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ANALYSIS OF WAVE CHARACTERISTICS IN THE BLACK SEA BASIN USING SATELLITE ALTIMETRY DATA AND SWAN MODEL SIMULATIONS

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Rezumat. *Scopul acestei lucrări este acela de a analiza parametrii de înălțime semnificativă a valului, perioada valului și lungimea valului din bazinul Mării Negre în perioada 2017 – 2021. Pentru atingerea acestui obiectiv, au fost utilizate măsurători satelitare de altimetrie din baza de date IMOS și comparate cu valorile simulărilor modelului SWAN. Rezultatele obținute în urma prelucrărilor acestor două seturi de date contribuie la înțelegerea mai aprofundată a caracteristicilor valurilor de vânt din Marea Neagră datorită importanței deosebite din punct de vedere științific, economic, politico-militar și strategic al acest spațiu geografic.*

Abstract. *The aim of this paper is to analyze the parameters of significant wave height, wave period and wave length in the Black Sea basin in the period 2017 – 2021. To achieve this objective, satellite altimetry measurements from the IMOS database were used and compared with the values of SWAN model simulations. The results obtained from the processing of these two data sets contribute to a more in-depth understanding of the characteristics of wind waves in the Black Sea due to the special importance from a scientific, economic, political-military and strategic point of view of this geographical space.*

Keywords: Black Sea, numerical modelling, satellite altimetry

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1. Introduction

Satellite data plays a crucial role in both operational activities and scientific research, providing valuable measurements that undergo a series of processing steps. These steps include acquisition, homogenization, quality control, cross-calibration, product generation, and final quality control. Throughout this process, various algorithms are applied to derive a final gridded product.

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In the field of wave modeling, third-generation wave models such as SWAN, WAM, and Wave Watch 3 are widely utilized for studying wave forecasts and climate patterns. Among the analyzed parameters, the significant wave height (H_s) stands out, representing the average height (from trough to crest) of the highest one-third of waves. The other parameters are reprezented by the wave period (T) and wave length (L) which are defined as the time it takes for two successive crests to pass a specified point and the horizontal distance between two successive crests or troughs respectively, as seen in Figure 1.

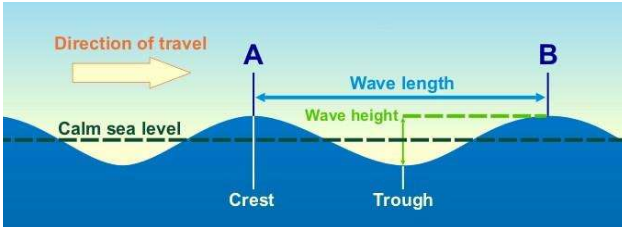

Fig. 1. Ocean wave parameters

Previous scientific studies have extensively discussed the primary strategies for simulating waves in both coastal zones and open seas [1]. In another study, the significant wave height was analyzed by comparing numerical wave models, satellite data, and in-situ measurements, revealing a strong correlation between the datasets [2]. Additionally, a study conducted in 2015 focused on storm cases in the Western Black Sea, comparing SWAN numerical wave simulations with satellite data and in-situ measurements [3].

By integrating satellite data, numerical wave models, and in-situ measurements, researchers have gained valuable insights into the characteristics of wave patterns in the Black Sea basin. These findings contribute to a better understanding of wave dynamics, enabling improved forecasting and mitigation strategies for coastal regions. In Figure 2 we can see the geographical area of the Black Sea.

