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Wave energy in the Mediterranean

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Theoretical background

Evaluation of wave energy flux for real sea states

- Real sea states are not composed of deterministic simple harmonic waves
- Different propagation directions, lengths and frequencies
- Stochasticity should be also included

According to Pierson and Longuet-Higgins model, the sea surface elevation is described as a stationary, ergodic and Gaussian stochastic process

$$\eta(t;\beta)=\sum_{i=1}^{N} A_i \cos(\omega_i t+\phi_i(\beta)),$$

where $\eta(t;\beta)$ denotes the sea surface elevation, A_i, ω_i, and ϕ_i are the amplitude, frequency and phase of the harmonic component i, respectively. ϕ is a random variable uniformly distributed in $[0,2\pi]$. Sea state parameters can be derived by using the wave power spectral density function $S(f)$, where f is the frequency.

Use is made of specific spectral parameters, such as: the significant wave height H_S, the mean energy period T_e, the spectral peak wave period T_P. The wave power per unit wave-crest length for a real sea state is estimated as follows:

$$P=\frac{\rho g^2}{64\pi}H_S^2 T_e,$$

where ρ is the sea water density (1025 kg/m^3) and the significant wave height and the energy period are defined through the zeroth and negative first – order spectral moments, i.e.:

$$H_S=4\sqrt{m_0}, \qquad T_e=\frac{m_0}{m_{-1}},$$

where

$$m_n=\int_0^{2\pi}\int_0^{\infty} f^n S(f,\theta)\,df\,d\theta,\ n=\cdots,-1,0,1,2\ldots$$

Wave Data

Wave reanalysis data

- Med – WAV, Copernicus Marine Service
- 1993 – 2020, with a temporal resolution 1-h
- Spatial resolution 1/24° x 1/24° ~3.65 km

In – situ wave measurements

- Greek Seas: POSEIDON marine monitoring network (3-h)
- Spanish Seas: Spanish Port Authority (1-h)

Evaluation of the reanalysis wave data

Collocate the reanalysis dataset with the buoy data in space and time based on the four nearest grid points, applying the inverse distance weighting interpolation function:

$$Hs_R=\frac{\sum_{i=1}^{4}\frac{Hs_{Ri}}{d_i^2}}{\sum_{i=1}^{4}\frac{1}{d_i^2}},\ i=1,2,3,4,$$

where, $Hs_{Ri}, i=1,2,3,4$ is the significant wave height in the 4 nearest (to the buoy location) grid points and $d_i, i=1,2,3,4$, are the corresponding distances from the buoy location.

- Compare the significant wave heights H_{SR} from reanalysis dataset and H_{SB} from the buoys
- Evaluation parameters : mean relative absolute error ($MRAE$), mean absolute error (MAE), $Bias$, root mean square error ($RMSE$) and Pearson correlation coefficient (ρ).

Numerical results

Evaluation of the reanalysis dataset

Greek Seas

- Best performance of the model in Pylos: $MRAE$ =0.180, MAE=0.168 m, $bias$=0.080 m, $RMSE$=0.237 m, ρ = 0.959
- Good performance in Athos: $MRAE$ (0.290), MAE (0.170 m), $bias$ (0.064 m), $RMSE$ (0.239 m), correlation coefficient (0.953).
- Lower performance in Santorini: $MRAE$ (0.290), MAE (0.231 m), $bias$ (0.161 m), $RMSE$ (0.3189 m), correlation coefficient (0.913).

Spanish Seas

- The model was effective at different examined locations: $MRAE$ ~ 0.18, MAE ~ 0.18 m $bias$ -0.064 m - 0.049 m, $RMSE$ 0.226 m - 0.289 m (the overall highest in Begur).

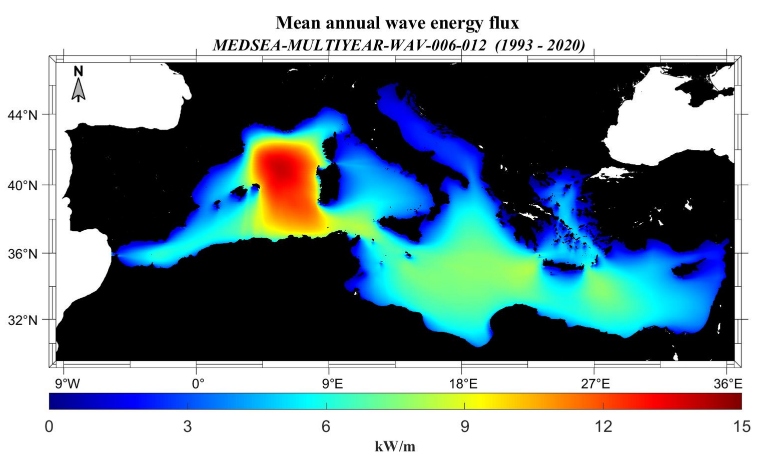
Locations with high wave power

Criteria: 1) high values of mean annual wave power density;
2) low seasonal variability; 3) a relative shallow water depth (maximum depth of 100 m) combined with a short distance from the coast

