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Evaluation of the wave energy resources in the Cape Verde Islands

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ABSTRACT

The Cape Verde Islands form an archipelago off the African coast in the Atlantic Ocean. Since it is highly dependent on fossil fuels, Cape Verde decision makers have started to take into account also the potential of renewable energies, especially wind and solar. In particular, wind power has already 26 MW installed. From this perspective, the present work aims to be a first step in the evaluation of a different source of renewable energy, the wave energy. Using reanalysis data from ECMWF, the SWAN model was run for a 10-year period, covering the time interval 2004–2013, using a methodology already implemented in other island environments. Moreover, three years of this high resolution data are compared with the available altimetry data. In this way, a dataset of the sea state conditions around Cape Verde Islands was produced. This dataset is further used for wave climate analyses and wave energy resource assessments. This study indicates that the coastal environment of the Cape Verde Islands, and especially some particular areas, present considerable wave energy resources that should be taken in consideration for extraction in the near future.

1. Introduction

The Cape Verde archipelago is formed by 10 volcanic islands located 620 km off the coast of Africa, in the Atlantic Ocean between 10°30′ and 17°30′ N and 22°30′ and 25°30′ W. This archipelago belongs to a climatological region that includes the Azores, Canary Islands, Madeira and the Savage Islands, designated also as Macaronesia. This region is an important transitional climatic zone that encompasses a large part of the eastern north Atlantic, which is influenced by the semi-permanent Azores high-pressure system, prevailing north-easterly trade winds and the surrounding ocean [1].

Cape Verde Islands represent the most southern part of Macaronesia, and their climate ranges from tropical dry to semi-desertic, mainly governed by seasonal changes in the location of the Azores anticyclone, the Intertropical Convergence Zone (ITCZ), and the mid-Atlantic air masses. These islands are subjected to the northeast trade winds throughout the year that affect especially the northeastern slopes above 300–400 m in the mountain islands. Another important wind mass is the Harmattan, a dust- or sand-laden, hot, dry wind that occasionally blows from the southern Sahara Desert and is more common in the period between November and May [2]. Conversely, just to the west of the Cape Verde Islands lies the birthplace of some of the most intense hurricanes that have the potential to severely affect the Caribbean and eastern United States [3].

The energy sector in Cape Verde is characterized by a high dependency on the imported oil products, but renewable energy resources, in particular wind, have been used in the last decades [4].

As most islands, Cape Verde depends mainly on fossil fuels import (mainly oil) for both the production of electricity and fresh water (usually very scarce in islands), leading to high power costs and greenhouse gas emissions usually associated to this type of fossil fuel [5]. Nevertheless, the islands of the archipelago usually have a considerable potential in renewable energies and the use of this potential could represent a large fraction of the total energy distribution [6]. Being surrounded by the ocean, the wave energy is abundant and should be considered, together with the wind and the solar energy. This could contribute to the energetic autonomy of local communities in places were the price of conventional energy is very high, but could also lead to a decrease of the greenhouse gases emissions to the atmosphere, decreasing in this way also the carbon footprint.

Although the wave energy seems to be the most promising among the marine renewable resources, the potential for wave energy extraction needs to be assessed from wave climate information, for each region. The higher energy ocean waves are concentrated off the western coasts, in the 40°–60° latitude range

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north and south, due to the prevailing westerly winds [7]. Moreover, Mørk et al. [8] performed a global evaluation of the wave energy potential using data from the operational European Centre for Medium range Weather Forecast (ECMWF) wave model and showed that there are other regions, outside this latitude belt that also present interesting theoretical wave power results. In particular, for the Cape Verde region, the theoretical wave power is estimated to be between 15 and 20 kW/m.

In the recent years, several studies have been published evaluating the potential of the wave energy in island environments. In particular, a number of studies assessing the wave energy were made for all archipelagos of Macaronesia, except for the Cape Verde Islands. Thus, Sierra et al. [9] assessed the wave energy in nine sites around Lazarote, one of the Canary Islands, using hindcast, forecast and observational data, and found that the wave energy resource shows a clear seasonal pattern with an energetic winter and a mild summer. The high energy area has an average wave power exceeding 31Kw/h and a total 270Mwh/m (average annual wave energy). Another study for the Canary Islands was performed by Gonçalves et al. [10], using hindcast data produced by SWAN model (acronym from Simulating WAves Nearshore, [11]) and it was validated against both buoy and satellite data. It found an average power per unit width of about 25 kW/m, which although being lower than the more intense locations in the Atlantic European coast, is still appreciable for wave energy exploitation. An energy assessment of the Azores Islands (also belonging to the Macaronesian region), was performed by Rusu and Guedes Soares [12] using remotely sensed and hindcast data. They found significantly higher wave power values in these islands than in the Portuguese continent nearshore, especially during the winter, their results indicating almost the same order of wave power magnitude with the Hawaiian Islands [13]. Although providing high wave power potential, the Azores Islands are often subjected to very severe conditions that can lead to significant wave height values above 14 m and maximum height greater than 20 m, and that could lead to severe damage of the most of the currently available operating systems for the wave energy conversion. The wave patterns around the Madeira and Porto Santo Islands were also studied [14,15].

