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Wave energy potential and variability for the south west coasts of the Black Sea: The WEB-based wave energy atlas

Bilal Bingölbali [a], Halid Jafali [a], Adem Akpınar [a, *], Serkan Bekiroğlu [b]

[a] Bursa Uludağ University, Department of Civil Engineering, Gorukle Campus, Bursa, Turkey
[b] Yıldız Technical University, Department of Civil Engineering, İstanbul, Turkey

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ABSTRACT

This study aims at the assessment of wave energy potential and its spatial and temporal variability along the south-west coasts in the hot-spot areas of Black Sea. For this purpose, third-generation numerical wave hindcast model Simulating WAve Nearshore (SWAN), which is based on a set of nested SWAN model with increasing spatial resolutions (a coarse grid, then a fine grid, and then three sub-grids), forced with the Climate Forecast System Reanalysis (CFSR) winds is used to produce long term wave characteristics during the 31 years in the areas of interest. For the south-west coasts of the Black Sea the best nested SWAN model configuration, developed in our previous studies [1,2], with tuned coefficients for all of the deep and shallow water source terms in modelling of the wind-generated waves is run to obtain spatial and temporal outputs of several wind wave parameters for the assessment of wave energy potential and its variability. By using this data set, temporal and spatial variability of wave energy potential along the south western Black Sea is analysed in detail, considering annual, seasonal, and monthly spatial variation maps of wave power for each of the sub-grids. In addition, annual, seasonal, and monthly wave power potential variability, the exceedance probability curves, the value of wave energy resource potential, and wave power roses are established for several locations. The value of energy density, spatial variation of the stability of energy density (the coefficient of variation, monthly variability index, seasonal variability index, and persistency analysis), spatial variation of total storage and exploitable storage of wave energy resource are also analysed. Finally, it was determined that in the regions (Karaburun SD3 sub-grid domain) where the average wave energy flux is high, the wave energy flux has a high coefficient of variation, and thus the regions (Filyos SD2 sub-grid domain) having lower wave energy flux have a stable wave energy flux which is ideal for energy exploitation from waves. Annual average wave energy in the southwestern part of the Black Sea is concentrated at 0.2–1.5 m significant wave height range, and also the concentration is between 2 and 5 s in Karaburun SD3, 3–7 s in Filyos SD2 and 2.5–6.5 s in Sinop SD1 sub-grid domains in terms of the wave energy period.
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1. Introduction

Electricity consumption in the world is rapidly increasing due to industrial development, developing technology and production techniques, economic development, increasing population, and welfare improvement. The 2019 edition of British Petroleum's Energy Outlook reports that global energy demand grows by around a third by 2040 – a significantly slower rate of growth than in the previous 20 years or so. In order to meet this increase in demand, all countries have entered into quests for existing, new, and renewable energy resources that are inexhaustible, sufficient, high quality, reliable, economical, environmental and human-health sensitive. The same situation is observed for Turkey, the future high growth rate and its Vision 2023 goals together with the young and growing population support the prediction that future energy consumption will increase rapidly. As it is known, Turkey is an externally dependent country at a significant level (about 74%) in terms of energy, and this imported energy has the greatest share in the current budget of the country. Reduction of external dependence on energy is extremely important for the prosperity and competitiveness. For this, the most important option is to introduce domestic, renewable, alternative and environmentally friendly energy

* Corresponding author.
E-mail address: ademakpinar@uludag.edu.tr (A. Akpınar).

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sources. Wave energy is an energy source with the greatest marine energy density available in coastal areas. At the same time, it is considered as an alternative energy source in all over the world. Moreover, renewable and alternative energy sources are becoming more and more attractive all over the world due to the CO_2 emission reduction as well as positive political point of view. Sea waves, or wind-generated waves, resulted from the wind blowing over the free surface of the oceans and other bodies and which can travel thousands of miles in the oceans before reaching land, are known to be one of the most prominent forms of this type of energy source. Because of this, many wave energy conversion devices using different technologies have been developed and are still being developed on the basis of energy acquisition from waves in recent years. Today, pilot installations in some countries such as Australia, China, Denmark, India, Japan, Norway, Portugal, Sweden, United Kingdom (UK) and the United States are in operation. In the UK

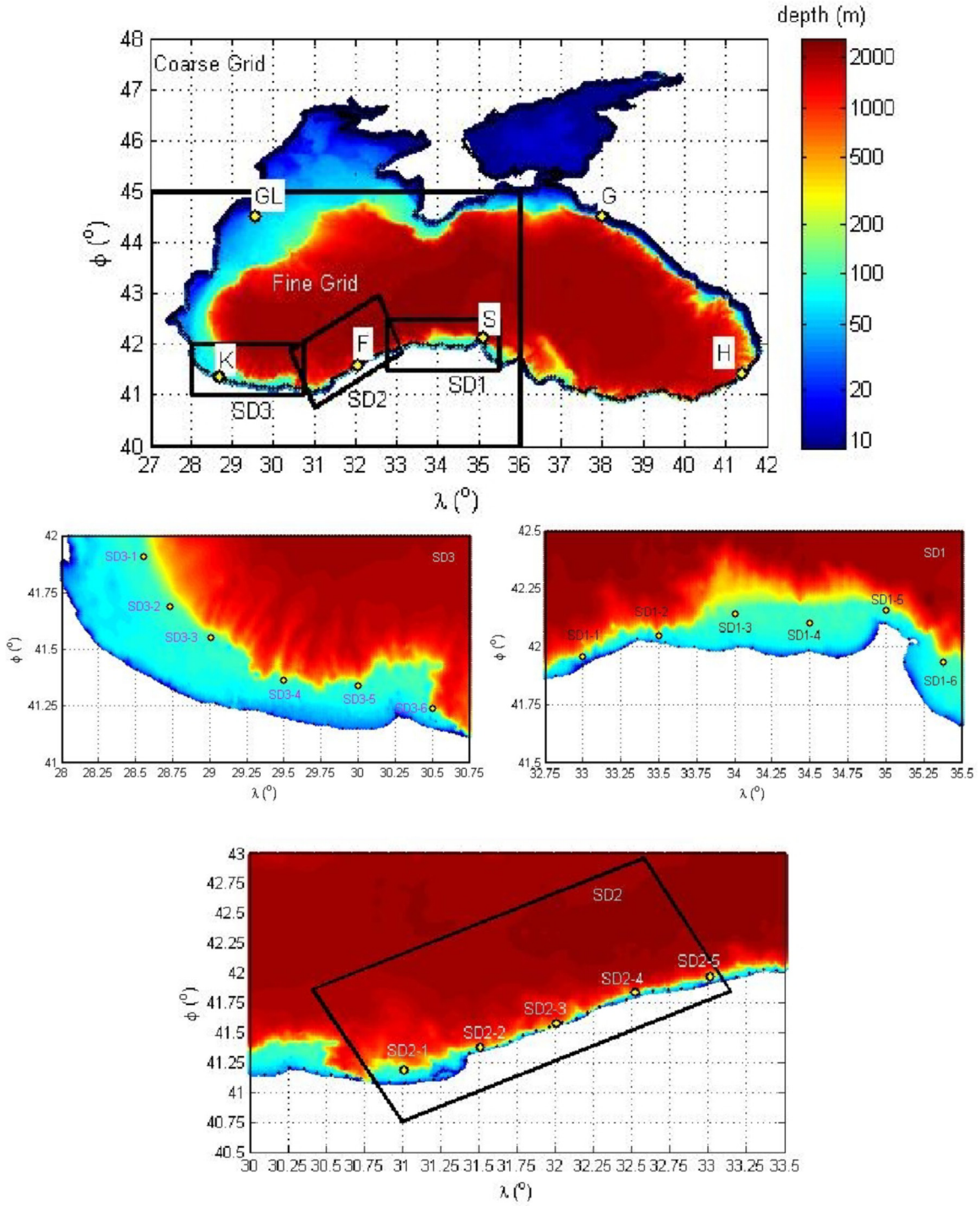


Fig. 1. Nested SWAN model system (one coarse grid, a fine grid, and three sub-grids Karaburun SD3, Filyos SD2, and Sinop SD1), bathymetry of the Black Sea, positions of the measurement locations (K: Karaburun, F: Filyos, S: Sinop, H: Hopa, GL: Gloria, and G: Gelendzhik) and the plots for the sub-grids show the positions of the locations used in the detailed analysis.

