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The Changes of Theoretical Wave Power from Offshore to Coast in the South-western Black Sea

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Abstract. This study concentrates on the changes of theoretical wave power from offshore to coastal regions of south-western Black Sea. The investigation also offers a long-term (31-year) wave power quantification analysis between 1979 and 2009 using the SWAN version 41.01AB numerical wave model. The wave resource assessment is performed in terms of its seasonal and monthly variability of wave power, annual wave power directional distributions and the comparison of the maximum and median values of some important wave power parameters in the west of Istanbul a major city in Turkey that straddles Europe and Asia across the Bosphorus Strait. For this analysis, 10 point locations distributed on two perpendicular lines (KA and KE) to the coastline with five different depths (5, 25, 50, 75, and 100 m) in the areas of interest were selected. The data needed was extracted from the dataset produced by [1, 2] using a calibrated nested layered wave hindcast model SWAN forced with CFSR winds. The results show that the wave energy resource in the study area is high, and the potential locations can be considered for extracting wave electrical power.

1 Introduction

By the time energy demand is increasing very fast on the earth, if we do not find various clean energy resource options, fossil energy will cause lots of negative impacts on the environment. One of these impacts is the greenhouse gasses, which is a fatal warning for lives on the earth. The power in the ocean waves is a very good candidate to become one of the options of future renewable energy. The ocean wave power is a vast clean energy source, but it's very new and under investigation. If we look back to twenty years ago, the wind energy was in the same place as ocean wave energy is today. The most familiar and common method to extract energy is using steam and turbine mechanism. The only problem to extract the huge wave electrical power is designing a suitable technology for wave power. A lot of research companies and universities nowadays are working hard to solve this problem. There are many prototype wave energy farms working nowadays, but they are not commercial yet. Another essential aspect for extracting wave power is to investigate the interested geographical locations to have some ideas about the status of waves and the wave power, the continuity, or the variability of wave power distribution in time. It's also very important to choose the most energetic place with the lowest variability in wave power seasonally and annually. The characteristics mentioned above are investigated in five different depths from very deep water to very shallow water (shoreline).

2 Study area and the wave data

The Black Sea is located between 40°.56'-46°.33N' latitudes and 27°.27'-41°.42'E Longitudes. It has 461000 km^2 surface area, including the Azov Sea, with a 0.55 million km^3 water volume. The Black Sea has a total of 8350 km of coast length, with approximately 1300 m mean and 2588 m maximum water depth. This study focuses on the high energy potential areas (the south-west) of the Black Sea [2]. The 31-year (1979-2009) long-term estimations of wave parameters along the south-west coast of the Black Sea were produced for every location under our previous TUBITAK Project [3] are extracted from the database of intense wind and wave data for each location. This data set was produced using a three nested grid system, which contains a coarse grid including all of the Black Sea, a fine grid including the western Black Sea, and a sub-grid domain including near Karaburun in the south-west of the Black Sea. In this layered nested grid system, waves are firstly generated on a regular computational domain which covers the entire Black Sea; then calculations are made on a finer regular grid covering the western part of the Black Sea with boundary conditions from the previous regular grid domain which covered all the Black Sea. Finally, with the boundary conditions provided by this fine domain, a long-term wave database is created in a high-resolution sub-grid domain Karaburun. Detailed information on the calibration and verification of the coarse grid can be found in [1]. Furthermore, although

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an article on the detailed calibration and verification of the nested grid system is already published [4], the initial findings are presented in a conference paper [5]. Therefore, all the wave parameters needed for each location from this specified data set are taken for 31 years (1979-2009) at a time resolution of 2 hours. The bathymetry, fine grid, and nested domain Karaburun are shown in Fig.1.

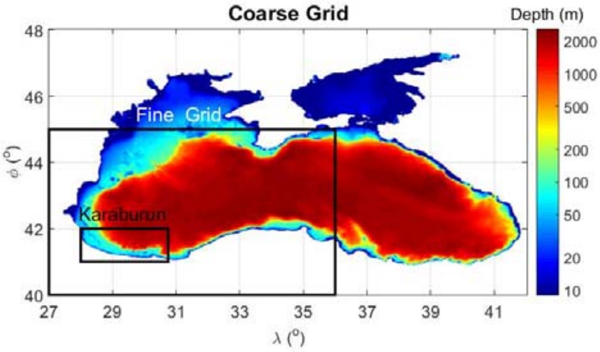

Fig. 1. The bathymetry map of the Black Sea, The coarse grid, Fine grid, and sub-domain Karaburun.

The bathymetry for the wind-wave modeling of the Black Sea was obtained from General Bathymetric Charts of Oceans [6], which is prepared by The British Oceanographic Data Center (BODC). The resolution of latitude and longitude was 0.008333°. For the forcing of the SWAN model, the CFSR winds [7] at 10 m above the surface of the water with a spatial resolution of 0.3125° and a time resolution of 1 hr was used. The coordinates and depth of the chosen 10 locations in the study area are given in Table 1.

