“Wave Energy Potential in the Mediterranean Sea: Insights from High-Resolution Satellite Altimetry and In-Situ Data”.

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WAPOSAL

Wave-**P**ower-**S**atellite-**A**ltimetry

Centre for Marine Technology and Ocean Engineering

Challenges and facts

Lack of wave data

Lack of studies considering different climatic scenarios needed for the WEC design

High cost of maintaining WECs

Lack of studies focusing on the resource variability (a cost driver)

Power matrices are based on old sea surface elevation statistics (*Nolan et al 2007; Mérigaud, A., & Ringwood, J. V. 2018*)

The wave period is changing in the North Atlantic, affecting the WEC design (*Uliaza et al 2023*)

Besides, wave energy is a more persistent and reliable resource than wind or solar encompassing Europe and America (*Bhattacharya et al, 2021; Pennock et al., 2022*)

WAPOSAL objective

The main goal is to build a database of wave power density along coastal areas using high-resolution altimetry data from the OCRE-EO database, available in the Altimetry Virtual Lab.

The project aims to develop an innovative digital tool that uses Earth observation data to create a state-of-the-art database of wave renewable energy in coastal areas.

Project W A P O S A L (Wave Power Satellite Altimetry), European Space Agency CfP/6-60008
ESA Co. 4000144113/24/I-DT-bgh Kick-Off: 1st July 2024, duration 15 months

Outcomes

- Mapping the distribution of the wave energy resource can support post-analysis of locations with optimal wave power density, which can be exploited to convert clean energy from ocean waves into electric power.
- Provide the ideal coastal locations for the installation of WECs.

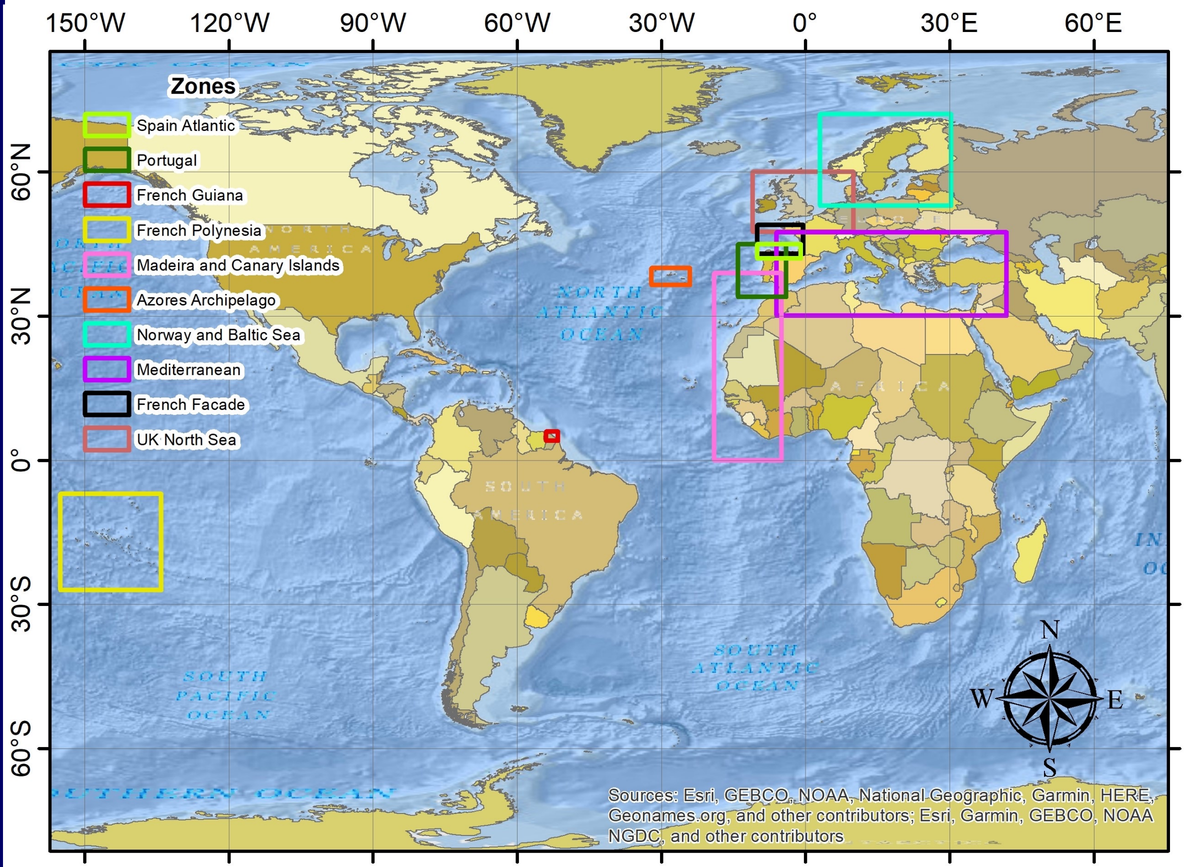
Previous work:

Ponce de León, S.; Restano, M.; Benveniste, J. 2024. Assessing the Wave Power Density in the Atlantic French Façade from High-Resolution CryoSat-2 SAR Altimetry Data. Energy, ELSEVIER, 131712, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2024.131712

Ponce de León S., J.H. Bettencourt, J. V. Ringwood, J. Benveniste. 2024. Assessment of combined wind and wave energy in European coastal waters using satellite altimetry. Applied Ocean Research, Volume 152,104184, ISSN 0141-1187, https://doi.org/10.1016/j.apor.2024.104184

Ponce de León, S.; Restano, M.; Benveniste, J. 2023. Assessment of Wave Power Density Using Sea State Climate Change Initiative Database in the French Façade. J. Mar. Sci. Eng. 2023,11,1970. https://doi.org/ 10.3390/jmse11101970

WAPOSAL regions & Data



https://avl-repo.earthconsole.eu/sarvatore/CENTEC_OCRE/

High-Resolution OCRE-EO data 2022-2023: European Commission HORIZON2020 Open Clouds for Research Environment (OCRE) Earth Observation (EO) call

Distributed by Earth Console

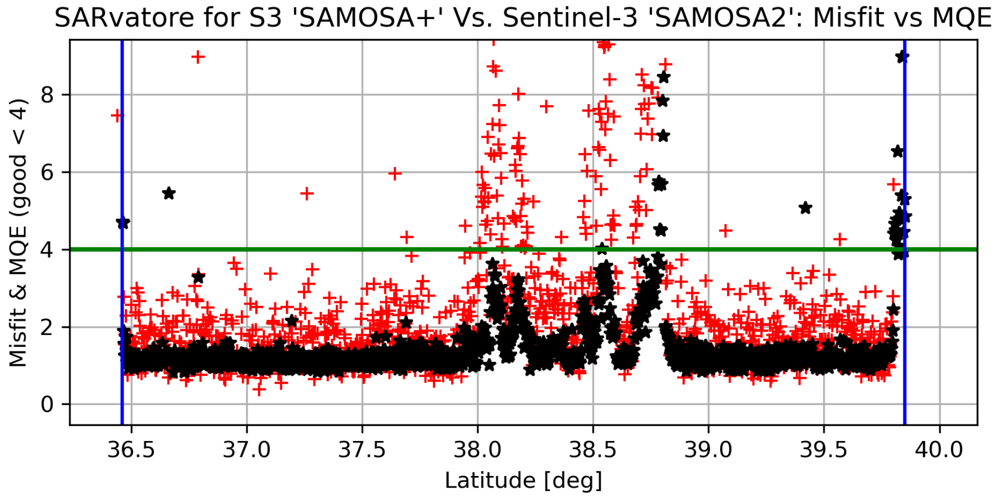
The total number of wave buoys used is 124, comprising 82 real wave buoys and 42 ERA5 virtual stations.