(2 MW), Portugal (400 kW), Spain (296 kW), China (190 kW), Sweden (150 kW), Denmark (250 kW) and New Zealand (4 kW) electricity is commercially produced from wave energy. However, one of the most realistic and important steps towards the use of wave energy is to uncover the source potential of the seas. This can be demonstrated by determining the wave climate in terms of wave power instead of the standard wave characterization (average and extreme wave climate) that has been widely applied in ocean/coastal engineering applications such as offshore and coastal structures, marine transport and artificial coastal nourishment projects. Therefore, considerable work has been undertaken on this issue in recent years, and ocean wave energy sources have been assessed for selected locations and, in some cases, spatial and areal variability on a global scale (e.g. [4,5]) as well as regional and terrestrial scale (e.g. [6–29]) have been conducted more recently. Although many of these studies have been performed for areas exposed to high energy wave conditions, some efforts have been made for areas where light wave conditions are subjected (e.g. [30–35]). However, despite the disadvantage of achieving lower energy production rates, areas with light wave conditions offer substantial practical advantages for the application, operation and maintenance of wave energy conversion devices [31], which provide feasibility for energy production. This is also the case for enclosed or/and semi-enclosed sea basins, such as the Black Sea, where only a few wave energy studies have been carried out [36–39]. Two of these studies [38,39] focused only wave energy analysis for locations in different regions of the Black Sea, based on the results of a 15-year numerical simulation for the whole Black Sea and examined only the temporal changes of the wave energy potential in these stations. Akpınar and Kömürcü [37] identified areas of the Black Sea with high-wave energy potential based on numerical model with default settings developed for a coarse resolution for a period of 15 years. The results of these three studies show that the Black Sea's wave energy potential is higher in the south-west coasts. Beside these, Rusu [36] focused on several storms and examined only the energy state of the waves during these storms. As seen in the literature review, the long-term detailed analysis of temporal and spatial variation of the nearshore and coastal wave energy potential of the south-west coasts of the Black Sea is not examined, mapped and quantified. In addition, Cavaleri [40] suggests that by working with multiple computed domains in nested domains, instead of modelling by choosing a single computed domain, focusing on the desired region increases the energy transferred from wind to wave. For this reason, this study focuses on wave energy resource characterization and variability in hotspots areas using high resolution and nested domains and developing a high resolution and numerically and physically adapted offshore and nearshore numerical wave hindcast model developed for the southwestern coasts of the Black Sea. For this, a nested SWAN model [1] focusing on the southwestern coasts of Black Sea is developed by investigating numerical and physical setting of the nested SWAN model (the main domain including whole the Black Sea, a fine domain focusing on southern part of the Black Sea, and three sub-domains in the southwestern coasts of the Black Sea, please see Fig. 1) at each domain and performing calibration of the adjustable parameters in offshore and nearshore source expressions. Then, the developed nested SWAN model is validated and a database including a lot of integral wave parameters is produced during 31 years between 1979 and 2009. Information on development, calibration, and validation of the developed nested SWAN model can be found in [2,3]. This study presents a detailed analysis of wave energy resource characterization and variability in hotspots areas for the south-west coasts of the Black Sea using this database. Analysis results are presented in two forms, spatial distribution maps, and location-based results. As a spatial analysis, variations of yearly, seasonal, and monthly averaged mean wave power are firstly discussed. Variability of wave energy potential is secondly revealed based on the coefficient of variation (COV), monthly and seasonal variability indices. Thirdly, total and exploitable wave energy reserves showing proper areas for the installation of wave energy converters or farms are computed. After that, as location-based results, a statistical analysis of wave energy potential and variability for selected locations along the south-west coasts of the Black Sea is performed. For this, roses and probability distributions curves of wave power in each location are discussed. The last analysis is carried out as a discovery of wave energy source characterization against significant wave height (H_{m0}) and wave energy period (T_{m-10}).

2. Methods

The most common method used for the estimation of wave energy in many studies is the wave power calculation method using the significant wave height and energy period [10,41,42]. This method was also applied in this study. Hence, in this study, based on the estimated significant wave height and energy period, wave power or energy flux is calculated by following the steps given below. Wave energy density (E) based on water density (ρ), gravitational acceleration (g) and significant wave height (H_s), which is the average height of the highest one-third of all waves occurring in a given period, is given as follows [43]:

$$E = (1/16)\ \rho\ g\ H_s^2 \tag{1}$$

The wave power (P) can be determined by multiplying the amount of energy (E) transported by the group speed (C_g) as follows:

$$P = E\ C_g = E\ C\ n \tag{2}$$

In which C is the wave speed and n shows the ratio of wave group speed (C_g) to the wave speed and is approximately equal to 0.5 in deep water. Wave velocity is the ratio of wavelength (L) to wave period (T) and can be determined by $C = gT/2\pi$ in deep water. So, the wave power can be calculated as follows:

$$P = (1/16)\ \rho\ g\ H_s^2\ (g\ T\ /\ 2\pi)\ \Big/ 2 \tag{3}$$

Real marine conditions are a form brought by many irregular waves coming together. A variance spectral density function is, thus, used to define this case which is a mixture of different amplitudes, frequencies and directions. The wave power potential of the unit width of irregular waves in deep water, with the seawater density for the Black Sea, is taken as a typical value of 1015 kg/m^3, can be obtained as follows:

$$P\ (kW/m) = 0.486\ H_s^2\ T_e \tag{4}$$

where T_e is known as the energy period.

Cornett [44] pointed out that the coefficient of variation (C_v), showing the scattering nature of the data, is necessary to consider in determining the location for a wave power plant. Stable energy concentration is convenient for accumulating energy. By calculating the coefficient of variation of the wave energy in different months, the stability of the wave energy can be presented. The lower the coefficient of variation, the better the stability of the energy density. The calculation method is as follows:

$$C_v = S/x_{mean} \tag{5}$$

Table 1
The coordinates and depths of the locations selected in the three sub-domains.

Grid	Location	Longitude (°)	Latitude (°)	Depth (m)
Karaburun (SD3)	SD3-1	28.556	41.904	99
	SD3-2	28.731	41.687	102
	SD3-3	29.006	41.552	99
	SD3-4	29.500	41.365	106
	SD3-5	30.000	41.339	102
	SD3-6	30.500	41.239	108
Filyos (SD2)	SD2-1	31.010	41.187	99
	SD2-2	31.510	41.382	107
	SD2-3	32.004	41.575	107
	SD2-4	32.520	41.839	107
	SD2-5	33.015	41.966	102
Sinop (SD1)	SD1-1	33.000	41.957	100
	SD1-2	33.500	42.048	92
	SD1-3	34.000	42.139	100
	SD1-4	34.500	42.100	101
	SD1-5	35.000	42.157	99
	SD1-6	35.381	41.930	100

$$S = \sqrt{\frac{\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2 \Big/ n}{n-1}} \tag{6}$$

in which S, x_i, n, and x_{mean} are standard deviation, each of the simulated values of the data, the number of data points, and mean value, respectively. In this study, the monthly variability index of the wave energy flux was also investigated. The larger monthly variability index represents a larger monthly variation in wave energy. This means less stability. The monthly variability index can be calculated as follows:

$$M_v = \frac{P_{M1} - P_{M12}}{P_{mean}} \tag{7}$$

where P_{M1} is the month with the most energy density, P_{M12} is the month with the lowest energy density, and P_{mean} is the annual average energy flux. Monthly averages of wave energy flux are calculated during the considered time period and the monthly variability index of the wave energy flux is derived for this time period.

In order to obtain the seasonal variability index (S_v), the method used in calculating the monthly variability index is applied. Only that here, instead of monthly averages, the seasonal mean wave energy fluxes are determined and the seasonal variability index is calculated as follows:

$$S_v = \frac{P_{S1} - P_{S4}}{P_{mean}} \tag{8}$$

where; P_{S1} is the season with the most energy density, and P_{S4} is the season with the least energy density. All these three variability indexes provide information about where the wave energy conversion system to be installed will be able to work in a stable state along the south-west shoreline of the Black Sea. Therefore, these evaluations give detailed information about the place where the wave energy conversion systems should be installed, as well as the variability of the energy that can be obtained in the case of system operation.

Zheng et al. [45] states that several of today's excellent wave power conversion devices can absorb wave energy well at wave heights of 0.5 m and above. This means that wave energy can be exploited at these significant wave heights. In this study, using the method proposed by Zheng et al. [45], the percentages of occurrence of the significant wave height that can be explored on the south western coast of the Black Sea are spatially determined. Then, the exploitable wave energy source potential is calculated. The calculation method for this is given below:

$$E_{PT} = P_{mean} * T \tag{9}$$

$$E_{PE} = P_{mean} * T_E \tag{10}$$

where, T is the total time of the year (365 days * 24 h = 8760 h), E_{PT} is the total reserve of wave energy resource, E_{PE} is the exploitable reserve of wave energy resource, and T_E is the total occurrence time of the significant wave height that can be exploited throughout the year.

3. Results and discussion

The wind-generated wave simulations were carried out for a period of 31 years, and thus a lot of integral wave parameters were accumulated for the three sub-domains based on the nested SWAN model developed by focusing on southwestern coasts of the Black Sea. Utilizing the data accumulated for 31 years separately for each of the three sub-domains, existence and variability of wave energy potential were assessed by considering the following annual, seasonal and monthly average changes, spatial variations of annual and seasonal variation coefficient, spatial variation of the monthly and seasonal variability indexes of the wave power for 31 years during 1979–2009 were analysed. Total reserve wave power and discoverable wave power potential were also identified as spatially. Besides, annual and seasonal wave power roses, curves for wave power probability of exceedance, annual mean wave energy at

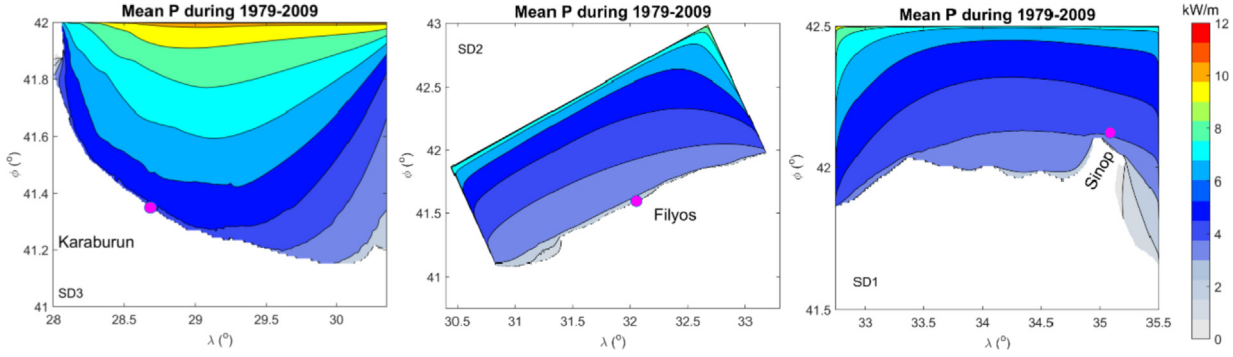


Fig. 2. Averaged wave energy flux during 31 years from 1979 to 2009 belonging to SD1 (Sinop), SD2 (Filyos) and SD3 (Karaburun) domains.

