platform developed by Sinergise that provides Sentinel data access and visualization services. This is a private platform with public access. Sinergise does not provide a diagram of the system architecture used by Sentinel Hub nor information about how data is stored or processed

This data may be analyzed and visualized using a variety of tools provided by the platform, which makes it suitable for a variety of applications such as forestry, urban planning, environmental monitoring, and agriculture; According to their documentation [32].

Sentinel Hub's capacity to quickly and effectively process and serve up massive volumes of satellite imagery is one of its primary characteristics. The platform's utilization of data streaming and cloud computing technologies, which allow users to access and analyze data in real time, makes this possible [3].

Sentinel Hub's user-friendly interface, which makes it simple for non-experts to view and operate with satellite imagery, is another crucial feature. The platform provides a variety of tools for displaying and analyzing data, including the capacity to layer various information on top of one another and alter color schemes [3].

Gomes et al. [3]. state that SH offers a variety of sophisticated capabilities for consumers with more specialized needs in addition to its fundamental functionality. These include the capacity to utilize cutting-edge machine learning techniques for image analysis, interface with third-party tools and APIs, and design unique processing chains.

2.4.3 Open Data Cube (ODC)

Open Data Cube (ODC) is an open-source platform for managing and analyzing large amounts of geospatial data. It is intended to be efficient, scalable, and available to users of all skill levels. Users of the platform can carry out numerous operations, such as data intake, indexing, querying, and analysis. It is created using a distributed computing architecture.

ODC's capacity to manage huge amounts of data from many sources, such as satellite imagery, meteorological information, and other geospatial datasets, is one of its important characteristics. The platform offers a uniform data model that makes it simple to combine data from various sources and carry out intricate analytics [3].

Along with a variety of tools for data visualization and analysis, ODC also gives users the option to design their workflows and scripts in well-known programming languages like Python and R. Various third-party tools and services, such as cloud computing infrastructures like Amazon Web Services and Google Cloud, can also be integrated with the platform.

The community-driven development model of ODC is another significant feature. A large global community of programmers, researchers, and other stakeholders supports the platform and helps to keep it updated and maintained. This guarantees that the platform stays current with the most recent geospatial technology breakthroughs and is available to a wide variety of users with varied degrees of experience explains Gomes et al. [3].

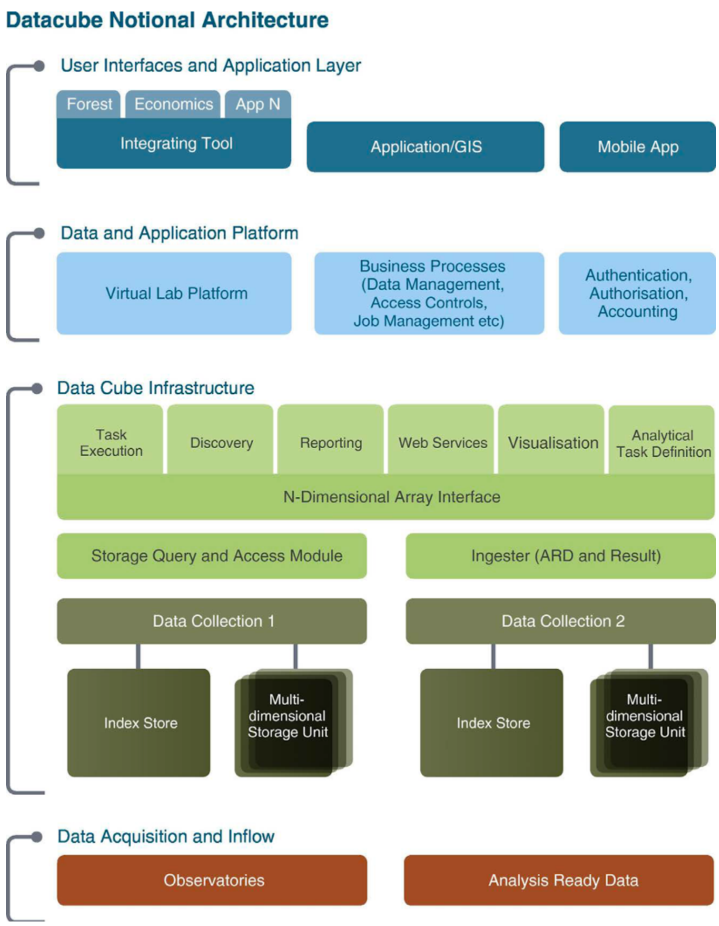

Figure 2.2: Architecture diagram of the Open Data Cube (ODC) platform [38].

When looking at Figure 2.2 we would expect the Analysis Ready Data to contain the tool that will be developed in this work.

2.4.4 ArcGIS

ArcGIS [39] is a Geographic Information System (GIS) software suite developed by Esri. ArcGIS is a framework for capturing, managing, analyzing, and visualizing geographic data to support decision-making processes.

ArcGIS is split between ArcGIS Online [40] and ArcGIS marketplace [41]. ArcGIS Online allows users to create, manage, and share geographic information and maps through a cloud-based system. On the other hand, the ArcGIS marketplace acts as a marketplace for both developers and users, providing a centralized location to find solutions and resources related to GIS and spatial analysis.

For managing EO data throughout its lifecycle, ArcGIS provides a complete set of tools and functionalities. Large volumes of geospatial data, including satellite imagery, elevation models, and other relevant datasets, can be imported, stored, and managed by users. These data can be structured, allowing for effective sharing and storage among individuals, groups, or entire organizations. To provide a thorough understanding of the Earth's features and their interactions, EO data can be combined with other geospatial information, such as administrative boundaries, infrastructure networks, or socioeconomic data [39].

CHAPTER 3
COPERNICUS DATA

The Copernicus program provides information services that make use of data from in-situ environmental observations and satellite Earth observation. The products are downloadable through various access points. Users must register to download the data even though it is free and open.

Copernicus data sources include sentinel data from ESA, sentinel data from EUMETSAT, data from contributing missions and in situ data.

ESA is responsible for the development of the space segment component of the Copernicus program and operates the Sentinel-1 [42], Sentinel-2 [43] and Sentinel-5P [44] satellites. ESA also delivers the land mission from Sentinel-3 [45].

EUMETSAT is responsible for operating the Sentinel-3 [46] and Sentinel-6 [43] satellites and will also operate and deliver products from the Sentinel-4 [47], and Sentinel-5 [48], instruments onboard Meteosat Third Generation [49] and Metop Second Generations satellites [50], respectively.

The Copernicus contributing missions deliver data that complements the output of the Copernicus Sentinel missions. These missions are missions from ESA, its Member States [51] and other European and international third-party operators. These missions include the CryoSat-2 [52], SMOS [53], and Swarm [54] missions from the ESA, the Jason-3 mission from the French Space Agency (CNES) [55], and the SARAL/AltiKa mission from the Canadian Space Agency (CSA) [56]. These datasets can be accessed from their specific website [57].

In order to provide reliable integrated information and to calibrate and validate the data from satellites, Copernicus services rely on data from in situ monitoring networks (e.g., ground-based weather stations, ocean buoys, river gauges, and air quality monitoring networks) [58]. Data is made available to the services through the in situ networks, which are governed by member states and international organizations and describe measurements made of environmental factors like temperature, humidity, and precipitation on the ground.

Figure 3.1 is a representation of the Copernicus data sources.

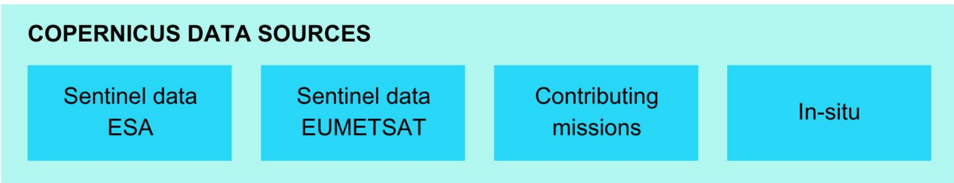

Figure 3.1: Copernicus data sources diagram.

Copernicus Open Access Hub [51] was the primary means of accessing the data provided by Sentinels. Presently, the Copernicus Data Space Ecosystem [60] is the new gateway to access Sentinel data as well as Earth Observation data and services.

The Copernicus Data Space Ecosystem is an infrastructure that has evolved from the Copernicus Open Access Hub and that has the information of the Data and Information Access Services (DIAS) [61]. The DIAS are five cloud-based platforms shown in

Figure 3.2 each providing access to Copernicus data and information, as well as processing tools.

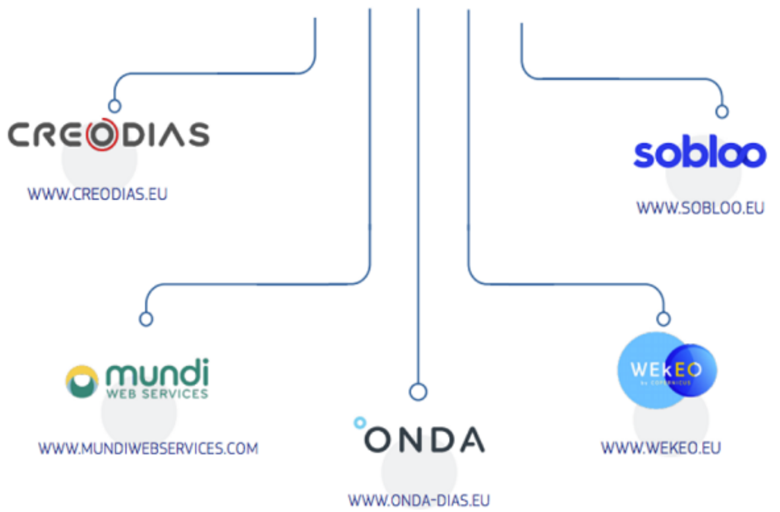

Figure 3.2: DIAS platforms [61]. Source: Copernicus.