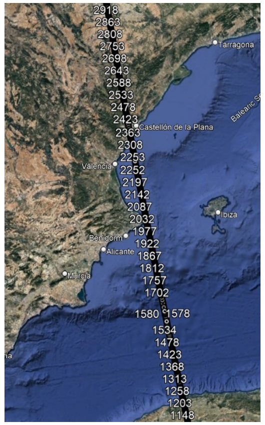
This data was used to perform the collocation between CryoSat-2, Sentinel-3 A/B, and the wave buoys.

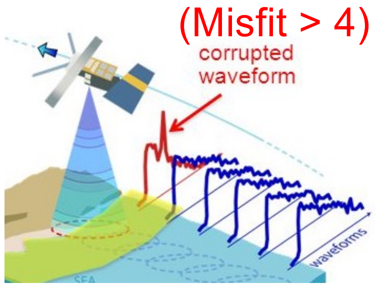
High-resolution altimetry products

The Unfocused SAR high-resolution processing (Raney 1998) provides data at a posting rate of 20 Hz (i.e 300 m between two estimates in the along-track direction).

Estimating the wave power density every 300 m has many advantages, considering that wave energy conversion machines operate and will be installed in the coastal zone.





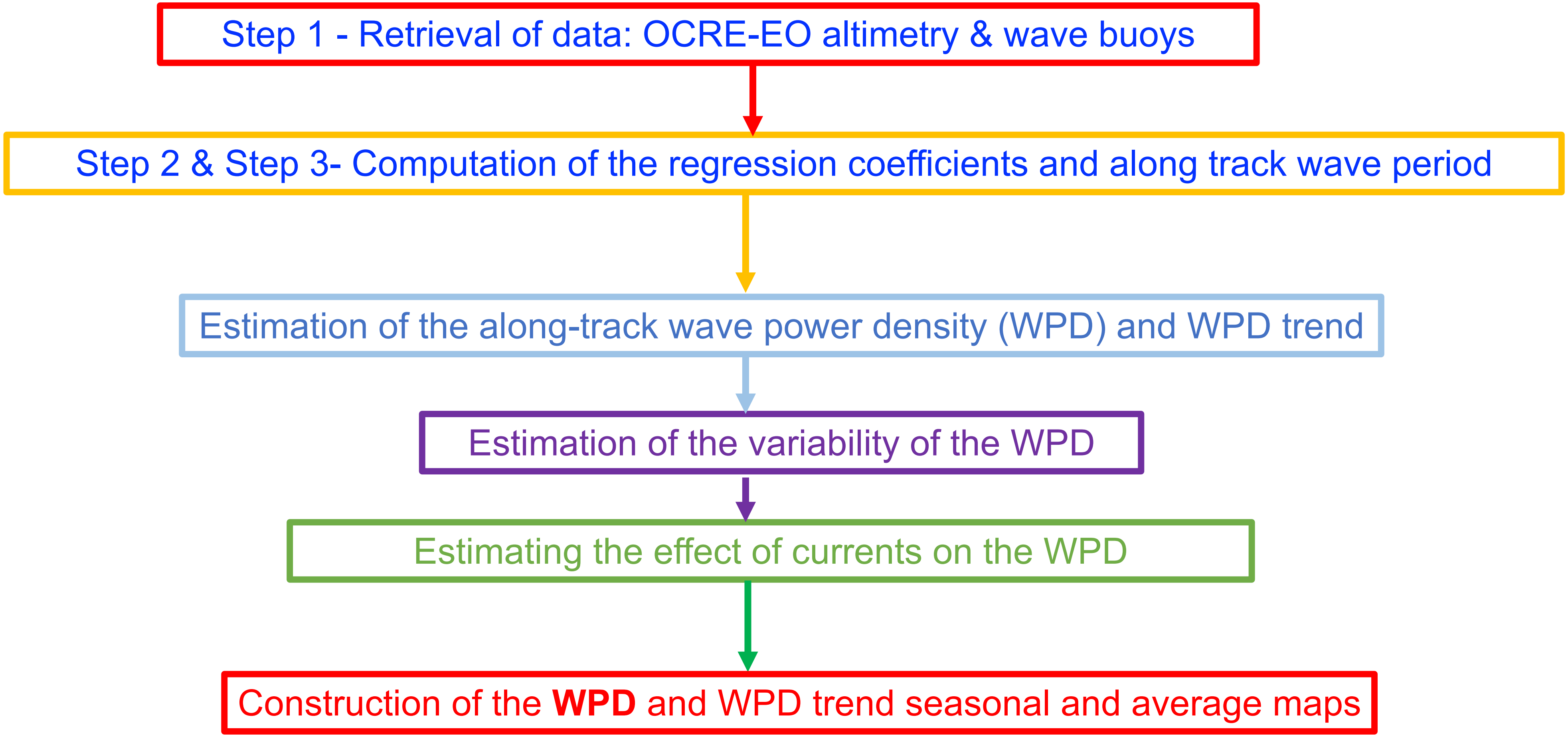


Courtesy: Dr Marco Restano & Dr Jérôme Benveniste

The misfit parameter measures the mean squared error between the waveform and the model, providing an indication of the quality of the estimates.

A misfit < 4 indicates reliable estimates (Dinardo et al., 2018). The value is higher in the presence of islands or when approaching the coastal zone

Flow Chart of the Scientific/Technical steps



Methods

The wave power P_{wave} can be computed using the expression (Mackay 2012):

$$P_{wave} = \frac{\rho g^2}{64\pi} T_e H_s^2 \qquad \text{(W/m)} \qquad (1)$$

In (1), $\boldsymbol{\rho}$ is sea water density (1025 kg/m^3), $\boldsymbol{g}$ is the acceleration of gravity (9.81 m/s^2),

H_s is the significant wave height (m) (the mean of the 1/3 highest waves)

T_e is energy period, defined by m(-1)/m(0).

T_e can be derived from the zero-crossing period T_z , as T_e = 1.18 * T_z

P_{wave} (units of Watts per meter of wave crest)

Mackay, E. B. L. Resource assessment for wave energy. In Ali Sayigh, editor, Comprehensive Renewable Energy, page 11–77 (Elsevier, Oxford, 2012). https://doi.org/10.1016/B978-0-08-087872-0.00803-9

The model of Gommenginger et al., (2003)

Using altimetry data, we have Hs directly from the altimeter, but not the wave period, so we apply a linear method to estimate Tz from the altimeter Hs and σ^0.

