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A 35 year high-resolution wave atlas for nearshore energy production and economics at the Aegean Sea

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A B S T R A C T

The study enhances the coastal resource knowledge and discusses opportunities for wave energy in the Aegean Sea. A fine-resolution numerical wave model is utilised to provide results for the Greek coastal regions. The model ran for 35 years (1980–2014) estimating wave characteristics, and quantifying the wave energy potential in coastal areas. The results deliver the energy potential, variability, and site characterisation for the Aegean Sea.

The dataset is coupled with wave energy converters power matrices to provide for the first time a long-term analysis of expected power production. Performance of devices is highly dependent on matching the power matrix to the local resource, suitable devices can obtain capacity factor up to 20% and favour operation for low wave heights and high frequencies.

Based on energy analysis data, an economic performance and payback period of a hypothetical wave farm is examined. With little information on wave energy in the region, this preliminary cost-to-benefit analysis shows the viability of wave converters. Even with high capital expenditure associated with novel technologies, certain scenarios achieve amortization periods at 7.5 years for a properly selected converter. Results are comparable with previous renewable schemes aimed at increasing the cumulative installation of other early stage technologies.

1. Introduction

The Mediterranean Sea is a semi-enclosed basin with small water boundaries, to the West at the Straits of Gilbratar, North-East a channel connects Northern Aegean with the Marmara Sea, finally at the South-East the Nile river connects the Egyptian Sea with the Suez Gulf and the Red Sea. External wave boundaries are not significant for the Mediterranean Sea, but the high distribution of islands around the Mediterranean increases the difficulties for wave estimates.

Study of the Mediterranean area has been indicated [1] for wave climate analysis and wave energy quantification. The past years studies have been conducted, with some drawbacks on temporal and/or spatial attributes. Spatio-temporal limitations are either focused on either very small areas [2] or encompass a limited duration period of analysis [3–5]. Such studies provided significant improvements in understanding of the regional wave climate, limitations in time duration, scale, and level of resolution are important to note.

To date most long term studies are associated with the Mediterranean Sea, amongst the first in 2004 a consortium of several institutions delivered 10 year Wind-Wave Atlas for the region, based however on a coarse oceanic model [6]. Ratsimandresey et al. [7] used the same coarse oceanic model to provide a 44 years ocean and atmospheric hindcast for the Western part of the Mediterranean. Recent studies by Mentaschi et al. [8] and Ponce de Leon et al. [9] presented Mediterranean wave power potential for 35 and 29 years respectively. The first study focused on Italy [8] and the second in the Balearic Sea [9], both of them using an oceanic model. Majority of studies are based on oceanic models with spatial resolution hindering extrapolation of results to coastal areas, as discussed in Canellas et al. [10]. Usual spatial resolution utilised for numerical wave models in the region are between 0.1^o ($\approx 11 Km$) and 0.04^o ($\approx 4.4 Km$) [3,6–8,11–14].

Concerning the Aegean Sea, most recent long-term and up-to-date wave climate analysis (42 years) is by Zacharioudaki et al. [15], using the oceanic model WAM and assessed the wave climate from 1960 – 2001, with dynamically downscaled winds at 50 km and a spatial resolution of 0.1^o. The outcome assessed wave height

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variations and return periods, after an application of correction factors [15]. Emmanouil et al. [16] used the same oceanic model forced by 3 hourly winds from the SKIRON model, and provided a 10 year hindcast on the wave content of the region (2001–2010). The study utilised spectral discretisation of 25 frequencies and 24 direction, with a spatial resolution of 0.05^o, and assessed several key statistical indices over the domain. Additionally, studies using unstructured meshes offered wave power resource estimates for the Aegean, using a 15 years hindcast [17,18]. Prior to them a wind and wave Atlas 10 years in duration was presented by Soukissian et al. [14] utilising an oceanic model. A summary of studies focused in the Aegean region are presented in Table 1, with information on models used, durations, and outcomes.

For the Aegean majority of studies use oceanic models with coarser resolution, this study aims to contribute and fill in the gap of fine-resolution information on the wave power resource for the Aegean Sea. The finer resolution with tuning of nearshore components, delivers detailed long-term energy estimates and allow to assess the opportunities for wave energy converters.

The temporal length of the datasets allows us to establish a comprehensive database of wave energy and device performance in the Aegean Sea. This is of major importance to decide on energy performance indices and outline the potential benefits for the Greek energy system. Results go further than just a wave climate analysis and contribute to energy assessment of wave converters in the milder waters of the Aegean Sea. The results are quantified per region and technology, allowing estimations concerning wave energy converters and deliver an up-to-date resource and techno-economic assessment.