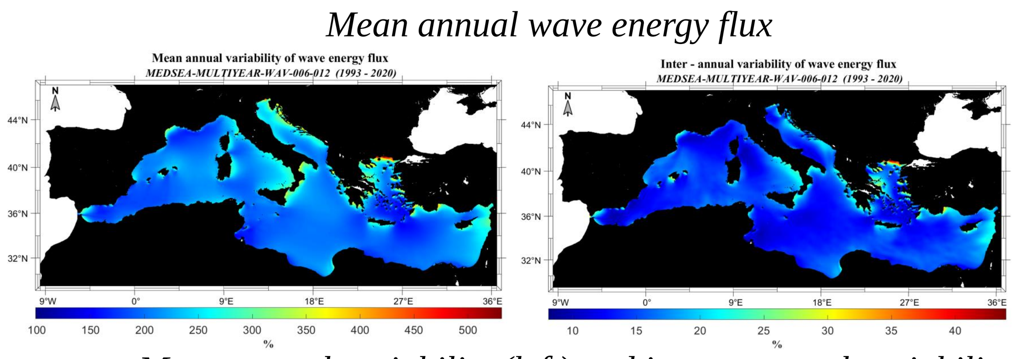
Potential locations for WEC development

Location	Mean values of wave power (kW/m) AN	W	SP	SU	A	Prevailing directions
Menorca	9.31	15	8	5	10	0°-15°
Alghero	11.03	18	10	5	11	295°-315°
Annaba	7.75	14	6	3	8	300°-345°

Wave energy flux – annual scale



Mean annual wave energy flux

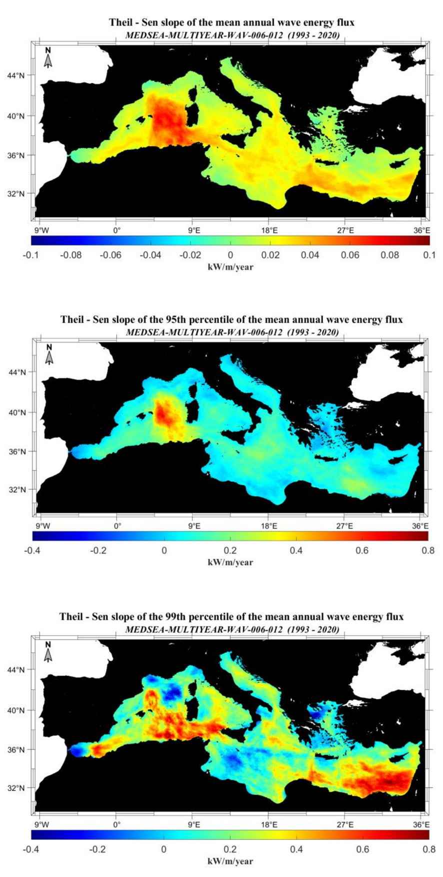


Mean annual variability (left) and inter – annual variability (right)

Annual Slopes

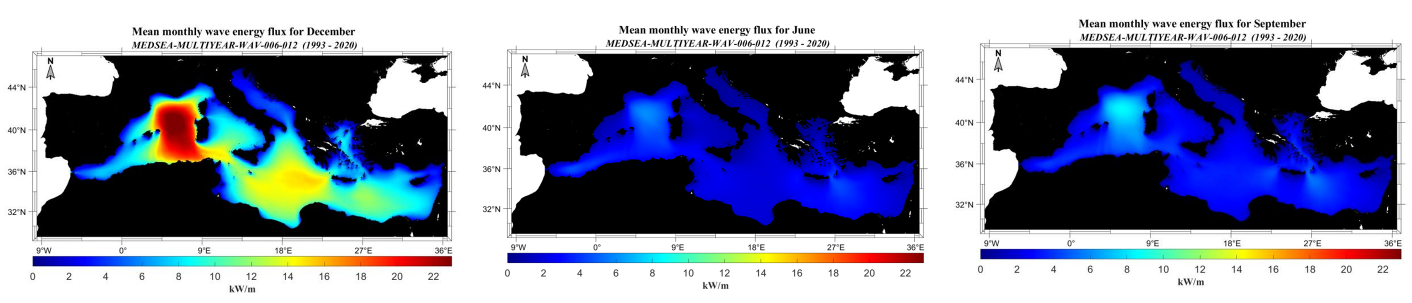
Increasing trend:
~ 0.07 kW/m/year, Gulf of Lyon, Sardinia Isl. and the coasts of Algeria.

Increasing trend for the extremes:
~ 0.2 kW/m/year, Several areas of the Mediterranean Sea (especially at the SE part of the basin).