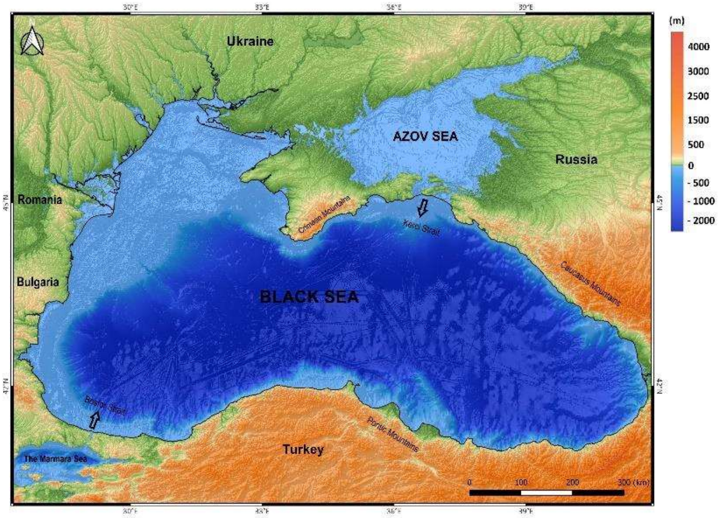

Fig. 2. Black Sea topographic map

2. Satellite altimetry

In this particular study, satellite altimetry data was employed as a fundamental technique for measuring the time it takes for a radar signal to travel from the satellite antenna to the surface of interest and back to the sensor. This technique harnesses a high-frequency signal emitted towards the Earth and reflected by the target surface, encompassing a wealth of information that finds applications in various fields, as seen in Figure 3. It proves to be an efficient method for assessing the state of oceans and seas, as well as the natural conditions of extensive water surfaces [4].

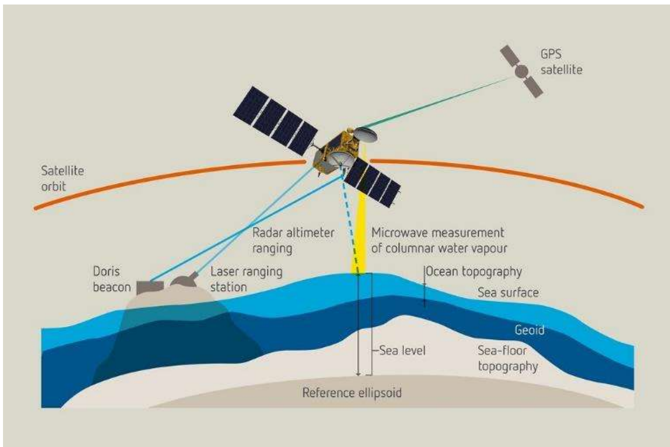

Fig. 3. Satellite altimeter wave measurement

The satellite altimetry data utilized in this study were sourced from the IMOS (Integrated Marine Observation System) database, developed by the Department of Infrastructure Engineering at the University of Melbourne, Australia. This comprehensive database, established in 2019 and regularly updated every six months, can be accessed through the AODN (Australian Ocean Data Network) online portal. It encompasses global data on significant wave height and wind speed over oceans and seas, derived from satellite altimetry missions spanning from 1985 to the present. Specifically, the data includes backscatter coefficients and wave height measurements in both the Ku-band (with wavelength ranging from 2.5 cm to 1.67 cm and frequency ranging from 12 GHz to 18 GHz) and the C-band (with wavelength ranging from 7.5 cm to 3.75 cm and frequency ranging from 4 GHz to 8 GHz). These data enable the determination of key parameters related to wind-sea interaction, such as wave periods and wind speed near the sea surface. Figure 4 shows the electromagnetic spectrum indicating the bands used in satellite altimetry measurements.