Gommenginger et al (2003), proposed a simple linear relationship between the variable $X=(\sigma^0\, Hs^2)^{0.25}$ and T_z:

$$T_z = a * X + b \qquad (a \text{ and } b \text{ to be computed})$$

σ^0-radar backscatter coefficient

The coefficients *a* and *b*, are computed from values of *X* derived from the altimeter measurements and T_z values from wave buoys.

To obtain the (X, Tz) pairs, the altimeter and buoy measurements must be collocated.

The wave energy period can be derived from zero-crossing period Tz as:

$$Te = 1.18\ Tz$$

Table 1. Error statistics resulting from the collocation of Sentinel-3AB and CryoSat-2 data for the Hs and Tz at the locations of the wave buoys in the Mediterranean Sea.

Mediterranean (period: 2011-2022) Sentinel-3AB & SAMOSA+

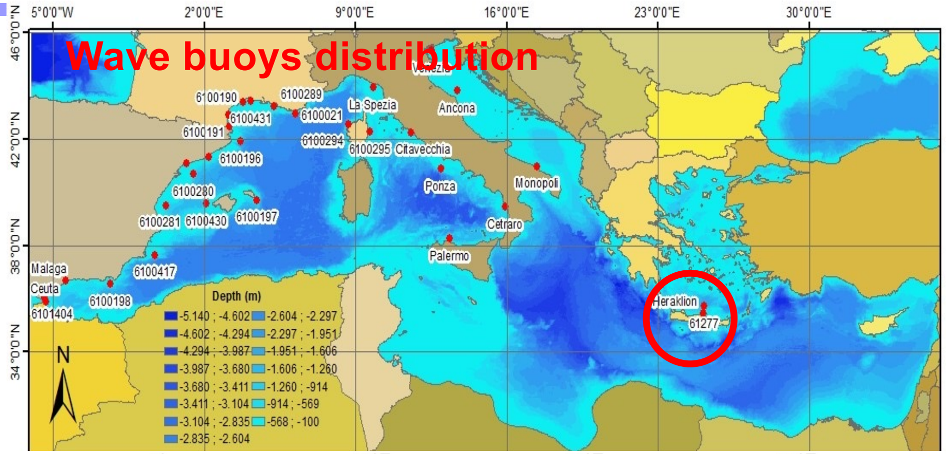
Wave Buoys	Regression Coefficients	Wave period Tz wave buoy & satellite fit	Hs wave buoy & satellite fit
61277 Greece	a=1.625 b=0.93392	Scatter Index =0.074; Bias=-0.0008;CC=0.93	Scatter Index =0.123; Bias=0.0016;CC=0.984
6100417 Cabo de Palos	a=1.4858 b=1.1189	Scatter Index =0.124; Bias=0.0012;CC=0.793	Scatter Index =0.177; Bias=0.0166;CC=0.955

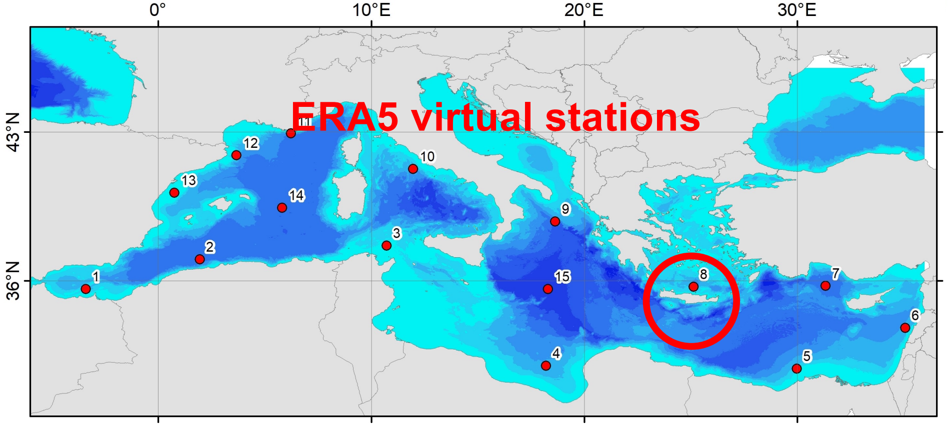
Mediterranean (period: 2011-2022) CryoSat-2 & SAMOSA+

Wave Buoys	Regression Coefficients	Wave period Tz wave buoy & satellite fit	Hs wave buoy & satellite fit
61277 Greece	a=1.2508 b=1.725	Scatter Index =0.09; Bias=0.0162;CC=0.824	Scatter Index =0.142; Bias=0.0498;CC=0.978
6100417 Cabo de Palos	a=1.4347 b=1.1926	Scatter Index =0.1; Bias=0.0005;CC=0.851	Scatter Index =0.168; Bias=0.046;CC=0.962

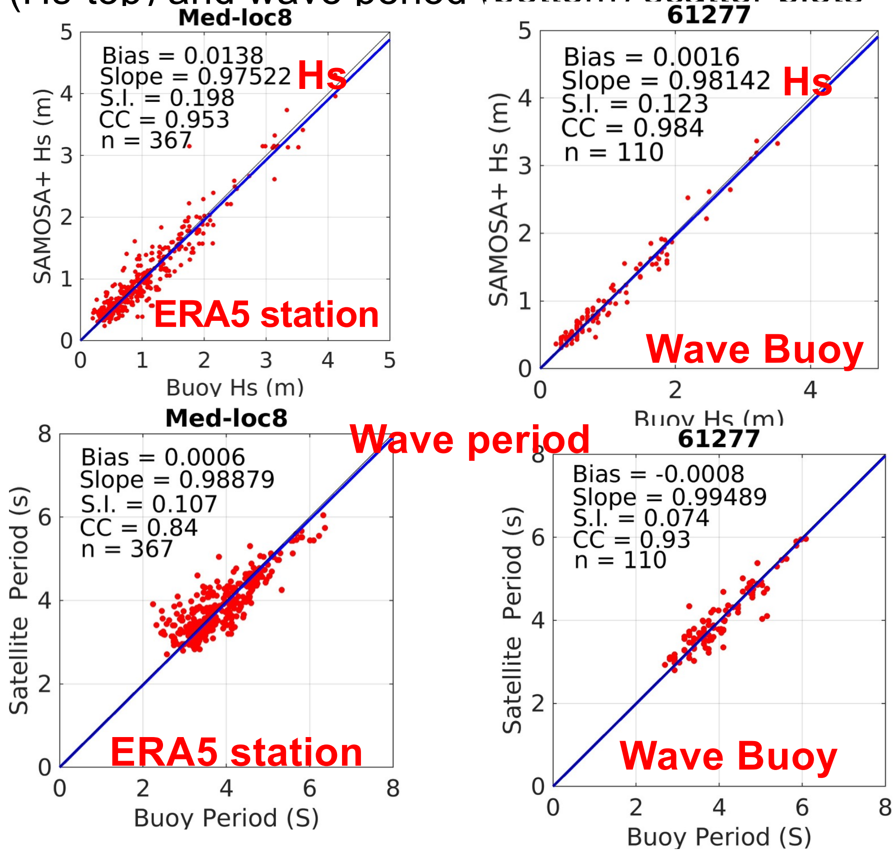
Mediterranean Sea – WAPOSAL results

Mediterranean Sea





Wave buoy and Sentinel-3 significant wave height (Hs-top) and wave period (bottom) scatter plots

