Artificial Intelligence to Monitor our Seas

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AIMS

Artificial Intelligence to Monitor our Seas

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Lead author(s)	Giulia Cervelli, Politecnico di Torino (Polito)
Contributors	Giuseppe Giorgi, Politecnico di Torino (Polito)

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SHORT ABSTRACT FOR DISSEMINATION PURPOSES

Abstract

The "Report and dataset from satellites" outlines the potential of satellite data and highlights how AIMS promotes the advancement of these data sources. Despite the limited number of measurable parameters, the complexity of access and management, and the discontinuous spatial and temporal availability, satellite data remains highly promising but not yet fully exploited. These limiting factors hinder the optimal use of satellite information. However, the potential for such data to enhance the understanding and monitoring of environmental phenomena remains high, and AIMS points to unlock this potential. By integrating various satellite and in-situ sources and applying artificial intelligence models, AIMS seeks to overcome current challenges, promoting a more efficient and extensive use of satellite and in-situ data.

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LIST OF PARTNERS

N°	Logo	Name	Short Name	City
1	Politecnico di Torino 1859	Politecnico di Torino	POLITO	Torino
2	ROMA TRE UNIVERSITÀ DEGLI STUDI	Universitá degli studi di Roma Tre	ROMA3	Roma
3	Italian National Research Council	Consiglio Nationale delle Ricerche	CNR	Firenze

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ABBREVIATIONS

Acronym	Description

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EXECUTIVE SUMMAY

The "Report and dataset from satellite" offers a comprehensive framework for understanding the potential of satellite data by examining its limitations and benefits. This document outlines the main characteristics of wave and wind satellite measurements, providing an overview of the altimetric methodology, satellite data processing, and the various satellite products available. Additionally, it details the satellite dataset obtained to support AIMS activities.

Satellite data collection techniques, including in-situ measurements, satellite remote sensing, and numerical modelling, are explored in depth. A significant focus of the deliverable is on the radar altimeter technique employed for satellite measurements, which utilizes active radar remote sensing systems to measure wave and wind characteristics. This method's ability to operate under any weather condition and at any time makes it particularly effective and powerful.

A fully calibrated and validated wave and wind satellite data product, the WAVE_GLO_PHY_SWH_L3_MY_014_005 product, is identified as the most promising one for AIMS applications. An explanation of the reasons and rationale behind the choice is given.

Moreover, the deliverable specifies the spatial and temporal features of the satellite dataset obtained for AIMS, focusing on the marine area between 42°N and 44.5°N latitude and 9°E and 11°E longitude. Finally, the deliverable provides information on the dataset files delivered.

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1. SATELLITE TECHNIQUES

Wave and wind data sources can be classified by the technique used in collecting the information: the in-situ instruments, satellite remote-sensing and numerical modelling are the main data sources (Holthuijsen, 2010).
The in-situ technique involves the direct measurement of the variables of interest offering a high-quality data, obtained through the installation of the sensor directly on the observation site. In-situ measurements are known for their accuracy and directly record the behaviour of waves and winds at the exact observation point. However, their implementation may be limited by narrow spatial coverage, frequent data losses due to malfunctions and the need to install instruments in specific locations, characterized by high times and costs.
Satellite techniques, on the other hand, allow measurements of the parameters of interest to be collected from a distance, through the use of sensors mounted on satellites in Earth orbit. This approach offers global coverage and a comprehensive view of oceanic and atmospheric phenomena (Young, 2019). Although satellite measurements are generally accurate, they can have limitations in terms of spatial and temporal resolution. However, due to their ability to monitor large areas efficiently, they are invaluable for understanding large climate patterns and variations on a global scale and are frequently used for numerical modelling calibrations and validations (Ribal, 2019).
Finally, numerical modelling techniques are based on the use of mathematical models to simulate environmental phenomena. This approach allows to obtain forecasts and projections based on empirical or physically based equations describing the behaviour of waves (Thomas, 2015) and winds (Martinez-Garcia, 2021). While numerical modelling provides useful data, it is important to consider that the accuracy of that output data depends on the quality of the input data and the accuracy of the model itself. It is essential to calibrate and validate the model before using its data. This activity is generally carried out comparing satellite and in-situ data with numerical one.

Among these categories, in-situ measurements are often the most used, due to their high accuracy. They provide time series of the parameters of interest generally at a regular sampling rate, usually hourly. However, they may be subject to malfunctions and damage due to the harsh environment

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in which they are installed. In contrast, satellite data is reliable as it is not subject to the same environmental risks as in-situ instruments. They can cover larger areas but may be affected by spatial and temporal resolution limitations while maintaining high accuracy. Satellite measurements provide information on offshore waves and winds through observations made above the sea surface, with sensors mounted on satellites and based on the reception of signals reflected from the sea surface itself.

1.1 Radar altimeter technique

Satellites typically carry one or more instruments on board and operate across different bands of the electromagnetic spectrum, from visible to microwave wavelengths. This enables simultaneous measurement of a multitude of environmental parameters through various sensors.

A key distinction from traditional in-situ wave recorders and satellite measurements lies on the temporal and spatial approach. In-situ sensors monitor the temporal movement of the water surface and wind speed at specific point and compute the parameters of interest through statistical analyses based on the temporal evolution of these phenomena, usually on a 30-minute time window. Otherwise, satellite sensors interrogate a larger zone, called footprint, having an average coverage of 50 square kilometres. They provide measurements of average conditions over the entire footprint area, with a much shorter measurement period, usually lasting only a few fractions of seconds.

Various satellite instruments are employed to observe the ocean surface and measure wave characteristics. These instruments utilize different techniques and technologies to gather valuable data for oceanographic research. In particular, active radar remote sensing systems such as altimeters are advanced instruments that play an essential role in acquiring information about wave and wind characteristics. These systems operate by sending a signal and receiving its echo, allowing for the detection and mapping of various attributes of the observed environment (Vignudelli, 2023). Processing the return signal in terms of time, known as waveform analysis, enables the calculation of wave and wind parameters. The most significant advantage of active radars is their ability to operate effectively at any time, both day and night, and under any weather conditions,

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overcoming the limitations of other observation methods that may be impeded by clouds or other adverse weather conditions.

1.1.1 Significant wave height and wind measurements from altimeter

Satellite-mounted radar altimeters play a crucial role in ocean observations by measuring the radar echo bounced off the ocean surface, known as the ocean waveform (Figure 1). This waveform contains valuable information about the dynamics of the ocean.