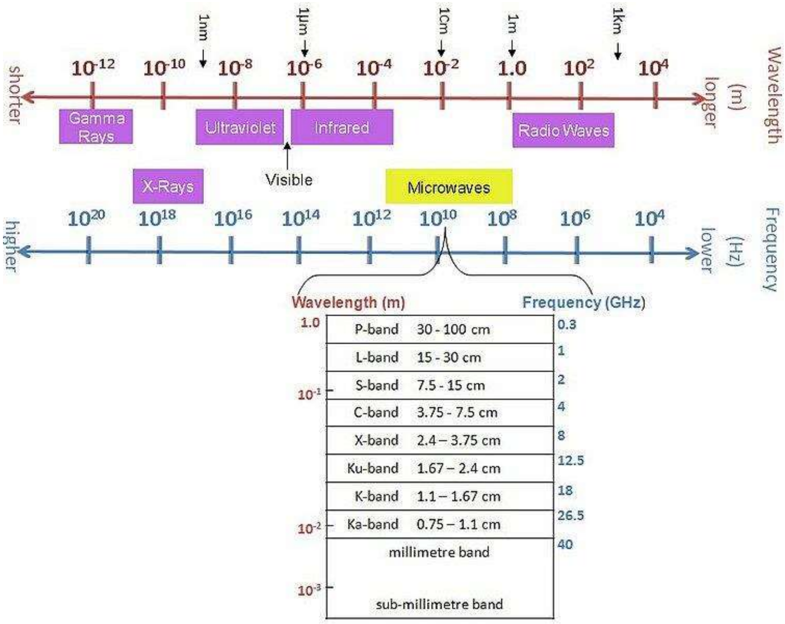

Fig. 4. The electromagnetic spectrum

For the purposes of this paper, significant wave height (H_S), wave period (T) and wave length (L) data derived from satellite altimetry measurements collected by five satellites were utilized. These satellites covered the Black Sea basin within their respective orbits between 1 January 2017 and 31 December 2021. Detailed information regarding the specific satellites used in this study is presented in Table 1.

Table 1. List of altimetry satellites

Satellite	Launch date (dd/mm/yyyy)	End date (dd/mm/yyyy)	No. of processed measurements
Jason-2	20/06/2008	10/10/2019	55987
Saral	25/02/2013	ongoing	109762
Jason-3	17/01/2016	ongoing	122198
Sentinel-3A	16/02/2016	ongoing	115123
Sentinel-3B	25/04/2018	ongoing	81300

3. Numerical wave modelling

Numerical models of ocean waves play a crucial role in the study of wind wave phenomena, providing valuable insights into the underlying physical concepts. The pioneering work of Sverdrup and Munk in 1947 [6] introduced the first wave prediction technique, which was a statistical approach based solely on wind wave heights. Early numerical models utilized coarse grids that favored deep-water regions, but more precise modeling, especially in coastal areas, necessitates finer resolutions and more intricate computations.For the purposes of this study, we used the SWAN (Simulating Waves Nearshore) model, a state-of-the-art third-generation numerical model widely utilized to obtain realistic estimates of wave parameters in coastal, lake, and estuary environments. Developed at the University of Delft in the Netherlands, the SWAN model integrates the energy conservation equation in the absence of currents. It comprehensively simulates the generation, propagation, and transformation of waves by accounting for three and four-wave interactions, current-wave interactions, non-stationary depths, whitecapping, bottom friction, depth-induced breaking, wave energy dissipation induced by turbulent flow, viscous fluid mud, vegetation, as well as wave transmission and reflection against obstacles [7].

To run the SWAN model, input data on wind, waves, and bathymetry of the Black Sea basin were required. The necessary information for wind and wave datasets was obtained from the ERA5 database, maintained by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5 represents the latest atmospheric reanalysis dataset from ECMWF, offering a spatial resolution of approximately 31 km (0.28° × 0.28°) on 137 levels from the surface up to 0.01 hPa (~80 km). The bathymetric data were sourced from The General Bathymetric Chart of the Oceans (GEBCO), providing a spatial resolution of 15 arc-seconds, equivalent to approximately 330 meters at a latitude of 45°.

For this research, we utilized version 41.31AB of the SWAN model. Simulations were conducted with a time step of 6 hours and a mesh resolution of 0.05 x 0.05 (as depicted in Figure 5). The simulations incorporated 36 directional bins and 30 frequency bins ranging from 0.1 Hz to 1 Hz, with a fixed number of 10 iterations per time step, as exemplified in Figure 6.