Moreover, the island environments have often the particularity that their coastal areas are characterized by high bathymetric gradients that can be associated with locations with significant wave energy concentrations, usually designated as “energy hot spots”. Locations with such characteristics have been already identified in the Azores Islands [12] and in Madeira [14]. In the Portuguese mainland coast, such “hot spots” have been also identified [7].

In this context, having as main objective the study the wave climate and of the wave energy resources in the Cape Verde coastal environment, and in particular the identification of possible wave energy hot spots, a 10-year high resolution wave data set is produced using the state of the art wave model SWAN forced by wind and spectral boundary conditions from the reanalysis data. This high resolution wave dataset is validated using three years of altimetry data. Finally, the spatial distribution of the wave power is evaluated together with the seasonal variability and moreover some hot spots are also identified.

2. The wave prediction system for Cape Verde Islands

2.1. The wave model

An evaluation of the wave conditions around Cape Verde Islands is made using the SWAN model. This is one of the state-of-the-art wave models based on the spectrum concept, which solves the spectral wave action balance equation:

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial \lambda} c_\lambda N + \frac{1}{\cos \varphi} \frac{\partial}{\partial \phi} c_\phi N \cos \phi + \frac{\partial}{\partial \sigma} c_\sigma N + \frac{\partial}{\partial \theta} c_\theta N = \frac{S_{tot}}{\sigma}. \quad (1)$$

where: N is the action density spectrum (defined as the ratio between the energy density and the relative frequency σ), t is the time, (λ) represents the longitude, (φ) the latitude and (θ) is the wave direction. c_λ and c_ϕ are the components of the relative group velocity $\vec{c}_g$ for the geographical space ($\vec{c}_g = \partial\sigma/\partial \vec{k}$, with k the wave number), $c_\sigma = \dot{\sigma}$ and $c_\theta = \dot{\theta}$ are the propagation velocities in the spectral space. The total source (S_{tot}) is expressed in terms of energy density and has various source terms related to the most important physical processes that affect the wave propagation from deep to shallow water.

The wave model is first run in a large area, forced by boundary conditions and wind fields from the Era-Interim reanalysis data set [16] provided by the ECMWF. Reanalyses are designed to provide gridded representations of the atmospheric-ocean-land-ocean sea ice system over a long historical period of time [17]. The Era-Interim is the latest ECMWF global atmospheric reanalysis covering a period from 1979 to the present and has been widely used for meteorological and climatological studies. The 10 m wind field data from Era-Interim was interpolated to 0.5° spatial grid and 6 h temporal resolutions. The resolution of the wind fields used to force the wave models influences the accuracy of the results obtained in SWAN simulations (see Ref. [18]). The horizontal resolution of the wave model in ERA-Interim is 110 km and wave spectra are discretized using 24 directions and 30 frequencies.

The outputs of these simulations (Level I) are field data for various wave parameters with a 3 h temporal resolution and also the boundary conditions for the higher resolution area which is nested inside the larger domain. The second runs (Level II) are made in this higher resolution area that also includes all the islands. The geographical domains corresponding to the SWAN model simulations are illustrated in Fig. 1 while the characteristics of the corresponding computational grids are presented in Table 1.

The implementation of the SWAN model was made considering 36 directions and 30 frequencies logarithmically spaced from 0.04 Hz to 1 Hz at intervals of $\Delta f/f = 0.1$. Some information regarding the input and the physics considered in the numerical simulations carried out in each computational domain are provided in Table 2. Model simulations have been carried out for a ten-year period (2004–2013) using the version 40.91ABC of the SWAN model.

Similar wave prediction systems, SWAN based, were focused on the Portuguese archipelagos Azores and Madeira with the aim to assess the wave energy spatial distribution and to identify the hotspots characteristic of the targeted island areas [11,13]. The methodology is also in line with the one considered for the European continental nearshore and in some examples related to the Iberian Peninsula [7,22].

2.2. Validation of the wave prediction system

With no wave buoy measurements in the vicinity of Cape Verde Islands, the significant wave heights (Hs) obtained through the numerical modelling are compared with satellite measurements. From this perspective, validations of the results provided by the wave prediction system herewith implemented were made for a 3-year time interval (2011–2013). Corresponding to this period, Hs altimeter data provided by the six altimeter missions ERS-2, ENVISAT, JASON-1, JASON-2, Cryosat-2 and SARAL/AltiKa were considered.

The wave model outputs provided in the coarse SWAN computational domain (Level I) were spatially interpolated from