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Improving the assessment of wave energy resources by means of coupled wave-ocean numerical modeling

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ABSTRACT

Sea waves energy represents a renewable and sustainable energy resource, that nevertheless needs to be further investigated to make it more cost-effective and economically appealing. A key step in the process of Wave Energy Converters (WEC) deployment is the energy resource assessment at a sea site either measured or obtained through numerical model analysis. In these kind of studies, some approximations are often introduced, especially in the early stages of the process, viz. waves are assumed propagating in deep waters without underneath ocean currents. These aspects are discussed and evaluated in the Adriatic Sea and its northern part (Gulf of Venice) using locally observed and modeled wave data. In particular, to account for a "state of the art" treatment of the Wave–Current Interaction (WCI) we have implemented the Simulating WAves Nearshore (SWAN) model and the Regional Ocean Modeling System (ROMS), fully coupled within the Coupled Ocean Atmosphere Wave Sediment Transport (COAWST) system. COAWST has been applied to a computational grid covering the whole Adriatic Sea and off-line nested to a high-resolution grid in the Gulf of Venice. A 15-year long wave data set collected at the oceanographic tower "Acqua Alta", located approximately 15 km off the Venice coast, has also been analyzed with the dual purpose of providing a reference to the model estimates and to locally assess the wave energy resource. By using COAWST, we have quantified for the first time to our best knowledge the importance of the WCI effect on wave power estimation. This can vary up to 30% neglecting the current effect. Results also suggest the Gulf of Venice as a suitable testing site for WECs, since it is characterized by periods of calm (optimal for safe installation and maintenance) alternating with severe storms, whose wave energy potentials are comparable to those ordinarily encountered in the energy production sites.

1. Introduction

In a context of oil fields depletion and environmental care, community interest on renewable and sustainable energy resources is growing year by year. Marine energy, i.e. derived from wind, tides and waves, is considered as one of the most promising energy resources. Hence, many efforts are being globally invested in the research. The development of standards and protocols for the deployment of marine energy devices is one of the targets of the EU projects ORECCA (Off-shore Renewable Energy Conversion platforms – Coordination Action [1]), MARINA (Marine Renewable Integrated Application Platform [2]) and EquiMar (Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact [3]).

Wind waves spanning the world seas represent a strategic power source, globally estimated to be 2.11 TW [4]. Indeed, several Wave Energy Converters (WEC) have been designed and tested [5] to make wave energy also an economically appealing resource. An accurate assessment of the potential energy that can be extracted from wind waves in a particular site of interest remains a crucial step in the deployment process of a "wave energy farm" [6,7]. Estimated wave energy potentials have been collected in atlases and databases. WorldWave Atlas [8] provides worldwide average wave power data while WERAtlas [9] covers the North-Eastern Atlantic Ocean, the North Sea, the Norwegian Sea, the Barents Sea and the Mediterranean Sea. However, the accuracy of the wave power characterization may be affected by several aspects, that have been recently remarked in the context of the EU project EquiMar [3]. Firstly, when assessments are based on wave time

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series, measured or modeled, these should be long enough to be representative of the wave climate at the chosen sea site. A minimum duration of 10 years should be advisable, to catch the interannual variability of the resource. Secondly, wave power is a depth-dependent quantity, hence an accurate evaluation should consider the actual relative water depth (d/L, being d water depth and L wavelength). A deep waters approximation could be used only in the early stages of the deployment process, unless the WEC is indeed positioned in deep waters. Then, wave power fields obtained from numerical models should result from a complete modeling of the phenomena involved in the wave evolution and affecting it, e.g. accounting also for Wave–Current Interactions (WCI). EquiMar protocols recommend ocean currents modeling if their velocity is greater than 2–3% of the local group velocity of the dominant waves (e.g. for an 8 s period deep-waters wave, current must be taken into account if greater than 0.2 m/s). Finally, regarding model grid a spatial resolution of 1.0–5.0 km, increased in case of wave-current modeling (<0.5 km), is recommended. If bathymetry data availability and computational resources allow it, 0.2 km is the spatial resolution advised.

All these aspects are here discussed performing wave energy assessments from both high-resolution numerical modeling and wave measurements. The test field chosen is the northern Adriatic Sea (Fig. 1), where the average wave power was estimated in the order of 2–3 kW/m [10,11], less than other seas characterized by stronger wave climates, e.g. the eastern Atlantic Ocean (50 kW/m of average wave power), deeply investigated from Ireland down to Spain, since the 1980s [12]. On the contrary, the whole Mediterranean basin has been less studied until now with the needed accuracy. However, Mediterranean wave energy potentials can be easily obtained by consulting the ORECCA WebGIS (map.rse-web.it/orecca/map.phtml), collecting WorldWave Atlas and WERAtlas databases in the Mediterranean Sea. The average wave power there can exceed 10 kW/m, as other authors showed [11,13].