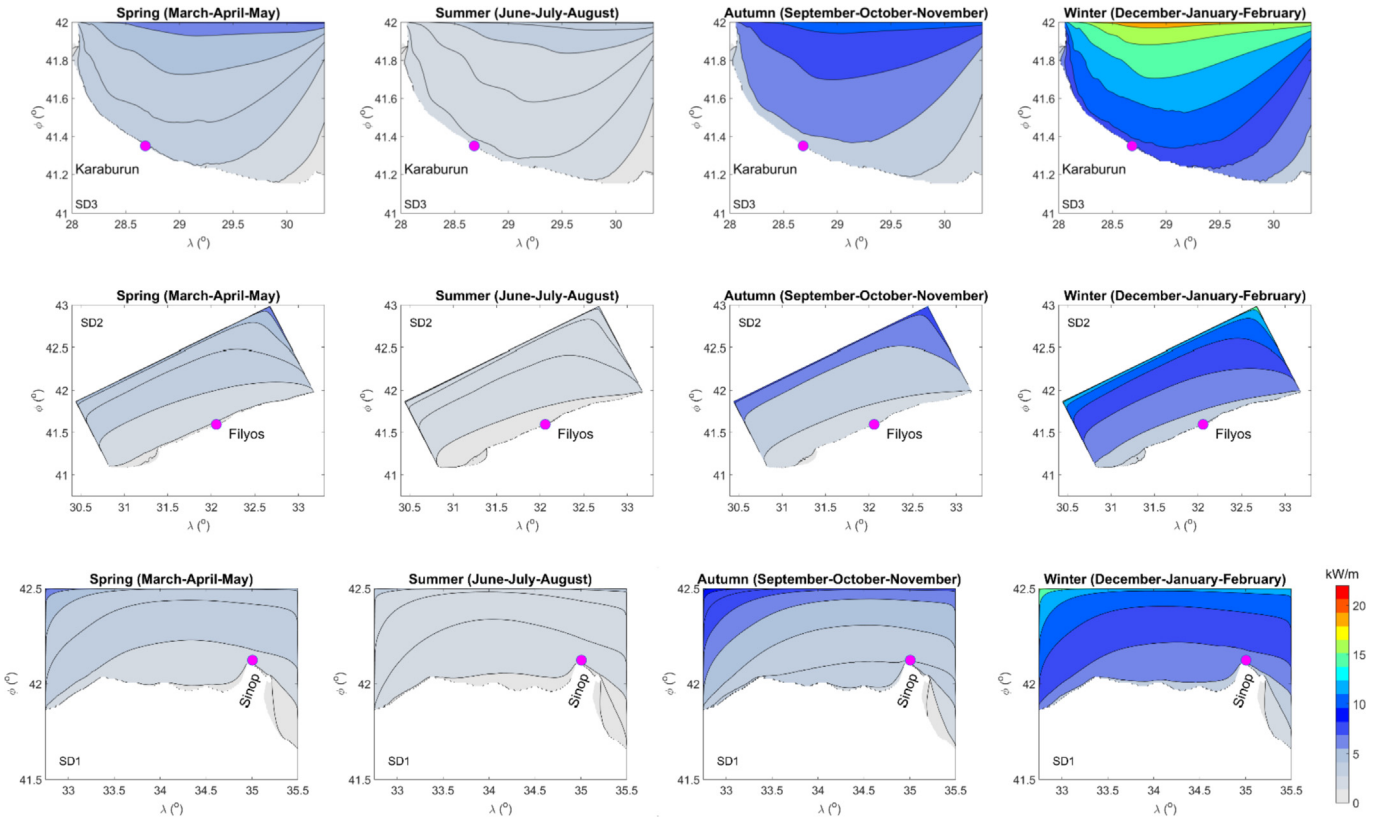


Fig. 3. Seasonal averaged wave energy flux during 31 years from 1979 to 2009 belonging to SD1 (Sinop), SD2 (Filyos) and SD3 (Karaburun) domains.

different wave periods and height ranges were discussed for the locations (please see Fig. 1 and Table 1) selected along with the southwestern Black Sea.

3.1. Long-term annual, seasonal and monthly means

Using the data sets containing 31 year long-term wind and wave parameters generated for each sub-domain, the instantaneous wave energy fluxes were calculated as described in the section 2. For example; since wave data for the Sinop domain was accumulated at a time resolution of 20 min, wave energy flux was also determined at 20 min resolution using concurrent significant wave height and wave energy period data based on Eq. (4). Using these calculated wave power fields, spatial variations (Figs. 2 and 3) of long-term annual and seasonal average wave energy fluxes ere determined. In all sub-plots of these figures, pink points show the position of the measurement locations whose values were used in the development, calibration, and validation of the SWAN model for these sub-domains. In addition, averaged annual, seasonal and monthly wave energy fluxes for each sub-domain were calculated for each year separately but they are not present here to gain space and reduce figures. They can be found in http://www.blackseawaveenergypotential.com/.

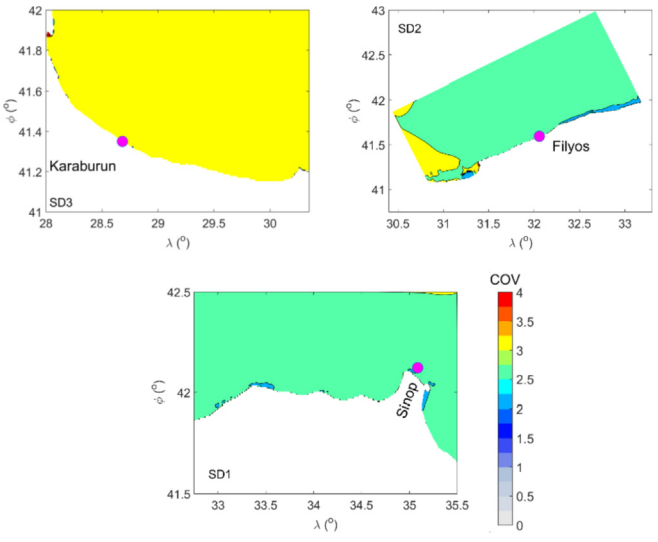


Fig. 4. Spatial distributions of coefficient of variation (COV) of wave energy flux based on all data for SD1 (Sinop), SD2 (Filyos) and SD3 (Karaburun) domains over 31 years (1979–2009).

As seen in Fig. 2, wave energy flux from east to west of Karaburun SD3-domain is increasing. Karaburun has an average wave power of 5 kW/m from the measurement station to the Bulgarian border which is the westernmost of the domain. In the Filyos and Sinop domains, wave energy flux tends to increase from the shoreline seaward. There is 4 kW/m and below wave energy in the near coastal area of Filyos and even lower wave energy flux in the near coastal area of Sinop domain. Fig. 3 shows the spatial distribution maps of the seasonal averaged wave energy flux for 31 years from 1979 to 2009 for Sinop SD1, Filyos SD2 and Karaburun SD3 domains. According to these maps, the lowest wave energy flux in all domains is 2 kW/m and/or lower in summer. In all domains, the spatial distributions of wave energy flux in each season are very similar to the annual averaged spatial distribution curves based on the whole data, but there are