ONDA (Open Network for Data Access), WEKEO (We Knowledge Earth Observation), and Mundi Web Services are public initiatives managed by the EU.

ONDA aims to offer a user-friendly interface and tools for data analysis while also enabling users to host data and build applications in the Cloud. ONDA's focus is on providing efficient access to a broad range of Copernicus data sources.

WEkEO is developed by EUMETSAT, ECMWF, EEA and Mercator Océan. It provides a comprehensive platform for accessing and analyzing environmental data. WEkEO's strength relies on its distributed data and infrastructure centers which are not duplicated but rather linked together, reducing costs and giving users direct access to the most up-to-date Copernicus data.

Mundi Web Services is operated by Sinergise and offers access to EO data with a focus on enabling users to build applications and solutions using geospatial data.

Sobloo is a commercial service provided by Airbus, Orange Business Services and Capgemini. Sobloo is a collaborative platform that aims to foster interaction and innovation, expand and diversify data collection, create a sustainable economy, and advance European cloud technology [62].

CREODIAS provides commercial services for Copernicus Data Space Ecosystem, offered by a Consortium consisting of: T-Systems as a leader, CloudFerro, Sinergise, VITO, DLR, ACRI-ST, and RHEA.

On the other hand, EUMETSAT also provides data access through EUMETCast [63] and the EUMETSAT Data store [64]. EUMETCast is a data dissemination system developed by EUMETSAT that aims to distribute meteorological and environmental data and products to users worldwide. Access to the Data Store is through a web user interface or a series of application programming interfaces, allowing users to select a set of different parameters to refine their search in the catalog.

As mentioned before, there are 6 core services in Copernicus. The data from each service can be directly accessed from the specific website.

Figure 3.3 represents the different paths to accessing Copernicus data.

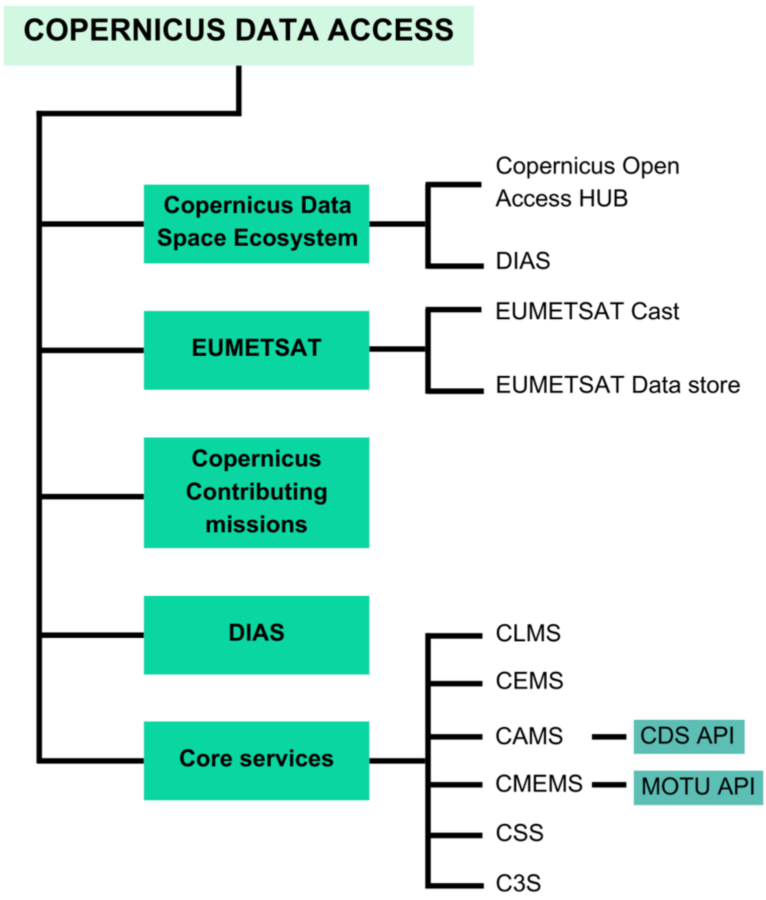

Figure 3.3: Copernicus access diagram**.**

It is important to keep in mind that Copernicus does not provide raw data. Raw data refers to unprocessed, unstructured, and uninterpreted information collected directly from various sources. It represents the original form of data before any manipulation, transformation, or analysis takes place. Raw data often includes observations, measurements, survey responses, or any other unaltered data points. It serves as the foundation for research and analysis, requiring careful consideration and post-processing to extract meaningful insights and facilitate accurate interpretations.

The data provided by Copernicus consists of simulated data. Simulated data refers to artificially generated information that imitates real-world data patterns and characteristics. It is created using mathematical models, algorithms, or computer simulations to mimic the behavior of actual data. Simulated data is often utilized when real data is scarce, expensive, or impractical to obtain. It enables researchers to explore hypothetical scenarios, test theories, validate methodologies, and gain insights into complex systems. However, it is crucial to acknowledge the limitations of simulated data and ensure its appropriateness for the research objectives at hand.

The Copernicus service that received the most attention in this work was CMEMS. As stated before, the case study that was used to develop the tool is a model of the evolution of the coastline.

However, CAMS was also studied in order to find relevant data for the case studies of tropospheric ozone and pollution by nitrogen dioxide.

Details of the some of the products offered by CAMS and CMEMS will be presented in Chapter 4.

3.1 Copernicus Atmosphere Monitoring Service (CAMS)

CAMS [25] provides ongoing data and information on atmospheric composition. Its core services include, among others, the daily creation of near-real-time analyses and forecasts of global atmospheric composition, European air quality products with an ensemble system of regional models, and solar and ultraviolet radiation products.

Applications of CAMS data include:

- Tracing pollution across areas [65].
- Anticipating the influence of climate change [66].
- Monitoring air quality in cities [67] [68].
- Forecasting the spread of wildfires [69] and other natural events [70].

In this case, the data can be extracted using the Atmosphere Data Store [71].

3.2 Copernicus Marine Service (CMEMS)

CMEMS [26] provides a wide range of data and products related to the Earth's oceans and marine environment. It provides free, regular and systematic authoritative information on the state of the Blue (physical), White (sea ice) and Green (biogeochemical) ocean, on a global and regional scale [72]. The CMEMS is funded by the EC and implemented by Mercator Océan.

Applications of the CMEMS data include:

- Forecasting weather patterns [73].
- Oil spill monitoring [74].
- Tracking species [75].
- Managing fisheries [76].
- Combating litter pollution [77].
- Tracking the effects of climate change [78].
- Coastal management [79].

In this case, the data was extracted using the Copernicus Marine Data Store [80].

CHAPTER 4
A PIKSEL MODEL CASE STUDY

PIKSEL addresses different cases using different modeling techniques. In this section, three of these will be introduced.

4.1 PIKSEL Architecture and Case Studies

4.1.1 PIKSEL architecture

The platform is be made up of three main parts: an e-commerce component, support services, and the platform's central component, content management and interoperability. APIs will be used for all connections between resources and components.

Figure 4.1 shows a conceptual diagram of the suggested system. The GIS component is created separately and independently. Models and data can be hosted on the system or connected remotely as resources.

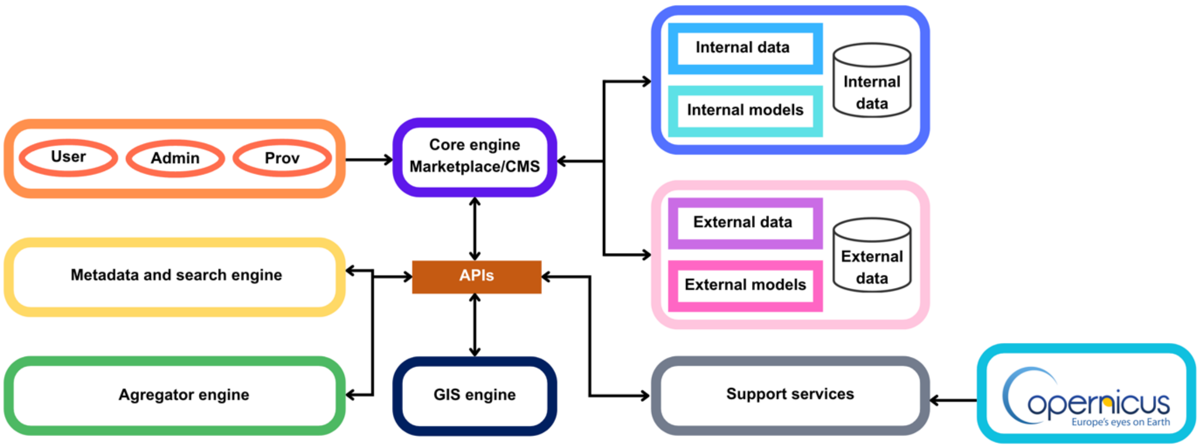

Figure 4.1: PIKSEL architecture.

When looking at Figure 4.1 the support services contain the tool developed in this work. Copernicus is a prominent support service that provides essential functionalities to PIKSEL which can be accessed using APIs.

4.1.2 Pollution by Nitrogen Dioxide NO_2

Air pollution is a significant environmental issue affecting urban areas globally, with over 75% of city residents exposed to levels of pollution above World Health Organization limits.