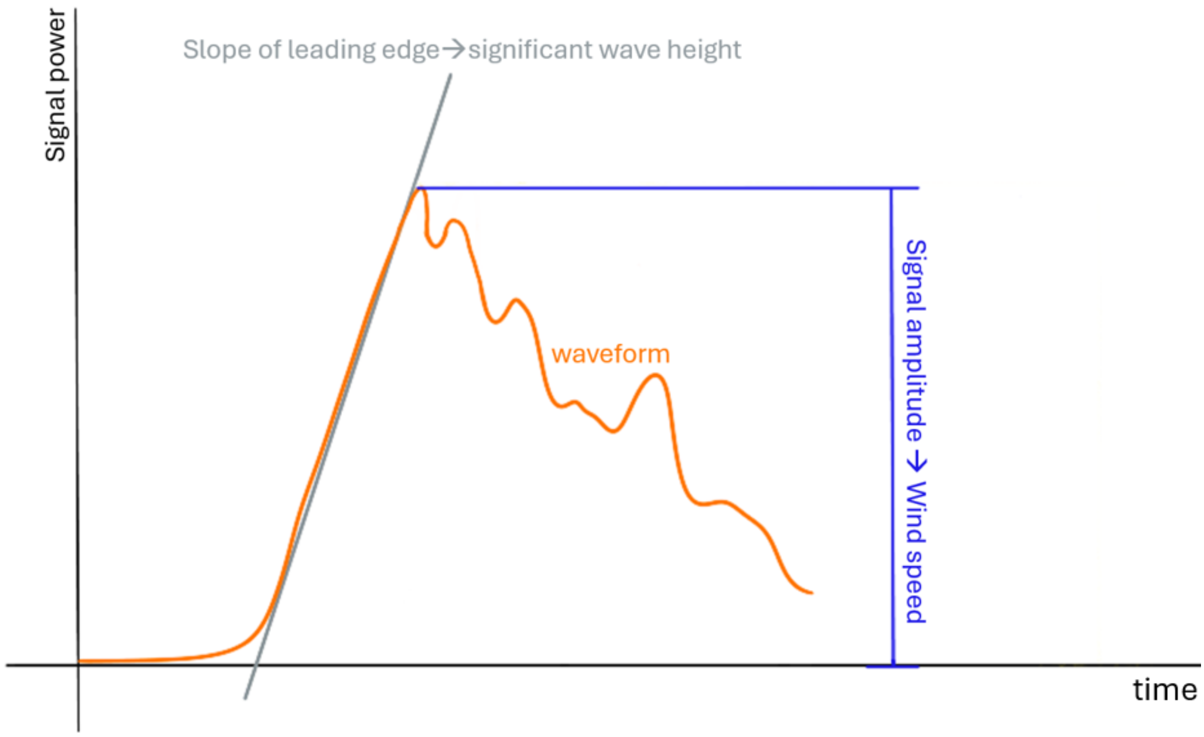

Figure 1 - Waveform obtained by a radar echo reflected from the sea surface

The slope of the leading edge of the waveform, especially the first edge of the pulse, is of considerable importance in determining the significant wave height (Chelton, 2001). When the ocean surface is flat since no waves are occurring, the reflection from the surface is completely mirrored, resulting in a vertical leading edge of the waveform. However, the presence of ocean waves alters this scenario, causing the leading edge of the waveform to tilt. This skew occurs because the part of the signal reflected from the wave crests reaches the altimeter before the part reflected from the wave trough, creating a spectrum of intermediate reflections.

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Furthermore, the amplitude of the waveform provides information on the speed of the wind. The presence of wind disturbs the sea surface, making it rough and dispersing the radar signal in various directions. As a result, only part of the echo is received by the altimeter. In particular, the stronger the wind, the rougher the surface becomes, resulting in a decrease in the signal received by the altimeter. Therefore, the analysis of waveform amplitude allows the estimation of the wind speed at the water surface.

In particular, altimetric measurements are based on three methods: LRM, SAR altimetry and PLRM. The LRM (Low Resolution Mode) is the conventional method and constructs a waveform by measuring the reflected signal as it spreads radially across the surface. However, recent technical advances have made it possible to use a Synthetic Aperture Radar (SAR) approach, which exploits delay/Doppler effects in the returning signal. The latter approach, employed by CryoSat's SRAL and Sentinel-3 altimeter, offers higher resolution than its LRM counterpart. SAR in altimetry is a higher resolution technique that allows for high-density data collection over a smaller footprint area.
Finally, Pseudo Low Resolution Mode (PLRM) is a processing technique that emulates LRM mode using data collected in SAR mode. The PLRM is designed to provide continuity with historical LRM data by processing the data in SAR mode to mimic the characteristics of LRM measurements. This approach allows comparison and combination of SAR and LRM datasets, facilitating long-term climate studies and other applications that rely on consistent data records.

1.1.2 Satellite data processing

Typically, satellite observations are delivered with different data processing levels according to the systematic operations carry out on the data:

- Level-0 (L0): This product involves raw data extracted and decoded from the instrument's source package.
- Level-1 (L1): At this level, Level-0 data undergo correction for instrumental effects, with special attention given to factors like date and location variables.
- Level-2 (L2): Level-1 data are further processed to correct for geophysical effects, and parameters of interest are calculated.

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- Level-3 (L3): Data at this stage are calibrated and validated using in-situ instruments and other satellite measurements.

The main focus of AIMS activity is addressed to Level-3 data products due to their provision of accurate and calibrated values of wave height and wind speed. In contrast, Level-2 data requires preprocessing before use, as it may contain measurement errors and noise. Additionally, L2 products are not calibrated against other satellite and in-situ data sources.
Since the accuracy of the data obtained by AIMS through artificial intelligence algorithms depends significantly on the precision of the input datasets and the correct implementation of the models, the use of L3 products is advantageous since these products offer higher reliability and accuracy compared to L2 products.

2. COPERNICUS MARINE SERVICE WAVE-TAC

The Copernicus Program is the Earth observation program of the European Union (Jutz, 2020), dedicated to monitoring our planet and its environment for the maximum benefit of all European and global citizens.
One of the specific Copernicus programs is the Copernicus Marine Service, which focuses on ocean monitoring (Le Traon, 2019). This service provides free, open, standardized and systematic reference information on the state of the oceans, sea ice and biogeochemical aspects. It also analyses the variability and dynamics occurring in the global ocean and European regional seas.
Collecting and analysing ocean data is critical to Earth's survival, helping us understand and predict changes in climate, weather, oceans and coasts. Indeed, Copernicus Marine has one of the largest gatherer of high-quality ocean data, derived from satellites, in-situ sensors and numerical models covering the global ocean.

In this context, the WAVE Thematic Assembly Center (WAVE-TAC) plays a crucial role, providing accurate satellite wave observation data (Ollivier, 2024). Wave and wind measurements derive by multiple missions and sensors and data correction is based on the intercalibration of measurements between different satellites and in-situ buoys. This methodology guarantees accurate and reliable data, essential for oceanographic and climate analyses.

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2.1 WAVE-GLO_PHY_SWH_L3_NRT_014_001 product

Numerous efforts have been undertaken to generate reliable and cohesive datasets from various altimetry missions. These efforts aim to improve the accuracy and usability of data collected by satellites. In this context, the WAVE_GLO_PHY_SWH_L3_MY_014_005 Level-3 product (Charles, 2021) provides calibrated and validated satellite wave and wind measurements suitable for AIMS' objectives. This product is provided by WAVE-TAC and includes only valid data, based on rigorous quality control and calibration processes. The altimetry measurements included in these datasets are based on the Sentinel-6A, Jason-3, Sentinel-3A, Sentinel-3B, SARAL/AltiKa, CryoSat-2, HaiYang-2B, HaiYang-2C, CFOSAT, and SWOT satellite missions.
In particular, data from these missions is cross-calibrated using reference missions to ensure consistency and accuracy. Such reference missions are Jason-3 until April 2022 and Sentinel-6A thereafter. Furthermore, an intercalibration is carried out between satellite measurements and in-situ instrument recordings, ensuring that the datasets are robust and reliable.

The Level-3 product WAVE_GLO_PHY_SWH_L3_MY_014_005 is particularly suitable for AIMS purposes because:

- Provides crucial parameters such as significant wave height (Hs) and wind speed at 10 meters above sea level (W10m).
- Provides a calibrated and validated dataset ensuring that measurements are reliable, allowing AIMS to apply artificial intelligence models to accurate datasets and understand ocean and atmospheric dynamics.
- Consists of a multitude of satellite constellations, improving temporal and spatial resolution compared to using a single constellation.
- The update every 3 hours allows you to obtain continuous data and guarantee monitoring even in future phases of the AIMS project.