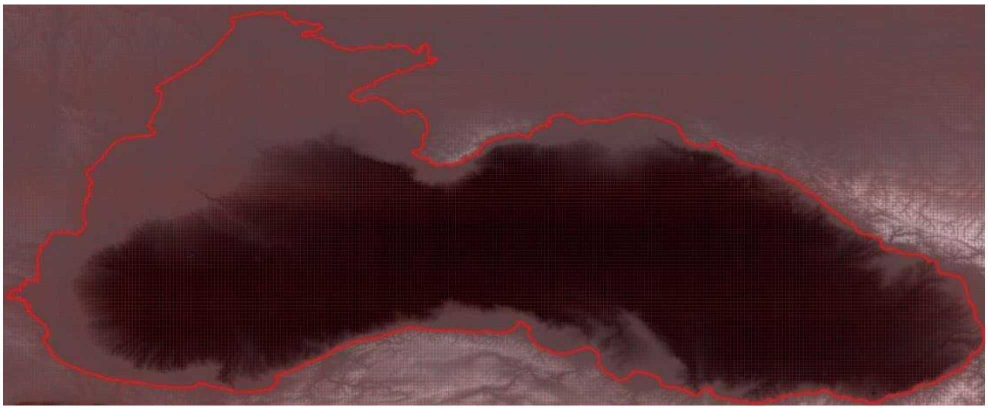

Fig. 5. Structured mesh for the SWAN model in the Black Sea

A set of tests was carried out to assess various SWAN model physics components under Black Sea wave conditions. The investigation focused on analyzing the impacts of default formulations pertaining to a range of physical processes, including whitecapping, dissipation, depth-induced, wave breaking, shallow water dissipation, nonlinear wave-wave interactions, as well as different values of their adjustable parameters. The results of these adjustments are summarized in Table 2, providing valuable insights into their influence on the wave field.

Table 2. Activated physical processes and formulations

Physical processes	Parameters
Wind input	cds2=0.5e-5
Whitecapping	cds1=0.5 delta=1
Quadruplets	iquad=8 Cnl4=5e7
Depth-induced breaking	alpha=1.0 gamma=0.73
Bottom friction	0.038
Triads	trfac=0.10 cutfr=2.5

In the final configuration of the model, the wind input formulations proposed by Komen et al. [8] and the whitecapping formulation developed by Janssen [9] were employed.

The processing of SWAN model simulations yielded a total of 358 Network Common Data Form (NetCDF) files covering the specified study period. These simulation results were then matched with the corresponding values of significant wave height (H_s), wave period (T) and wave length (L) obtained from satellite measurements. The matching process was based on the temporal and spatial coordinates of each satellite trajectory. For every altimetry point in the satellite data, the corresponding H_s, T and L values from the SWAN model was determined and paired accordingly.

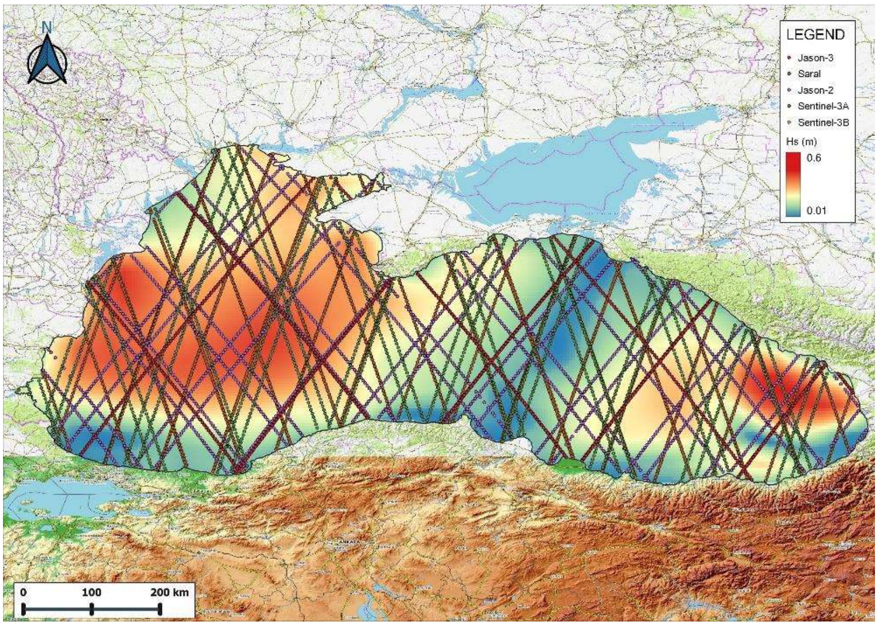

Fig. 6. SWAN simulation of the significant wave height [m] in the Black Sea basin with satellite ground tracks, 07.08.2018, time 12:00 UTC

4. Results and Discussions

The visual depictions illustrating the temporal changes in H_s, T and L values provide insights into the distinctive characteristics of the maximum values within the daily averages. Regarding the averaged values, a consistent pattern is observed, with variations ranging between 1.5-2 m for significant wave height, 1-2 seconds for wave period and 3-12 m for wave length.

