WAPOSAL: A Multi-Regional Wave Dataset from Satellite Altimetry for Significant Wave Height, Period Estimation, and Wave Power Density

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Abstract. Accurate assessment of wave power density (WPD) is essential for marine renewable energy development and for validating numerical wave models, particularly in coastal and nearshore regions where in situ observations are sparse. This study presents a high-resolution, multi-region wave dataset generated within the WAPOSAL (Wave Power & Satellite Altimetry) project, derived from Synthetic Aperture Radar (SAR) altimetry data acquired by the Sentinel-3A/B and CryoSat-2 missions. Significant wave height and normalized radar cross-section were obtained using the SAMOSA+ retracker, and zero-crossing wave period was estimated based on an empirical regression method calibrated with in situ buoy and ERA5 data. Wave power density was then computed along altimeter tracks across eleven regions: Norway & Baltic Sea, UK & North Sea, French Facade, Spain Atlantic, Portugal, Mediterranean sea, Madeira, Canary Islands, Azores Archipelago, French Guiana and French Polynesia. The temporal coverage spans 2011–2023, depending on the region and the satellite mission considered. The present paper describes the database and illustrates its use through simple application examples. The dataset in its current format and version can be discovered, shared and cited via the following link: https://doi.org/10.57780/ESA-1AB8CF3 (Ponce de Léon et al., 2026).

1 Introduction

The growing interest in renewable energy sources for electricity generation, driven by the fight against climate change, the demand for a low-carbon economy, rising global energy consumption, and competition for land use (agriculture, urban planning, and protected areas), together with high population density, makes marine renewable energy a good option for countries with extensive maritime zones (O'Connell et al., 2024; Orlov, 2024). Among marine renewable energy options, wave energy

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is recognized as a promising source due to its high energy density and predictability compared with wind and solar energy (Gu et al., 2025).

20   There are diverse methodologies for determining wave power density, which focus on obtaining the significant wave height H_s and the energy period T_e. Among these is the use of in-situ wave measurements, which is considered highly accurate because buoys record data directly from the sea surface (Dunnett and Wallace, 2009; Kasiulis et al., 2015). However, their low spatial distribution and heterogeneity make it difficult to estimate wave power density at a macro-scale, especially in countries without sustained monitoring networks and in remote ocean areas (Ponce de León and Orfila, 2013).

25   Third-generation wave models (e.g., WAM (WAMDI Group, 1988), SWAN (Booij et al., 1999), WAVEWATCH/III (Tolman, 2009)), on the other hand, are widely used tools for determining wave power density, solving problems such as spatial resolution and macro-scale coverage (Besio et al., 2016; Görmüş et al., 2024; Vázquez et. al. , 2025). Nevertheless, they present inconsistencies and gaps in coastal areas, thereby losing important information on the interaction between waves and the seabed, crucial for determining wave energy potential near the coast (Ponce de León and Orfila, 2013).

30   In contrast, satellite altimetry has become a cost-effective alternative for determining potential energy density, providing consistent global time series with excellent spatial coverage. Furthermore, thanks to recent advances in technology, measurements in nearshore waters can now be obtained with significantly higher resolution, expanding its possible applications (Ponce de León and Orfila, 2013; Vignudelli et al., 2019; Dong et al., 2023).

In this context, one of the results of the WAPOSAL (Wave Power & Satellite Altimetry) project was the generation of a high-
35 resolution, validated, multivariable dataset from satellite altimetry, with a special emphasis on estimating the period and calculating wave power density (WPD). The WAPOSAL project webpage is available at https://eo4society.esa.int/projects/waposal/.

The dataset integrates corrected satellite altimetry data using the SAMOSA + and retracker algorithm (Dinardo et al., 2018), from the Sentinel-3 A/B and CryoSat-2 missions, covering various oceanic and coastal regions including: Norway & Baltic Sea, UK & North Sea, French Facade, Spain Atlantic, Portugal, Mediterranean sea, Madeira, Canary Islands, Azores Archipelago,
40 French Guiana and French Polynesia as shown in Figure 1. The information on significant wave height H_s and normalized radar cross section σ^0 was obtained using the retracking procedure, while the zero-crossing wave period T_z was estimated from H_s and σ^0 based on the regression method (Gommenginger et al., 2003).

