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Assessment of wave energy resource of the Black Sea based on 15-year numerical hindcast data

Adem Akpınar [a,*], Murat İhsan Kömürcü [b]

[a] Gümüşhane University, Civil Engineering Department, 29000 Gümüşhane, Turkey
[b] Karadeniz Technical University, Civil Engineering Department, 61080 Trabzon, Turkey

HIGHLIGHTS

- ▶ This study deals with variability of wave energy resource in the Black Sea.
- ▶ The wave parameters hindcasts were performed using Simulated WAves Nearshore – SWAN.
- ▶ The areas with the highest wave energy resource were determined.
- ▶ The south-west coasts of the Black Sea are suggested as the best site.

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ABSTRACT

In this study, the existence and variability of wave energy resource potential of the Black Sea based on 15-year hindcast data is described in detail. The hindcasts of wave parameters were carried out by using the third generation wave prediction model (Simulated WAves Nearshore – SWAN), which is one of the most popular numerical wave models and has been widely used for estimating ocean waves. The model was forced with the ECMWF ERA Interim wind fields and applied with a spatial resolution of about $0.0167° \times 0.0167°$ and a model time step of 6 h to resolve efficiently offshore and nearshore wave conditions. The results were presented in the form of charts of the spatial distribution of significant wave height and wave power, on a monthly, seasonal and annual basis. Annual energy was calculated in the study region with the hindcast data set covering 15 years (1995–2009). The areas with the highest wave energy resource were determined and the south west coasts of the Black Sea are suggested as the best site for the installation of a wave farm. It was determined the western parts of the Black Sea (especially the south-west) are exposed to energetic waves more than the eastern parts.

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1. Introduction

The sustainable development of economic activities in the marine environment requires long term data about environmental conditions such as waves [1]. Availability of long-term wind and wave data in offshore and coastal areas is important to a number of marine applications and operations, such as the design and construction of offshore and coastal structures, the management and protection of coastal environment, tourist and land-planning development of coastal areas and islands, vulnerability and risk analysis of inhabited coastal areas, as well as the feasibility analysis for wind and wave energy utilization in specific sea areas [2]. However, field measurements of waves over a long period are extremely difficult and expensive. Therefore, there is a lack of such information in many regions, or in most cases, little measuring wave data are available for engineering purposes. For a region, long-term wind data can be generally reached more easily than long-term wave data. The desired sea-state information or long-term information of wave parameters has thus been obtained by using reliable wave models. Previously, several approaches have been proposed for wave prediction, which include empirical-based, soft-computing-based, and numerical-based approaches [3,4]. In this study, the SWAN third generation numerical model, one of the most popular numerical wave models and widely used for estimating ocean waves, was utilized for hindcasting of desired wave parameters.

The ocean is a vast repository of energy that can be extracted from its motion, temperature, or chemistry. Ocean energy can be recovered from waves, tides, marine currents, thermal gradients, and differences in salinity. Among all these options, the most

* Corresponding author. Tel.: +90 456 233 7425x1127; fax: +90 456 233 7427.
E-mail addresses: aakpinar@ktu.edu.tr, aakpinar@gumushane.edu.tr (A. Akpınar).

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challenging may be wave energy extraction. Wave energy technologies extract energy from the movement of the ocean's waves, which are created by wind interacting with the ocean surface [5].

World energy demand is steadily increasing along with the population growth and improved living conditions, and the ratification of the Kyoto protocol increases the need for CO_2-free energy sources. Wave energy is a renewable energy source with high power density, relatively high utilization factor, low visual impact and presumed low impact on environment compared to other renewable sources [6]. Gaps between domestic energy production and consumption of the countries are increasingly growing because increasing energy needs of countries, especially Turkey, cannot afford their own resources, and thus, foreign-source dependency of the countries on energy continues. Therefore for the future the use of indigenous and renewable energy sources is very important [7,8]. In this context, developed countries have tended to search for alternative energy resources due to increasing prices after crude oil crises over the past few years. The research and development works on electrical energy production from solar, wind, and water has made that these technologies compete with nuclear power plants today. While the research and development on nuclear energy have mainly focused on the storage of waste, studies and technologic developments on electric generation from solar, wind, and water are rapidly growing. In recent years, the researches on the energy of sea currents and waves have started to spread all over the world because the energy source does not adversely affect the environment and human health, and it is also an indigenous and renewable energy source [9].