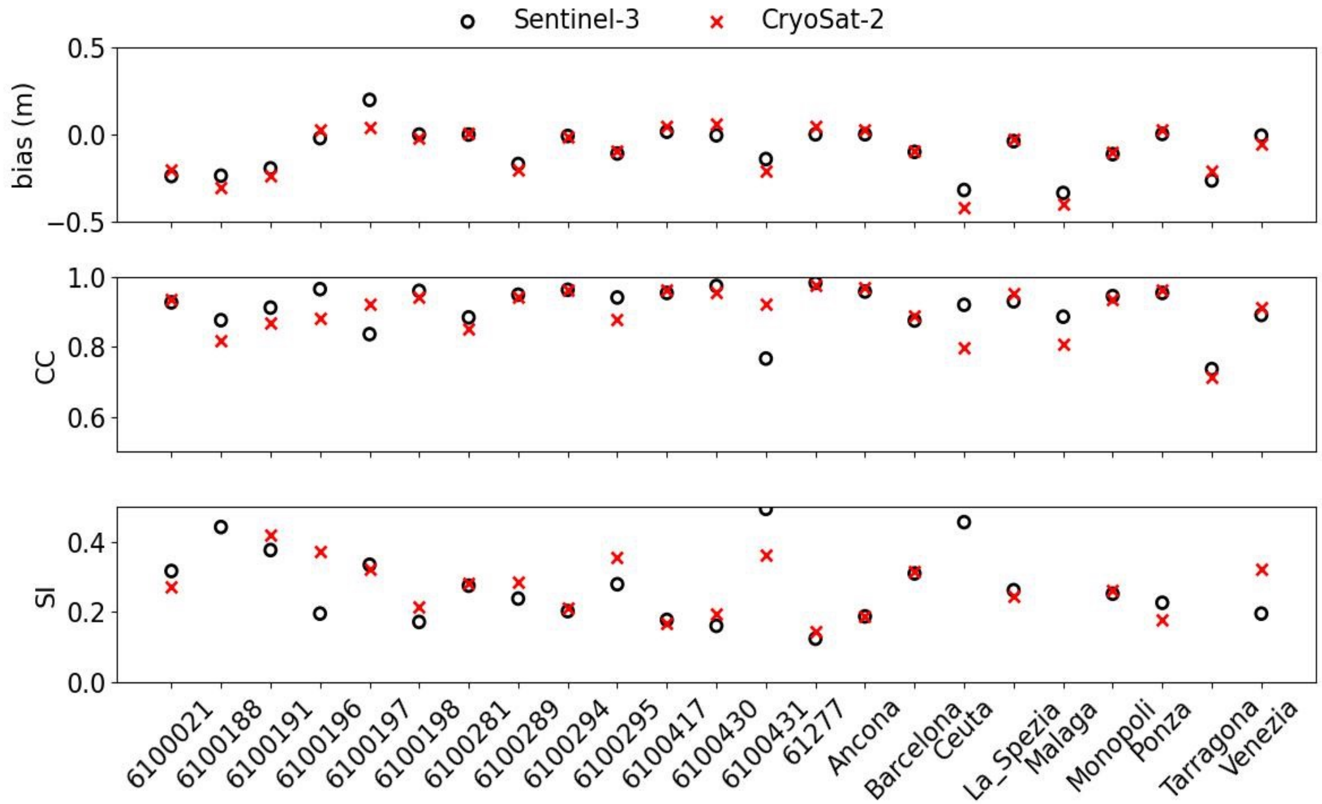


2025 Wave Energy Potential in the Mediterranean: Insights from High-Resolution Satellite Altimetry, In-Situ Data and the ERA5 reanalysis.
Ponce de León S, A. Orejanera, M. Panfilova, M. Restano, J. Benveniste, R. Sabia. PROCEEDINGS OF THE 16TH EUROPEAN WAVE AND TIDAL ENERGY CONFERENCE, 7–11 SEPTEMBER 2025, MADEIRA https://doi.org/10.36688/ewtec-2025-732

CryoSat-2 and Sentinel-3AB altimeters' statistical metrics show similar results

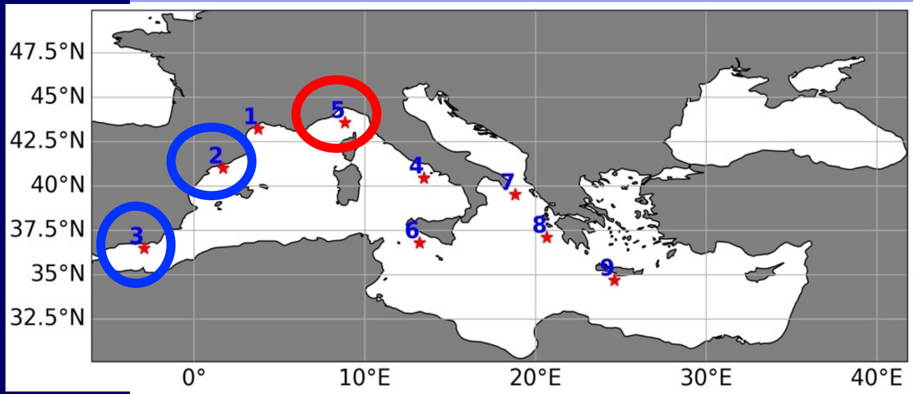
Sentinel-3AB (O)
CryoSat-2 (x)

Mediterranean Sea 2011-2022



Wave Buoys

Variability



Two measures of variability are the COV and the SVI, as described by *Ringwood and Brandle (2015)*. COV is the wave density time series standard deviation σ normalized by the mean wave power density time series P_a:

$$COV=\sigma[P_a(t)]/\langle P_a(t)\rangle$$

The SV can be calculated as:

$$SV=(Pmax-Pmin)/P$$

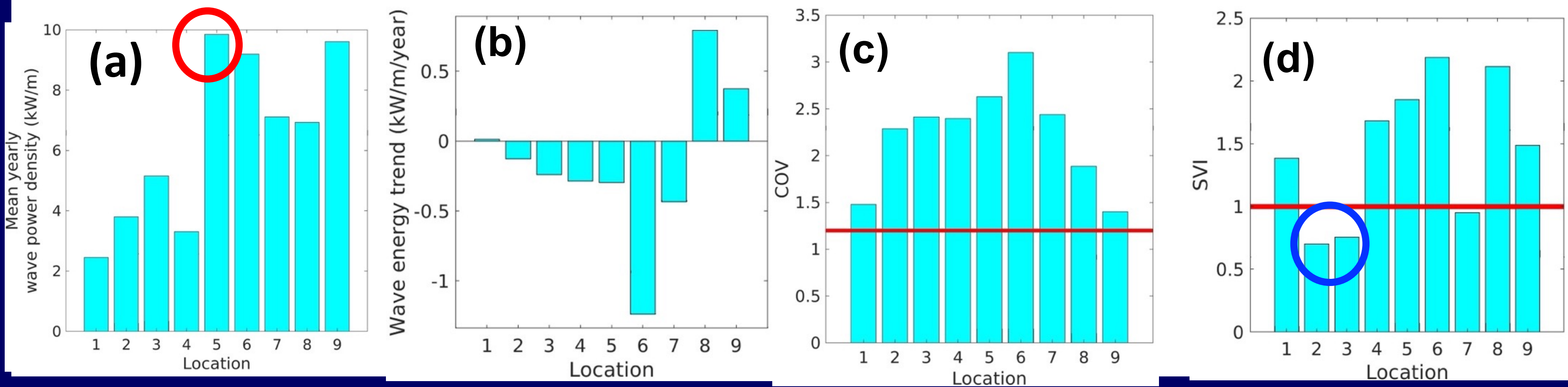
where Pmax and Pmin are the maximum and minimum of the wave or wind power density time series.

(a) Mean yearly wave power density

(b) Wave energy trend

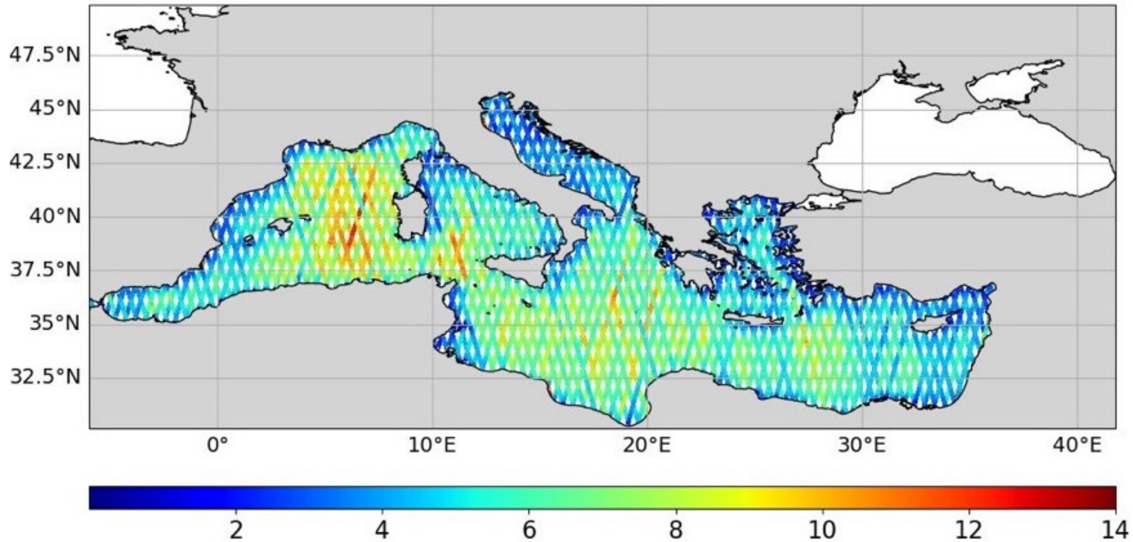
(c) COV- Coefficient of Variability

(d) SVI- Seasonal Variability Index



WAPOSAL reports

WAPOSAL along-track average wave power density (kW/m) Sentinel-3 A/B data 2011-2023



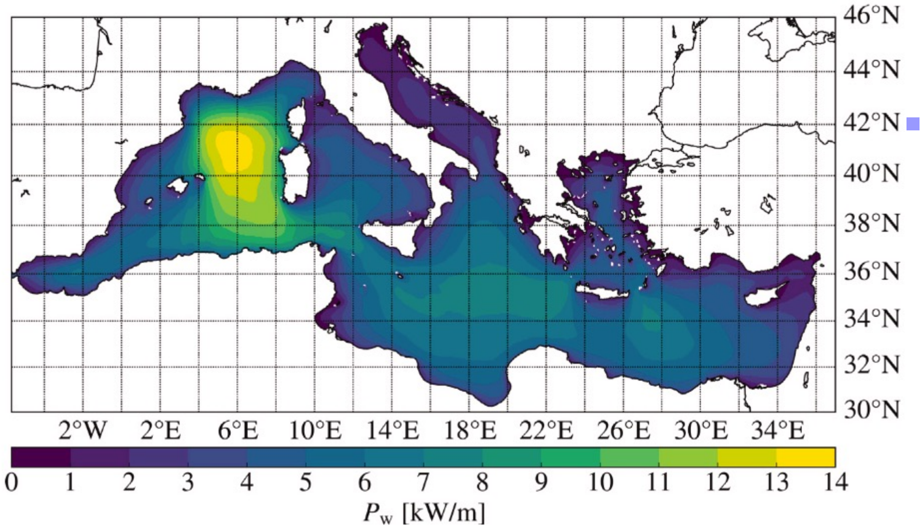
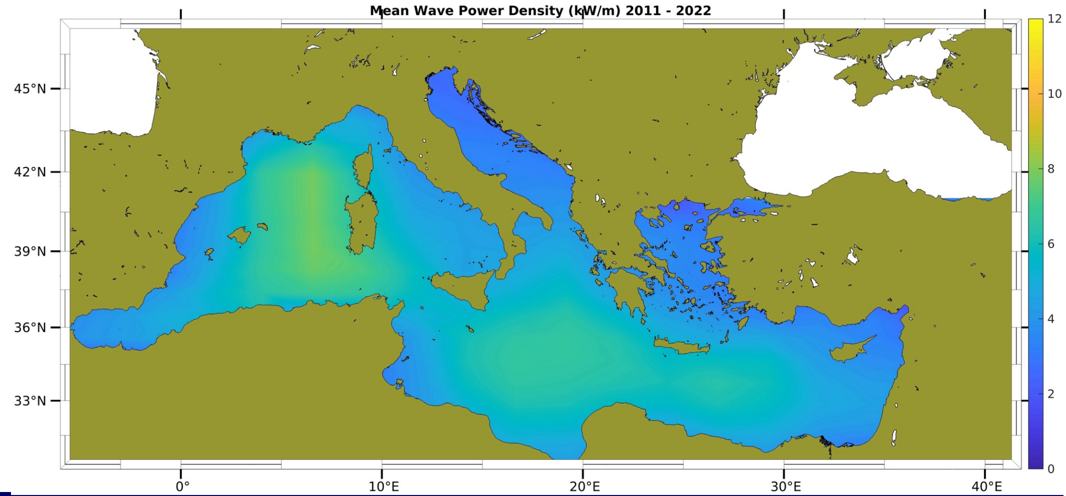


Fig. 6. Mean wave energy flux based on the 30-year long reanalysis.