The estimated H_s and T_z data were validated against in-situ wave buoy and/or ERA5 data, for each study area. Subsequently, the wave power density was computed along the available tracks for each region, producing a homogeneous database suitable
45 for marine energy applications.

In this article, the method used to determine the wave period, the validation of the H_s and T_z obtained from satellite altimetry, the structure of the final dataset, and the applications of the wave power density dataset are described. The resulting database is an open-access, standardized resource that can be utilized by the scientific community, monitoring institutions, and marine energy developers.
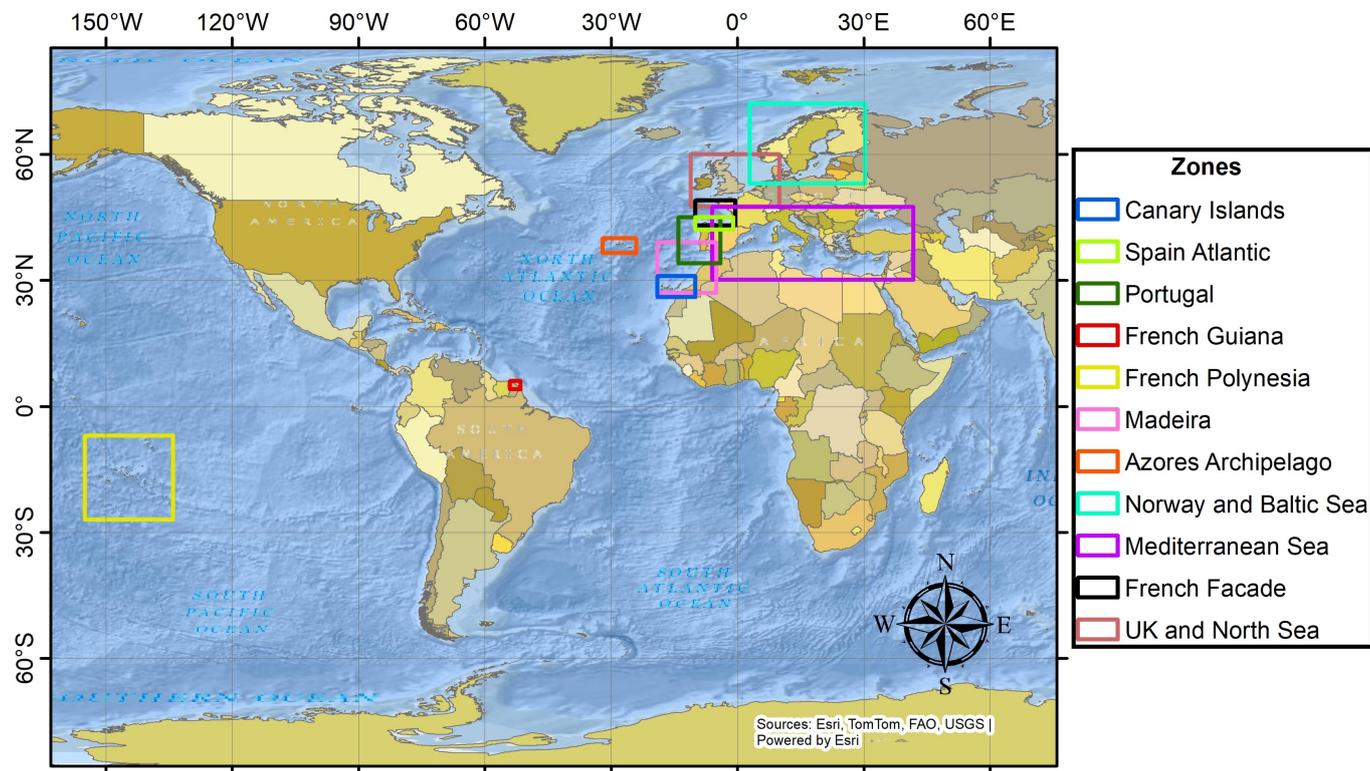
Figure 1. WAPOSAL regions: the bounding boxes show the combined spatial extent of the Sentinel-3A/B and CryoSat-2 dataset.