Table 1. The coordinates and depth of the chosen locations in the study area

Location	Location ID	Xp(°)	Yp(°)	Depth(m)
KA1	1	28.0625	41.8913	4.1
KA2	2	28.0938	41.8913	25.2
KA3	3	28.1250	41.8913	54.3
KA4	4	28.2437	41.8913	74.8
KA5	5	28.5688	41.8913	99.5
KE1	6	30.3188	41.2043	7.2
KE2	7	30.3188	41.2174	25.9
KE3	8	30.3188	41.2348	50.8
KE4	9	30.3188	41.3000	75.7
KE5	10	30.3188	41.3348	99.3

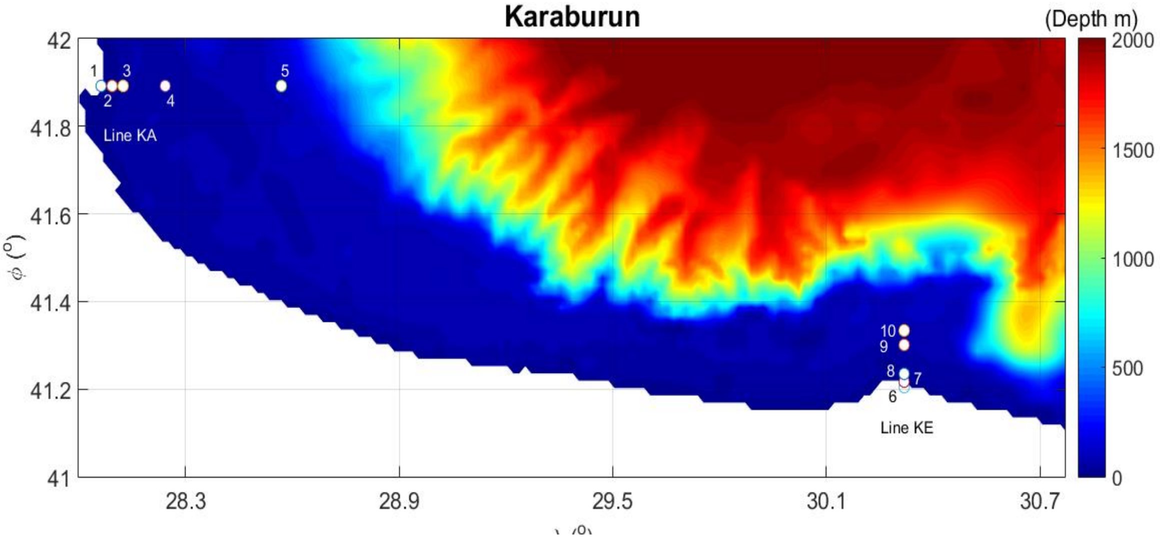

Fig. 2. The sub-domain Karaburun with the selected 10 locations on two perpendicular lines to the coastline

As the water density is 800 times more than air, sea waves have the highest energy density among the other renewable energy resources. Prof. Salter from the University of Edinburgh under the lab conditions has shown that it's possible to convert more than 81% of wave energy into electricity [8]. The wave power is calculated with the following equation.

$$P_w = \frac{\rho g^2 T_e H_s^2}{64\pi} \qquad (1)$$

In the above equation, P_w is wave power in deep water, ρ is water density (1030 kg/m^3), g is gravity constant (9.81 m/s^2), T_e is wave energy period, and H_s is the significant wave height [9].

3 Results

The mean annual wave power at every location is given in Table 2. If we compare the first 5 locations which are located on the line KA, the mean wave power is almost three times higher than the locations on the line KE. Thus, in Karaburun for establishing a wave energy converting farm, the line KA is the possible choice.

Table 2. 31-year long-term annual mean wave power at all selected locations

Location	Annual Mean Power (kW/m)	Location	Annual Mean Power (kW/m)
KA1	2.62	KE1	1.87
KA2	5.67	KE2	2.40
KA3	6.34	KE3	2.67
KA4	7.18	KE4	2.90
KA5	8.29	KE5	3.03

In order to have an idea about the wave power variability in 31-year long-term wave analysis, the monthly and seasonal wave power variability indices (Fig. 3) are calculated with the following equation.

$$V_i = \frac{(P_{w\max} - P_{w\min})}{P_{wmean}} \qquad (2)$$

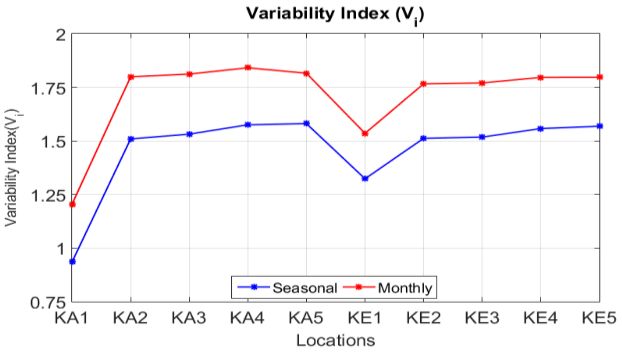

Fig. 3. Seasonally and monthly wave power variability indices at all the selected locations

As it was expected, the locations with the lowest depth have the most moderate variability in wave power. It is also seen that seasonally variability is lower in comparison with the monthly variability.