Among the various air pollutants found in cities, NO_2 is a primary pollutant that poses one of the highest concerns for human health. Therefore, the presence of NO_2 in urban areas is widely used as an air quality indicator. Long-term exposure to NO_2 has been linked to reduced lung function and increased risk of respiratory symptoms, particularly in children and people with asthma. NO_2 is commonly regarded as a primary pollutant and its main source is motor vehicles from traffic.

As such, traffic restrictions could help control NO_2 levels in cities and ensure compliance with human health protection limits. Thus, predicting NO_2 distribution accurately is crucial for effective traffic restriction implementation.

The main objective is to design a high resolution forecast model that allows the simulation of the concentrations of pollutants on a street scale level in particular, the pollution by NO_2. The implementation will ease the evaluation of the evolution of environmental air pollution episodes and ensuing/preventing restrictions. On the other hand, the model will provide the public with basic information on emissions and immissions of the different areas of the city [81].

Using mathematical models, the computational model named Piplates-R4 will use the incorporated data to calculate the speed of the wind and the concentration of NO_2 in the streets of the study area. The model requires a series of simplifications, in order to avoid turbulent phenomena, but it also allows obtaining a high resolution of the air quality in the streets [82].

4.1.3 Tropospheric Ozone (O3)

Three oxygen atoms make up the molecule of ozone, which is found naturally in the stratosphere, one of the layers of the atmosphere, at a height of about 20 km. Ozone is recognized for generating the "ozone layer," which shields us from ultraviolet light. It is a substance known as stratospheric ozone.

On the contrary, tropospheric ozone is found in the troposphere, the part of the atmosphere that is 10 km or closer to the surface of the Earth. It is classified as a secondary pollutant because, unlike stratospheric ozone, tropospheric ozone is not produced naturally in the atmosphere but rather results from the chemical reaction of two other pollutants (nitrogen oxides and volatile organic compounds) in the presence of strong solar radiation.

The health impacts of tropospheric ozone can include coughing, discomfort, and breathing problems. Thus, ozone exposure at high levels can lead to an increase in population mortality or morbidity.

The objectives of the PIKSEL tool include [83]:
- Identifying meteorological situations that can lead to episodes of atmospheric ozone pollution.
- Identifying zones or regions with ozone incidents only under certain weather conditions.
- Assessing which variables play a more relevant role in ozone production at given measurement point.
- Predicting dangerous situations related to air quality.

The implemented methodology is based on a data science approach and has developed models that use large amounts of data that are used to train artificial neural networks. The model incorporates the historical data, structures it, and learns from it during a first diagnostic phase. In a second prognostic phase, it generates prognostic output data that meet the required objectives.

This PIKSEL tool will make it possible to predict and manage tropospheric ozone pollution at a regional scale by predicting episodes that may exceed legally permitted tropospheric ozone concentration limits.

4.1.4 Evolution of the coastline

The model [84] focuses on predicting how the sediments on the coast will evolve in the mid term (several months) as a result of the actions by the waves. Also the flooding areas are identified taking into account the different climate change scenarios. This will serve to generate a tool that allows regulating and managing the economic activities that are located on the beaches following the forecasts of the evolution of the coastline.

The beaches of the Catalan coast support an intense human and economic activity, while at the same time, they suffer a significant setback due to the imbalance in the sedimentary balance. The Administration aims to determine whether this activity can continue to be carried out in safe conditions and to improve the environmental quality of coastal ecosystems.

The goal is to respond to this problem by creating a predictive tool for the state of beaches in the future.

A model that takes into consideration all or the majority of the complexity of the problem and aids in predicting future sand availability along the shoreline is required. This application will make it easier for administrations to play their part in granting activity permissions and schedule the efficient use of resources for dispersing sand. In order to counter the partially supported arguments in the public debate that could politically stymie the administrations, it is also crucial to provide objective justifications for the decisions made regarding the issuance of activity permits as well as the redistribution of sediments.

The purpose is to identify the places that might be inundated by the sea in catastrophic events and to offer detailed and objective information on the coastal dynamics of sediments and the corresponding configuration of the coastline.

On the one hand, the goal is to completely characterize the coastal dynamics of every coastline segment. The wave propagation analysis, the sediment transport vector field, and the corresponding sediment balance rate; for every possible sea state, along with the statistics of the sea state's occurrence (annually, monthly, and seasonally), will be provided. This will develop into a highly useful database that will aid in understanding the dynamics of each beach and charting their development. The flooding areas for various return periods, linked to extreme events, are also included in the characterization. What is more, the characterization of the sediment contributions to the coastline made by the various rivers completes the sediment dynamics.

Furthermore, a thorough probabilistic analysis of the upcoming sea states over various time scales is also offered. This probabilistic analysis builds on the statistical information provided by Copernicus Marine Service reanalysis product, which provides information of the sea state hour by hour since 1993. This probabilistic approach enhances the information given to decision-makers by enabling the analysis of various scenarios in light of their likelihood of occurring.

Finally, the tool will combine a sophisticated beach profile model with a thorough characterization of sediment dynamics and probabilistic analysis of the possible combinations of sea states that might occur for various timescales in order to represent on the map potential coastline positions along with their corresponding probabilities of occurrence.

For the development of this tool, computational models are used. These models use the factors that govern coastal dynamics, such as a map of the seabed, the amount of sand and the characterization of the wave.

Firstly, two computational models developed by the University of Delft, in the Netherlands, will be used to diagnose the dynamics of beaches the SWAN model and the Model X-Beach.

Secondly, a forecast phase will be carried out using two programs: the parabolic formulation of Hsu and Evans (1989) and the inverse problem technique. Both are used to determine the coastline. On the other hand, probabilistic methods will be used to forecast sea states.

The computational model SWAN is a third-generation model for the spectral modeling of coastal areas. This model is used to propagate the waves for every sea state from high seas to near shore. X-Beach is used to determine how the propagated waves break once at shallow depths and the currents they generate when they break. To carry out this diagnosis, it is necessary to incorporate the seabed map using detailed bathymetry, data provided by the Cartographic and Geological Institute of Catalonia (ICGC, acronym in Catalan).

On the other hand, it is also important to incorporate the statistical characterization of the sea states (wave rose, table of encounters and significant wave height versus wave period diagrams), made from a numerical model for predicting the swell belonging to the Spanish Ports Administration (Puertos del Estado in Spanish), or, as intended in this work: using the reanalysis data from Copernicus Marine Service[1].

Once the data has been incorporated, the model aims to characterize the distribution of water currents around the beach for each wave climate, and also the flood level.

The computational model X-Beach, which feeds on the data generated by the SWAN model, allows the potential transport of sediments to be calculated.

By combining the two models, the sedimentary behavior of the beach can be characterized against the range of wave climates that affect it.

The parabolic formulation of Hsu and Evans (1989) is a coastal engineering model that is automatically programmed to predict the top view (plan) configuration of the beach.

The inverse problem is an engineering technique that will be used to determine the position of the coastline (further forward or backward) based on the probable overall sedimentary balance, that is, the amount of sand that the beach will probably have in the future.

With all this, the prediction of the coastline is obtained.

On the other hand, with probabilistic it is possible to determine with which probability a given sea state will occur at a particular time of the year. And thus, also the probability of occurrence of a given sequence of sea states for a particular period of time can be computed.

Finally, a forecast of the coastline and waves has been obtained, including the possibility to factor in the changes caused by climate change.
From all this data, a resilience index will be calculated, which is the final value that will make it possible to know whether a certain beach is more or less resilient over time.

4.2 CAMS products

The Copernicus service that provides suitable data and information for the tropospheric ozone and nitrogen dioxide use cases is CAMS.

When looking at interesting data available at CAMS for the mentioned use cases we can differentiate CAMS European air quality forecasts and CAMS European air quality reanalyses.

The CAMS European air quality forecasts [85] is a 3-year rolling archive that provides daily air quality studies and forecasts. Eleven air quality forecasting systems from throughout Europe are used in the creation of this dataset. Since ensemble products generally outperform individual model products in terms of performance, a median

[1] Accessing Copernicus Data Accessing Copernicus Data seems complicated, but it is at least systematic. On the other hand, accessing data from Puertos del Estado is not automatic and specific requests have to be made.

ensemble is derived from individual outputs. To calculate the forecast uncertainty, a spread between the eleven models is used. Depending on the air-quality forecasting system employed, the analysis assimilates model data with observations from the EEA to provide a complete and consistent dataset. In addition, forecasts for the next four days' worth of air quality are created once each day. There are eight height levels (surface, 50, 250, 500, 1000, 2000, 3000, and 5000 meters) with hourly time steps for both the analysis and the forecast.

The CAMS European air quality reanalysis [86] provides annual air quality reanalyses for Europe based on unvalidated and validated observations. As the CAMS European air quality forecasts, this dataset production is based on an ensemble of nine air quality data assimilation systems across Europe. Based on the unvalidated near-real-time observation data stream that has not yet been completed through quality control by the data providers, an unvalidated reanalysis for the previous year is supplied every year. A final validated annual reanalysis is offered once the fully quality-controlled observations are made available from the data provider, usually after an additional delay of around a year. There are also eight height levels (surface, 50, 250, 500, 1000, 2000, 3000, and 5000 meters) with hourly time steps for both the analysis and the forecast.

When studying the relevant CAMS datasets mentioned above for the ozone and nitrogen dioxide case and comparing them with the GEE ones [87] [88], it was found that the latter had better resolution than CAMS. In particular, the resolution was $1113.2\ m$ in comparison with $10\ km$ for CAMS datasets [85] and [86].

Considering the case study of pollution by nitrogen dioxide, after going through the available data, it was confirmed that the resolution provided by Copernicus was too low to be able to use the data in the models. Therefore, this use case was not carried on.