2   Methods

2.1   High resolution altimeter data on significant wave height and normalized radar cross section

The radar altimetry data used to generate this Dataset across the 11 study areas (see Figure 1) are from the European Space Agency (ESA) missions CryoSat-2 and Sentinel-3 A/B. The data in high resolution Synthetic Aperture Radar (SAR) mode were considered and reprocessed.

Reprocessing was performed using the ESA-developed cloud service SARvatore (SAR Versatile Altimetric Toolkit for Ocean Research & Exploration), which processes SAR altimetry data. This service incorporates the SAMOSA+ model and retracker algorithm, specifically designed for the altimeter waveform interpretation and parameter estimation under challenging coastal conditions, to optimize data in coastal environments (Dinardo et al., 2018).

From a computational perspective, the reprocessing campaign leveraged EarthConsole®'s P-PRO (Parallel Processing) environment, which dynamically allocates computing resources across a distributed cluster. This parallel architecture significantly reduced overall CPU time by executing multiple processing chains concurrently and by colocating Earth Observation input

data with the computing infrastructure. Data transfer overheads were minimized and task execution was accelerated, enabling the efficient handling of large data volumes.

65   As a result, along-track significant wave height H_s and normalized radar cross-section σ^0 were obtained along the altimeter track with a resolution of 300 m. Additionally, the dataset contains the information on the 'misfit' between the model and measured altimeter waveform, that was later used for quality control.

The altimeter data were reprocessed as part of the OCRE EO (Open Clouds for Research Environments Earth Observations) project to generate high-resolution marine and coastal products. The data are freely available online in the EarthConsole® Virtual Altimetry Laboratory for registered users (https://avl-repo.earthconsole.eu/sarvatore/CENTEC_OCRE).

70   ## 2.2   Wave Period and Wave Power Density Estimate

Within the WAPOSAL project framework, based on the results of the OCRE project discussed above, estimates of wave period and wave power density were computed from along-track altimeter data. Information on H_s and σ^0 and a 'misfit' was used. The samples with a 'misfit' greater than 4 counts are eliminated.

We estimated the zero-crossing wave period T_z as follows. In (Gommenginger et al., 2003), it was shown that T_z is linearly

75   related to the combination of significant wave height and NRCS, $X = (Hs^2 \cdot \sigma^0)^{0.25}$, where σ^0 is expressed in natural units (non-dB). Therefore, with a collocated array of in situ wave buoy data on T_z and altimeter data on H_s and σ^0, it is possible to evaluate the coefficients (a and b) of the linear regression from equation

$$T_z = aX + b \tag{1}$$

and subsequently calculate T_z along the altimeter tracks based on H_s and σ^0.

80   To perform linear regression and validate altimeter measurements, data from 82 wave buoys within the study areas were used. The buoy data from the Copernicus Marine Environment Monitoring Service (IN-SITU OCEAN TAC) database, available at the website of Copernicus Marine Service (https://marineinsitu.eu/dashboard/), were used to validate the T_z and H_s obtained from satellite altimetry data in the UK, the Baltic, Norway, the French Coast, Portugal, Northern Spain, and the Mediterranean Sea. Additionally, within the Mediterranean Sea, in situ buoy data for the Italian coast were obtained from the website of

85   RON database (Italian National Wave Network) available at the website https://dati.isprambiente.it/dataset-2/ron/. In other regions—such as the Azores, French Guiana, French Polynesia, Madeira, and the Canary Islands—where buoys were not installed, the selected ERA5 grid nodes with available time series for wave parameters were used for validation. The data were downloaded from the website of Copernicus Climate Data Store (https://cds.climate.copernicus.eu).