Oikonomou et al. 2024 (30-year simulations 1993-2022) WAM model

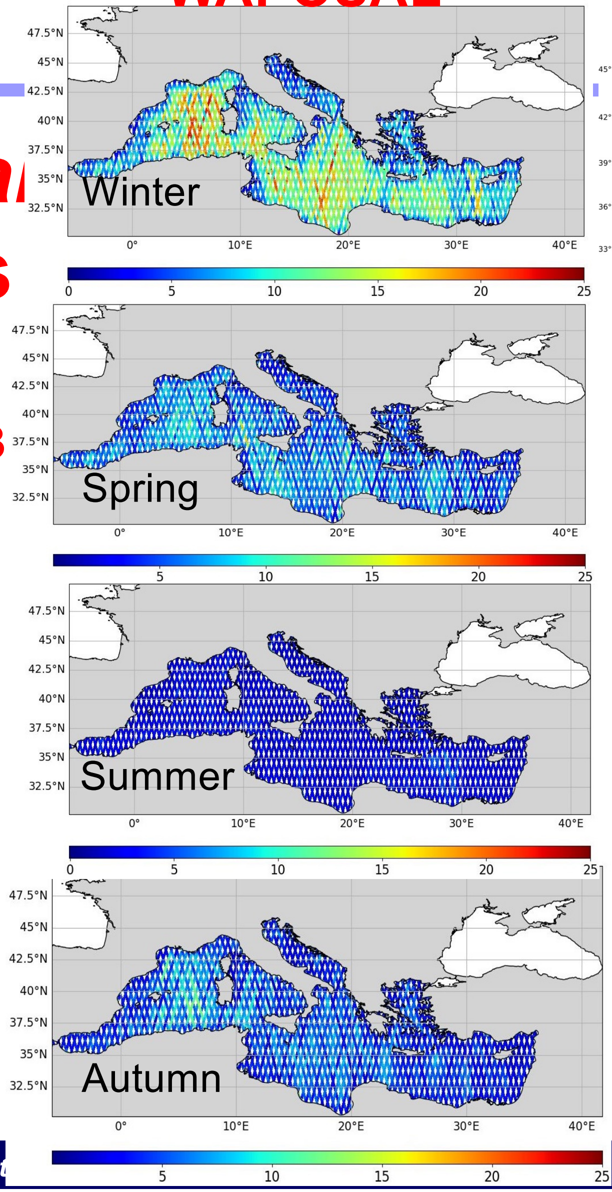
WAPOSAL average map CS2 &S3 A/B - 12 years



Seasonal Analysis

2011-2023

WAPOSAL



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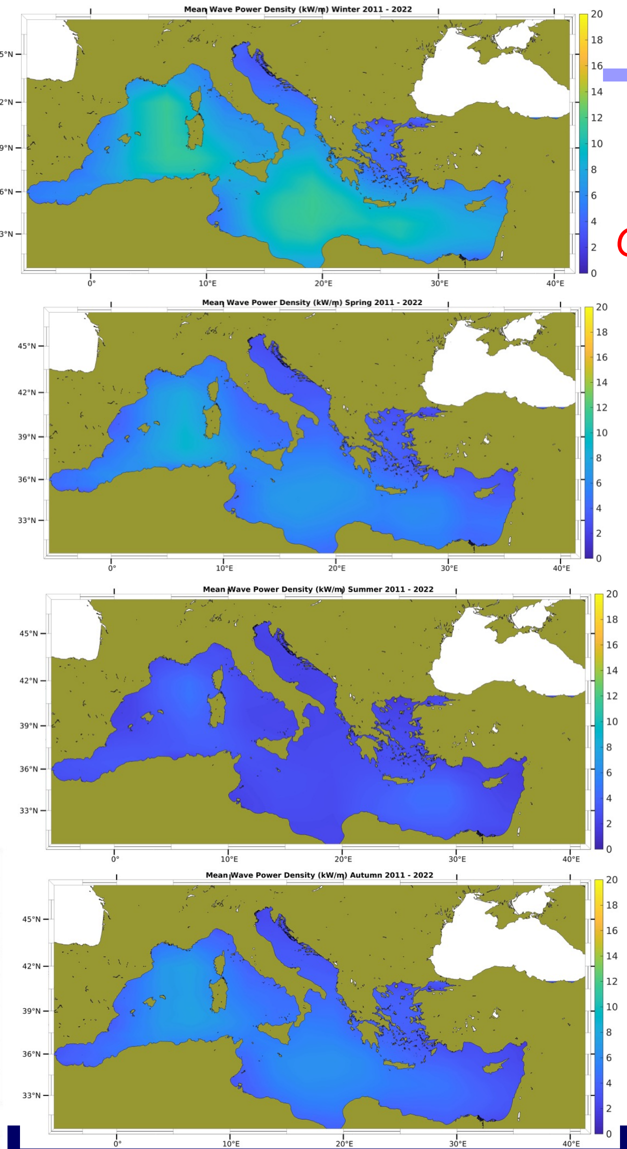
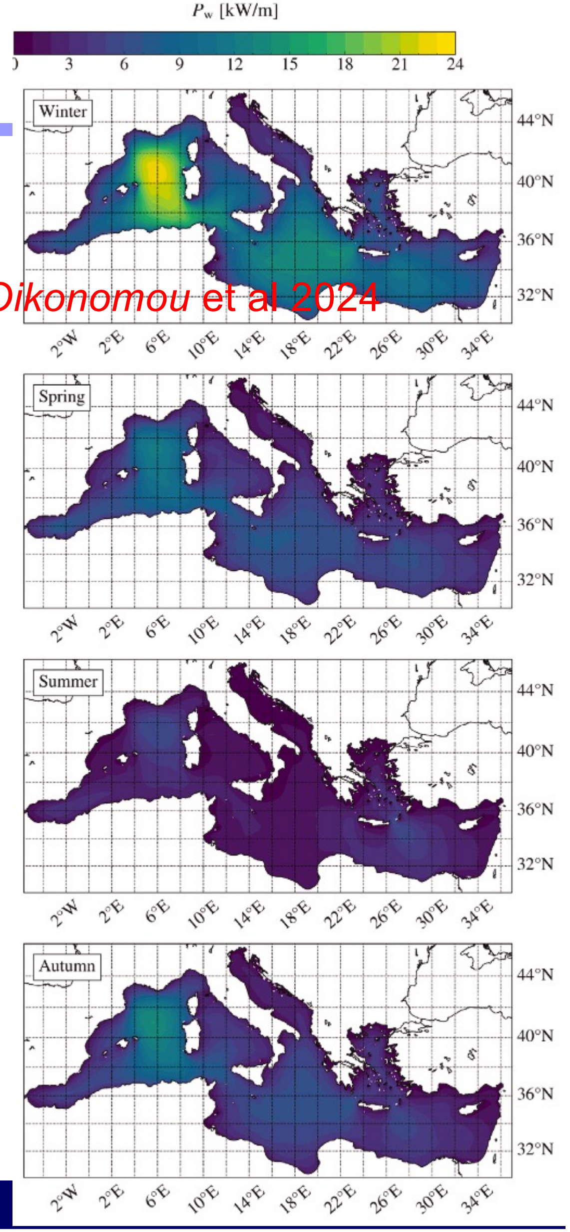
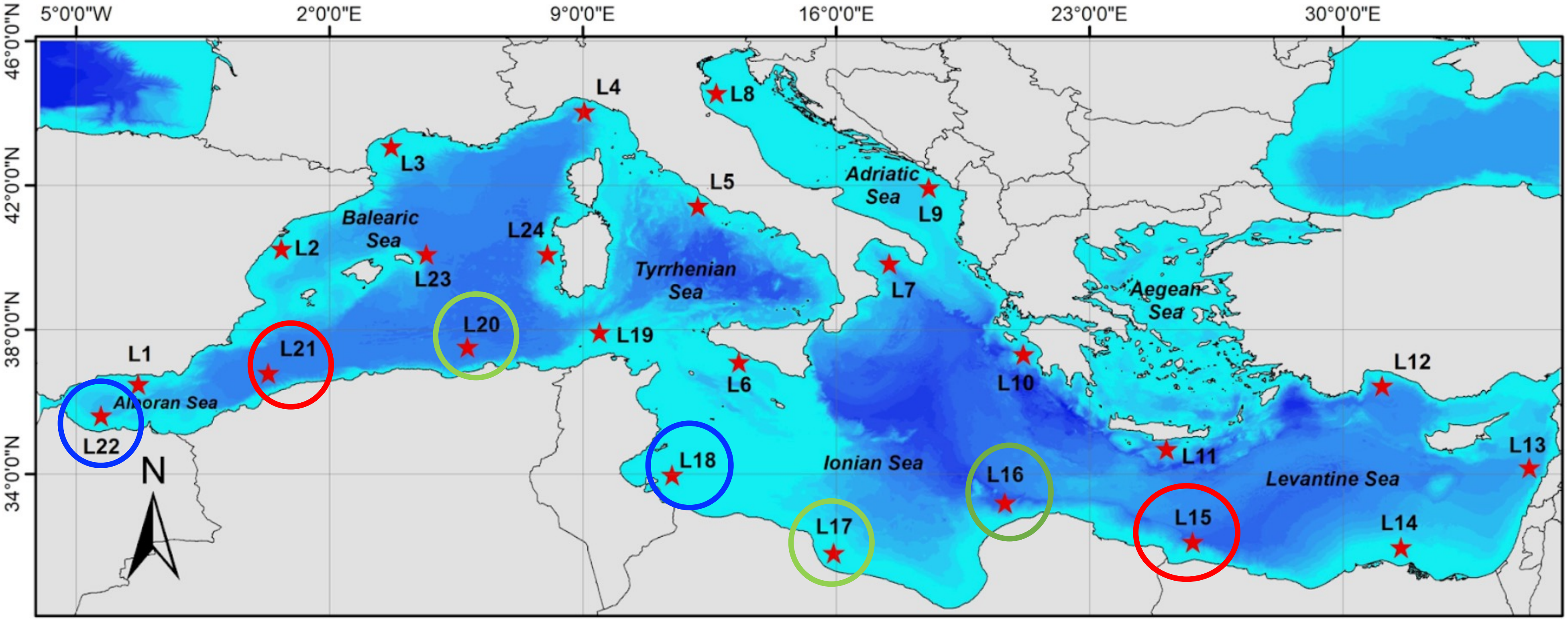