On the other hand, researchers responsible for the O_3 case study have prioritized other research lines and have provisionally discarded the use of CAMS data.

4.3 CMEMS products

In the case of the evolution of the coastline, the most suitable Copernicus service is the Copernicus Marine Service.

High-level datasets derived from satellite and in-situ observations processed through thematic assembly centers (TACs) as well as model reanalyses, analyses, and forecasts processed through monitoring and forecasting centers (MFCs) are examples of Copernicus Marine products [89]. They are based on modeling and data assimilation techniques, near real-time data transmission, and cutting-edge data processing.

Satellite imagery (infrared, microwave, and visible light), radar altimetry, and scatterometers are used to generate observations using raw data from the satellite's orbit. In order to make the product more readable and with wider geographic coverage, the results are occasionally smoothed and interpolated with other data. They operate continuously and cover the entire world, making them a crucial source of information.

In situ observations are local measurements made on-site of the characteristics of seawater. They are gathered using on-site sensors on board a variety of platforms, including ships of opportunity or research vessels and autonomous maritime observatories (such as floats, drifting buoys, gliders, moorings, etc.). They make it possible to record ocean variability at various scales.

Complex ocean simulation systems (numerical models) are able to describe, analyze, and forecast the physical, sea ice, and biogeochemical state of the ocean at any given time, at the surface or depth, on a global scale or for a specific zone, in real-time or delayed mode. These systems are based on the assimilation of ocean observation data (satellite and In Situ).

The environment along the coast is quite active. In itself, its definition is dynamic because of how the waves launder the coastline. The dynamic nature of the coast, brought about by the effects of the waves and winds on the sediments deposited along the beaches, creates an ecosystem that is always changing. This interaction is simultaneously under intense economic and demographic pressure.

Beaches are excellent protectors for coastal assets and infrastructures, specifically from storm damage. Also, beaches are of primary importance for tourism and wildlife habitats. Beaches are crucial to the environment and the economy (P.A. Ubach, personal communication, July 26, 2023).

Numerous factors have an impact on how readily available sediments are at the beaches. Specifically, the sediments that rivers and streams deposit along the shoreline, the longitudinal and transverse movement of sediments by waves and winds, and the sediments themselves.

In this study the focus was put on two CMEMS products, the Mediterranean Sea Waves Analysis and Forecast and the Mediterranean Sea Wave Reanalysis.

Regarding these products, several variables can be obtained. Table 1 shows all the mentioned variables.

Concerning the case of the evolution of the coastline, the variables from Table 1 that are of interest are Sea surface wave from direction (VMDR), Sea surface wave period at variance spectral density maximum (MWT) and Sea surface wave significant height (SWH).

SWH can be defined as the average height of 1/3 of the highest waves. Four times the standard deviation of the sea surface elevation is the recommended definition by the World Meteorological Organization [90] for SWH.

VMDR indicates the direction from which the velocity vector of the sea surface wave is coming. The direction is a bearing in the usual geographical sense, measured positively clockwise from due north.

The sea surface wave period at variance spectral density maximum (MWT) is the direction from which the most energetic waves are coming.

The spectral peak is the most energetic wave period in the total wave spectrum. The phrase "from_direction" is used in the construction X_from_direction and indicates the direction from which the velocity vector of X is coming. The direction is a bearing in the usual geographical sense, measured positively clockwise from due north.

The wave directional spectrum can be written as a five-dimensional function $S(t, x, y, f, \theta)$ where t is time, x and y are horizontal coordinates (such as longitude and latitude), f is frequency and θ is direction. S has the standard name “sea surface wave directional variance spectral density”. S can be integrated over direction to give:

$$S_1 = \int S \; d\theta \qquad (\mathbf{4.1})$$

and this quantity has the standard name “sea surface wave variance spectral density”.

Variables	**Code**
Sea surface wave significant height	VHM0 [m]
Sea surface primary swell wave significant height	VHM0_SW1 [m]
Sea surface secondary swell wave significant height	VHM0_SW2 [m]
Sea surface wind wave significant height	VHM0_WW [m]
Sea surface wave from direction	VMDR [°]
Sea surface primary swell wave from direction	VMDR_SW1 [°]
Sea surface secondary swell wave from direction	VMDR_SW2 [°]
Sea surface wind wave from direction	VMDR_WW [°]
Sea surface wave from direction at variance spectral density maximum	VPED [°]
Sea surface wave stokes drift x velocity	VSDX [m/s]
Sea surface wave stokes drift y velocity	VSDY [m/s]
Sea surface primary swell wave mean period	VTM01_SW1 [s]
Sea surface secondary swell wave mean period	VTM01_SW2 [s]
Sea surface wind wave mean period	VTM01_WW [s]
Sea surface wave mean period from variance spectral density second frequency moment	VTM02 [s]
Sea surface wave mean period from variance spectral density inverse frequency moment	VTM10 [s]
Sea surface wave period at variance spectral density maximum	VTPK [s]

Table 1. Table with the variables in the Mediterranean Sea Waves Analysis and Forecast and the Mediterranean Sea Wave Reanalysis**.**

The geographic coverage of the Mediterranean Sea Wave Reanalysis and the Mediterranean Sea Waves Analysis and Forecast is shown in Figure 4.2.

The files downloaded for these products are in NetCDF format. This format is self-describing, meaning that it includes information about the data it contains. It is also architecture-independent, which implies that it can be accessed by computers with different ways of storing integers, characters, and floating-point numbers. It is direct access thus, a small subset of a large dataset may be accessed efficiently, without first reading through all the preceding data.

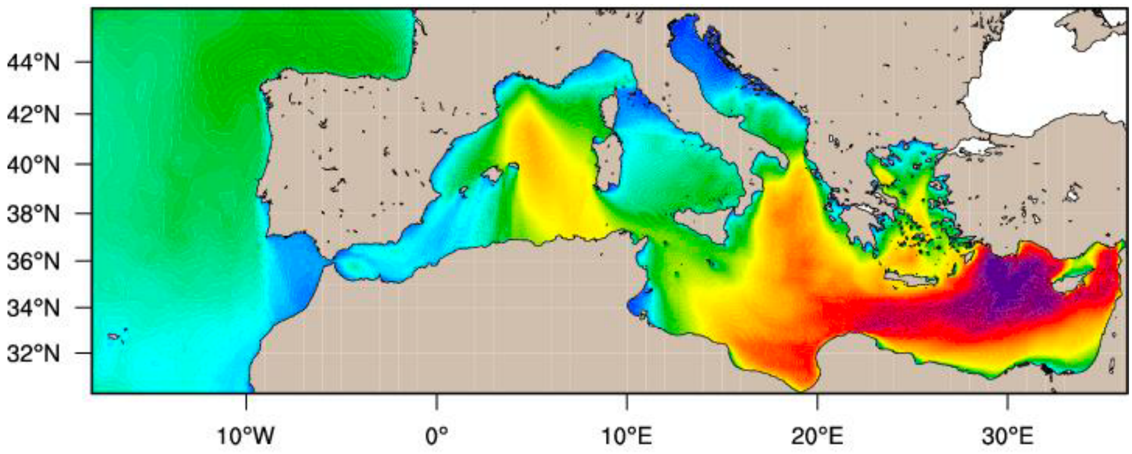

Figure 4.2: Geographic coverage of the Mediterranean Sea Wave Reanalysis and the Mediterranean Sea Waves Analysis and Forecast, the grid covers the geographical area from18.125ºW to 36.2917ºE and from 30.1875ºN to 45.9792ºN and its size is 1307 x 380 at 1/24° horizontal resolution [91] [92].

4.6.1 Mediterranean Sea Wave Reanalysis

The MEDSEA_MULTIYEAR_WAV_006_012 [91] is the multi-year wave product of the Mediterranean Sea Waves forecasting system at surface level.

The product is called multi-year because it covers a continuous and extended period of multiple years. What is more, reanalysis refers to the process of combining observational data with numerical models to generate a consistent and continuous dataset for a specific region or variable over an extended time period. This product is useful for studying long-term climate trends and variations in wave behavior across the Mediterranean Sea.

The Reanalysis dataset is a multi-year wave reanalysis starting from January 1993, composed by hourly wave parameters at 1/24° horizontal resolution, covering the Mediterranean Sea and extending up to 18.125W into the Atlantic Ocean.

This product is based on wave model WAM 4.6.2 and has been developed as a nested sequence of two computational grids (coarse and fine) to ensure that swell propagating from the North Atlantic (NA) towards the strait of Gibraltar is correctly entering the Mediterranean Sea.

It is organized in four datasets:

- med-hcmr-wav-rean-h containing 1-hourly instantaneous values for all the variables with data from 01/01/1993 00:00 to 30/06/2021 23:00.
- cmems_mod_med_wav_myint_4.2km_PT1H-i containing interim 1-hourly instantaneous values for all the variables
- cmems_mod_med_wav_my_4.2km_static containing the coordinates, mask and bathymetry which is the study of the measurement of the depth.

4.6.2 Mediterranean Sea Waves Analysis and Forecast

The MEDSEA_ANALYSISFORECAST_WAV_006_017 [92] is composed by hourly wave parameters at 1/24º horizontal resolution at surface level. The waves forecast component (Med-WAV system) is a wave model based on the WAM Cycle 6.

The Med-WAV modeling system resolves the prognostic part of the wave spectrum with 24 directional and 32 logarithmically distributed frequency bins and the model solutions are corrected by an optimal interpolation data assimilation scheme of all available along-track satellite significant wave height observations.