Altimeter and buoy or ERA5 data were matched in space and time. The matching time interval was 45 minutes, and the

90   spatial distance was 40 km. Data where the distance to the coast exceeds 1 km were excluded. Altimeter data on σ^0 and H_s within a 40 km radius of the buoy or ERA5 node location were cleaned of outliers and averaged. Using the resulting arrays (σ^0, H_s, T_z) for each buoy, the regression coefficients a and b were determined.
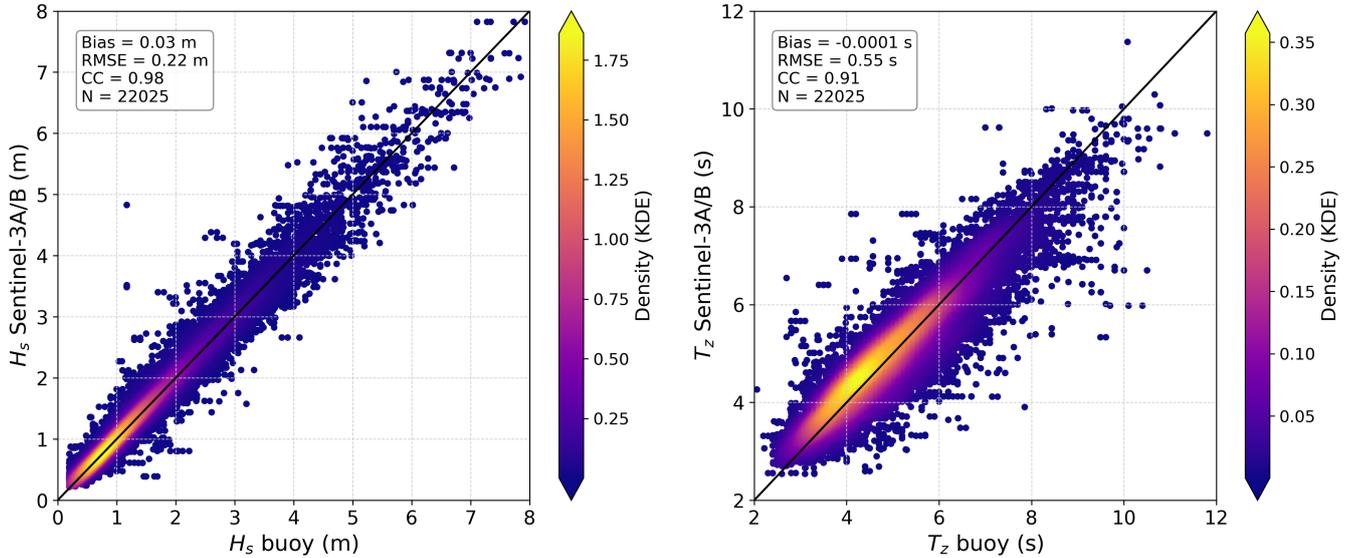
Figure 2. Comparison of buoy and Sentinel-3A/B significant wave height (left) and zero-crossing wave period (right).

The collocated altimeter and buoy dataset was split into two equal parts: training and validation. Based on the training dataset, the coefficients a and b were obtained. Based on the validation dataset, the comparison of H_s and T_z obtained from
95 satellite data is performed.

In Figure 2, scatter plots of H_s and T_z in the validation dataset, which includes all real buoy data and Sentinel-3A/B data, are shown. For CryoSat-2, similar results are obtained.

For H_s, the altimeter's bias relative to buoy measurements is 0.03 m, with an RMSE of 0.22 m and a correlation coefficient of 0.98. For T_z, the altimeter's bias relative to buoy measurements is -0.0001 s, with an RMSE of 0.55 s and a correlation
100 coefficient of 0.91.

The strong agreement between buoy and altimeter measurements at the selected locations demonstrates the reliability of the altimeter data across the full coverage area. Therefore, the results of the linear regression are robust. The values of a and b, obtained at locations near buoys, were interpolated to the coordinates of the altimeter antenna footprints, and T_z was calculated along track using the equation (1). More details about this procedure are provided in (Gommenginger et al., 2003; Ponce de
105 León et. al. , 2023, 2024a, b).