The graphical representations also indicate a correlation between the wave model results and the satellite-based wave measurements. However, it is not possible to definitively conclude that the wave model consistently underestimates the measured waves, as there is a noticeable correlation between the simulated values and satellite measurements.

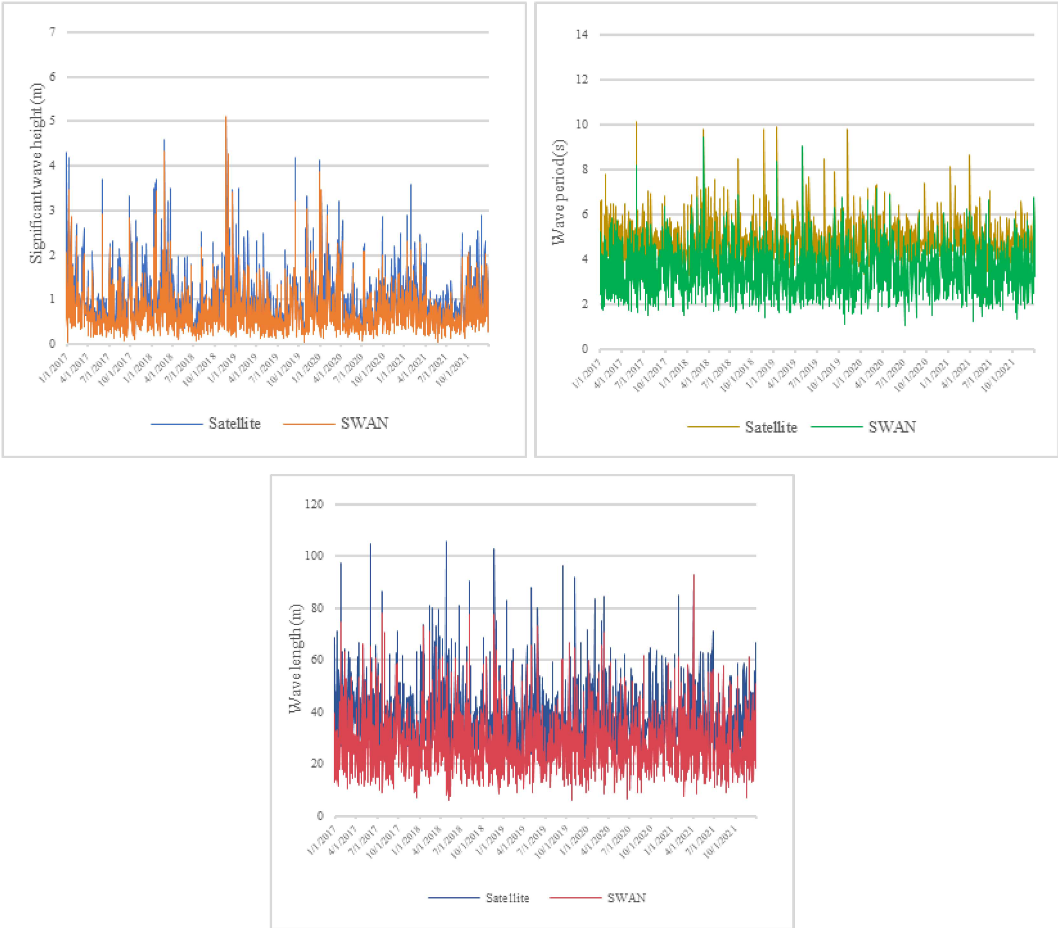

Fig. 7. Variation of the daily average values of the significant wave height H_S (m), wave period T (s) and wave length L (m) from satellite data and from SWAN model simulations 01.01.2017–30.09.2021

The results depicted in Figure 7 illustrate the temporal distribution of H_s, T and L daily average values, revealing that satellite altimetry measurements generally exhibit higher values during the cold season compared to the warm season. These differences are emphasized by the variation in the daily average values of the three wave parameters. The statistical analysis results are presented in Table 3.

For example, the height differences of H_s between the two seasons range from approximately 0.5 m to 2 m, except for extreme situations, such as January 29, 2020, when the Saral satellite recorded a maximum value of 5.1 m. Similar tendencies were also highlighted in a previous paper by Onea F and Rusu L [10].