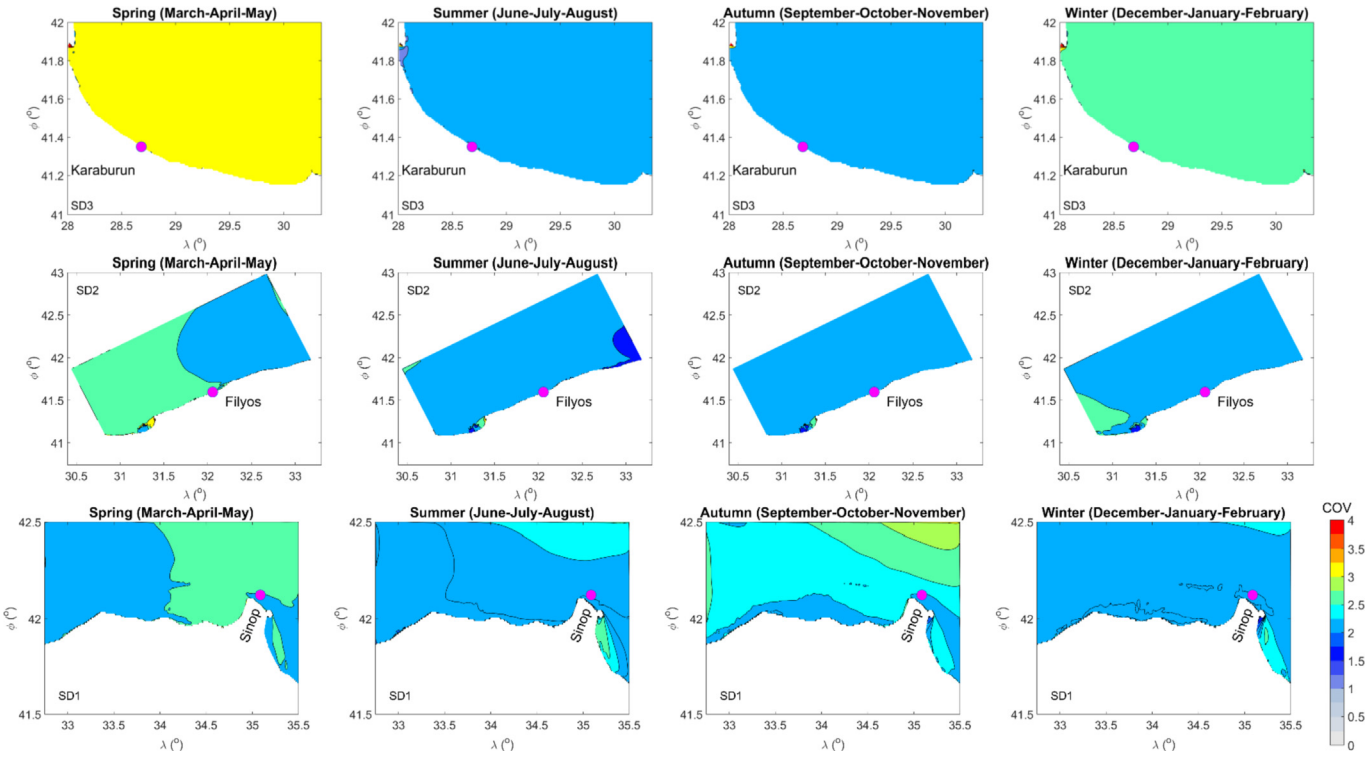


Fig. 5. Spatial distributions of seasonal coefficient of variation of wave energy flux for SD1 (Sinop), SD2 (Filyos) and SD3 (Karaburun) domains over 31 years (1979–2009).

differences in values. It is seen that the highest wave energy flux occurs in the winter season followed by the autumn season in all domains. During the winter season, there is a 6 kW/m average wave energy flux along the Sinop coast, whereas slightly lower energy is observed along the coast in Filyos domain. The highest average wave energy flux of around 10 kW/m can occur in the western region of Karaburun domain.

Spatial distribution maps (not shown here) of the monthly averaged wave energy flux for the period between 1979 and 2009 belonging to Karaburun SD3 domain show that April, May, July, August and September are similar both in terms of spatial distribution curves and values. Here, June has the lowest energy. These 6 months represent a period of low energy. In the other 6 months with higher energy, an average wave energy flux of 5 kW/m is observed in the western part of the domain in March, October and November, while a wave energy flux of around 10 kW/m is observed in the west part of the domain in the winter months. As the maps obtained for Filyos SD2 and Sinop SD1 domains, a similar situation with Karaburun domain is also present here. April to September is a period with the lowest energy. March, October and November are months with higher energy and winter months make up a period with the highest energy. A wave energy flux of 6 kW/m along the coast is detected during the winter months except for the bay area in the east of Sinop Headland within these domains.

3.2. Yearly and seasonal coefficient of variation

The coefficient of variation, which can be determined as the ratio of the standard deviation of the current data to the average, is a criterion for determining whether the energy that can be generated is sufficient. Low coefficient of variation indicates that the wave energy density is stable and therefore suitable for exploitation. Therefore, spatial distributions of the annual, seasonal and monthly variation coefficients of the wave energy flux for each subdomain were calculated using the calculated wave energy flux maps. Fig. 4 presents the annual variation in wave power variation coefficients for the SD1 (Sinop), SD2 (Filyos) and SD3 (Karaburun) domains for 31 years. According to sub-plots of this figure, it is determined that the whole of Karaburun domain and a small area in the border region of the western part in the Filyos domain is in the range of 3–3.25 of the annual variation coefficient. The rest part of Filyos domain and in the entire Sinop domain, this value is between 2.5 and 2.75. It is understood from this that in regions where the average wave energy flux is high, wave energy flux has also a high coefficient of variation. From Fig. 5, the variation coefficient of the wave energy flux is in the range of 2–2.25 in summer and autumn in almost the entire Karaburun domain and 2.5–2.75 in winter for the whole domain. In the spring season, this value ranges between 3 and 3.25 in the entire domain. The variation coefficient of wave energy flux in the west of Filyos (Filyos domain) monitoring station in spring varies between 2.5 and 2.75 and between 2 and 2.25 in the east. The entire domain in the autumn season and most of the domain in the summer and winter seasons are in the range of 2–2.25. For the Sinop domain, the western side of the domain in the spring season shows a variation coefficient between 2 and 2.25 and the eastern side between 2.5 and 2.75. The east side of Sinop headland has a slightly lower coefficient of variation which increases again toward the bay area. In the summer season, most of the domain has a variation coefficient in the range of 2–2.25, whereas a higher variation coefficient is observed in the northeast of the domain. The variation coefficient increases to 2.75 toward the east of the Sinop domain. In the autumn season, the coefficient of variation of the wave energy flux has values in the range of 2–2.25 along the coast, increasing towards the open sea and in the northeastern direction. The value is also high in the bay area to the east of the headland of Sinop. In winter, almost the whole domain has a coefficient of variation between 2 and 2.25. From this, it is

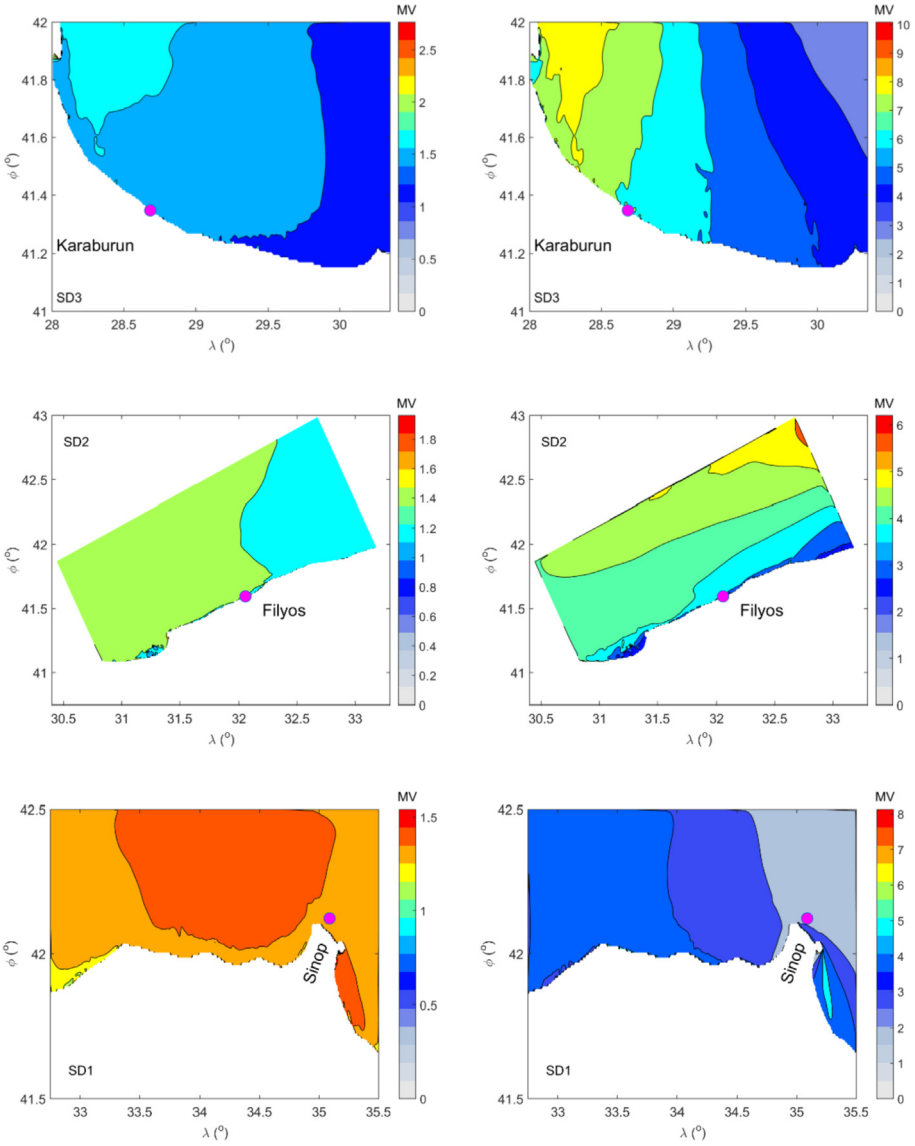


Fig. 6. Monthly variability index of the wave energy flux for 31 years (1979–2009) belonging to SD1 (Sinop), SD2 (Filyos) and SD3 (Karaburun) domains.

seen that Karaburun and Filyos domains in spring and Sinop domain in autumn show a higher variation coefficient of wave energy flux compared to the other seasons. It is not possible to have a stable wave energy flux in these seasons and thus, not suitable for wave energy exploitation.