3. AIMS SATELLITE DATASET

From the WAVE_GLO_PHY_SWH_L3_MY_014_005 Level-3 product, wave and wind data are extrapolated specifically to the marine area of interest. In particular, the region between 42°N and 44.5°N latitude and 9°E and 11°E

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longitude is the area of analysis. Satellite measurements belonging to this region are acquired by Copernicus Marine Viewer[4] (MyOcean Pro) portal.

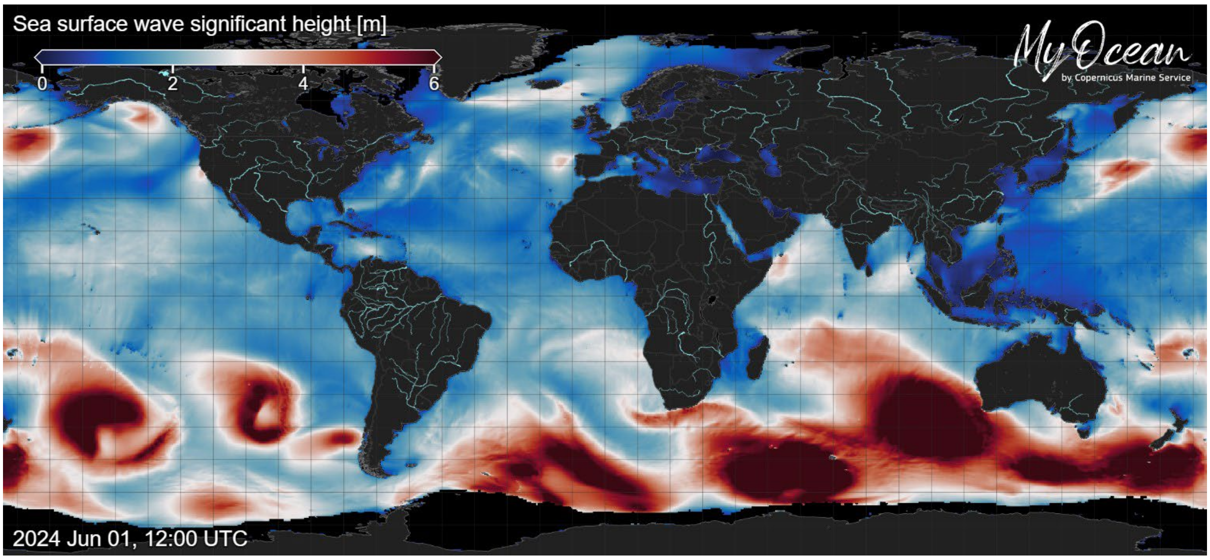

Figure 2 – Example of MyOcean Pro portal in regard to the global significant wave height

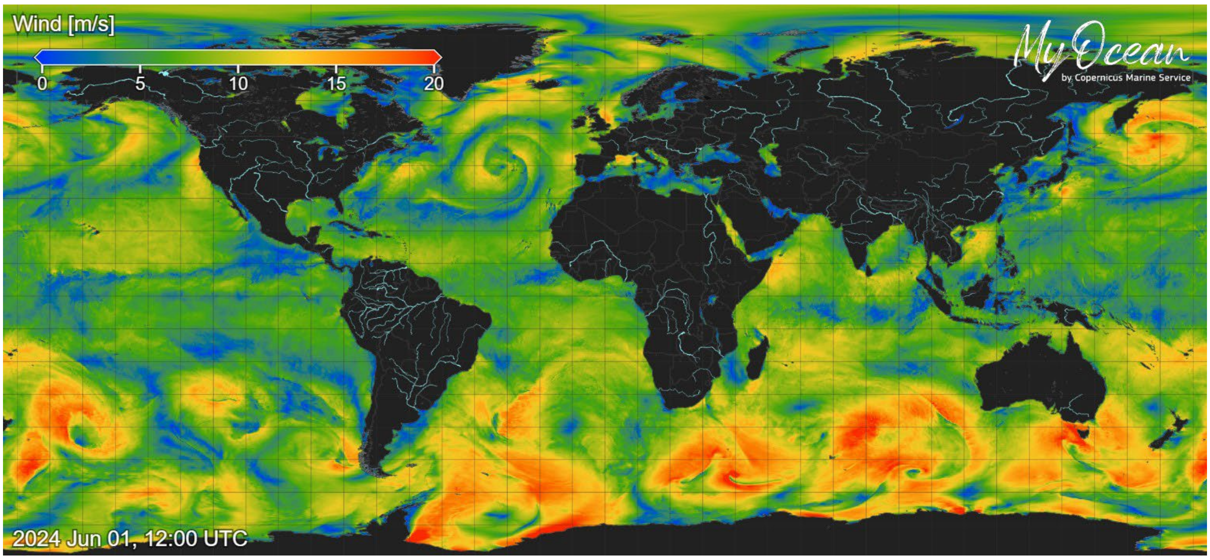

Figure 3 - Example of MyOcean Pro portal in regard to the global wind speed

As regards the temporal coverage, it is complete with respect to the data available up to 27/May/2024. This spatial and temporal selectivity ensures that the analysis is focused and relevant, providing precise and as extensive information as possible for the study region.

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[4] https://data.marine.copernicus.eu/viewer/

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The following table provides a general overview of the satellites included in the Level-3 product and detailed information on the parameters provided and the mode used for the parameter's calculation.

Table 1 - Overview of the operating mode and parameters obtained from the satellites

Satellite	Parameters	Mode
CFOSAT	Hs	LRM
Cryosat-2	Hs and W10m	LRM
HaiYang-2B	Hs and W10m	LRM
HaiYang-2C	Hs and W10m	LRM
Jason-3	Hs and W10m	LRM
SARAL-Altika	Hs and W10m	LRM
SWOT	Hs and W10m	LRM
Sentinel-3A	Hs and W10m	PLRM
Sentinel-3B	Hs and W10m	PLRM
Sentinel-6A	Hs and W10m	LRM

As shown in the table, all satellites included in the WAVE_GLO_PHY_SWH_L3_MY_014_005 product, except for CFOSAT, provide significant wave height (Hs) and wind speed at 10 meters above sea level (W10m). For CFOSAT, formulations to derive wind speed from the waveform have not been developed. Consequently, while CFOSAT contributes valuable data regarding wave height, it does not provide wind speed measurements, distinguishing it from the other satellites in the dataset.

3.1 Temporal coverage

The time coverage analysis of various satellite missions is provided, focusing on both the time span of the dataset and the cycle length of each satellite. The time frame refers to the period between the first measurement provided by the WAVE_GLO_PHY_SWH_L3_MY_014_005 product and the last measurement acquired for the creation of this deliverable. Cycle length indicates the time it takes for the satellite to complete a full sequence of orbits, covering the entire Earth's surface. This cycle length is essential for understanding how often the satellite revisits the same location.

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Table 2 – Overview of the temporal coverage of the satellites

Satellite	Time span	Cycle duration [days]
CFOSAT	05/01/2021-present	13
Cryosat-2	14/01/2021-present	29
HaiYang-2B	05/01/2021-present	14
HaiYang-2C	01/12/2022-present	10
Jason-3	07/01/2021-present	10
SARAL-Altika	06/01/2021-present	Non-cyclic
SWOT	08/08/2023-present	28
Sentinel-3A	02/01/2021-present	27
Sentinel-3B	16/01/2021-present	27
Sentinel-6A	04/09/2021-present	10

An overview of the wave and wind time series of the various satellites in the area of interest is provided. Specifically, the information is referred to each individual satellite as well as a comprehensive summary that integrates data from all satellites.