Another important parameter which is investigated in here is the directional distribution of wave power (wave power roses). The annual wave power roses of all selected locations are shown in Fig. 4.

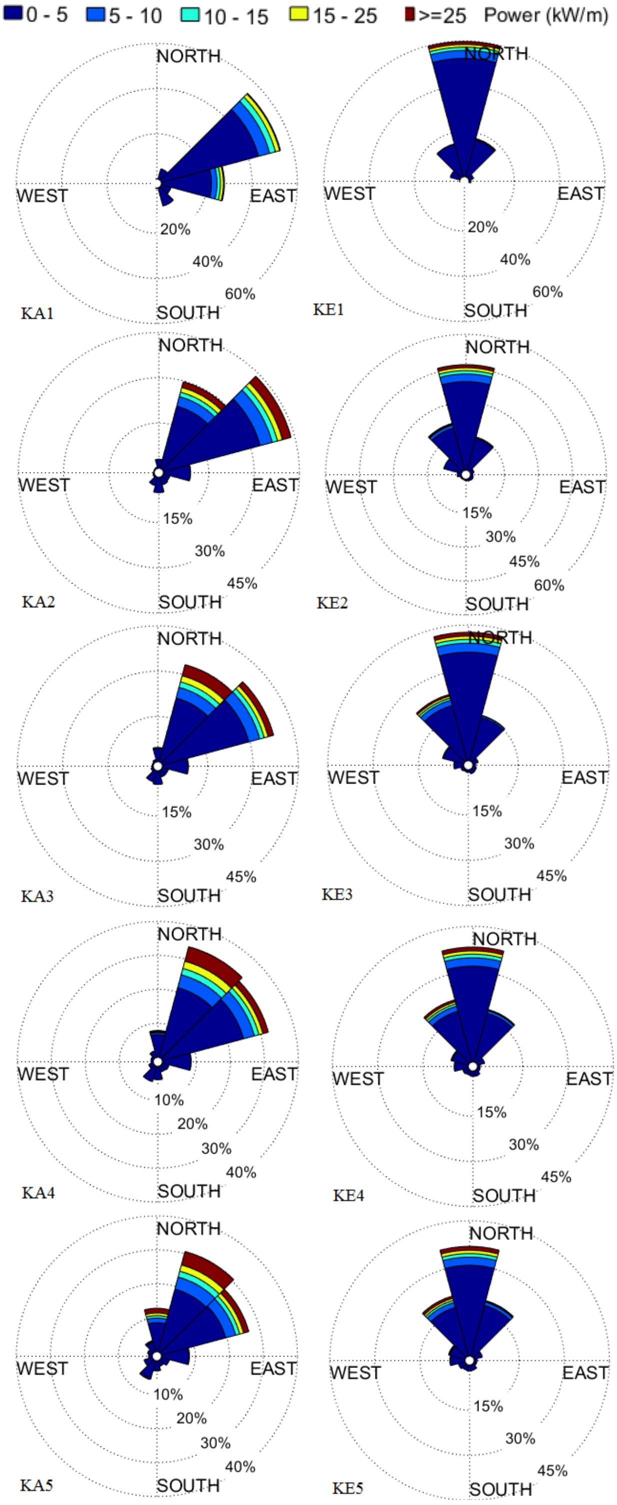

Fig. 4. Wave power roses. The five locations of the line KA are in the left column, and the five locations of line KE are in the right column of the figure.

According to the wave power roses in Fig. 4, the dominant annual wave direction for the locations on the Line KA is between NNE-NEE, and for the locations on the Line KE, the wave direction varies between NNW-NE.

Median and maximum values for the main wave parameters in the Karaburun computational domain for 10 locations in two different lines perpendicular to the coastline as the result of the SWAN simulation performed in a 31-year time period (1979-2009) in Table 3. The comparison of the main wave parameters for winter and summer median values in the Karaburun computational domain for 10 locations in two different lines perpendicular to the coastline as resulting of SWAN simulation performed in a 31-year time period (1979-2009 are given in Table 4.