The atmospheric forcing is provided by the operational ECMWF Numerical Weather Prediction model and the wave model is forced with hourly averaged surface currents and sea level obtained from MEDSEA_ANALYSISFORECAST_PHY_006_013 at 1/24° resolution. The model uses wave spectra for Open Boundary Conditions from GLOBAL_ANALYSIS_FORECAST_WAV_001_027 product. The wave system includes 2 forecast cycles providing twice per day a Mediterranean wave analysis and 10 days of wave forecasts. This product leverages historical data from buoys on the sea to calibrate the model for the forecast.

The daily prediction system runs two cycles per day. Each cycle is scheduled to simulate 252 hours: 12 hours in the past (analysis) blending through data assimilation model results with available SWH satellite observations and 240 hours into the future (forecast). An archive of this product over the last two years up to real-time is available.

This product is composed of three datasets:

- med-hcmr-wav-an-fc-h
- MEDSEA_ANALYSISFORECAST_WAV_006_017-staticsbathy
- MEDSEA_ANALYSISFORECAST_WAV_006_017-staticscoords

The first one contains 1-hourly instantaneous values for all the variables, the second one contains the bathymetry and the last one contains the coordinates.

CHAPTER 5
TOOL DEVELOPMENT

Copernicus Marine service provides a broad range of APIs to access its vast pool of marine data. These APIs facilitate data exploration, extraction, and processing, enabling users to fully exploit the potential of the marine datasets [93].

5.1 Copernicus data download using the MOTU API

Some of the APIs allow retrieving only the needed data, by taking criteria into account, such as the MOTU services [94].

MOTU Service is a web server that allows to handle and extract oceanographic huge volumes of oceanographic data, creating the connection between heterogeneous data providers and end-users. Copernicus Marine Products hosted on MOTU service can be remotely subset and downloaded via MOTU Client API which is for end-users. The MOTU Client is a multiplatform and easy-to-use Command Line Interface. It enables interaction between a Copernicus Marine user and the MOTU HTTP server via script. The main advantage is that the process of downloading data can be automated.

The MOTU Client can be installed on any OS, being a Python module, the only requirement is to have Python version 3.

It is important to bear in mind that the exact coordinates (latitude and longitude) of the area of interest, the specific product ID and the specific dataset ID are required to download the data.

On the other hand, it is compulsory to have a Copernicus Marine user account. What is more, it is necessary to install the MOTU Client Python library running the script pip install motuclient=1.8.4. It is important to use this specific version of MOTU Client as today's latest version has some issues when using it with Python.

A Python code (Annex A) was developed to create a command that downloaded the desired data for the evolution of the coastline case study from Copernicus.

There were several requirements to fit the case study's needs. In the first place, there was a need to select points in particular, not a region.

The grid for CMEMS was needed in order to know where the calculation points were. The first step was to obtain the Copernicus Grid. To obtain a representation of the calculation points the MED-MFC_006_017_coordinates.nc was used which can be found in the MEDSEA_ANALYSISFORECAST_WAV_006_017-staticscoords dataset mentioned in section 4.6.2. After downloading the file, it was represented in ArcGIS.

Figure 5.1 shows the representation of the Copernicus grid on the surface of Catalunya.

On the other hand, the particularities of the model implied to use data from the Mediterranean Sea. Another requirement was to be able to select one or more variables from the Mediterranean Sea Waves Reanalysis product.

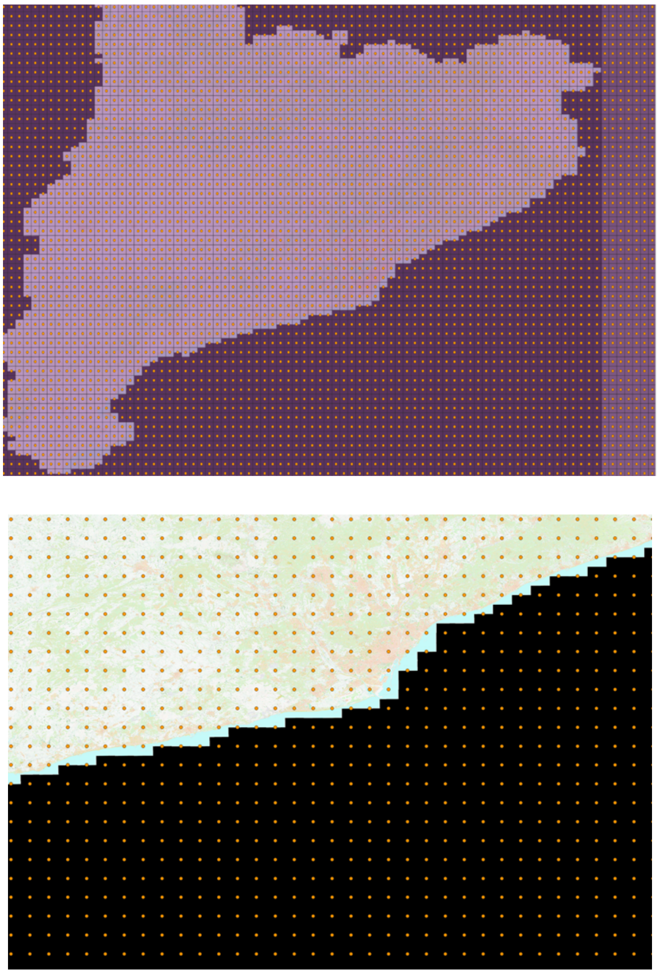

Figure 5.1: Representations of the Copernicus grid on the surface of Catalunya.

The code has been developed using the Python library tkinter [95] which is used to create Graphical User Interfaces (GUIs). It provides a set of tools and widgets for building windows, dialogs, buttons, menus, and other graphical elements that allow users to interact with the program.

Figure 5.1 represents a Workflow of the windows of the developed Python code for the Copernicus Selector tool.

The first window that appears when running the code has three selection options. In the first place, the source needs to be selected. The Source options are the Copernicus Marine Service, Copernicus Atmosphere Monitoring Service, Copernicus Land Monitoring Service, Copernicus Emergency Management Service, Copernicus Security Service and Copernicus Climate Change Service.

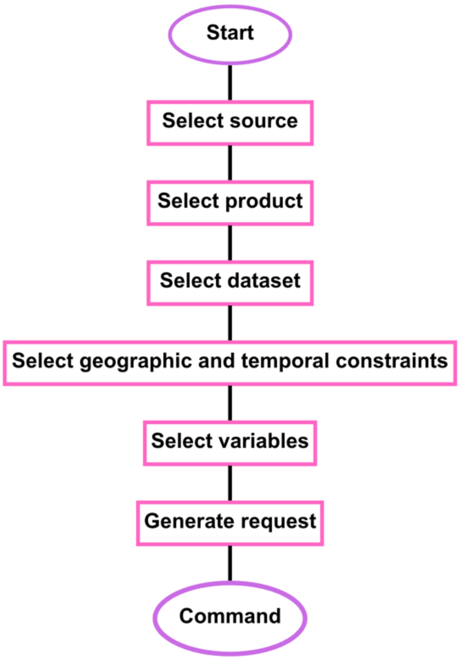

Figure 5.1: Workflow of the windows of the Python code that has been developed.

The second selection option is the product selection. When selecting the source, its particular products will appear. For example, when selecting Copernicus Marine Service several products will be available for selection. The last selection is the dataset selection, the dropdown menu will show the particular datasets for the selected product.

In the case of selecting the MEDSEA_MULTIYEAR_WAV_006_012-TDS product, three datasets will appear for selection. In the example shown in Figure 5.2, the selected source is the Copernicus Marine Service, the selected product is MEDSEA_MULTIYEAR_WAV_006_012-TDS and the selected dataset is med-hcmr-wav-rean-h (this dataset contains 1-hourly instantaneous values for all the variables from Table 1).

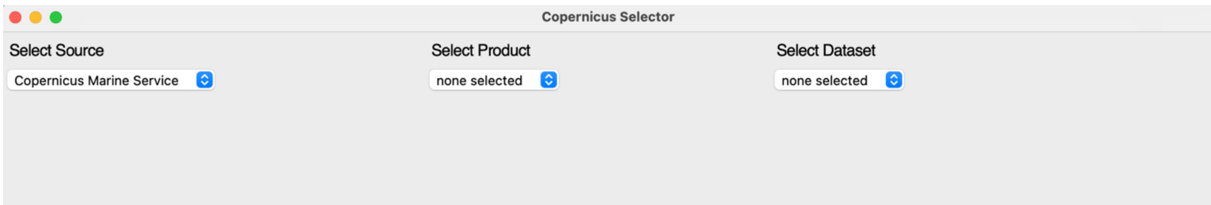

Figure 5.2: Copernicus Selector tool showing source, product and dataset.

After selecting the dataset, the desired region has to be defined. In this case for this particular product, the coverage is 18.125ºW to 36.2917ºE and from 30.1875ºN to 45.9792ºN covering the Mediterranean Sea and a portion of the Atlantic Ocean. Thus, only data from this geographical area is available for download.

To retrieve data from a specific location, the same latitude has to be introduced for the N and the S coordinates and the same longitude has to be introduced for the E and the W coordinates.

On the other hand, the desired time range has to be specified. In particular, the format is yyyy-mm-dd hh:mm:ss.

Finally, a list of the variables available for the chosen dataset is displayed. One or more variables can be selected for download. For example, VHM0, VTPK and VPED among others. Figure 5.3 shows all the selection parameters for the particular case of the med-hcmr-wav-rean-h dataset.

The button generates request will create a command with all the specified parameters and characteristics chosen during the process. This command will be shown below the variable list in the white box.