3.3. Monthly and seasonal variability indexes

The stability of wave power in a region means that more energy can be obtained in that region. Monthly and seasonal variability indices, which are determined as the ratio of the differences between the highest and lowest monthly and seasonal wave energy flux (energy density) to the average wave energy flux of all years, determine the energy stability of a region. The higher the index of variability, the lower the energy stability in that region. Thus, energy exploitation in that region is unsuitable relative to low variability regions. Here, the variability index is calculated in two different ways. In the first, only average wave energy fluxes determined for 4 seasons for a period of 31 years were used. That is, the seasonal variability index was calculated as the ratio of the differences between average wave energy flux values of summer and winter seasons based on the whole data to the average wave energy flux values based on the whole data (left columns in Figs. 6 and 7). Monthly variability indices are determined by the ratio of the differences between wave energy flux values of the highest energy months of December, February and December and the lowest-energy months of August, July and August to the average wave energy flux based on the whole data in Karaburun, Filyos and Sinop domains, respectively. In the second, the calculation was made taking into account the average wave energy fluxes of the seasons and the months of each year for 31 years (right columns in Figs. 6 and 7). For example, the seasonal variability index for Karaburun was determined as the ratio of the differences between the most energetic 1981 winter season's average wave energy flux values and the least energetic 1981 summer season's average wave energy flux values among all years to average wave energy flux values based on whole data. The monthly variability index for Karaburun has been calculated as the ratio of the differences

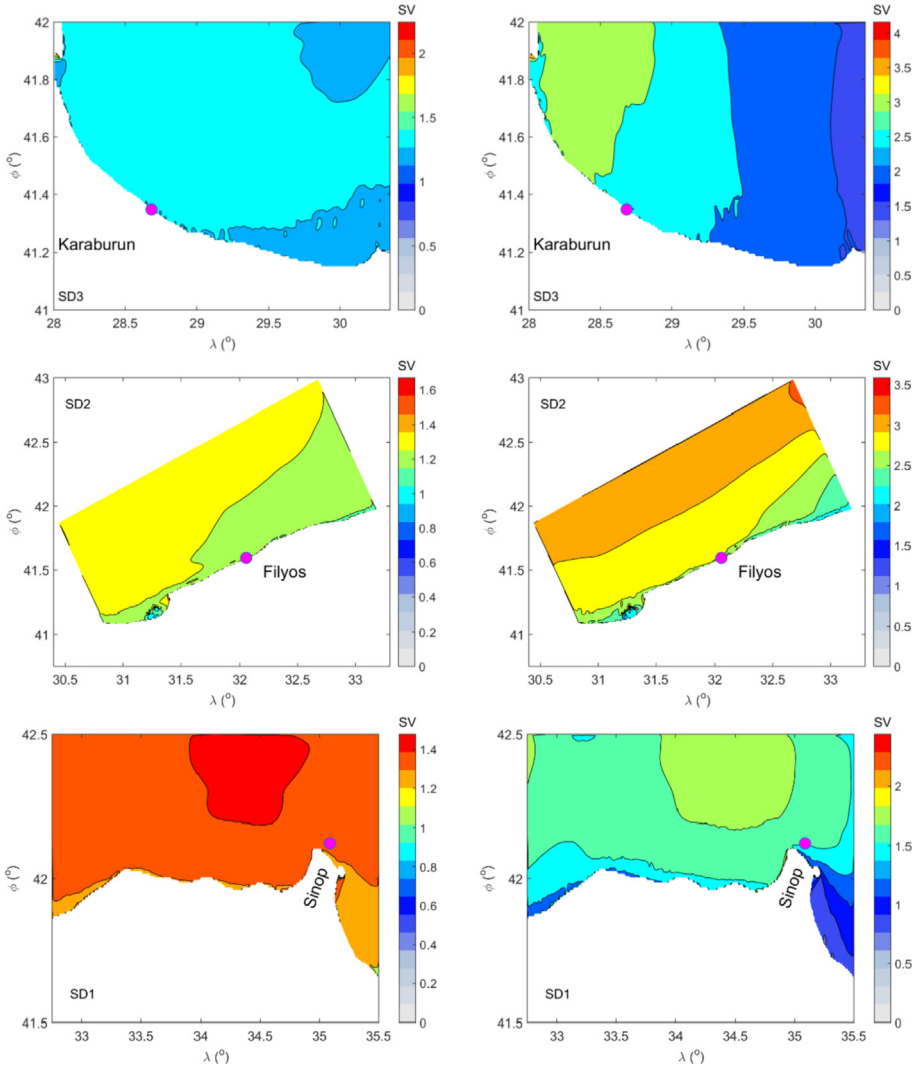


Fig. 7. Seasonal variability index of wave energy flux for 31 years (1979–2009) belonging to SD1 (Sinop), SD2 (Filyos) and SD3 (Karaburun) domains.

between the most energetic month of January 1981's average wave energy flux values and the least energetic month of May 1979's average wave energy flux values among all years to the average wave energy flux values based on whole data. Monthly and seasonal variability indices (right columns in Figs. 6 and 7) determined according to the second method provided higher values in each domain compared to those determined using the first method (left columns in Figs. 6 and 7). The monthly variability index in Karaburun domain (left column in Fig. 6), determined according to the first method, increases from 1 in the east to 1.7 on the Bulgarian border toward the west. Based on the second method (right column in Fig. 6), the monthly variability index increases from 4 in the east to a value of 8.1 toward the west of the domain. In Filyos, the monthly variability index in the west of the domain according to the first method decreased from 1.4 to 1.2 in the east. In Sinop, a monthly variability index of 1.3 was found in nearly the entire coastline, a value of 1.5 in the bay area east of the Sinop headland and a value of 1.2 along the coast from Kerempe headland toward the western part. According to the second method, the monthly variability index along the coast in Filyos was 4 and lower, while a monthly variability index lower than this value was obtained in the whole domain of Sinop.

The seasonal variability index determined by the first method (left column in Fig. 7) is approximately 1.25 across Karaburun. The value in Filyos is 1.2 along the shoreline and 1.3 offshore, while the entire domain of Sinop has values greater than 1.2. The seasonal variability index determined using the second method (right column in Fig. 7) is 1.5 on the east side of the Karaburun domain and increases to around 3 in the west. There is a seasonal variability index of around 2.7 in the middle of the Filyos domain. This value decreases towards the shore on both the east and west side of the domain having values in the range of 2.5–2. In Sinop, the seasonal variability index is around 1.5 along the coastal strip of the domain and this value decreases further towards the bay region to the east of the Sinop headland. As can be understood from all these results, in the regions where the wave energy flux is low, the variability index values become low and thus, it is more convenient to generate energy from the waves in such areas.

3.4. Total and exploitable wave energy reserves

The total and exploitable wave energy potentials for the three sub-domain regions are calculated based on Eqs. (9) and (10), and the spatial distributions for each sub-domain are given in Fig. 8.

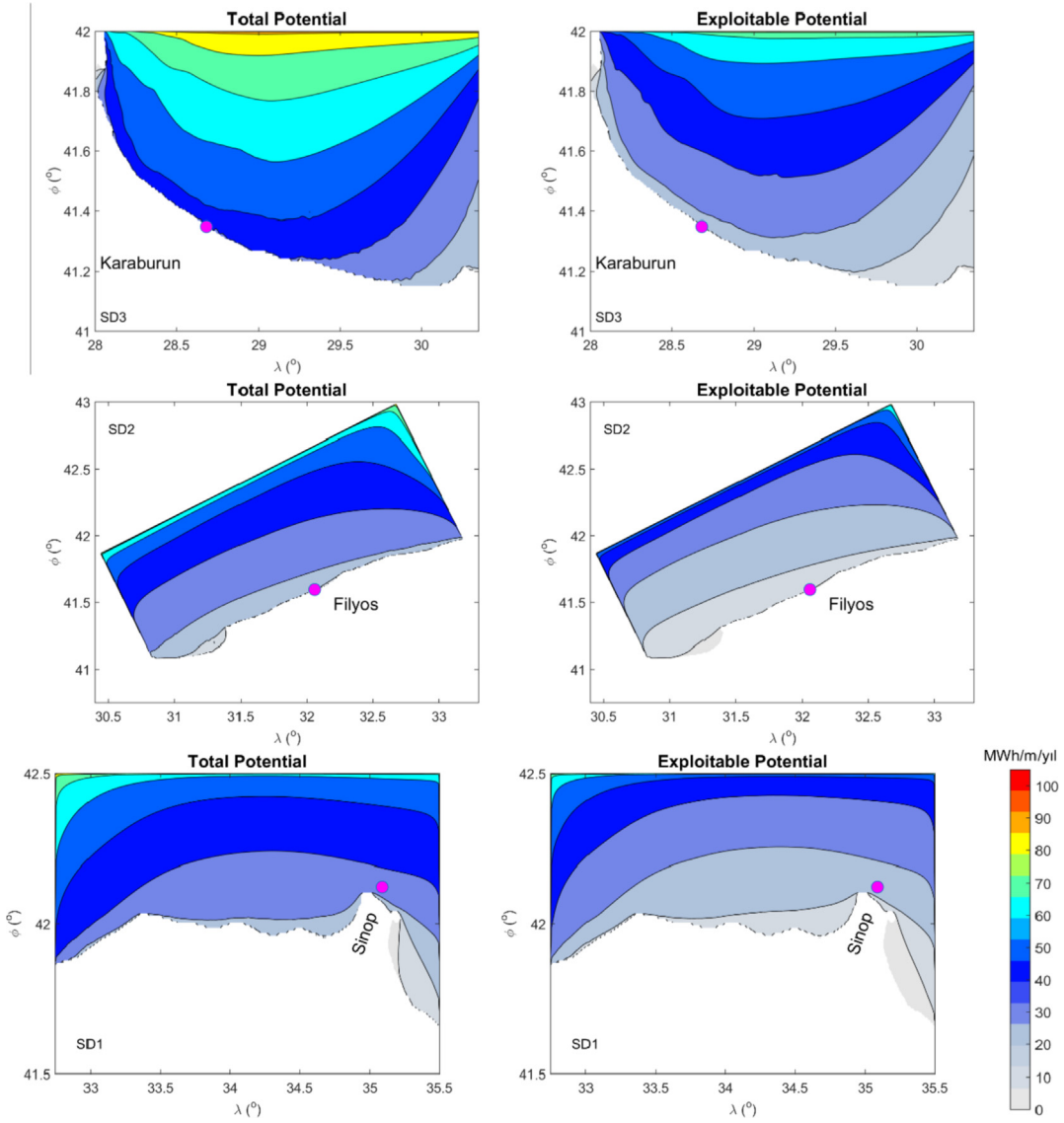


Fig. 8. Wave power total and exploitable potentials (MWh/m/yr) for years between 1979 and 2009 belonging to SD1 (Sinop), SD2 (Filyos) and SD3 (Karaburun) domains.