Wave power density is calculated from measurements of H_s and T_z along the track using the following equation:

$$P = \frac{\rho g^2 H_s^2 T_e}{64\pi} \tag{2}$$

where $\rho = 1025$ kg/m^3 is the density of seawater, $g=9.8$ m/s^2 is the acceleration due to gravity, and T_e is the energy wave period. The energy wave period is related to the zero-crossing wave period obtained along track as follows (Cahill 2012):

110 $T_e = 1.18 T_z$ $\tag{3}$

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Calculation of the along-track zero-crossing wave period and wave power density was performed by the WAPOSAL team at CENTEC, Instituto Superior Técnico, University of Lisbon.

3 Dataset description

The dataset generated within the WAPOSAL project, as described above, contains the following variables along the altimeter
115 tracks:

- Temporal and spatial information: latitude, longitude, and observation time in seconds since 01-01-2000 for each antenna footprint;

- The data transferred from the initial dataset used in the work from the ESA Altimetry Virtual Lab on Earth Console®: significant wave height, normalized radar cross-section, distance to the coast, and a 'misfit' between the power waveform
120 model and the power waveform data;

- The variables obtained within the WAPOSAL project: zero-crossing wave period, wave power density, quality flag. Quality flag identifies outliers as significant wave height or normalized radar cross section values exceeding the 99.87th percentile of their regional distributions.

CryoSat-2 data are available for the period 2011-2022 for the following regions: Baltic & Norway, UK & North Sea, Spain
125 Atlantic, Madeira, Azores Archipelago, French Polynesia, Portugal, Mediterranean Sea; and for the period 2011-2023 only for French Facade. Sentinel-3A data are available for the period 2016-2022, and Sentinel-3B for 2018-2022, for Baltic & Norway, UK & North Sea, Spain Atlantic, Madeira, Azores Archipelago, French Polynesia, Portugal, Mediterranean Sea, Canaries Islands, and French Guiana. For the French Facade region, Sentinel-3A and Sentinel-3B data are available for 2016-2023 and 2018-2023, respectively.

130 The bounding boxes in Figure 1 represent the combined spatial extent of the Sentinel-3A/B and CryoSat-2 dataset. The coverage for each individual mission is not identical. For details, please consult the metadata for each region.

The dataset is published by ESA and hosted at the EarthCode Data Repository platform as the ESA Open Science Catalogue WAPOSAL collection (https://opensciencedata.esa.int/products/waposal-waves/collection). The dataset and its specifications can be found in the metadata description on the website.

135 The dataset is available in the repository in two formats. The first is a .zip file containing netCDF files, each with information for a separate track. It can be accessed via the 'Access' option on the collection page. The second format is a set of data cubes containing along-track data for a particular mission – Sentinel-3A, Sentinel-3B, and CryoSat-2 – and a particular region. For example, the file 'waposal-uk-cs2.zarr' includes the along-track data for CryoSat-2 for the region around the British Isles, while the files 'waposal-uk-s3a.zarr' and 'waposal-uk-s3b.zarr' correspond to the Sentinel-3A and Sentinel-3B satellites, respectively.
140 The example of how to access .zarr files is given in the Appendix A.

The .zarr file for a particular region contains data for several tracks, organized as a data cube with dimensions $M \times N$, where M is the number of tracks in the region and N is the length of the longest track. Tracks shorter than N are padded with NaN values.

The metadata contains information on the start and end times of the entire dataset and its spatial extent. The EarthCODE Data
145   Engineering team has performed the data processing and transformation of the original dataset. The following license: CC-BY-
SA-4.0 has been assigned to the entire collection. The dataset in its current format and version can be discovered, shared and
cited via the following link: https://doi.org/10.57780/ESA-1AB8CF3 (Ponce de Léon et al., 2026).

4   Example of the Data Application

To illustrate wave power density measurements, first, the along-track average was calculated from Sentinel-3A/B data; second,
150   the local time series of wave power density was derived from Cryosat-2 data.