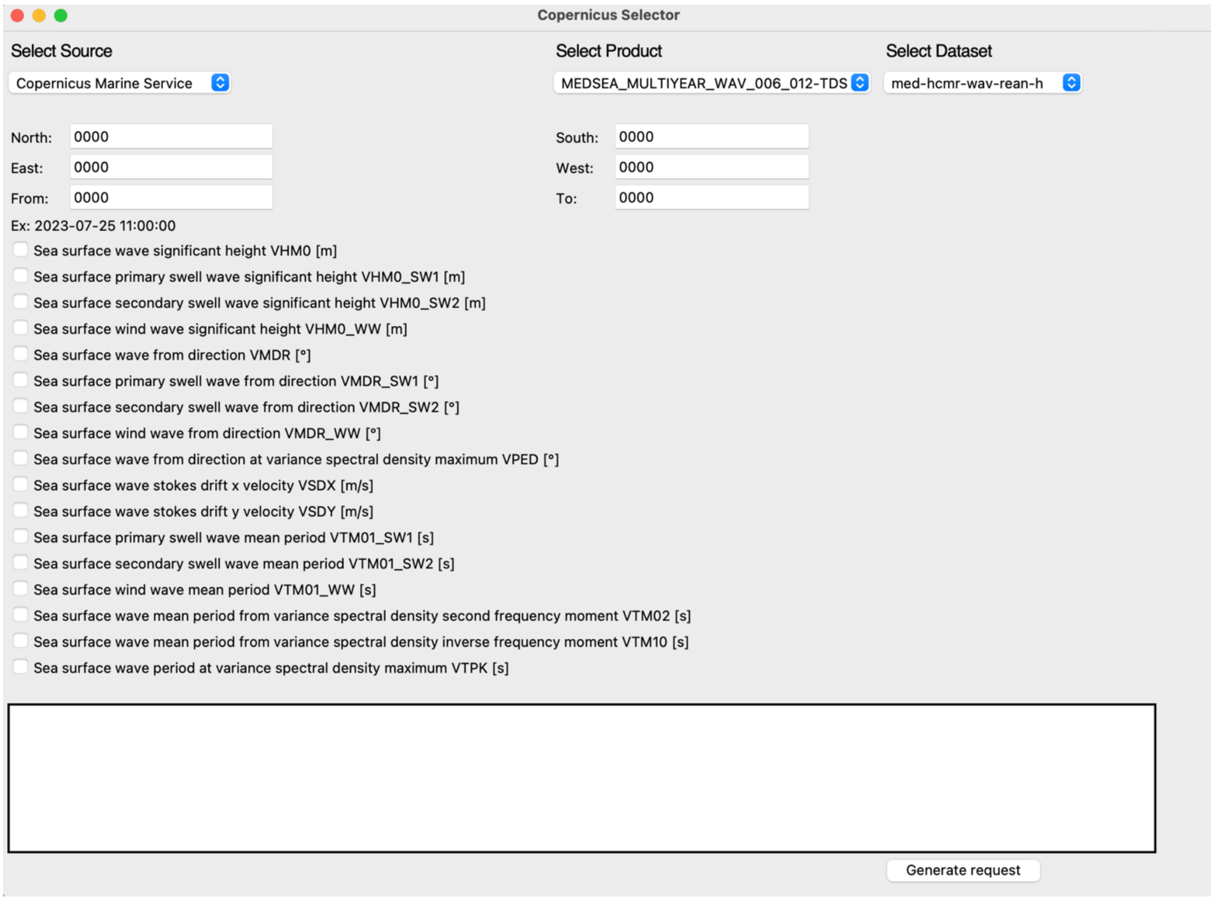

Figure 5.3: Copernicus Selector tool showing all the parameters that can be selected.

This command has to be modified by the user to be able to run it. The user will have to specify the output directory where the file will be saved, the output name of the file, the username and the password of the Copernicus Marine account.

An example of the regenerated request is shown in Figure 5.4.

```
python -m motuclient --motu https://my.cmems-du.eu/motu-
web/Motu --service-id MEDSEA_MULTIYEAR_WAV_006_012-TDS --
product-id med-hcmr-wav-rean-h --longitude-min 2.337 --
longitude-max 2.337 --latitude-min 41.417 --latitude-max
41.417 --date-min "2021-06-28 23:00:00" --date-max "2021-06-29
23:00:00" --variable VHM0  --out-dir
/Users/paulalomascolo/Downloads --out-name output30.nc --user
ppujado --pwd **********
```

Figure 5.4: Command obtained from the Copernicus Selector tool.

When running the command, the data will be downloaded in NetCDF format.

As mentioned earlier, this is a simplified example therefore, only the specified source, product and dataset can be downloaded. The other sources, products and datasets are marked as not implemented.

5.2 Copernicus Image download using Web Map Service (WMS) API

WMS is a standard protocol developed by the Open Geospatial Consortium for serving georeferenced map images and metadata over a web browser or adapted GIS.

The WMS API delivers georeferenced map images. Different map layers from various sources can be displayed by a GIS tool simultaneously as long as they share the same reference points on the Earth's surface.

It is useful for visualizing data on maps, allowing users to inspect particular geographic areas without needing to process large amounts of raw data. The main disadvantage of this API is that it provides images, not numerical data, limiting the ability to conduct advanced analysis or modeling.

By making a URL request to the server, metadata (information such as available layers, coordinate systems and supported formats among others) about the WMS service, a map image, or attribute data related to a particular feature can be retrieved.

Attribute data is information associated with specific geographic features on the map. For example, if the map represents countries, attribute data might include details like population, area, and capital city for each country.

The server's response can be viewed in the browser and comes in the form of either an XML document or an image in particular in the form of PNG or JPEG.

To automatically access and save map images from a WMS server using code, the Python “requests library” can be used to send a “GET request”, which is a type of HTTP request, to the WMS server. This GET request asks the server for the map images, and once received they can be saved to a computer or server without manual intervention.

An example of how Python can be used to request a map image from the WMS server and save it to a file can be found in Annex B.

The URL string has to be replaced with the actual WMS request URL for the Copernicus data we're interested in. The URL will contain parameters that specify the data we want, the geographic area, the image size, etc.

This particular script saves the image as a PNG file. If the WMS server returns a different type of image (like a JPEG), 'map.png' has to be changed to the appropriate filename and extension (like 'map.jpg'). This example code does not handle errors beyond checking the HTTP status code. Hence, error-checking functionality will be implemented in the future.

To customize the XML document or image wanted, different parameters can be specified directly from the endpoint WMS URL by providing a value for the REQUEST parameter.

GetMap is an operation that retrieves a map image for a specified area and content. As an example, the value of the REQUEST parameter can be set equal to GetMap. To retrieve the image, ?REQUEST=GetMap has to be added to the WMS URL.

An example is shown below:

https://nrt.cmems-du.eu/thredds/wms/med-hcmr-wav-an-fc-h?REQUEST=GetMap
&VERSION=1.3.0&LAYERS=VMDR&CRS=EPSG:4326&BBOX=30.1875,-
10,45.9792,36.2917&HEIGHT=1500&WIDTH=4500&STYLES&FORMAT=image/png

Copy-pasting the WMS URL in the web navigator, Figure 5.5 will be obtained. In particular, the map obtained will represent the VMDR variable in .png format with a size of 1500x4500 pixels for the Mediterranean region, bounded by the coordinates [<min_lat>,<min_lon>,<max_lat>,<max_lon>]=[30.1875,-10,45.9792,36.2917] in the EPSG:4326 projection.

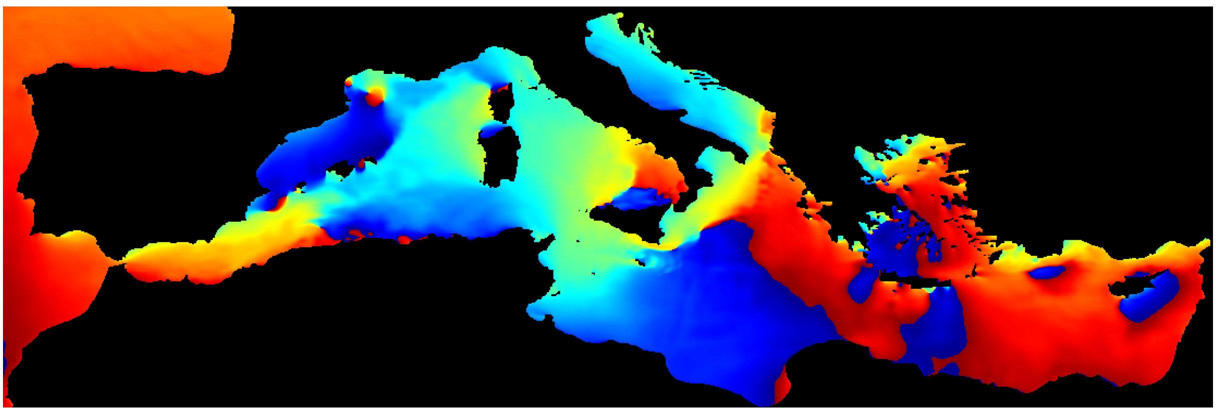

Figure 5.5: Image obtained from the URL using GetMap.

5.3 Proposal for the integration of Copernicus Marine Service in PIKSEL

The proposal consists of a system for selecting and downloading Copernicus Marine Service data sets from PIKSEL for use in local modeling and analysis.

Figure 5.6 represents the PIKSEL interface where the source Copernicus can be selected.

Figure 5.6: PIKSEL interface.

The option of Copernicus under the menu sources would lead us to a selection of the Copernicus theme areas as mentioned before.

After going through the process explained in Chapter 5.1, the data will be downloaded to the server by means of the corresponding call from PIKSEL to Copernicus with Motu API and once the file is received, it will be delivered to the user for local download and could be stored in the PIKSEL server.