According to this figure, there is a total potential of 30 MWh/m/year on the eastern part of the Karaburun domain, 40 MWh/m/year along the shoreline from Şile to the Bulgarian border and 80 MWh/m/year towards the offshore. In the same domain, the exploitable wave energy potential has a spatial distribution similar to the total potential. However, a potential of 25 MWh/m/year is available off the Karaburun monitoring station toward the offshore and an even lower potential is registered in the other regions. Filyos has a total potential of 30 MWh/m/year and less along the entire coast of the domain and an exploitable wave energy potential of less than 20 MWh/m/year. The total potential in Sinop is less than 30 MWh/m/year along the coast, while the exploitable potential is less than 20 MWh/m/year and both total and exploitable potentials are increasing toward the offshore in the domains.

3.5. Annual and seasonal wave power roses

Some wave energy conversion systems remain stationary at the location where they are placed and can convert energy from approaching waves in a specific direction. In this case, when positioning wave energy conversion systems on a site, the directional analysis of the waves formed in that region is very important. Therefore, annual wave power roses based on whole data at all the selected stations in each sub-domain were obtained. In addition to these, due to seasonal variations being effective in the region, seasonal wave power roses are also obtained along with annual roses, but they are not present here to gain space and reduce figures. They can be found in http://www.blackseawaveenergypotential.com/. As seen in Fig. 9, energy can be generated from the waves coming from North (N) - East Northeast (ENE) at stations SD3_1 and SD3_2, North-Northeast (NE) at stations SD3_3 and SD3_4, West Northwest (WNW) - NE at station SD3_5, and Northwest (NW)-North Northeast (NNE) at station SD3_6. At all stations in this domain, most of the wave power is found between 0 and 5 kW/m. Except for station SD3_6, which has less than 10%, approximately 15% of the wave power at the other stations is greater than 5 kW/m. Despite the dominant direction being NNE, stations SD2_1 – SD2_3 within Filyos domain will be able to generate energy from the waves coming from West Northwest (WNW) –NE. In stations SD2_4 and SD2_5, energy would be produced from waves coming from West (W) - NE

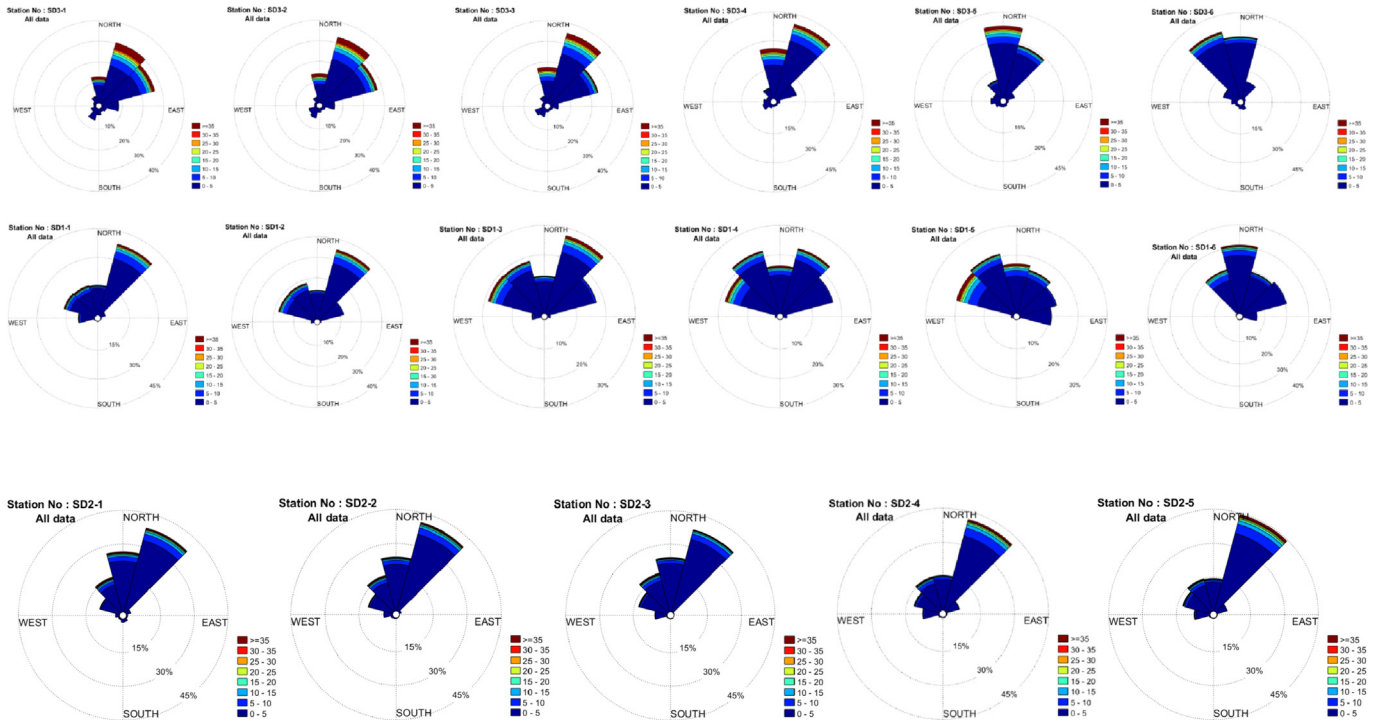


Fig. 9. Wave power roses for the selected stations within Karaburun SD3 (upper panel), Sinop SD1 (middle panel), and Filyos SD2 (lower panel) domains created on the basis of whole data (1979–2009).

directional range. About 10% of the waves present a wave power greater than 5 kW/m at all stations in this domain. At station SD1_1 within the Sinop domain, energy can be generated from waves in the direction W-NE, whereas at station SD1_6, energy would be generated from waves coming from NW-East (E). At the remaining stations in this domain, WNW-E directional range provides all available energy. Approximately 15% of the waves at all other stations except station SD1_6 (around 10%) have a wave power greater than 5 kW/m.

3.6. Probability exceedance curves

Cumulative probability density curves showing how dense the wave power in a zone is between the values or which values and their degree of exceedance are obtained based on the whole data (31 years) period for all selected stations in each sub-domain and are presented in Fig. 10. As seen from this figure, the wave power decreases from station SD3_1 to SD3_6 in Karaburun domain. This fall continues in Filyos domain, however, there is an increase at stations SD2_4 and SD2_5. The wave power potential also drops at station SD1_6 after the headland of Sinop. The probability of the wave power, which is greater than 1 kW/m and 10 kW/m, is 30% and 2.5% at station SD3_6, 41% and 8.5% at station SD3_5 and about 58% and 17.5% at station SD3_1, respectively. In the Filyos domain, the probability of the wave power being over 1 kW/m is 40% at stations SD2_1 – SD2_3, 47% at stations SD2_4 and SD2_5, and around 3.5% of being above 10 kW/m at all stations in this domain. Finally, in Sinop, the probability of wave power being greater than 1 kW/m is 52% at stations SD1_4 and SD1_5 and 9% of being over 10 kW/m. These values are approximately 41% and 5%, respectively, at station SD1_6.

3.7. Annual average wave energy at different wave period and height intervals

Wave energy converters have a power matrix for different significant wave height and energy period ranges for wave energy conversion. Thus, wave energy conversion is determined by establishing a correlation between the power matrix values and the current wave climate for these different wave heights and energy period ranges. Determining the annual mean energy amount at different significant wave height and energy period intervals in a region is, therefore, extremely important. It was therefore obtained for all selected stations in each sub-domain and the results were presented in Figs. 11 to 13. Annual mean wave energy at all stations in the Karaburun domain is concentrated over a significant wave height range of 0.2–1.5 m and an energy period of 2–5 s (Fig. 11). The highest annual average wave energy among the stations was observed at stations SD3_1. At stations belonging to the Filyos domain, the highest average annual wave energy is observed in the range of 0.2–1.5 m wave height and 3–7 s energy period (Fig. 12). Annual average wave energy has a maximum at 0.2–1.5 m significant wave height and 2.5–6.5 s wave period (Fig. 13) at stations within Sinop domain.