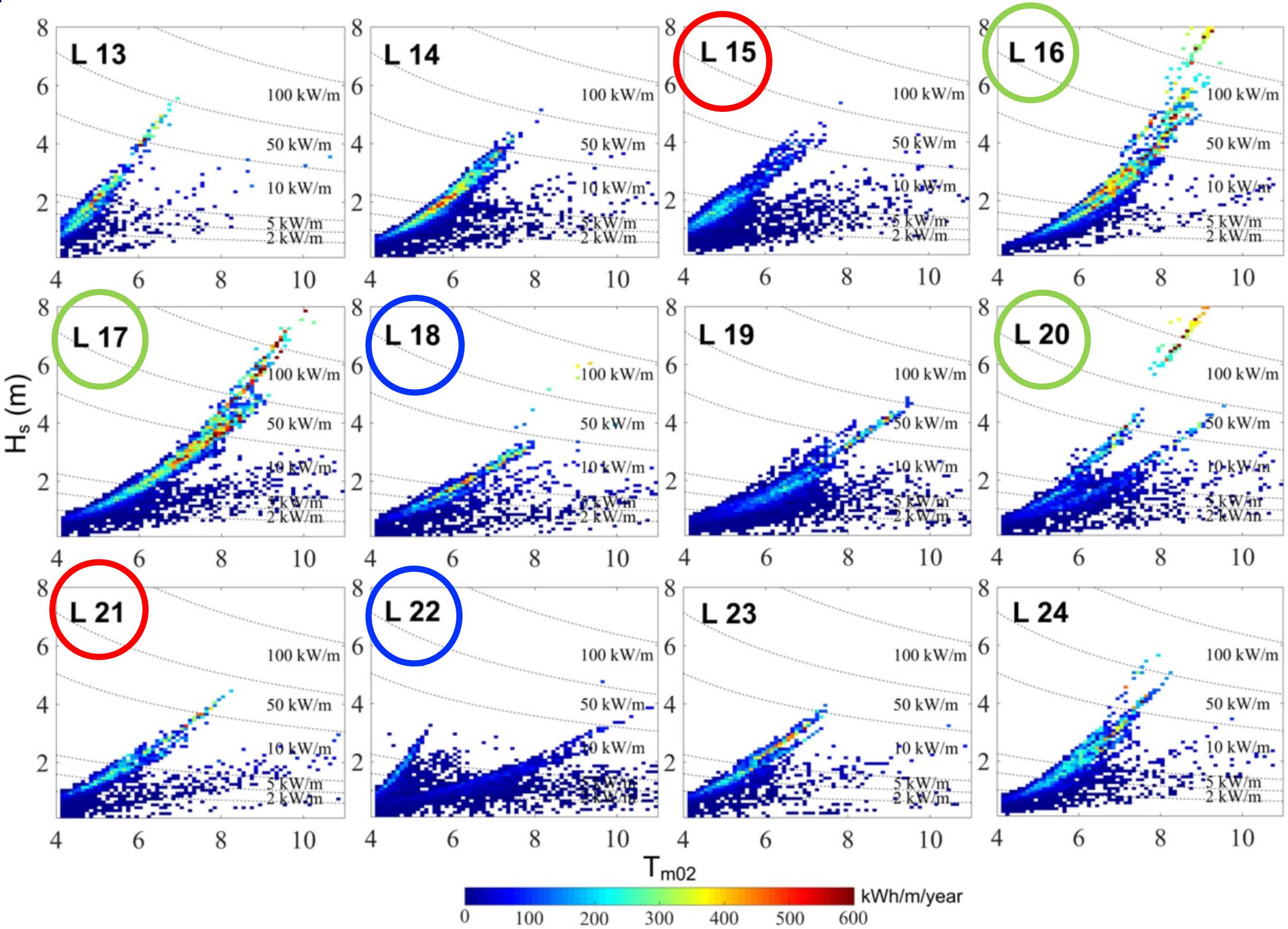


Oikonomou et al 2024

Mediterranean Sea African coasts assessment of wave power using high-resolution altimetry data (CrySat-S2 & Sentinel-3 A/B)