4.1   Along-track average wave power density

Sentinel-3A/B's revisit time is 27 days, that allows us to estimate the along-track average wave power density. It is assumed
that the location of the track is repeated; however, there is a small displacement in satellite movement. Let us call the planned
location of the repeated altimeter track the "trajectory". First, the tracks belonging to the same trajectory are grouped. In each
155   group of tracks, one reference track is selected. The coordinates of the altimeter resolution elements for this track are used as
the coordinates for the resulting average wave power density. The data from the other tracks in the group are resampled to the
coordinates of the reference track, and the average wave power density is then calculated.

The along-track average wave power density based on the Sentinel-3A/B data is shown in Figure 3 for all 11 regions. These
data can be interpolated and may undergo binning and smoothing. However, the along-track product contains high-resolution
160   measurements, which are essential in the coastal zone.

4.2   Wave power density time series locally

Based on the obtained dataset, the time series for the selected locations can be studied. Around the selected location, the
altimeter data are collected within the circle with the radius of 40 km, cleared of outliers and averaged. As an example, we
present the time series for the location situated offshore of São Miguel Island in the Azores archipelago. The time series for this
165   location, derived from 11 years of CryoSat-2 data, is shown in Figure 4. For comparison, the time series for the same location
is presented for ERA5 data.

Both altimeter and ERA5 datasets exhibit pronounced seasonal variability, with elevated WPD values during winter and
reduced energy levels during summer months, reflecting the dominant influence of North Atlantic swell and winter storm
activity in the region. The satellite-derived WPD closely follows the ERA5 observations.
170   Other potential uses of the present dataset may include seasonal variability analysis for the selected locations, as well as
correlation analysis with other geophysical parameters. The present dataset is a valuable source of information for validating
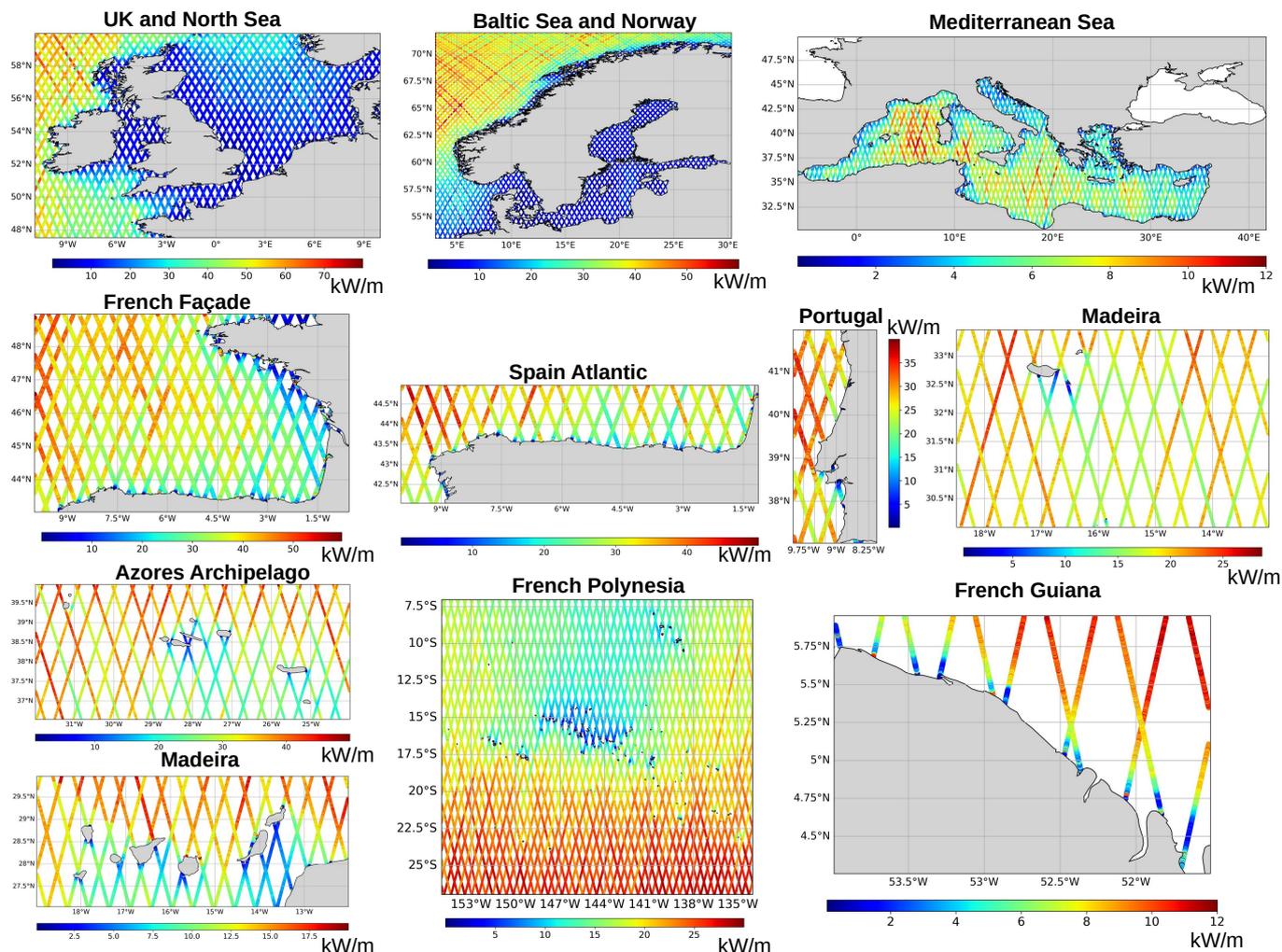numerical wave model results.

