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Wind and wave characteristics in the Black Sea based on the SWAN wave model forced with the CFSR winds

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A R T I C L E I N F O

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A B S T R A C T

Wind and wave characteristics and their long-term variability in the Black Sea over a period of 31 years are investigated in this study. The state-of-the art spectral wave model SWAN is implemented to perform a 31- year wave hindcast in the area of interest. The simulation results are used to assess the inter-annual variability and long-term changes in wind and wave climate in the Black Sea for the period 1979–2009. The SWAN model is forced with the Climate Forecast System Reanalysis (CFSR) winds. The model is calibrated and validated against available wave measurements at six offshore and near-shore locations spread over a large region in the Black Sea. The calibration was performed by tuning parameters in the white-capping and wind input formulations against available measurements for 1996 at three offshore locations (Gelendzhik, Hopa, and Sinop). The validation was carried out using measured data, at Gelendzhik, Hopa, and Sinop offshore locations, Gloria drilling platform and Karaburun and Filyos near-shore locations. From the 31-year simulation results, the long-term spatial distributions and changes of the mean wind and mean and maximum wave characteristics and their inter-annual variabilities were determined. The calibration improved SWAN model performance by 11.6% for H_{m0} and 3.3% for T_{m02} on average at three locations. The mean annual significant wave height (H_{m0}) and mean wind speed (WS) indicate the occurrence of higher wave heights and wind speeds in the western Black Sea compared to the south eastern coasts of the Black Sea. The coefficient of variation over the Black Sea for H_{m0} and WS shows that the variability for H_{m0} is higher than that of WS. It is also observed that the variability for H_{m0} is higher in areas (such as offshore Gelendzhik, Russia) where the variability of WS is high. Besides, the storms mentioned in the previous studies (such as Galabov and Kortcheva, 2013; Tarakcioglu et al., 2015) are observed in four interesting characteristic areas with maximum H_{m0} determined in this study over the Black Sea.

1. Introduction

Wind wave characteristics of normal and extreme conditions are of great importance in the design and construction of ports, waterways, bridges, oil platforms, undersea pipelines, coastal defense facilities, and other coastal engineering projects. In addition, wind waves can have significant impacts on the water circulation, pollutants and sediment transports in coastal areas (Lv et al., 2014). Studies into wind wave climate are also gaining more importance in the context of global climate change. A comprehensive understanding of the properties of the incident waves and their potential changes is the major knowledge necessary for sustainable management of both offshore activities and the coastal region. Moreover, the wave climate is one of the most sensitive indicators of changes in the wind regime and local climate in semi-enclosed sea areas (Weisse and von Storch, 2010; Soomere and Raamet, 2011).

As point measurements, buoy observations used as historical datasets may not accurately predict the wave climate at the study site, they either may not be close enough to the study site to be representative of the wave climate; or they may have an insufficient duration to accurately characterize the wave climate statistics. The duration can be especially important for characterizing extreme sea states, as well as normal sea states when inter-period climate oscillations occur on the order of a few years or decades (e.g., Wang and Swail, 2001; Vimont, 2004). A minimum duration of ten years is often recommended for characterizing normal sea states, and twenty years for extreme sea states to obtain reliable statistics with return periods in the order of 100 years. However, it is rare to find buoy observations that are both representative of the wave climate at the study site, and with durations longer than ten years. Therefore, model hindcasts of the wave climate offer an attractive alternative for wave characterization (Dallman et al., 2014). Thus, many efforts have been made in the last decade to

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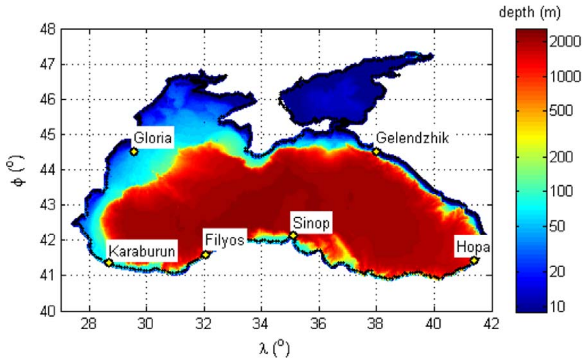

Fig. 1. Study area, bathymetry, and the measurement locations. The black circles filled with yellow color show the locations of the measurement stations.

produce spatially homogeneous long-time series of wave parameters through wind-wave numerical modelling based on global meteorological re-analyses (Paris et al., 2014; Akpinar et al., 2015).

Until today, many studies have analyzed ocean surface wave characteristics by using numerical wave models. For instance, Swail et al. (1999) used a global spectral ocean wave model for two long-term (40 years) wave hindcasts to analyse the trends and variability of changes in waves. Soomere and Raamet (2011), using the WAM wave model simulations of wave conditions for 1970–2007, revealed extensive spatial variations in long-term changes in both average and extreme wave heights in the Baltic Sea. Bosserelle et al. (2012) implemented the third generation spectral wave model (WAVEWATCH III) with a 40-year simulation to quantify the inter-annual variability and longer-term changes in the wave climate around Western Australia. Mirzaei et al. (2013) investigated long-term variability and wave characteristic trends in the southern region of the South China Sea implementing the WAVEWATCH III spectral wave model to simulate a 31-year wave hindcast. Lv et al. (2014) investigated the wave characteristics by using the SWAN model forcing with the ECMWF winds in Bohai Sea for the period from 1993 to 2012.