We have assessed the energy resource in the northern Adriatic Sea, in particular in the Gulf of Venice, using numerical data computed coupling the Simulating WAves Nearshore model (SWAN [14]) and the Regional Ocean Modeling System (ROMS [15]) on the same computational grid, within the COAWST modeling system [16,17]. A 1-year long simulation (September, 2010–August, 2011) has been run on the whole Adriatic Sea, with a 2.0 km spatial resolution, and nested in the Gulf of Venice to a 0.5 km computational grid over the winter season (January–March, 2011). We have performed coupled (waves and currents) and uncoupled (only waves) COAWST runs, to quantify for the first time the WCI effect on wave power estimation. Recently some authors [18–21] have highlighted the relevance of using high spatial resolution wind inputs to correctly reproduce the circulation patterns in the Adriatic Sea, especially those generated by Bora wind. Following these suggestions the atmospheric forcing was provided by the high-resolution (7.0 km) COSMO-I7 model [22]. This aspect was also stressed to be fundamental in order to estimate the wave energy distribution in the Adriatic Sea [11], and filling this gap is one of the purposes of the present work.

We also characterized the northern Adriatic Sea wave energy potential using 15 years (1996–2011) of wave observations, gathered at ISMAR-CNR oceanographic tower "Acqua Alta" (Fig. 1). Besides the purpose of a long-term evaluation from measured data, we have used this data set as the benchmark for comparing the numerical model estimate and check the improvement obtained in wave energy assessment by including WCI modeling. "Acqua Alta" tower data set has been also used to investigate the effect of using a depth-dependent wave power formulation rather than a deep-waters formula.

The paper is structured as follows. Section 2 describes theoretical, numerical and experimental tools used for the wave power assessments. Section 3 contains the energy resource characterization over the northern Adriatic Sea through numerical modeling and oceanographic tower "Acqua Alta" wave data set. Discussions on the improvements of energy resource assessment are herein included. Final considerations, in Section 4, complete the paper.

2. Theoretical, numerical and experimental tools

2.1. Wave power calculation

In random seas, the flux of wave energy, i.e. the wave power $\boldsymbol{P}$, is a vector quantity defined as [12]:

$$\boldsymbol{P}=\iint \boldsymbol{c_g}(\sigma,d)E(\sigma,\theta)\mathrm{d}\sigma\mathrm{d}\theta=\rho g\iint \boldsymbol{c_g}(\sigma,d)S(\sigma,\theta)\mathrm{d}\sigma\mathrm{d}\theta \quad (1)$$

where σ, θ, and d are the intrinsic wave frequency, direction of wave propagation and water depth respectively, and $\boldsymbol{c_g}(\sigma, d)$ is the wave group celerity vector. In Eq. (1) ρ is the water density in kg/m^3, and g is the gravitational acceleration. $E(\sigma, \theta)$ and $S(\sigma, \theta)$, the energy and variance directional spectra respectively, can be provided by directional wave measurements or numerical spectral wave models. Alternatively to Eq. (1), equations based on bulk spectral parameters, i.e. significant wave height H_{m0} (m), and mean wave period T_m (s), can be used to estimate $\boldsymbol{P}$. To this end, Eq. (1) is rewritten assuming a constant group celerity, corresponding to the spectral average frequency σ_m:

$$\boldsymbol{P}\simeq\boldsymbol{c_g}(\sigma_m,d)\rho g\iint S(\sigma,\theta)\mathrm{d}\sigma\mathrm{d}\theta = \boldsymbol{c_g}(\sigma_m,d)\overline{E} = \boldsymbol{c_{g,m}}\overline{E} \quad (2)$$

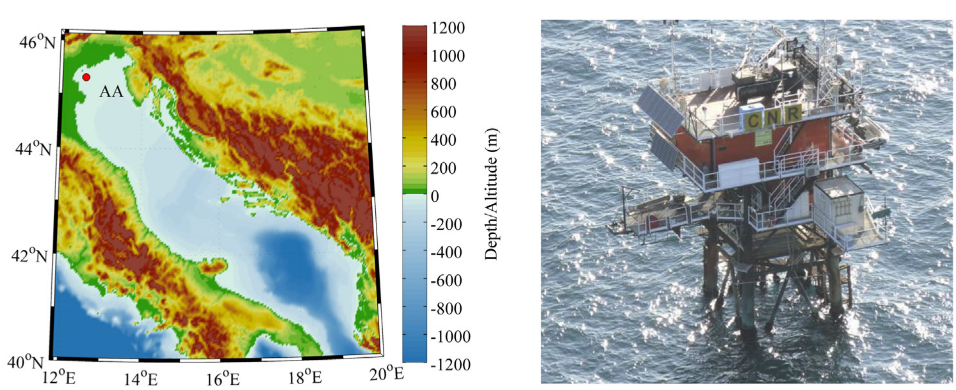

Fig. 1. Left: Adriatic Sea bathymetry and surrounding orography. Right: ISMAR-CNR oceanographic tower "Acqua Alta" (AA, in left panel).