Figure 3. Along-track average wave power density for 11 regions based on Sentinel-3A/B data.

5 Conclusion

This study presents the WAPOSAL wave dataset, a high-resolution, multi-region collection of significant wave height, wave pe-
riod, and wave power density derived from SAR altimetry observations from the Sentinel-3A/B and CryoSat-2 missions across
11 regions in continental coastal zones and around archipelagos. Significant wave height was derived using the SAMOSA+
retracking algorithm. The zero-crossing wave period was estimated using an empirical method based on in situ measurements.

Comprehensive validation against in situ buoy measurements and ERA5 reanalysis data shows strong agreement for both
significant wave height and zero-crossing wave period, supporting the methodology's robustness and the reliability of the
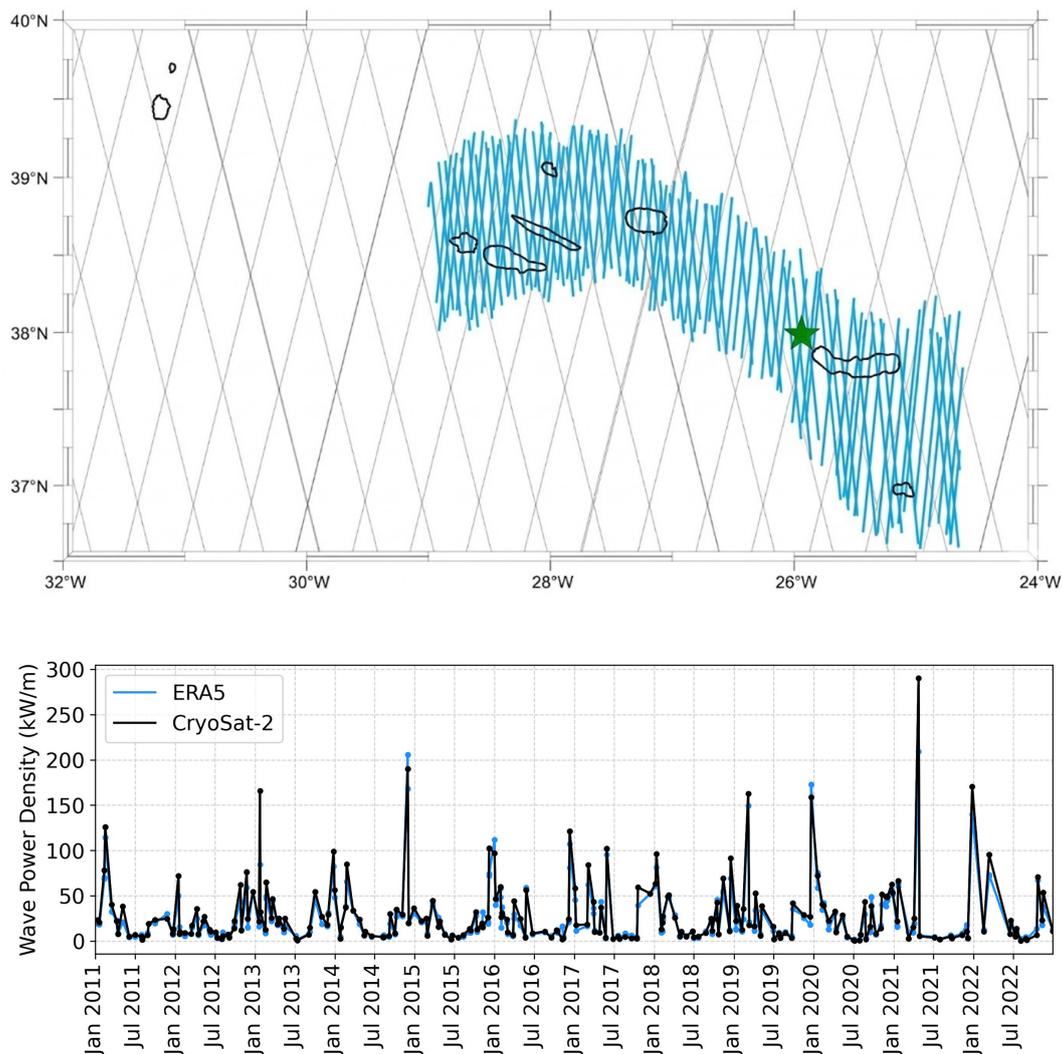
Figure 4. CryoSat-2 (blue) and Sentinel-3A/B (black) tracks in the Azores region for 2011. The time series location marked by an asterisk (top); Comparison of the wave power density-derived time series from ERA5 and CryoSat-2 (bottom).