Once the data has been downloaded, the model processes it by performing a statistical analysis of the waves and establishes the relationships between the probabilities of the occurrence of each wave with the effects of its propagation pre-calculated and stored in the platform; as well as recalculating the combinations of probabilities of occurrence of the different sequences of waves for any time interval.

Users could have a menu with their historical downloads and view the data from previous downloads on the PIKSEL interface itself, with PIKSEL being a repository of datasets downloaded by each user.

CHAPTER 6 CONCLUSIONS

During the realization of this work, several challenges were encountered. Firstly, data access varied across sources, necessitating distinct approaches for each. A lack of standardization among data channels will complicate the integration of discrete data sources into PIKSEL.

Moreover, disparities in resolution between Copernicus CAMS and GEE datasets raised issues in data consistency. In particular, some CAMS datasets for example [85] and [86] and have a resolution of 10 km in contrast with GEE datasets that have a resolution of 1 km [87] and [88]. It is not clear whether the higher resolution provided by GEE is native or if it is a result of a postprocess interpolation.

Acquiring Copernicus data proved complex, time-consuming, and challenging to understand, particularly for non-programming experts. Many EO data sources were tailored for users with programming skills, limiting accessibility for a broader audience.

Addressing the complexities faced during data acquisition, simplifying the user interface emerged as a crucial aspect. It will be an important consideration in the future development of this functionality and PIKSEL as a whole.

This work can be of particular interest to users with no programming skills that would be able to manage data with ease and provide a methodology to base development for other datasets. Users should only have knowledge of the variables mentioned in Table 1 to use the tool. The tool has been developed with several dropdown menus and check boxes to provide an intuitive user experience. Moreover, the tool provides access to the Copernicus data and prevents the user from having to deal with the different data sources discussed in Chapter 3.

While this project successfully provided the tools to integrate specific Copernicus services into the PIKSEL website, the continuous growth of the Copernicus program provides an opportunity for future expansion. Other Copernicus services should be considered for integration into the platform. In the future, efforts should be made to integrate other relevant sources into the platform.

Finally, as part of future work, the integration of the user interface into PIKSEL via a website platform using the existing methodology should be pursued. This would involve enabling users to sketch regions directly on the PIKSEL interface for region selection. Additionally, a feature allowing the direct execution of Python commands within the interface would enhance user convenience. Further enhancements could involve implementing an automated date and coordinate formatting system, streamlining these processes for a smoother user experience.

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ANNEXES

Annex A

This annex includes the developed code which creates a command that downloads the desired data for the evolution of the coastline case study from Copernicus.