Slopes of the mean annual wave energy flux (upper), the 95 (middle) and the 99 (lower) annual percentiles

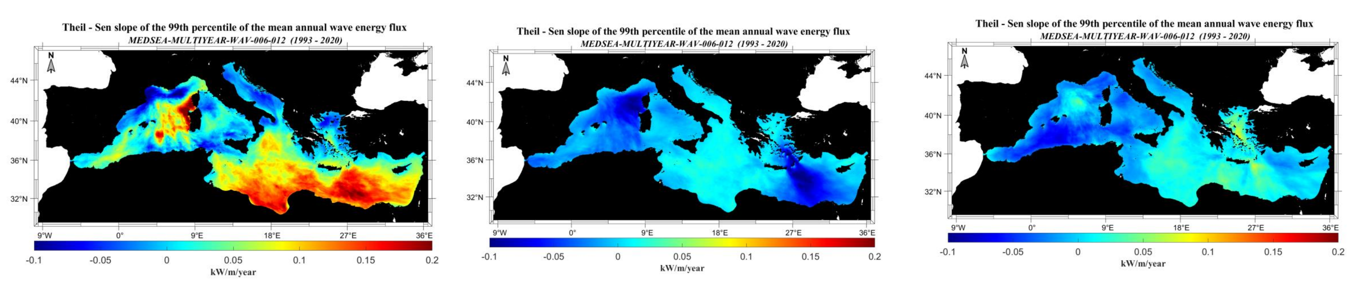
Wave energy flux – monthly scale



Mean monthly wave energy flux for December (left), June (middle), and September (right)

- **The highest values have been observed during winter**: ~ 22 kW/m, at the Gulf of Lyon and African coasts
- **The lowest values have been observed during June**: ~ 17 kW/m, only in the above-mentioned area and in the strait between Crete and Karpathos Isl. in the Aegean Sea

Monthly slopes



Slope of the mean monthly wave energy flux for December (left), June (middle) and September (right).

- **June:** Slightly increasing trend (~0.05 kW/m/year for the central Mediterranean Sea), decreasing (for the western and south eastern Mediterranean Sea).
- **September:** Increasing trend in the Aegean Sea (~0.07 kW/m/year) and a decreasing trend in western Mediterranean Sea.
- **December:** Important increasing trend ~ 0.25 kW/m/year W. coasts of Sardinia Isl. and offshore areas between Crete Isl. and the coasts of Egypt.

Conclusions

- Local winds significantly affect the wave energy flux in certain areas such as the Gulf of Lyon (Mistral) and the Aegean Sea.
- The highest wave power values have been observed in the area extending from the Gulf of Lyon to SW Sardinia Isl. through the Balearic Sea up to the coasts of Algeria.
- Alghero is characterized by the highest wave resource, while similar seasonal patterns characterize all three areas.
- The variability was generally more pronounced during winter and autumn.
- With new and scaled devices, the three examined areas (Menorca Isl., Alghero and Annaba), could potentially be suitable areas for the installation of WECs.
- The main contribution to the annual mean wave energy flux occurred during winter, reaching values up to 22 kW/m

Selected references

1. Besio, G., L. Mentaschi, and A. Mazzino, Wave energy resource assessment in the Mediterranean Sea on the basis of a 35-year hindcast. Energy, 2016. 94: p. 50-63.
2. Archambeau, P., et al., Sustainable Hydraulics in the Era of Global Change: Proceedings of the 4th IAHR Europe Congress (Liege, Belgium, 27-29 July 2016). 2016.
3. Guillou, N. and G. Chapalain, Annual and seasonal variabilities in the performances of wave energy converters. Energy, 2018. 165: p. 812-823.
4. Kardakaris, K., I. Boufidi, and T. Soukissian, Offshore Wind and Wave Energy Complementarity in the Greek Seas Based on ERA5 Data. Atmosphere, 2021. 12(10).
5. Soukissian, T.H. and F.E. Karathanasi, Joint Modelling of Wave Energy Flux and Wave Direction. Processes, 2021. 9(3): p. 460.
6. Soukissian, T.H., Probabilistic modeling of directional and linear characteristics of wind and sea states. Ocean Engineering, 2014. 91: p. 91-110.
7. Longuet-Higgins, M., On the statistical distribution of the heights of sea waves. Journal of Marine Research, 1952. 11(3): p. 245–266.
8. Pierson, W.J., A unified mathematical theory for the analysis, propagation, and refraction of storm generated ocean surface waves. New York University, College of Engineering, Dept. of Meteorology, 1952.
9. Korres, G., Oikonomou, C., Denaxa, D., & Sotiropoulou, M., Mediterranean Sea Waves Monthly Climatology (CMS Med-Waves, MedWAM3 system) (Version 1), Copernicus Marine Service (CMS), https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_WAV_006_012_CLIM. 2023.
10. Zacharioudaki, A., et al., Mediterranean Production Centre MEDSEA_MULTIYEAR_WAV_006_012, Issue: 2.3, Approval date by the CMEMS product quality coordination team: 22/11/2023. 2023.
11. Soukissian, T.H., et al., Advancement of Operational Oceanography in Greece: The Case of the Poseidon System. Journal of Atmospheric & Ocean Science, 2002. 8(2-3): p. 93-107.