Local distribution of the annual wave energy potential using Sentinel 3AB and Cryosat-2 data

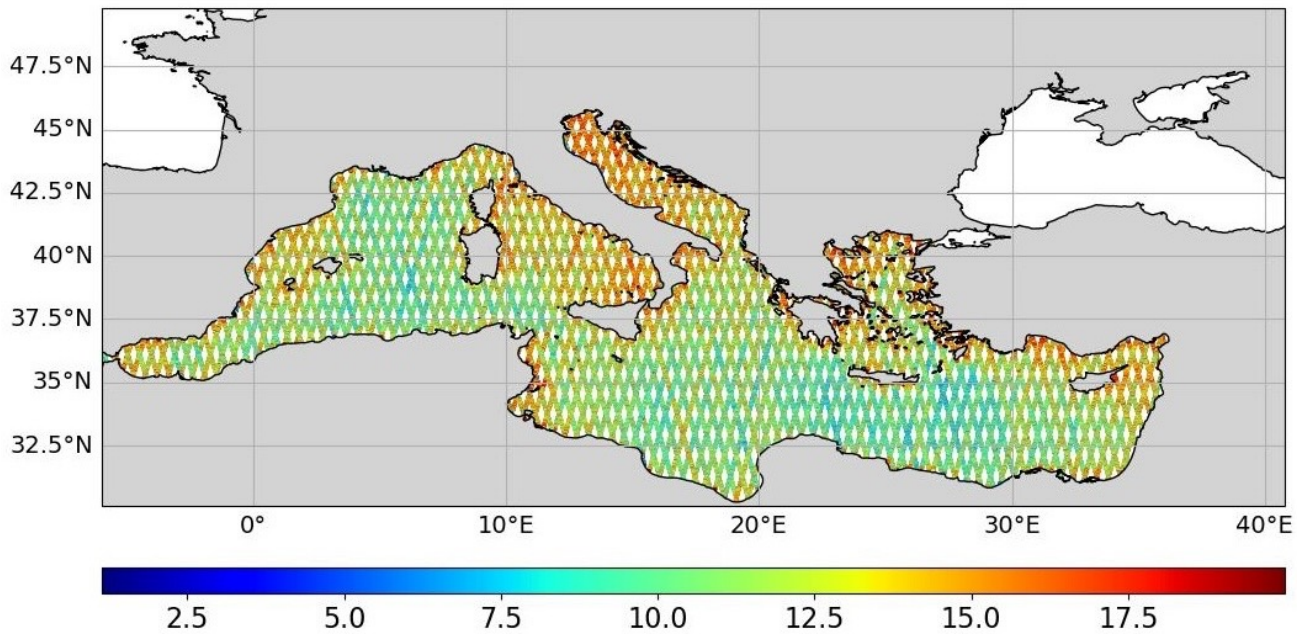


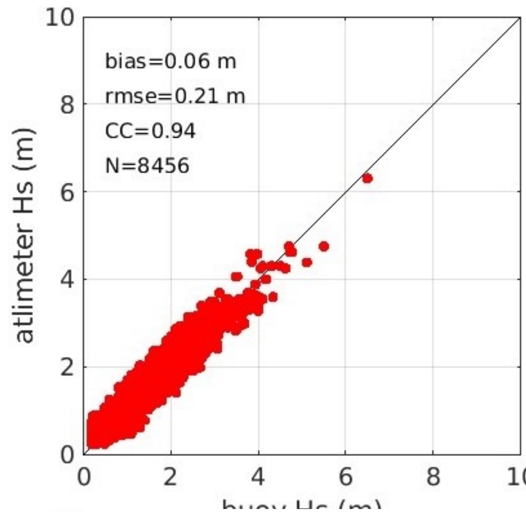
Wave power density in (kW/m) - dashed lines

The color scale represents the annual accumulated wave energy per bin in kWh/m/year.

Green circles-high energy
Blue circles-low
Red circles-

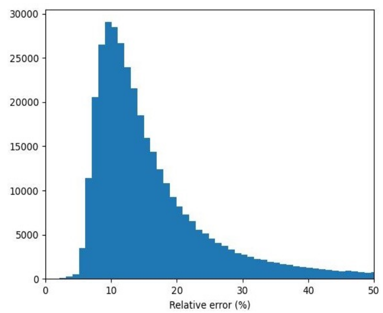
Relative error (%) of Wave Power Density Sentinel-3 A/B

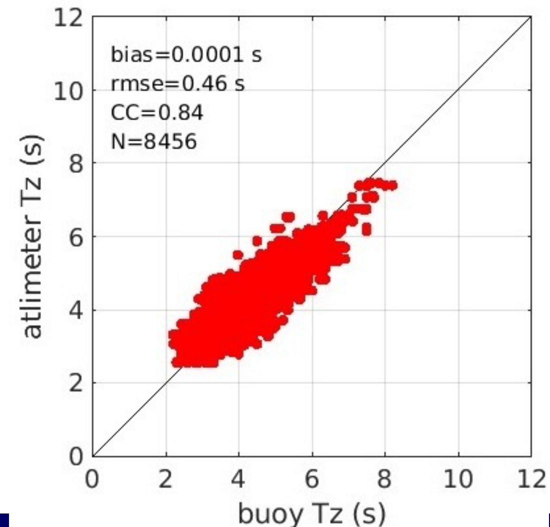




2% - 18.2%

Uncertainty: 12%





https://waposal.tecnico.ulisboa.pt/

Conclusions

- The Gommenginger et al. (2003) method was successfully applied to estimate the along-track wave periods required to determine the wave power density. The method shows a high correlation for both the Hs and the wave period (Tz) not only in the Mediterranean but also in all 11 regions.
- An along-track database was created for the eleven regions of the study. It contains crucial information based on observations that might help to advance the green energy transition.
- The Gommenginger method was tested using wave buoys and ERA5 virtual stations, reporting similar results.
- CryoSat-2 and Sentinel-3AB altimeters' statistical metrics were compared, showing similar results.
- A relationship was identified between ocean currents and wave power density, demonstrating a high correlation under specific environmental conditions.
- The wave power density trend and variability were estimated locally along coasts, indicating that some areas present a more favourable scenario (positive trends and low variability) for ensuring the future extraction of wave resources.
- WAPOSAL identified the best locations for installing WECs near the coast.

Acknowledgements

This research was funded by the European Space Agency Open Call (FUTURE EO-1 SEGMENT 2 OPEN CALL FOR PROPOSAL FOR EO INNOVATION) contract ESA Co. 4000144113/24/I-DT-bgh given for the WAPOSAL Project.

Thank you for your attention!

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