The base of this code was implemented using chatGPT [96].

```
!pip install motuclient==1.8.4

import tkinter as tk

parameters =  {}

urlroot = "python -m motuclient --motu https://my.cmems-du.eu/motu-web/Motu"
comfinal =" --out-dir <OUTPUT_DIRECTORY> --out-name <OUTPUT_FILENAME> --user <USERNAME> --pwd <PASSWORD> "
# Data for fields
# The list of keys is the list of Sources
# The value associated to a key is the list of products
SourcesProducts = {"Copernicus Marine Service": ["MEDSEA_ANALYSISFORECAST_PHY_006_013",

"MEDSEA_MULTIYEAR_WAV_006_012-TDS",

"MEDSEA_ANALYSISFORECAST_BGC_006_014",

"MEDSEA_MULTIYEAR_PHY_006_004",

"MEDSEA_ANALYSISFORECAST_WAV_006_017-TDS",

"MEDSEA_MULTIYEAR_BGC_006_008",

"INSITU_MED_PHYBGCWAV_DISCRETE_MYNRT_013_035"],
                    "Copernicus Atmosphere Monitoring Service": ["not implemented"],
                    "Copernicus Land Monitoring Service": ["not implemented"],
                    "Copernicus Emergency Management Service": ["not implemented"],
                    "Copernicus Security Service": ["not implemented"],
                    "Copernicus Climate Change Service": ["not implemented"]}
```

```
# The list of keys is the list of Products
# The value associated to a key is the list of Datasets
ProductsDatasets = {"MEDSEA_ANALYSISFORECAST_PHY_006_013":
["not implemented"],
                     "MEDSEA_MULTIYEAR_WAV_006_012-TDS":
["med-hcmr-wav-rean-h",

"cmems_mod_med_wav_my_4.2km_static_202211--ext--bathy",

"cmems_mod_med_wav_my_4.2km_static_202211--ext--coords" ,

"cmems_mod_med_wav_myint_4.2km_PT1H-i_202112"] ,
                     "MEDSEA_ANALYSISFORECAST_BGC_006_014":
["not implemented"],
                     "MEDSEA_MULTIYEAR_PHY_006_004": ["not
implemented"],
                     "MEDSEA_ANALYSISFORECAST_WAV_006_017-
TDS": ["not implemented"],
                     "MEDSEA_MULTIYEAR_BGC_006_008": ["not
implemented"],

"INSITU_MED_PHYBGCWAV_DISCRETE_MYNRT_013_035": ["not
implemented"]}

# The list of keys is the list of Datasets
# The value associated to a key is the list of Variables
DatasetsVariables = {"med-hcmr-wav-rean-h": [
                      "Sea surface wave significant height
VHM0 [m]",
                      "Sea surface primary swell wave
significant height VHM0_SW1 [m]",
                      "Sea surface secondary swell wave
significant height VHM0_SW2 [m]",
                      "Sea surface wind wave significant
height VHM0_WW [m]",
                      "Sea surface wave from direction VMDR
[°]",
                      "Sea surface primary swell wave from
direction VMDR_SW1 [°]",
                      "Sea surface secondary swell wave from
direction VMDR_SW2 [°]",
                      "Sea surface wind wave from direction
VMDR_WW [°]",
                      "Sea surface wave from direction at
variance spectral density maximum VPED [°]",
                      "Sea surface wave stokes drift x
velocity VSDX [m/s]",
                      "Sea surface wave stokes drift y
velocity VSDY [m/s]",
```

```
                      "Sea surface primary swell wave mean
period VTM01_SW1 [s]",
                      "Sea surface secondary swell wave mean
period VTM01_SW2 [s]",
                      "Sea surface wind wave mean period
VTM01_WW [s]",
                      "Sea surface wave mean period from
variance spectral density second frequency moment VTM02 [s]",
                      "Sea surface wave mean period from
variance spectral density inverse frequency moment VTM10 [s]",
                      "Sea surface wave period at variance
spectral density maximum VTPK [s]"],

"cmems_mod_med_wav_my_4.2km_static_202211--ext--bathy": ["not
implemented"],

"cmems_mod_med_wav_my_4.2km_static_202211--ext--coords": ["not
implemented"],
                      "cmems_mod_med_wav_myint_4.2km_PT1H-
i_202112": ["not implemented"]}

VariablesRequest ={"Sea surface wave significant height VHM0
[m]":"VHM0",
                      "Sea surface primary swell wave
significant height VHM0_SW1 [m]":"VHM0_SW1",
                      "Sea surface secondary swell wave
significant height VHM0_SW2 [m]":"VHM0_SW2",
                      "Sea surface wind wave significant
height VHM0_WW [m]":"VHM0_WW",
                      "Sea surface wave from direction VMDR
[°]":"VMDR",
                      "Sea surface primary swell wave from
direction VMDR_SW1 [°]":"VMDR_SW1",
                      "Sea surface secondary swell wave from
direction VMDR_SW2 [°]":"VMDR_SW2",
                      "Sea surface wind wave from direction
VMDR_WW [°]":"VMDR_WW",
                      "Sea surface wave from direction at
variance spectral density maximum VPED [°]":"VPED",
                      "Sea surface wave stokes drift x
velocity VSDX [m/s]":"VSDX",
                      "Sea surface wave stokes drift y
velocity VSDY [m/s]":"VSDY",
                      "Sea surface primary swell wave mean
period VTM01_SW1 [s]":"VTM01_SW1",
                      "Sea surface secondary swell wave mean
period VTM01_SW2 [s]":"VTM01_SW2",
                      "Sea surface wind wave mean period
VTM01_WW [s]":"VTM01_WW",
```

```
                      "Sea surface wave mean period from
variance spectral density second frequency moment VTM02
[s]":"VTM02",
                      "Sea surface wave mean period from
variance spectral density inverse frequency moment VTM10
[s]":"VTM10",
                      "Sea surface wave period at variance
spectral density maximum VTPK [s]":"VTPK"}

root = tk.Tk()
checkboxes = []

root.title('Copernicus Selector')
root.geometry("1200x800")

# configure the grid
root.columnconfigure(0, weight=1)
root.columnconfigure(1, weight=1)
root.columnconfigure(2, weight=1)
root.columnconfigure(3, weight=1)
root.columnconfigure(4, weight=1)
root.columnconfigure(5, weight=1)
root.columnconfigure(6, weight=1)

#root.rowconfigure(0, weight=1)
#root.rowconfigure(1, weight=1)
#root.rowconfigure(2, weight=1)
#root.rowconfigure(3, weight=1)
#root.rowconfigure(4, weight=1)
#root.rowconfigure(5, weight=1)
#root.rowconfigure(6, weight=1)

#root.columnconfigure(3, weight=3)

def buttonCallBack(textBox,checkboxes):
    global North, South, East, West, From, To, parameters
    com = urlroot +" --service-id " + parameters["option2"]+"
--product-id " + parameters["option3"]
    com = com + " --longitude-min " + West.get()
    com = com + " --longitude-max " + East.get()
    com = com + " --latitude-min " + South.get()
    com = com + " --latitude-max " + North.get()
    com = com + " --date-min " + '"' + From.get() + '"'
    com = com + " --date-max " + '"' + To.get() + '"'
    for item  in checkboxes:
        item[0]
        print(item[0].winfo_class())
        if item[0].winfo_class()=="Checkbutton":
            variable = item[0].cget('text')
```

```
            print(item[1].get(),variable)
            status = item[1].get()
            if status =="1":
                com = com + " --variable " +
VariablesRequest[variable] +" "
    com = com + comfinal
    textBox.delete("1.0",tk.END)
    textBox.insert('end',com)
    return

# Source Selection in GUI

def selection_changed1(value):
    global checkboxes
    global parameters
    #print(value)
    dropdown2["menu"].delete(0, "end")
    dropdown3["menu"].delete(0, "end")
    dropdown3["menu"].add_command(label="none selected"  )
    selected3.set( "none selected" )
    if len(checkboxes)>0 :
        for item in checkboxes:
            item[0].destroy()
        checkboxes = []
    for opt in SourcesProducts[value]:
        #print("inside1")
        dropdown2["menu"].add_command(label=opt , command
=tk._setit(selected2, opt, selection_changed2) )
        selected2.set(SourcesProducts[value][0])
    parameters["option1"]=value

def selection_changed2(value):
    global checkboxes
    global parameters
    #print(value)
   # print("inside2")
    dropdown3["menu"].delete(0, "end")
    if len(checkboxes)>0 :
        for item in checkboxes:
            item[0].destroy()
    checkboxes = []
    for opt in ProductsDatasets[value]:
        #print("inside2")
        dropdown3["menu"].add_command(label=opt, command
=tk._setit(selected3, opt, selection_changed3) )
        selected3.set(ProductsDatasets[value][0])
    parameters["option2"]=value

def selection_changed3(value):
```

```
    global checkboxes
    global parameters
    global North, South, East, West, From, To


    #print(value)
    #print("inside3")
    if len(checkboxes)>0 :
        for item in checkboxes:
            item[0].destroy()
    checkboxes = []

    parameters["option3"]=value
    #print(parameters)
    spacer1 = tk.Label(root, text="")
    spacer1.grid(row=2, column=0)
    checkboxes.append((spacer1,""))

    labelNorth = tk.Label(root, text="North:")
    labelNorth.grid(column=0, row=3, sticky=tk.W, padx=5,
pady=0)
    North = tk.Entry(root)
    North.insert("0", "0000")
    North.grid(column=0, row=3, sticky=tk.W, padx=60,
pady=0,columnspan=2)
    checkboxes.append((labelNorth,""))
    checkboxes.append((North,""))

    labelSouth = tk.Label(root, text="South:")
    labelSouth.grid(column=2, row=3, sticky=tk.W, padx=5,
pady=0)
    South = tk.Entry(root)
    South.insert("0", "0000")
    South.grid(column=2, row=3, sticky=tk.W, padx=60,
pady=0,columnspan=2)
    checkboxes.append((labelSouth,""))
    checkboxes.append((South,""))

    labelEast = tk.Label(root, text="East:")
    labelEast.grid(column=0, row=4, sticky=tk.W, padx=5,
pady=0)
    East = tk.Entry(root)
    East.insert("0", "0000")
    East.grid(column=0, row=4, sticky=tk.W, padx=60, pady=0)
    checkboxes.append((labelEast,""))
    checkboxes.append((East,""))

    labelWest = tk.Label(root, text="West:")
```

```
    labelWest.grid(column=2, row=4, sticky=tk.W, padx=5,
pady=0)
    West = tk.Entry(root)
    West.insert("0", "0000")
    West.grid(column=2, row=4, sticky=tk.W, padx=60,
pady=0,columnspan=2)
    checkboxes.append((labelWest,""))
    checkboxes.append((West,""))

    labelFrom = tk.Label(root, text="From:")
    labelFrom.grid(column=0, row=5, sticky=tk.W, padx=5,
pady=0)
    From = tk.Entry(root)
    From.insert("0", "0000")
    From.grid(column=0, row=5, sticky=tk.W, padx=60, pady=0)
    checkboxes.append((labelFrom,""))
    checkboxes.append((From,""))
    labelFrom2 = tk.Label(root, text="Ex: 2023-07-25
11:00:00")
    labelFrom2.grid(column=0, row=6, sticky=tk.W, padx=5,
pady=0)
    checkboxes.append((labelFrom2,""))

    labelTo = tk.Label(root, text="To:")
    labelTo.grid(column=2, row=5, sticky=tk.W, padx=5, pady=0)
    To = tk.Entry(root)
    To.insert("0", "0000")
    To.grid(column=2, row=5, sticky=tk.W, padx=60,
pady=0,columnspan=2)
    checkboxes.append((labelTo,""))
    checkboxes.append((To,""))



    spacer2 = tk.Label(root, text="")
    spacer2.grid(row=6, column=0)
    checkboxes.append((spacer2,""))

    i=0
    for opt in DatasetsVariables[value]:
        #print(opt)
        var = tk.StringVar(value=1)

        checkbox = tk.Checkbutton(root, text=opt,
variable=var)
        checkbox.deselect()
        checkbox.grid(column=0, row=7+i, sticky=tk.W, padx=5,
pady=0,columnspan=4)
        checkboxes.append((checkbox,var))
```

```
        i+=1

    spacer3 = tk.Label(root, text="")
    spacer3.grid(row=7+i, column=0)
    checkboxes.append((spacer3,""))

    textBox = tk.Text(root,height=10,width=150);
    textBox.grid(row=8+i, column=0,sticky=tk.W, padx=5,
pady=0,columnspan=6)
    text = 'python -m motuclient --motu https://nrt.cmems-
du.eu/motu-web/Motu --service-id
MEDSEA_ANALYSISFORECAST_WAV_006_017-TDS --product-id med-hcmr-
wav-an-fc-h --longitude-min 1.9037936160180973 --longitude-max
8.163180760093402 --latitude-min 39.55502474414008 --latitude-
max 43.421116803716004 --date-min "2023-07-25 11:00:00" --
date-max "2023-07-26 11:00:00" --variable VHM0 --variable
VHM0_SW1 --variable VHM0_SW2 --variable VHM0_WW --variable
VMDR --variable VMDR_SW1 --variable VMDR_SW2 --variable
VMDR_WW --variable VPED --variable VSDX --variable VSDY --
variable VTM01_SW1 --variable VTM01_SW2 --variable VTM01_WW --
variable VTM02 --variable VTM10 --variable VTPK --out-dir
<OUTPUT_DIRECTORY> --out-name <OUTPUT_FILENAME> --user
<USERNAME> --pwd <PASSWORD>'
    textBox.insert('end',text)
    checkboxes.append((textBox,""))

    buttonGenerar = tk.Button(root, text =" Generate request
", command = lambda: buttonCallBack(textBox,checkboxes))
    buttonGenerar.grid(row=9+i, column=4,sticky=tk.W, padx=5,
pady=0,columnspan=6)
    checkboxes.append((buttonGenerar,""))



options1 =  list(SourcesProducts.keys())
lbl1=tk.Label(root, text="Select Source", fg='black',
font=("Helvetica", 16))
lbl1.grid(column=0, row=0, sticky=tk.W, padx=5, pady=5)
# datatype of menu text
clicked1 = tk.StringVar()
# initial menu text
clicked1.set( "Copernicus Marine Service" )
dropdown1 = tk.OptionMenu(root, clicked1,
*options1,command=selection_changed1 )

dropdown1.grid(column=0, row=1, sticky=tk.W, padx=5,
pady=1,columnspan=2)
```

```
# Product Selection in GUI
options2 = ["none selected"]
lbl2=tk.Label(root, text="Select Product", fg='black',
font=("Helvetica", 16))
lbl2.grid(column=2, row=0, sticky=tk.W, padx=5, pady=3)
# datatype of menu text
selected2 = tk.StringVar()
selected2.set("none selected")
dropdown2 = tk.OptionMenu(root, selected2, *options2, command
= selection_changed2  )
dropdown2.grid(column=2, row=1, sticky=tk.W, padx=5,
pady=1,columnspan=2)

# Dataset Selection in GUI
options3= ["none selected"]
lbl3=tk.Label(root, text="Select Dataset", fg='black',
font=("Helvetica", 16))
lbl3.grid(column=4, row=0, sticky=tk.W, padx=5, pady=3)
# datatype of menu text
selected3 = tk.StringVar()
# initial menu text
selected3.set( "none selected" )
dropdown3 = tk.OptionMenu(root, selected3, *options3 )
dropdown3.grid(column=4, row=1, sticky=tk.W, padx=5,
pady=1,columnspan=2)



# Start the main loop
root.mainloop()
```

Annex B

This annex includes an example of how Python can be used to request a map image from the WMS server and save it to a file.

```
import requests

# Define the URL for the WMS GetMap request
# Note: This is just an example. You'll need to replace this with the actual URL for the Copernicus WMS server, as well as the parameters that match the data you're interested in.
url = ("http://example.com/wms"
       "?service=WMS"
       "&version=1.3.0"
       "&request=GetMap"
       "&layers=temperature"
       "&styles="
       "&bbox=2.0,41.0,3.0,42.0"
       "&width=256"
       "&height=256"
       "&srs=EPSG:4326"
       "&format=image/png")

# Send the request to the server
response = requests.get(url, stream=True)

# Check that the request was successful
if response.status_code == 200:
    # Save the returned image to a file
    with open('map.png', 'wb') as file:
        for chunk in response:
            file.write(chunk)
else:
    print("Failed to download image. HTTP status code: ", 
response.status_code)
```