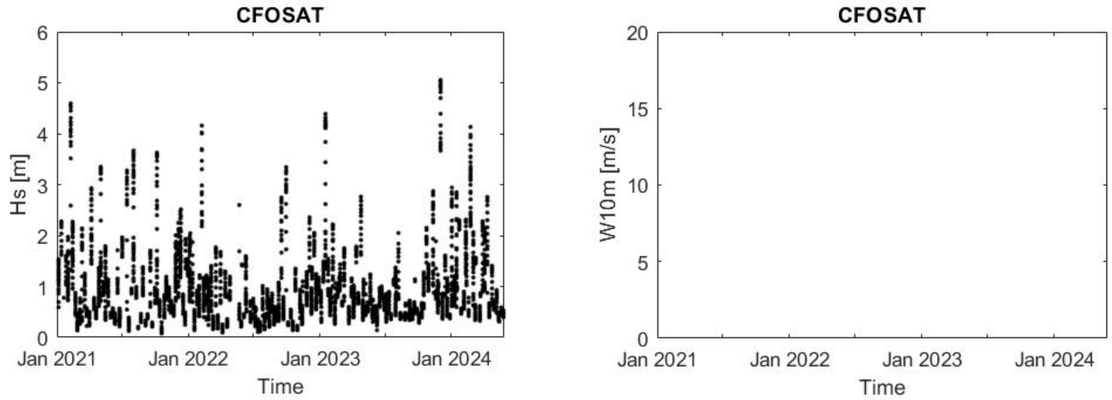

Figure 4 – Hs (figure on the left) and W10m (figure on the right) time series from CFOSAT in the study area

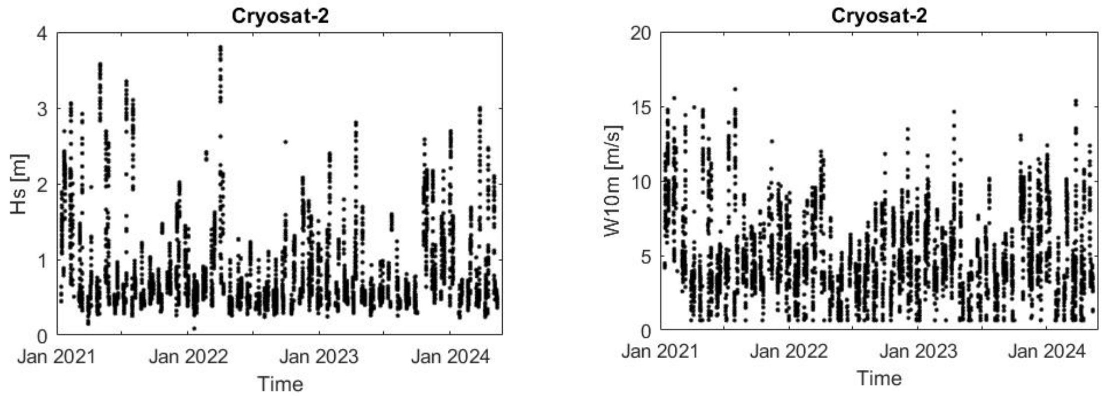

Figure 5 – Hs (figure on the left) and W10m (figure on the right) time series from Cryosat-2 in the study area

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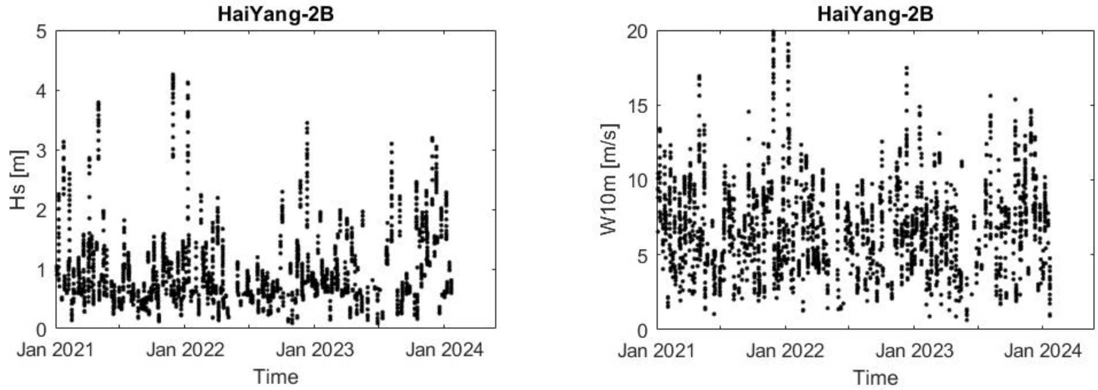

Figure 6 – Hs (figure on the left) and W10m (figure on the right) time series from HaiYang-2B in the study area

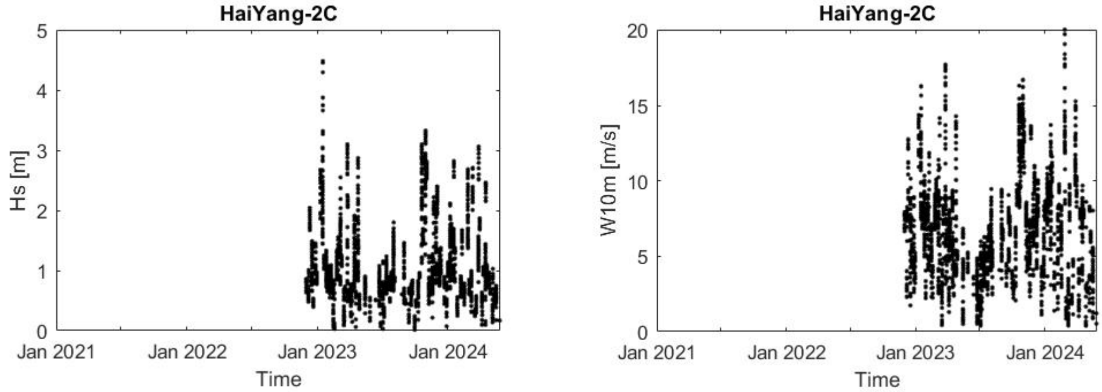

Figure 7 – Hs (figure on the left) and W10m (figure on the right) time series from HaiYang-2C in the study area

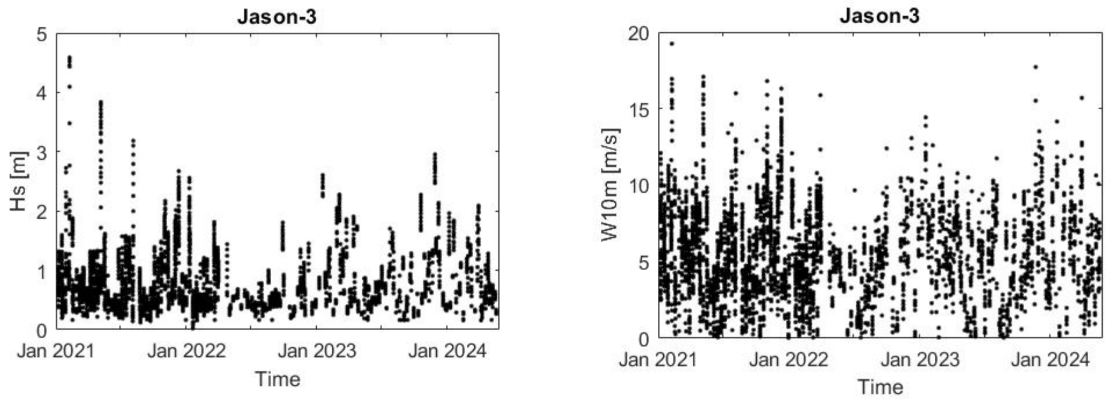

Figure 8 – Hs (figure on the left) and W10m (figure on the right) time series from Jason-3 in the study area