The study is separated in the following sections, Section 2 presents the datasets, numerical wave model calibration, buoy validation, and comparison with recent studies. Section 3 quantifies and examines the wave resource in the coastal Aegean Sea and site classification. Section 4 presents the energy results obtained and classifies the utilised wave energy converters, according to their performance in the Aegean Sea. Section 4.2 provides preliminary information, concerning payback periods of potential wave energy applications, considering current and past schemes of renewable energy frameworks in Greece. Finally, Section 5 presents a summary of results and discusses future work.

2. Material and methods

2.1. Model set up and areas of investigation

Simulating WAves nearshore (SWAN) is a third generation spectral phased-average model used for wave studies [21]. The wind input is provided by NCEP and the Re-Analysis package of the CFSR dataset with 1-h time intervals [22]. The model used a two way nesting for the Mediterranean and Aegean Seas, with a duration of 35 years from 1980 to 2014 for all domains, see Fig. 1. Buoy and additional selected locations for the Aegean Sea are given in Fig. 2.

The Mediterranean mesh was used to provide boundaries, the coarse resolution of the domain is 0.1^o. The Aegean Sea mesh used a nested domain and has a spatial resolution of 0.025^o. The resolution in combination with all nearshore source terms activated allows for a better representation of coastal waters, increasing the confidence of results in comparison with oceanic models [23,24].

Direction has been subdivided into 25 intervals and the frequency is discretised in 30 bins, highest wave frequency is set to 28 s, the lowest is 2 s and are distributed logarithmically ($\Delta f = 0.1f$). Selection and range of frequency and directional bins, have a direct effect on computational resources, with an increase in

Table 1
Implementation of Aegean models.

Region	Study	Model	Period (years)	Spatial resolution	Parameters
Aegean	[14]	WAM	10	0.1^{o}x0.1^o	Waves
Aegean	[19]	WAM	1	0.06^{o}x0.06^o	Waves
Aegean	[17]	MIKE21	15	Unstructured	Wave Power
Aegean	[20]	SWAN	1	0.1^{o}x0.1^o & 0.025^{o}x0.025^o	Waves, Wave Power
Aegean	[15]	WAM	42	0.1^{o}x0.1^o	Waves, Extremes
Aegean	[18]	MIKE21	15	Unstructured	Wave Power
Aegean	[16]	WAM	10	0.05^{o}x0.05^o	Waves, Wave Power

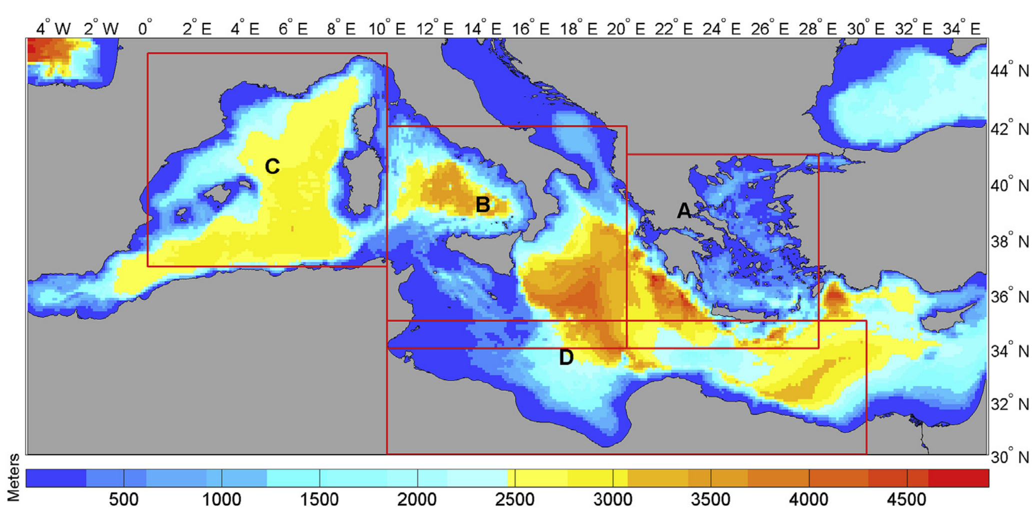

Fig. 1. Initial domain utilised and subsequent nestings, A: Aegean Sea B: Tyrrhenian Sea, West Ionian, C: Balearic Sea, D: Libyan Sea (colorbar depth in meters).