These inter-seasonal variations of the measurements can be attributed to the synoptic conditions of the cold season, which are more conducive to the formation of intense convective systems due to the influence of the Siberian Anticyclone.

This atmospheric pattern allows polar air masses to enter the Black Sea basin, generating strong winds and low temperatures [11] [12].

Table 3. Statistical results of significant wave height (Hs), wave period (T) and wave length (L) results as a ratio between the values obtained by satellites and the values obtained from the SWAN model simulations for the period 01.01.2017 - 31.12.2021

Parameter	**Satellite measurements (multiannual average)**	**SWAN simulations (medie multiannual)**	**Correlation coefficient (R)**
Significant wave height (Hs) [m]	1.20	0.87	0.83
Wave period (T) [s]	4.87	3.55	0.68
Wave length (L) [m]	38.4	29.8	0.79

The comparison of SWAN model simulations with satellite data reveals a good correlation, ranging from 0.79 for the Jason-2 satellite to up to 0.81 for Sentinel-3A. The use of an unstructured mesh in the SWAN wave model shows potential for improving significant wave height, wave period and wave length values, along with further adjustments to the physical processes and parameters, as well as higher resolution bathymetry data, particularly for coastal regions. It is worth noting that the underestimation of H_s, T and L values by the model may be attributed to the lower quality of input wind fields. Overall, the SWAN model simulations of wind waves provide reliable results for the enclosed basin of the Black Sea.

R E F E R E N C E S

[1]. Rusu, E., Strategies in Using Numerical Wave Models in Ocean/Coastal Applications. (Journal of Marine Science and Technology, **19,** 58–75, 2011).

[2]. Myslenkov, S. A, Chernyshova, A., Comparing wave heights simulated in the Black Sea by the SWAN model with satellite data and direct wave measurements. (Russian Journal of Earth Sciences, **16(5)**, 1–12, 2016).

[3]. Galabov, V., Kortcheva, A., Bogatchev, B., Tsenova, B., Investigation of The Hydro-Meteorological Hazards Along the Bulgarian Coast of The Black Sea by Reconstructions of Historical Storms. (Journal of Environmental Protection and Ecology, **16(3)**, 1005–1015, 2015).

[4]. Dudley, B., C., John, C., R., Bruce, J., H., Lee-Lueng, F., Phillip, S., C., Satellite Altimetry and Earth Sciences - A Handbook of Techniques and Applications. (Academic Press, **69**, 1–463, 2001).

[5]. Dobson, E., Monaldo, F., Goldhirsh, J., Wilkerson, J., Validation of Geosat altimeter-derived wind speeds and significant wave heights using buoy data. (Journal of Geophysical Research: Oceans, **92**, 10719–10731, 1987).

[6]. Sverdrup, H., U., Munk, W., H., Wind, sea and swell. Theory of relations for forecasting (U.S. Navy Hydrographic Office, **601**, 1–44, 1947)

[7]. SWAN Team 2021 SWAN User Manual/SWAN Cycle III version 41.31AB. (Delft University of Technology, Netherlands, 1–138).

[8]. Komen, G., J., Hasselmann, S., Hasselmann, K., On the existence of a fully developed wind sea spectrum. (Journal of Physical Oceanogaphy **14** 1271–1285, 1984).

[9]. Janssen, P., Quasi-linear theory of windwave generation applied to wave forecasting (Journal of Physical Oceanogaphy, **21** 1631–1642, 1991).

[10]. Onea, F., Rusu, L., A Long-Term Assessment of the Black Sea Wave Climate. (Journal of Sustainability, **9(10),** 1875, 2017).

[11]. Luca, E., Golumbeanu, M., Analysis of Significant Wave Height for The Black Sea Basin Using Aviso Satellite Altimeter Data. (Journal of Environmental Protection and Ecology, **21(2)**, 405–412, 2020).

[12]. Luca, E., Bandoc, G., Degeratu, M., Comparative analysis of significant wave height between satellite altimetry data and SWAN model simulations in the Black Sea basin. (IOP Conf. Series: Earth and Environmental Science **1185** (2023) 012022 IOP Publishing, doi:10.1088/1755-1315/1185/1/012022, 2023).