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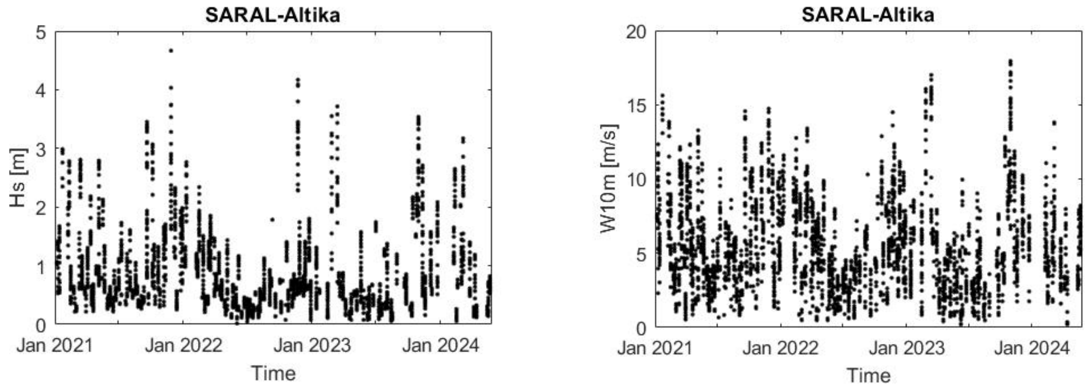

Figure 9 – Hs (figure on the left) and W10m (figure on the right) time series from SARAL-Altika in the study area

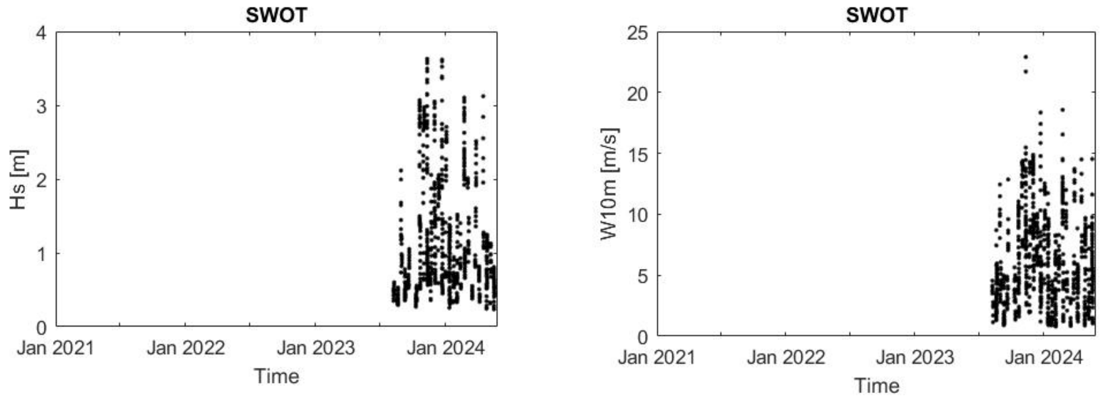

Figure 10 – Hs (figure on the left) and W10m (figure on the right) time series from SWOT in the study area

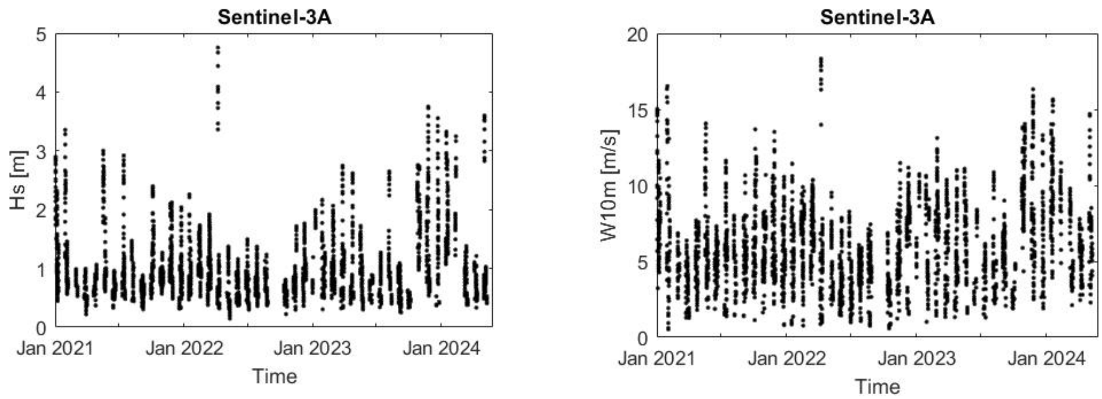

Figure 11 – Hs (figure on the left) and W10m (figure on the right) time series from Sentinel-3A in the study area

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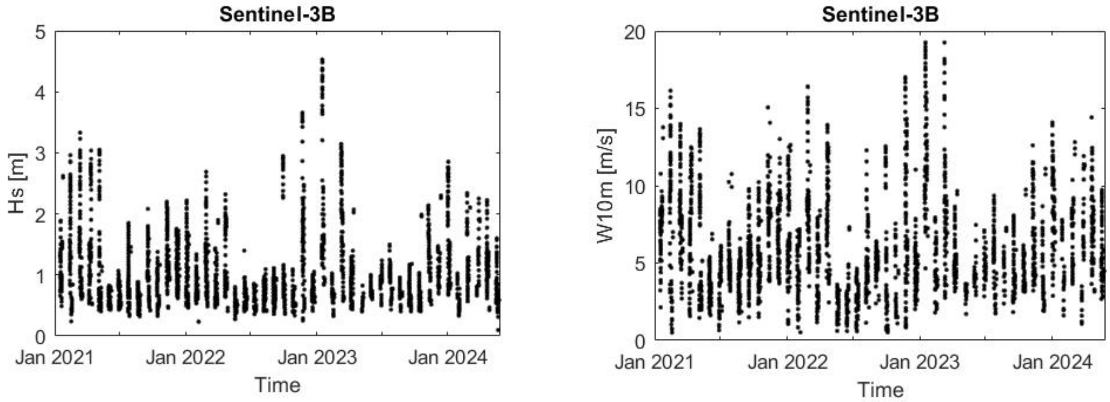

Figure 12 – Hs (figure on the left) and W10m (figure on the right) time series from Sentinel-3B in the study area

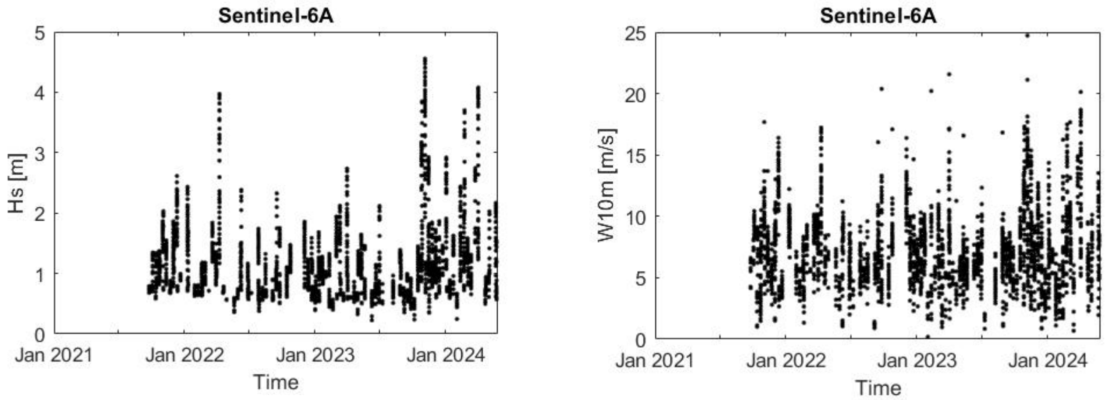

Figure 13 – Hs (figure on the left) and W10m (figure on the right) time series from Sentinel-6A in the study area