4. Conclusions

In this study which focuses on the analysis of the potential and variability of the wave energy of the south-west coasts of the Black Sea, a 31-year long-term simulation was performed to accumulate the desired wind/wave parameters. From these accumulated parameters, the wave energy flux of the study area was calculated. As a result, based on this long-term data, the wave energy of the region was revealed from different perspectives of its potential and variability. The results obtained can be summarized as follows.

- ✓ The wave energy flux in Karaburun SD3 sub-grid increases from the east towards the west.
- ✓ Karaburun has an average wave power of 5 kW/m from the monitoring station to the border of Bulgaria.

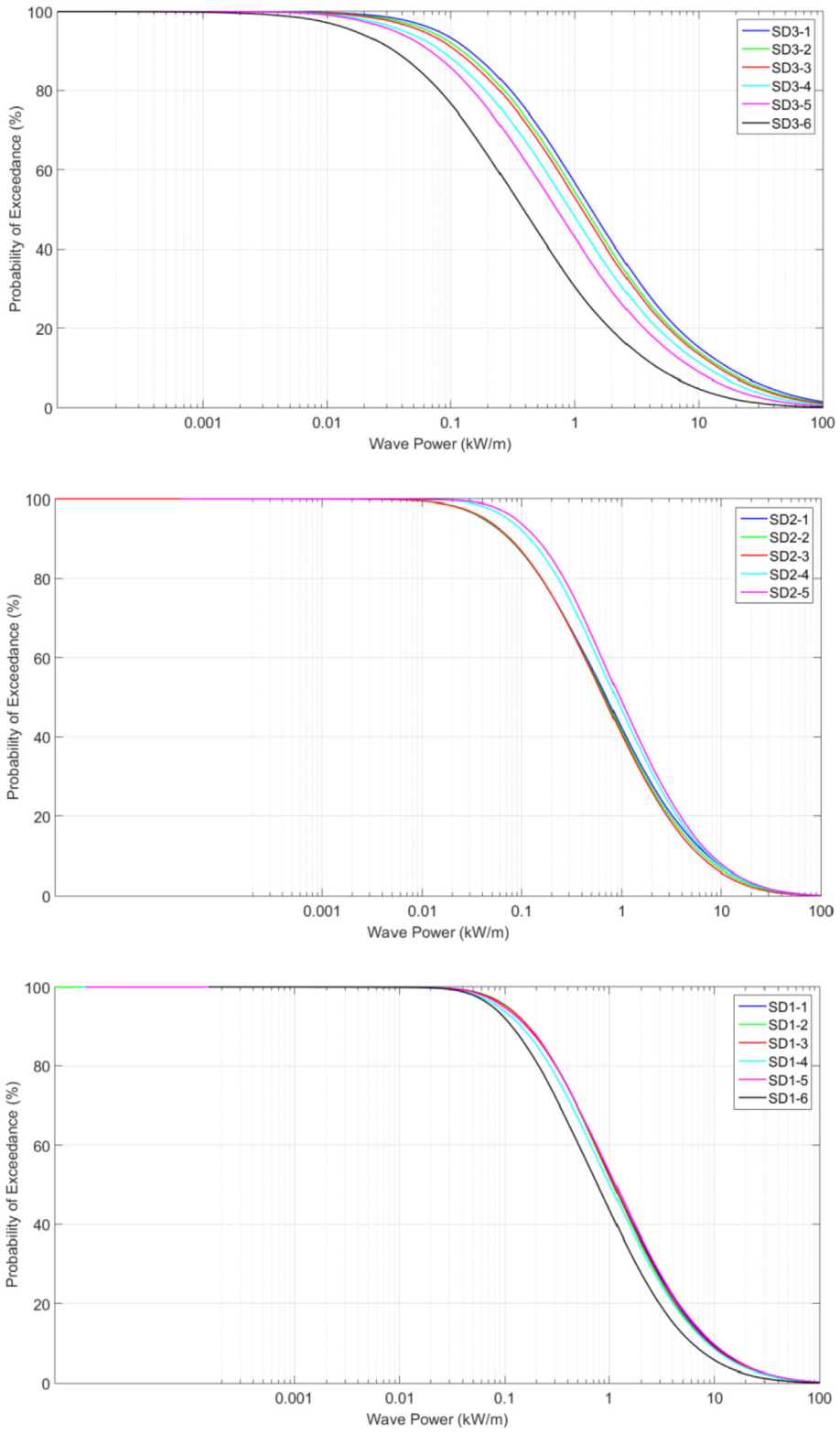


Fig. 10. Graphs for probability of exceedance of the wave power based on whole data (1979–2009) belonging to all selected stations within SD3 (Karaburun), SD2 (Filyos) and SD1 (Sinop) domains.

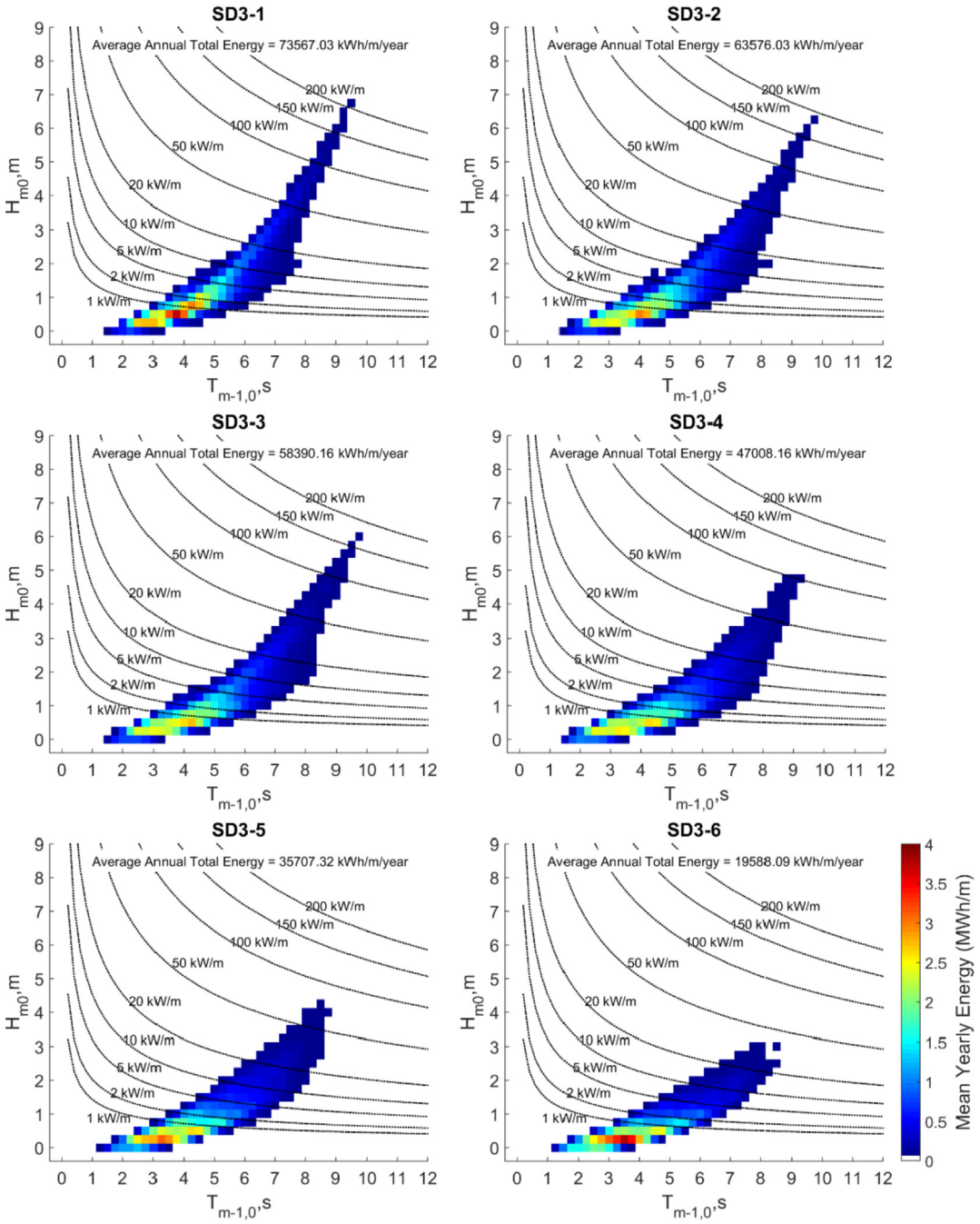


Fig. 11. Annual average wave energy available at different wave period and height intervals for all selected stations in SD3 (Karaburun) domain based on whole data (1979–2009).