The planning and operation of wave energy converters require reliable estimates of the available power and their seasonal variations [10]. It is also important to map the available energy to optimize the benefits from prospective developments [11]. In the last few decades, various areas of the world have been investigated for the availability of wave power for energy conversion. Researchers have applied spectral wave models to assess wave energy resources along and in the coasts of the Baltic Sea [6,12], California (USA) [13,14], India [15], Argentina [16], Hawaii [17], Australia [18], Portugal [19,20], Sweden [21], Korean Peninsula [22], Spain [23–27], the Northern coasts of the Gulf of Oman, Iran [28], European coasts [29], Atlantic coast of the southeastern USA [11], Global scale [10,30].

Much research on the wind and wave climate and the wave modeling in the Black Sea have been performed by countries that border the Black Sea. However, the results of these works are based on limited and sparse field data. Additionally, the NATO TU-WAVES project [31] was carried out as the first international research that included scientific institutions from all countries near the Black Sea. As a product of this project, wind and deep-water wave atlas of the Black Sea whose wave modeling was based on METU3 [32] and WAM [33,34] models was produced by Özhan and Abdalla [35]. Sağlam et al. [36] investigated wave energy and technical potential of Turkish coasts including the Black Sea by using this atlas. Also, Yılmaz [37] studied spectral characteristics of wind waves in the eastern Black Sea. Despite these attempts to develop wave forecasting systems for the Black Sea, we consider these systems not fully applicable for the present needs of providing accurate forecasts in view of recent progress in forecasting capabilities (e.g., Cavaleri et al. [38]) and improvements in the quality of the hindcast wind fields. In recent years, the SWAN model has been implemented to the Black Sea for wave prediction purposes (e.g., Rusu et al. [39]). They focused on the northern Black Sea in the verification and development of the model while we concentrated on the southern of Black Sea. The triad wave-wave interactions were not activated in their study. While they performed a short-term application we carried out a long-term implementation. The computational grid resolution of our study is much finer than that of Rusu et al. [39]. In contrast, the time step of their simulations is much better than that of our study.

This study investigates the quantity of wave energy resource in deep and shallow waters in the Black Sea and maps the available energy and its monthly and seasonal variations. To simulate wave parameters, the third generation spectral SWAN model using the European Centre for Medium-Range Weather Forecasts (ECMWFs) wind fields was utilized. Wave parameters were hindcasted for 15 years (from the beginning of 1995 to the end of 2009) and the annual, seasonal, and monthly mean wave energy were calculated by using this hindcast dataset. In addition, the wave energy resource was characterized in terms of sea state parameters for choosing the most appropriate sites which have the highest potential for wave farms.

2. Materials and methods

2.1. Area of interest and availability of data

The area of interest in the Black Sea is located in the Northern hemisphere in relatively low latitudes between 41° and 46° north latitudes and 28° and 41.5° east longitudes (Fig. 1). It extends over 1200 km from east to west and about 600 km in the north–south direction. The Black Sea can be characterized as a semi-closed basin. It has connection with the larger Mediterranean Sea by the narrow strait of Bosphorus in southwest and by the Crimean strait to the small and shallow Azov Sea in the north. The Crimean peninsula formally divides the northern part of the sea into two relatively detached basins. Most of the basin is deep as the bottom rises only near the coasts. The extensive shallow water regions in the north and northwest side are determined by the flow of large European rivers [40]. The presence of these shallow areas is due to sediments transported by river flow.

The atmospheric forcing data used as the principal input to the SWAN model to hindcast the wave parameters in this study were 6-h wind fields (four analysis fields per day, at 00, 06, 12, and 18 UTC) of the u and v wind components with spatial resolution of 0.25° in longitude and 0.25° in latitude at 10 m from the ECMWF ERA Interim re-analyses dataset. The dataset, which has 15 years of hindcast data, including predicted wave parameters by SWAN model using ECMWF ERA Interim wind fields was used for the determination and assessment of wave energy resource in the Black Sea.

In addition to these numerical data, the measurements from a directional wave buoy deployed at Hopa off-shore area for NATO TU-WAVES project in the south coast of the Black Sea were used to verify the numerical hindcast data. In this study, the 12-month wave record measured in 1995 year for Hopa buoy station moored at 41°25′24″ N and 41°23′00″ E and in 100 m of water was used to validate the wave model results.

2.2. Model description

In this study, the SWAN spectral wave model was used for wave simulation. The SWAN model is a numerical wave model that provides realistic estimates of wave parameters in coastal areas, lakes, and estuaries from given wind-, bottom, and current conditions. The model is a third-generation fully spectral model [41]. Holthuijsen et al. [42], Ris et al. [43,44] and Zijlema and Westhuysen [45] described the theoretical background.

The SWAN model calculates the development of a sea state by means of action density $N(\sigma, \theta)$ rather than by means of variance density $E(\sigma, \theta)$, as in the presence of currents action density is conserved whereas variance density is not. Action density, which is equal to variance density divided by relative frequency, stated as [41]:

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