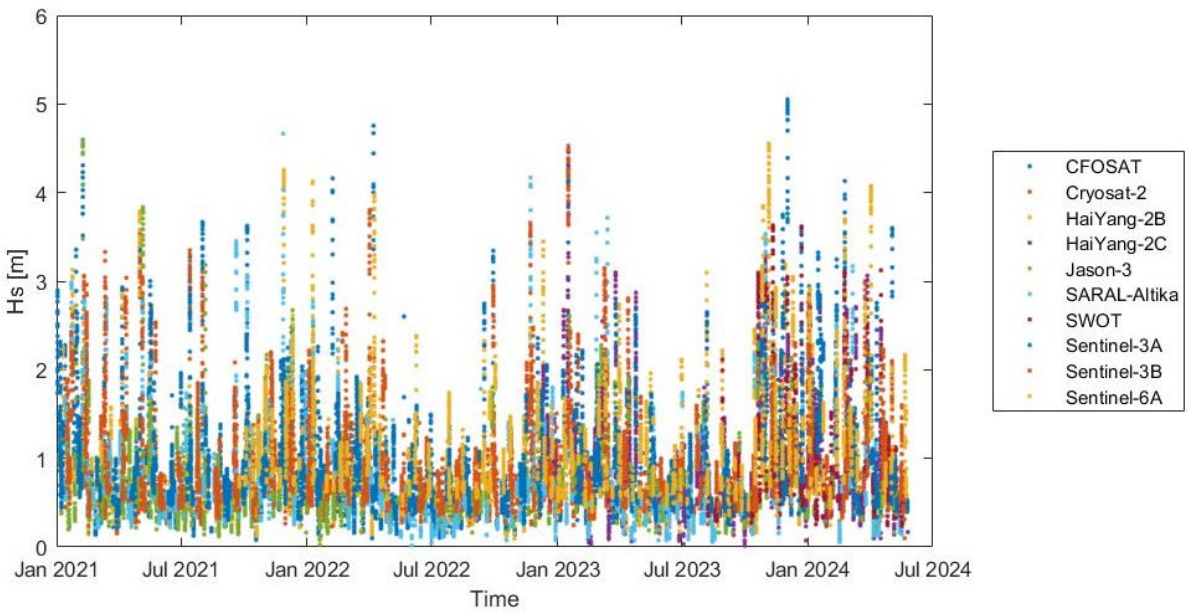

Figure 14 - Hs time series from all satellite available in the study area

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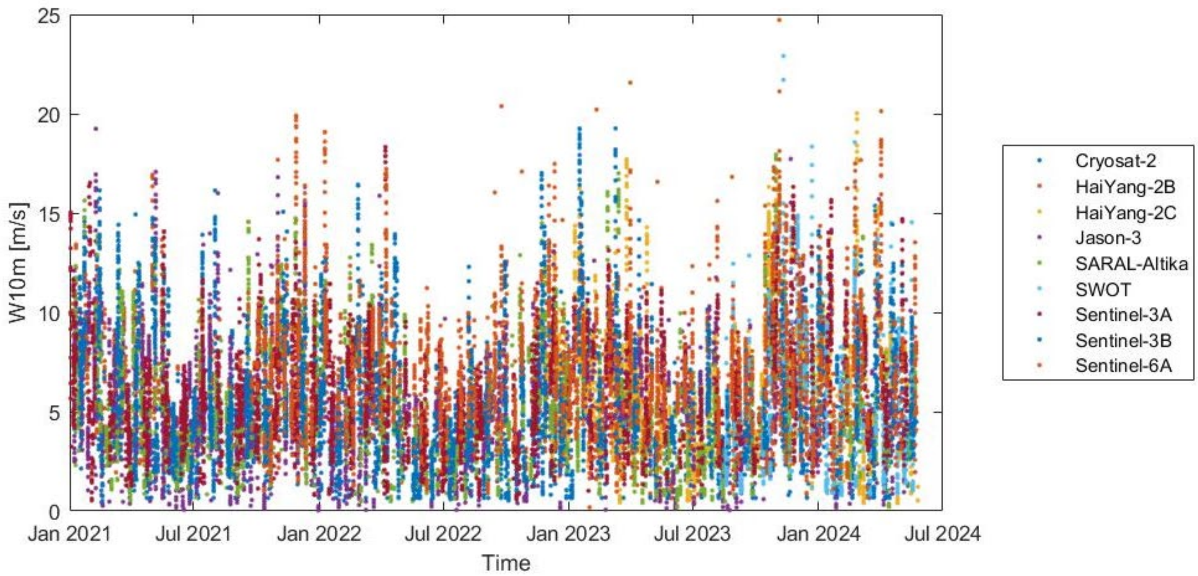

Figure 15 – W10m time series from all satellite available in the study area

3.1 Spatial coverage

The analysis of the spatial coverage of the different satellite missions is essential to understand the spatial characteristics of the measurements provided. The following table illustrates several key parameters of satellite missions, such as the number of tracks per cycle that describes the number of distinct orbital paths taken by the satellite in a single cycle. A greater number of traces per cycle implies a greater density of spatial measurements. The total number of measurements is provided and indicates the overall amount of data collected by the satellite in the area of interest during the analysis period. Finally, the number of collocations is reported and corresponds to the satellite passages within the study area in the time span of the dataset.

Table 3 - Overview of the spatial coverage of the satellites

Satellite	Number of tracks per cycle	Total measurements	Total collocations
CFOSAT	394	4280	220
Cryosat-2	840	4291	208
HaiYang-2B	386	2238	195
HaiYang-2C	274	2311	128
Jason-3	254	3886	216
SARAL-Altika	1002	3316	174

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SWOT	584	1012	63
Sentinel-3A	770	3623	206
Sentinel-3B	770	3305	207
Sentinel-6A	254	2689	124

CryoSat-2's orbit is designed to have extended coverage of high latitudes, ensuring numerous orbital track crossings. Unlike sun-synchronous orbits, CryoSat-2's orbit is not synchronous and is meant to have frequent measurements of the same sea area.

Similarly, SARAL-AltiKa and CFOSAT cover extensive marine areas, but operate in sun-synchronous orbits. This type of orbit allows them to provide temporally periodic observations, essential for continuous monitoring and long-term data collection. The sun-synchronous orbit allows SARAL-AltiKa and CFOSAT to have precise repeatability of observations. Their high spatial coverage is also favored by the large number of orbital tracks they perform per cycle, ensuring extensive and detailed data collection. Other satellite missions have less space coverage.

