



# Spatial variability of long-term trends of significant wave heights in the Black Sea

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## ABSTRACT

This study aims to estimate the spatial variability of the long-term trends of Significant Wave Height (SWH) in the Black Sea. A spectral wave model was used to hindcast 38 years of SWH forced by ECMWF ERA Interim wind fields. Long-term trends were estimated from normalized SWH (NSWH) data, for each month separately, by using two non-parametric methodologies; Line of best fit and the Theil-Sen estimator, and then mapped to show their spatial variability. Maps were generated for both mean SWHs and 95th percentile SWHs, the latter is considered to reflect the trends of the severe sea states. The basin-averaged analysis was also carried out to investigate the general tendency of SWHs in the Black Sea. The significance of the trends was evaluated by using Mann-Kendall test. The annual mean SWH is found to be increasing (up to 1.6%/year) in the eastern part of the Black Sea while the western part has a negative trend (down to  $-1.2\%$ /year). Long-term analysis of the 95th percentile SWHs revealed steeper trend slopes and higher statistical significance compared to the mean SWH trends, showing that storm SWHs have a higher tendency to increase than the mean SWHs. Statistically significant correlations between climate indices; North Atlantic Oscillation (NAO), Arctic Oscillation (AO), Antarctic Oscillation (AAO), Atlantic Multidecadal Oscillation (AMO), Pacific North American (PNA), East Atlantic (EA), East Atlantic/West Russia (EA/WR), Scandinavia (SCAND), Niño3 and the Black Sea wave fields were identified.

## 1. Introduction

Wave height is a key input for coastal engineering applications, construction of offshore structures and the maritime activities. Design wave heights are derived from the statistical evaluation of long-term wave data which may be extracted from spectral wave models, providing highly accurate wave database once they are calibrated and validated against measurement data. These extended datasets provide an opportunity to evaluate the long-term trends in the wave properties to provide a better estimation of the future wave climate as well as more reliable design wave heights for design and planning of marine operations. Vanem and Bitner-Gregersen [1] reported that the effect of long-term trends in the wave climate is not negligible and may have a considerable impact on load and response calculations of floating structures. Increasing magnitude and the frequency of the sea storms together with increasing sea level causes retreat of the vulnerable coastal areas such as deltas, pocket beaches or low lying areas all around the world [2]. Estimation of long-term trends in the SWH is important for the coastal erosion and rehabilitation studies as well. Hence, the analysis of the long-term trend of SWH will make a positive

contribution to improving the future predictability of ocean waves [3,4].

Various research studies have been conducted to estimate the long-term trends of both the mean SWHs and the extreme SWHs, recently. Different parametric and non-parametric methodologies exist for the estimation of the long-term trends in the SWH time series. Vanem and Walker [5] studied the trends in the ocean wave climate by using four different methods including the seasonal ARIMA (Auto Regressive Integrated Moving Average) modeling, Multiple Linear Regression modeling, Theil-Sen estimation and Generalized Additive Model (GAM). Authors reported that they had similar results for trend values from these different methods. As pointed out by Vanem and Walker [5], existing studies are mostly focused on the temporal variability of the SWHs at a particular location. Vanem et al. [6] proposed a Bayesian Hierarchical model to evaluate the spatial and the temporal variability of the SWHs.

Long-term changes in SWHs have been analyzed by many researchers both globally and regionally by using different types of data. Gulev and Hase [7] evaluated long-term trends of SWH as well as wind and swell sea states in North Atlantic based on visual wave estimate

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data extending in the period 1964–1993. They found that the SWHs increase at a rate of 10–30 cm/decade in a whole North Atlantic. They also reported seasonal trends from a buoy in North Atlantic which results in about 1–3%/year increase in SWH. Gulev and Grigorieva [8,9] revisited the long-term trends in SWH in North Atlantic with the addition of the Pacific Ocean and they updated their trend estimate to 14 cm/decade for North Atlantic Ocean for the period 1950–2002. Dodet [10] studied the wave climate variability in the North-East Atlantic in six decades (1953–2009) based on wave hindcast data from a spectral model WAVEWATCH III [11]. Authors concluded that the North Atlantic Oscillation (NAO) controls the SWH in the study area and they estimated 2 cm/year significantly increasing trend in the Northeast Atlantic Ocean. Semedo [12] provided a global analysis of long-term trends of SWH based on ERA-40 wave database. They found that statistically significant increasing trends exist in North Pacific and North Atlantic Oceans. Shope et al. [13] projected the changes in extreme wave climate during the 21<sup>st</sup> century and the authors stated that their results project significant changes in wave climates of tropical Pacific islands which will affect the island vulnerability under climate change. Young [14] studied global long-term trends in wind speed and wave height. Later, the extreme value return period estimates of wind speed and wave height by using altimeter data for nearly 20 years are presented in Young [15] and authors concluded that the longer datasets are required for long-term trend analysis. Reguero [16] created a global ocean wave database which was calibrated by using reanalysis data between 1948 and 2012. The global wave power assessment and its seasonal, interannual and long-term variability were studied in Reguero [17]. Hemer [18] reported a detailed analysis of projected changes in global wave climate by using multi-model ensemble dataset by emphasizing that the projections in wind-wave characteristics exhibit considerably low confidence. Zheng et al. [19] studied wind energy trends in the North Atlantic, including the Black Sea by using Cross-Calibrated Multi-Platform (CCMP) wind data.