The Black Sea is located between 40°56′ and 46°33′ north latitudes and 27°27′ and 41°42′ east longitudes and connected to the European Mediterranean Sea (Fig. 1). It is a semi-closed sea connected, respectively, to the Sea of Marmara and Aegean Sea by the Bosporus and Dardanelles straits, and also to the Sea of Azov by the strait of Kerch. For the surrounding nations it has a great importance in terms of oil and gas production, tourism and recreation, commerce, navigation and fisheries etc.

Various aspects of wind waves in the Black Sea have been widely studied by researchers from nearly all surrounding countries and a summary of the most relevant studies is given below. Özhan and Abdalla (2002) reconstructed the long-term extreme wind and wave climate of the Turkish coasts, which produced the international research project NATO TU-WAVES, based on wave hindcast simulations covering periods of various lengths (from 8 to 20 years), employing different models and eventually a wave atlas was created. Cherneva et al. (2008) described the set-up and application of the third-generation wave model – WAM Cycle 4 to the Black Sea by using the wind fields calculated by a regional atmosphere model (REMO), which was driven with the conditions from the global NCEP re-analysis project. Kortcheva et al. (2009) described the existing operational system, coupled atmospheric and wave numerical models aiming at a detailed and accurate sea state forecast on an operational level, for wind waves forecasting in the Black Sea. Rusu (2010) developed a methodology based on the spectral phase–averaging wave model SWAN (Booij et al., 1999) to predict the wave propagation in the coastal environment. Rusu (2011) illustrated the performances of the numerical wave models in ocean and coastal environment. Valchev et al. (2012) assessed trends in past and recent storminess in the western Black Sea. Akpınar et al., (2012) summarized the implementation of the SWAN model forced by the ECMWF ERA Interim dataset reanalyzed 10 m winds over the Black Sea. Mihailov et al. (2013) presented a detailed analysis of the surface wave regime at Constanta site and of the current regime using the measurements from the seasonal cruises along the Western Black Sea shore, about 30 miles seaward. Yılmaz and Özhan (2014) investigated characteristics of wind-wave spectra for the Eastern Black Sea, and thus, to have a better understanding of the nature of the waves occurring in the region utilizing the wave frequency spectra obtained from directional buoys deployed offshore Sinop and Hopa in Turkey and Gelendzhik in Russia. Arkhipkin et al. (2014) described seasonal averaged and maxima wind wave fields in the Black Sea by using the SWAN wave model on a 5×5 km rectangular grid for the period between 1949 and 2010 derived from the NCEP/NCAR reanalysis. Rusu et al. (2014) evaluated the performance of a wind-wave modelling system (WRF, Weather Research and Forecasting, for wind and SWAN for waves) applied to the Black Sea basin for a four-month period at the beginning of 2002. Besides, some studies focused on storm surges (Mungov and Daniel, 2000) and historical storms (Ivanov et al., 2013), wave energy (Rusu, 2009; Akpınar and Kömürcü, 2012a, 2012b; Aydoğan et al., 2013) extreme waves (Galiatsatou et al., 2012) in the Black Sea.

A comprehensive understanding of the characteristics of waves in the Black Sea has recently become important and popular. Studies on waves and their characteristics in the Black Sea are limited and only cover a short period of time such as a period between 8 and 15 years (Özhan and Abdalla, 2002; Akpınar and Kömürcü, 2012b; Aydoğan et al., 2013). Although many wave studies have been carried out for the Black Sea, a systematic analysis of long-term changes of wind and wave characteristics and their variabilities is still lacking. Therefore, our aim is to fill this gap in knowledge using a 31-year long hindcast. For this purpose, the present study focuses to understand the long-term spatial changes and inter-annual variability of winds and waves in the Black Sea covering a substantial historical time period of 31 years by using the calibrated SWAN model forced with the CFSR winds, which were demonstrated to be the best source for the wind-wave modelling in the Black Sea (Van Vledder and Akpınar, 2015). As this wind has yet not been used in the Black Sea for the assessment of long term climate variability, we expect to more accurate results compared to previous investigations. We presented preliminary results in Akpinar et al. (2015) and now we present a more comprehensive analysis.

The remainder of this paper is organized as follows: The materials and methods used in this study are described in Section 2. The results, with together by a detailed discussion, are given in Section 3, and Section 4 presents the conclusions.

2. Methodology

2.1. Model description

SWAN (Simulating WAves Nearshore) model is a third-generation wave model based on the action density balance equation. In this study, it has been implemented to the Black Sea to obtain the wave characteristics by using CFSR wind fields. The theoretical and numerical background of SWAN was presented in Holthuijsen et al. (1993), Ris et al. (1999), Booij et al. (1999), and Zijlema and Van der Westhuysen (2005). A recent applications of SWAN in the Black Sea can be found in Akpinar et al. (2012) and Van Vledder and Akpinar (2015).

In the SWAN model the evolution of the action density (N) is governed by the action balance equation as follows:

$$\frac{\partial}{\partial t}N + \frac{\partial}{\partial x}\left(c_x N\right) + \frac{\partial}{\partial y}\left(c_y N\right) + \frac{\partial}{\partial \sigma}\left(c_\sigma N\right) + \frac{\partial}{\partial \theta}\left(c_\theta N\right) = \frac{S\ (\sigma,\ \theta;\ x,\ y,\ t)}{\sigma} \quad (1)$$