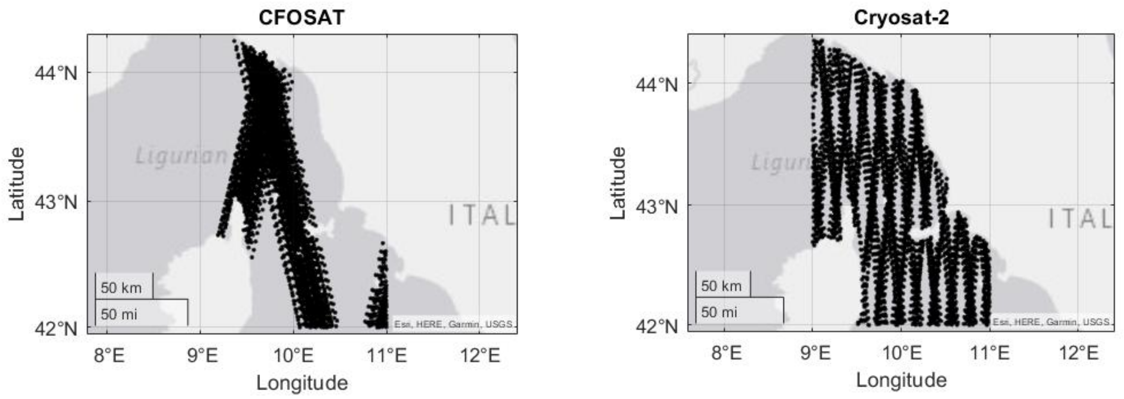

Figure 16 – Measurements spatial coverage for CFOSAT (figure on the left) and Cryosat-2 (figure on the right)

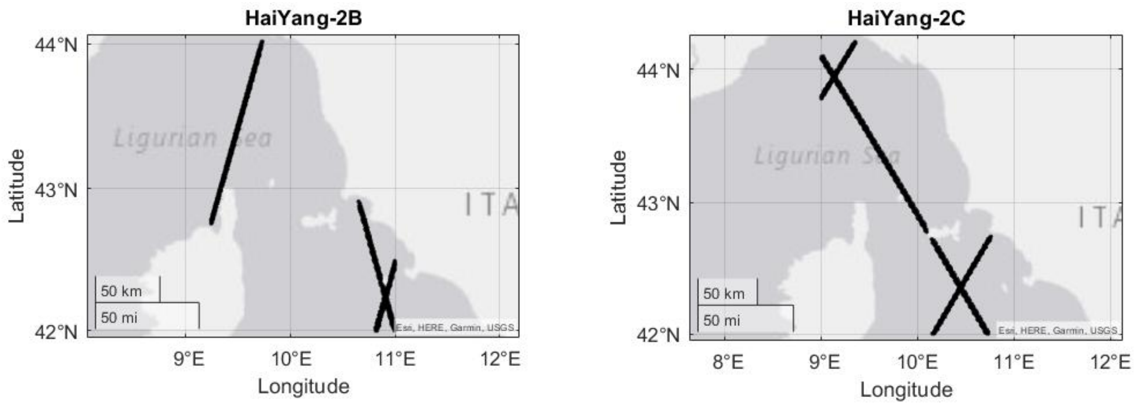

Figure 17 – Measurements spatial coverage for HaiYang-2B (figure on the left) and HaiYang- 2C(figure on the right)

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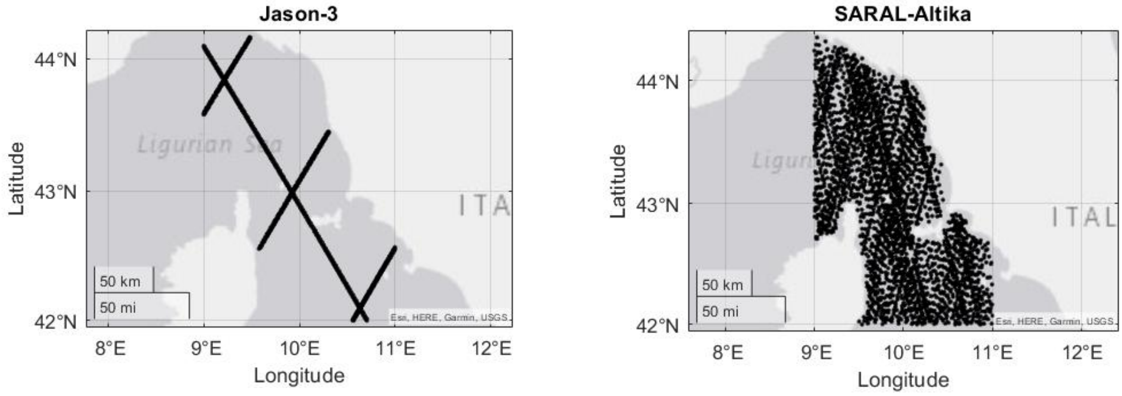

Figure 18 – Measurements spatial coverage for Jason-3 (figure on the left) and SARAL-Altika (figure on the right)

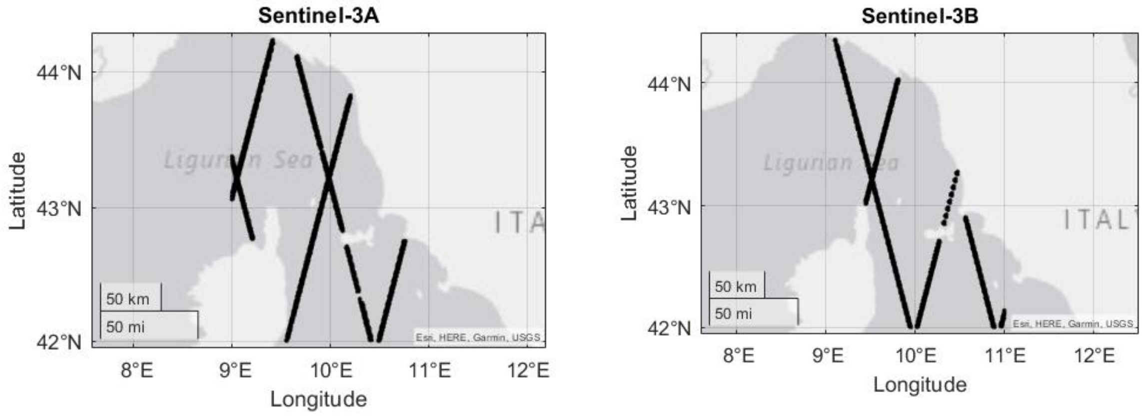

Figure 19 – Measurements spatial coverage for Sentinel-3A (figure on the left) and Sentinel-3B (figure on the right)

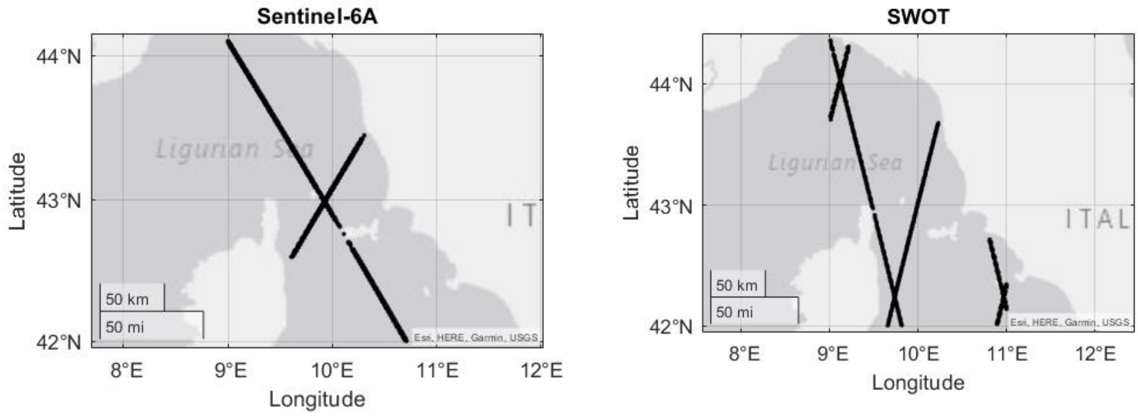

Figure 20 – Measurements spatial coverage for Sentinel-6A (figure on the left) and SWOT (figure on the right)