180   derived wave power density estimates. The high along-track spatial resolution (300 m) and extended temporal coverage enable detailed analyses of coastal and nearshore wave energy resources.

The dataset is openly available in standardized formats on the ESA EarthCode repository, enabling integration across a wide range of applications. By providing a validated, satellite-based wave power dataset, the WAPOSAL collection supports the Earth system science and marine renewable energy communities in sustainable ocean management and energy planning.

Appendix A

Zarr is a cloud-optimized format for multidimensional scientific data, which eliminates the need for manual download of individual data files. It allows users to specify a zarr reader to a root zarr store and specify analysis parameters so that only the data for the targeted region or time frame is automatically retrieved in an efficient manner. The URL to the .zarr files are available by clicking "copy URL".

As an example, the dataset can be accessed and loaded in Python using the following code:

```
import xarray as xr
data_url = "https://s3.waw4-1.cloudferro.com/EarthCODE/OSCAssets/waposal/AZ-CS2.zarr"
ds = xr.open_zarr(data_url, decode_times=False) # This dataset requires Zarr version 2
```

Using gdal command line tools:

```
gdalinfo 'ZARR:/vsicurl/https://s3.waw4-1.cloudferro.com/
EarthCODE/OSCAssets/waposal/AZ-CS2.zarr'
```

Code and Data Availability

The dataset is published by ESA and hosted at the EarthCode Data Repository platform as the ESA Open Science Catalogue WAPOSAL collection (https://opensciencedata.esa.int/products/waposal-waves/collection). The dataset in its current format and version can be discovered, shared and cited via the following link: https://doi.org/10.57780/ESA-1AB8CF3 (Ponce de Léon et al., 2026).

Author Contributions

SPL: Methodology, Software, Supervision, Resources, Lead of the WAPOSAL project, Writing – review and editing. MP: Data curation, Software, Validation, Visualization, Writing – original draft. AO: Data curation, Software, Validation, Visualization, Writing – original draft. MR: Supervision, Writing – review and editing. RS: Supervision, Writing – review and editing. JB: Supervision, Writing – review and editing.

Competing Interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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