- ✓ The Filyos sub-grid has a wave energy flux of 4 kW/m or less in the nearshore region, and Sinop sub-grid even lower wave energy in the nearshore.
- ✓ In all sub-grids, the lowest wave energy flux is found to be 2 kW/m and/or lower in the summer, and the highest wave energy flux is observed during the winter season followed by the autumn season.
- ✓ The highest average wave energy flux occurs at about 10 kW/m in the western region of Karaburun sub-grid.
- ✓ In the regions where the average wave energy flux is high, the wave energy flux has a high coefficient of variation, and thus the regions having lower wave energy flux have a stable wave energy flux which is ideal for energy exploitation.
- ✓ The monthly variability coefficient for the Karaburun and Filyos sub-grids decreases from the west toward the east. This suggests that the western regions are less suitable for energy extraction relative to the east.
- ✓ Monthly and seasonal variability index values are low in regions with low wave energy flux which are more convenient for energy exploitation.
- ✓ At the westernmost part of the Karaburun sub-grid, the total potential is 40 MWh/m/year, decreasing to 30 MWh/m/year in the east and the same value or slightly lower value is observed in Filyos and Sinop sub-grids.
- ✓ Although the exploitable wave energy potential is similar to total potential in terms of spatial distribution, the Karaburun

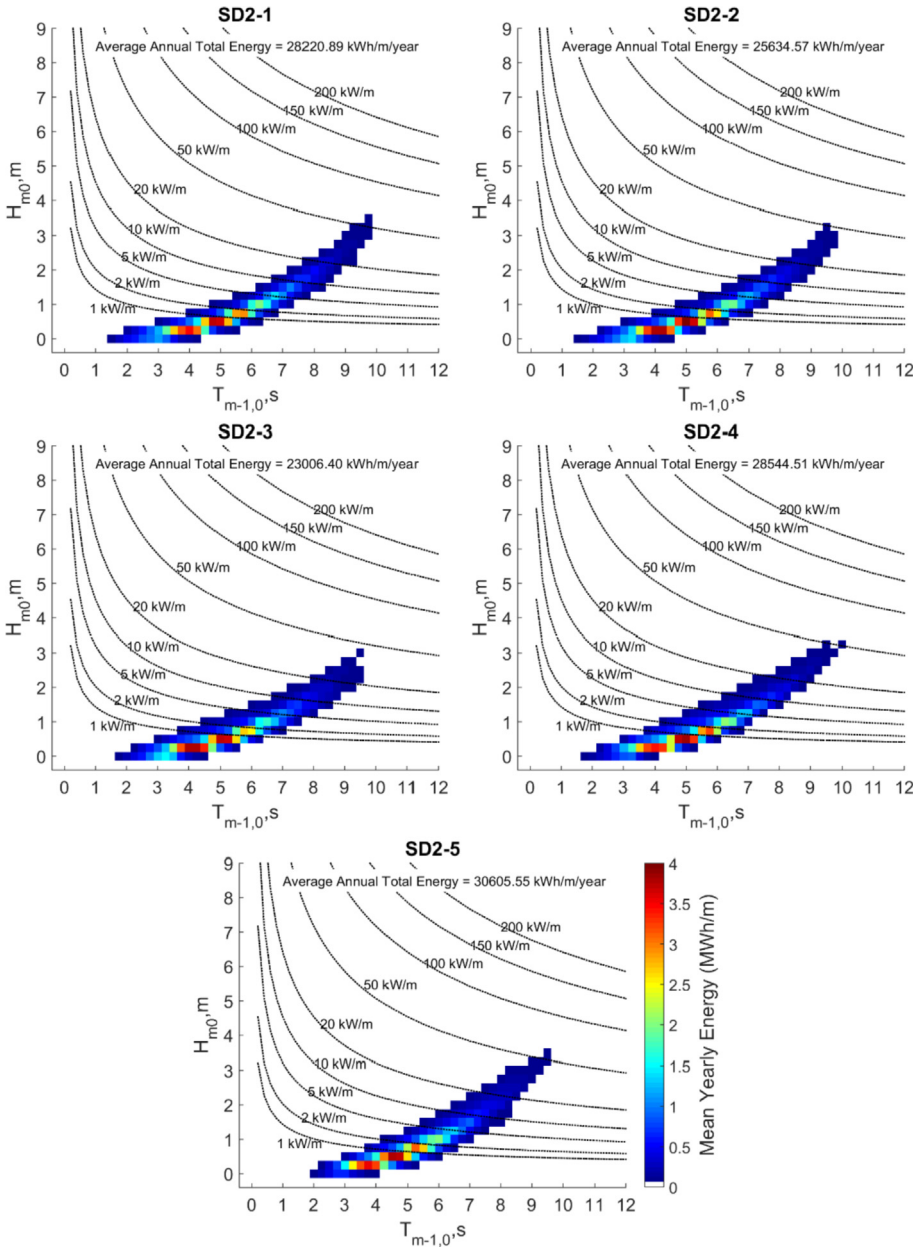


Fig. 12. Annual average wave energy available at different wave period and height intervals for all selected stations in SD2 (Filyos) domain based on whole data (1979–2009).

monitoring station has an exploitable potential of 25 MWh/m/year toward the offshore, while the potential is lower (less than 20 MWh/m/year) in the other regions.

✓ Among the stations selected in Karaburun sub-grid, the highest annual average total energy is at station SD3_1 in the west of the sub-grid with 73.57 MWh/m/year. The lowest is 19.59 MWh/m/year at station SD3_6 in the east.

✓ Annual average wave energy at all stations in all three sub-grids is concentrated at 0.2–1.5 m significant wave height range. The concentration is between 2 and 5s in Karaburun, 3–7 s in Filyos and 2.5–6.5s in Sinop in terms of the wave energy period.

All these results provide all necessary information on the energy that can be generated, the potential of wave energy and its variability, the value of installation, design, energy capacity, location of a wave energy power plant to be established in the area of interest and can serve as a guide for everyone interested in this sector. For Turkey, which imports a significant portion of the energy it consumes, putting wave energy as an alternative energy source, is thought to enable studies towards ways of benefiting from this source. Because of this, for the future studies, it is necessary to investigate the power production performance of existing wave energy converters at different depths in enclosed seas to see if the existing wave energy converters are suitable or not. If the existing devices are not suitable in the area, then it is recommended to scale the devices down or up and see their performances. In addition, for the stability and sustainability of the wave energy converters, it is highly recommended for future studies to look over the extreme wave conditions in the Black Sea.

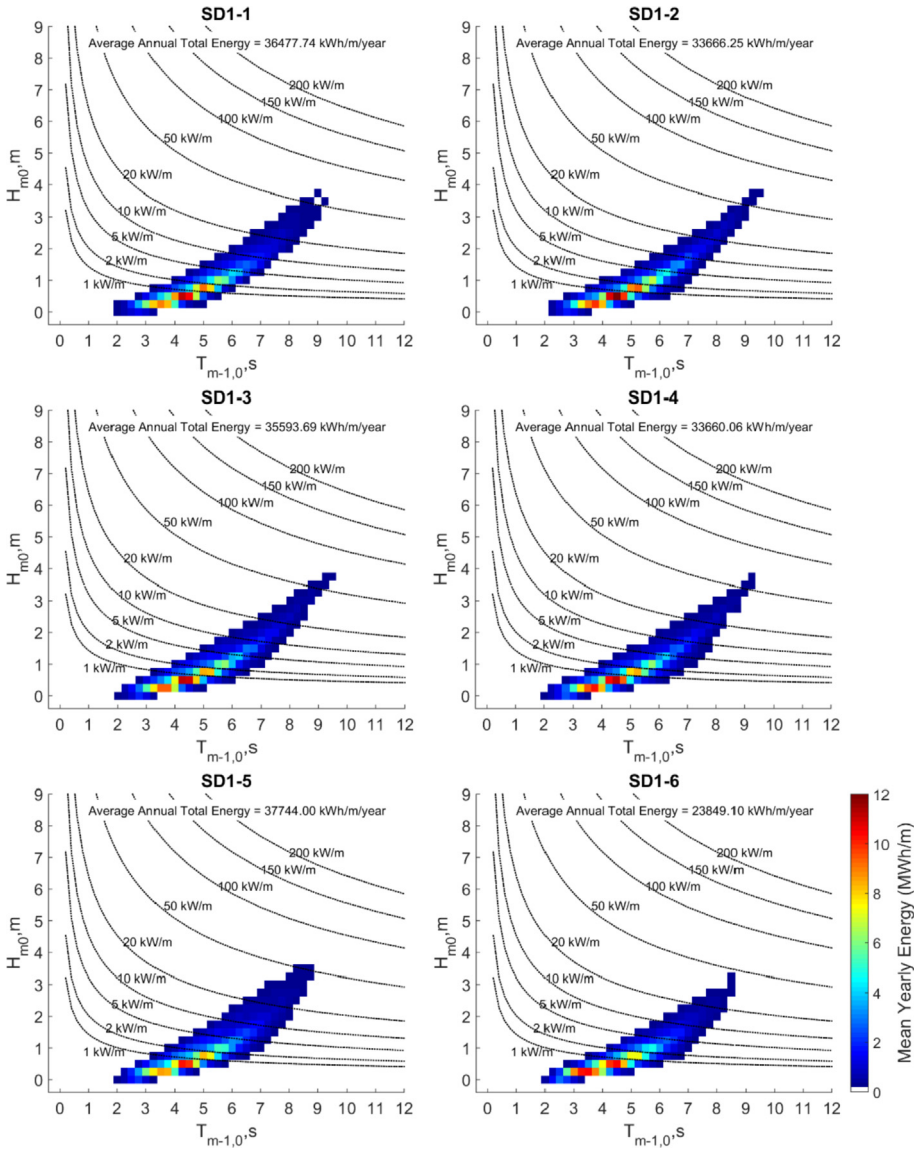


Fig. 13. Annual average wave energy available at different wave period and height intervals for all selected stations in SD1 (Sinop) domain based on whole data (1979–2009).

Credit author statement

Bilal Bingölbali: Methodology, Software, Investigation, Validation, Formal analysis, Resources, Data curation, Visualization. **Halid Jafali**: Methodology, Investigation, Writing- Original draft preparation. **Adem Akpınar**: Conceptualization, Writing- Reviewing and Editing, Project administration Supervision. **Serkan Bekiroğlu**: Software, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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