Wind and wave climate of the Black Sea has been investigated in previous studies [20–26]. Since continuous measurements of wave fields have short time durations and are spatially rare, the most commonly used methodology for investigating the wave climate is to analyze hindcasted wave data based on third generation spectral wave models. The spectral wave models used to model the waves in the Black Sea are; WAM [27], SWAN [28], WAVEWATCH III [11] and Mike21 SW [29]. Divinsky and Kosyan [30] reported that Mike21 SW and SWAN models give comparable results. Divinsky and Kosyan [31] tuned their Mike 21 SW model to separate the wind and swell dominated sea states and they defined the wind and swell dominated regions of the Black Sea. Different time coverages have also been considered in these studies starting from 13 years [20] to 37 years [24]. The time covered in the models actually depends on the currently available reanalysis datasets such as Modern-Era Retrospective Analysis for Research and Applications (MERRA) [32], NCEP–NCAR reanalysis [33], NCEP–Climate Forecast System Reanalysis (CFSR) [34], 40 year Re-Analysis (ERA-40) [35] and Interim Re-Analysis (ERA-Interim) [36] from European Centre for Medium-Range Weather Forecasts (ECMWF). They provide a spatial resolution of ~80 km and temporal resolution of 1–6 h.

Divinsky and Kosyan [24] studied the spatiotemporal variability of the Black Sea wave climate. Researchers analyzed the trends in storminess at three particular locations representing western, central, and eastern regions of the Black Sea. Storminess was evaluated by using a threshold value of wave power 20 kw/m. Authors concluded that there is a clear spatial and temporal inhomogeneity in the redistribution of wave energy with respect to the directions of its propagation. Since the storminess has been evaluated at three locations at the same latitude, this may not be enough to reflect the spatial variability of the wave climate in the whole basin.

Although the previous studies mostly deal with the wave energy, SWH is the most important wave parameter in the design of maritime structures and coastal engineering aspects. Akpınar and Bingölbalı [22]

studied long-term variations of wind and wave conditions in the coastal regions of the Black Sea using SWAN spectral wave model forced with CFSR wind fields for the period between 1979 and 2009. Authors selected 33 locations with water depths varying in between 44–1445 m near the coasts to analyze the trends in SWHs. An increasing trend for annual mean SWH was found at only one location while a decreasing trend was found at four locations among all 33 locations. Authors also reported no trend for annual maximum SWH. Although they have reported that there is a seasonal variation in  $H_{m0}$  in the selected points, seasonality of the trends of SWH was neglected in the analysis.

As a conclusion, there is still the need to conduct a comprehensive study on the spatial variability of the long-term trends of SWH in the Black Sea. Monthly variations of the trends of the mean and severe sea states as well as the higher resolution spatial variability of the trends in the Black Sea are still missing. This study aims to fill this gap by providing extensive data on long-term trends in SWHs and their significance covering the last 38 years. The spatial variability of the long-term trends in SWHs has been presented on maps covering the whole basin. The seasonality of the long-term trends in SWH time series has also been evaluated for each month separately. Upper and lower limits of the long-term trends in SWHs were presented for 95% confidence interval. All these analyses were conducted for both mean SWHs and 95th percentile SWHs to estimate the long-term trends in severe sea states as well as mean sea states.

## 2. Methodology and data

The study area covers the entire Black Sea and includes the Sea of Azov, the region spans between 27°–42°E and 40.5°–47.5°N coordinates. The Strait of Kerch connects the Sea of Azov to the main basin. The Black Sea extends for ~615 km in the north-south direction and ~1150 km in the east-west direction. The mean depth of the basin is 1240 m while the maximum depth is 2210 m. The Sea of Azov has a very shallow bathymetry where the deepest point is 14 m. Study area and mentioned locations are shown in Fig. 1.

To generate wave fields in the study area, a third generation spectral wave model was calibrated and run to hindcast 38 years of data. There are several alternative modeling softwares with similar capabilities such as WAM [27], SWAN [28], WAVEWATCH III [11] and Mike21 SW [29] which have been shown to present comparable accuracy [24]. In this study, MIKE 21 SW [29] was chosen for this purpose due to our experience with the software, its ease of use as a numerical tool and its powerful post-processing capabilities. The scientific background of Mike 21 SW can be found in [29].

### 2.1. Model set up

Unstructured spatial discretization was used in the modeling domain which enables a boundary-fitted flexible meshing with increased resolution near the coasts. Different mesh alternatives were tested for accuracy and computational speed. Kerr et al. [37] mention that they haven't found an increase of accuracy in prediction of SWH with higher mesh resolution while Cavaleri [38] argues that increasing the resolution will help to catch peaks in storms. Since this study is not focused on extreme wave events and our own comparisons support Kerr et al. [37]'s results we have chosen to operate on our optimized mesh consisting of 2678 triangular elements and 1712 nodes for the study. Bathymetric data with 30 arc-second resolution was obtained from General Bathymetric Chart of the Oceans (GEBCO) [39] and interpolated on to the model domain. Two-dimensional triangular computational mesh and the bathymetry of the Black Sea are shown in Fig. 2.

ECMWF Era Interim wind fields [36] were used to force the model. Wind velocity components of reanalysis data at 10 m above the sea surface extends for 38 years covering the time between 1979 and 2016. The temporal resolution of the wind fields is 6 h. The dataset was downloaded with an upscaled longitudinal and latitudinal resolution of

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