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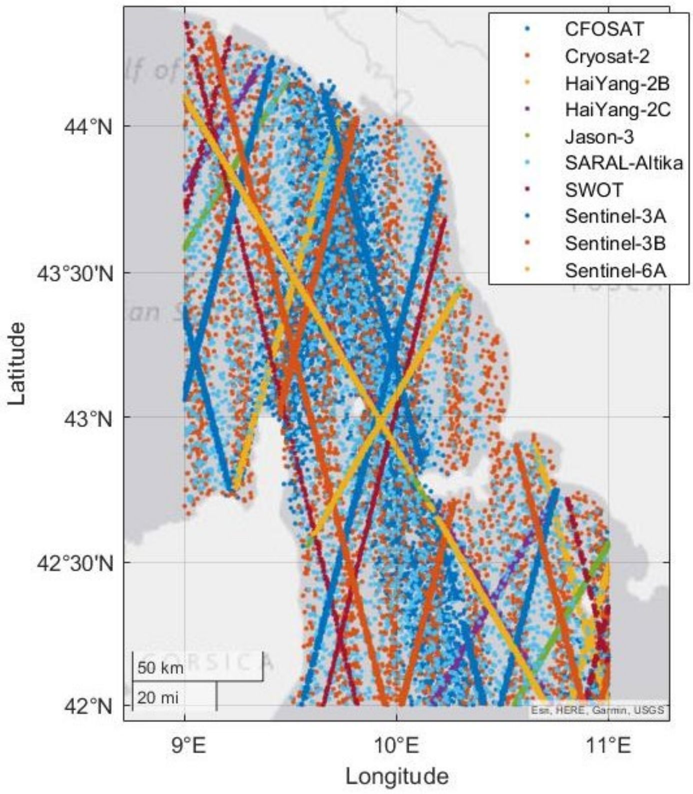

Figure 21 – Measurements spatial coverage for all the satellites available

3.1 Dataset files

Datasets are available in two main formats: NetCDF (Network Common Data Format) files and CSV (Comma-Separated Values) files. These formats are chosen for their ability to store large volumes of data with high efficiency and to facilitate interoperability between different platforms and applications.

3.1.1 NetCDF files

The products are stored using the NetCDF4 format. These products fully comply convention ensures that the data is structured in a standardized manner, facilitating interoperability and sharing across various platforms and applications. The adoption of the NetCDF4 format guarantees that the products are highly compatible and usable in a wide range of climatic and meteorological research contexts.

File name of example: CFOSAT_AIMS_Dataset.nc

Global Attributes:

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Parameters = 'Wind speed at 10 m above sea level (W10m) and significant wave height (Hs).'
Satellite = 'CFOSAT data delivered by WAVE_GLO_PHY_SWH_L3_NRT_014_001 product.'
Spatial_coverage = 'Sea area between 42°N and 44.5°N latitude and 9°E and 11°E longitude.'
Temporal_coverage = 'From 01/01/2021 to 27/05/2024'
Long_dataset_description = 'Wind speed at 10 m above sea level (W10m) and significant wave height (Hs) provided by CFOSAT data delivered by WAVE_GLO_PHY_SWH_L3_NRT_014_001 dataset product (by COPERNICUS) and concerning the sea area between 42°N and 44.5°N latitude and 9°E and 11°E longitude.'
Project_description = 'AIMS (Artificial Intelligence to Monitor our Seas) is funded by the European Union - NextGeneration EU within the PRIN 2022 PNRR program (D.D.1409 del 14/09/2022 Ministero dell'Università e della Ricerca). This dataset is included in the deliverable D1.2 Report and dataset from satellites.'

Dimensions:
time = 4280

Variables:
dateTime
Size: 4280x1
Dimensions: time
Datatype: double
Attributes:
units = 'hours since 1900-01-01 00:00:00.0'
long_name = 'Time of the Hs and W10m satellite measutements'
calendar = 'gregorian'
missing_value = 'NaN'
lat
Size: 4280x1
Dimensions: time
Datatype: double
Attributes:
units = 'degrees_north'
long_name = 'Latitude of the satellite measurements'
missing_value = 'NaN'
lon
Size: 4280x1
Dimensions: time
Datatype: double
Attributes:
units = 'degrees_east'
long_name = 'Longitude of the satellite measurements'
missing_value = 'NaN'
Hs
Size: 4280x1
Dimensions: time
Datatype: double
Attributes:
units = 'm'
long_name = 'Significant wave height provided by satellite measurements'
missing_value = 'NaN'
W10m
Size: 4280x1
Dimensions: time
Datatype: double
Attributes:

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units = 'm/s'
long_name = 'Wind speed at 10m above sea level provided by satellite measurements'
missing_value = 'NaN'

3.1.2 CSV files

CSV files are used to store data in a simple, readable tabular format. Each line of a CSV file represents a data record, with the fields separated by commas. They allow for easy viewing and manipulation of data with common tools such as Microsoft Excel.

File name of example: CFOSAT_AIMS_Dataset.csv

	A	B	C	D	E
1	Time	Latitude	Longitude	Significant wave height [m]	Wind speed at 10m above sea level
2	05.01.2021 18:03:04	42.01	10.178986	1.5350001	NaN
3	05.01.2021 18:03:05	42.076	10.158997	1.4820001	NaN
4	05.01.2021 18:03:06	42.135	10.140991	1.4560001	NaN
5	05.01.2021 18:03:07	42.195	10.122986	1.4280001	NaN
6	05.01.2021 18:03:08	42.261	10.102997	1.3640001	NaN
7	05.01.2021 18:03:09	42.326	10.083008	1.297	NaN
8	05.01.2021 18:03:10	42.386	10.063995	1.238	NaN
9	05.01.2021 18:03:11	42.445	10.04599	1.2090001	NaN
10	05.01.2021 18:03:12	42.511	10.026001	1.2260001	NaN
11	05.01.2021 18:03:13	42.577	10.005005	1.2550001	NaN
12	05.01.2021 18:03:14	42.636	9.987	1.2650001	NaN
13	05.01.2021 18:03:15	42.695	9.968994	1.218	NaN
14	05.01.2021 18:03:16	42.761	9.947998	1.143	NaN
15	05.01.2021 18:03:17	42.82	9.929993	1.1010001	NaN
16	05.01.2021 18:03:18	42.88	9.911011	1.118	NaN
17	05.01.2021 18:03:19	42.946	9.890991	0.86100006	NaN
18	05.01.2021 18:03:20	43.012	9.869995	0.59000003	NaN
19	05.01.2021 18:03:21	43.071	9.85199	0.694	NaN
20	05.01.2021 18:03:22	43.13	9.833008	0.9480001	NaN
21	05.01.2021 18:03:23	43.196	9.812988	1.0430001	NaN
22	05.01.2021 18:03:24	43.255	9.794006	1.1620001	NaN
23	05.01.2021 18:03:25	43.315	9.774994	1.322	NaN
24	05.01.2021 18:03:26	43.38	9.755005	1.439	NaN
25	05.01.2021 18:03:27	43.446	9.734009	1.4890001	NaN
26	05.01.2021 18:03:28	43.506	9.714996	1.4810001	NaN
27	05.01.2021 18:03:29	43.565	9.696014	1.4740001	NaN
28	05.01.2021 18:03:30	43.631	9.674988	1.473	NaN

Figure 22 - Example .csv file format

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