Table 3. Annual median and maximum values for the main wave parameters in the Karaburun computational domain for all the selected locations

Locations	H_{smed}/H_{smax} (m)	T_{emed}/T_{emax} (s)	T_{pmed}/T_{pmax} (s)	P_{wmed}/P_{wmax} (kW/m)	DIR_{med} (°)	E_{med}/E_{max} (kW/m*hr)
KA1	0.5/2.6	4.4/12.8	3.3/10.3	0.6/41.8	198.7	1.1/83.6
KA2	0.7/9.6	4.1/12.7	3.1/10.5	0.9/564.0	215.6	1.8/1128.0
KA3	0.7/10.1	4.1/12.5	3.1/10.3	0.9/608.7	218.4	1.9/1217.4
KA4	0.7/11.1	4.1/12.3	3.1/10.3	1/721.3	221.3	2.1/1442.5
KA5	0.8/12.8	4.1/12.7	3.2/10.9	1.2/1015.3	224.5	2.5/2030.7
KE1	0.4/4.4	3.8/13.7	2.9/11.4	0.3/130.4	270.9	0.6/260.7
KE2	0.5/9.8	3.8/13.6	2.8/10.9	0.4/637.0	276.2	0.8/1274.0
KE3	0.5/10.1	3.7/13.5	2.8/10.8	0.4/658.8	276.2	0.9/1317.6
KE4	0.5/10.3	3.7/13.1	2.8/10.4	0.5/667.0	273.1	1/1334.0
KE5	0.5/10.7	3.7/13.1	2.8/10.4	0.5/719.1	271.8	1/1438.1

Table 4. Comparison of median values of the main wave parameters for winter and summer in the Karaburun computational domain for all the selected locations

Locations	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
No	$H_{s\ med}$ (m)		$T_{e\ med}$ (s)		$T_{p\ med}$ (s)		$P_{w\ med}$ (kW/m)		DIR_{med} (°)	
KA1	0.58	0.51	4.50	4.15	3.31	3.16	0.73	0.50	200.5	200.2
KA2	0.77	0.65	4.22	4.03	3.17	3.12	1.20	0.81	222.2	216.3
KA3	0.80	0.66	4.23	4.02	3.17	3.11	1.30	0.84	226.9	218.4
KA4	0.89	0.68	4.25	4.01	3.28	3.10	1.58	0.89	231.4	221.5
KA5	1.00	0.71	4.37	4.00	3.43	3.12	2.07	0.98	235.7	225.6
KE1	0.45	0.44	4.30	3.56	3.32	2.77	0.42	0.34	274.2	265.6
KE2	0.56	0.49	4.22	3.60	3.15	2.76	0.61	0.42	281.8	268.9
KE3	0.61	0.50	4.18	3.58	3.11	2.73	0.70	0.42	282.9	269.0
KE4	0.67	0.51	4.09	3.54	3.07	2.69	0.86	0.44	279.1	267.3
KE5	0.70	0.52	4.09	3.53	3.08	2.67	0.95	0.46	277.1	266.2

Annual and seasonal mean and maximum wave power changes from 1979 to 2009 are respectively given in Fig 5 and Fig 6 at location KA5. The same figures for the other locations will be presented in the PowerPoint presentation.

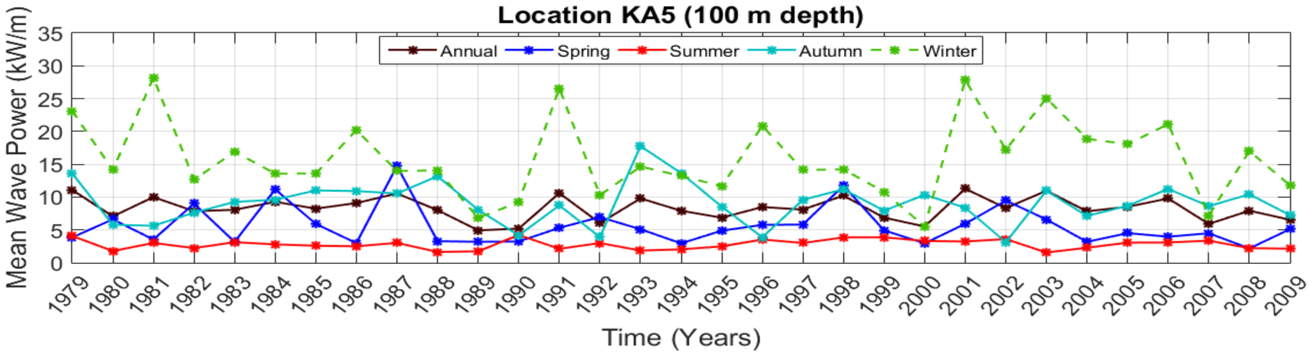

Fig. 5. The annual and seasonal variations of averaged theoretical wave power at location KA5 (100 m depth).

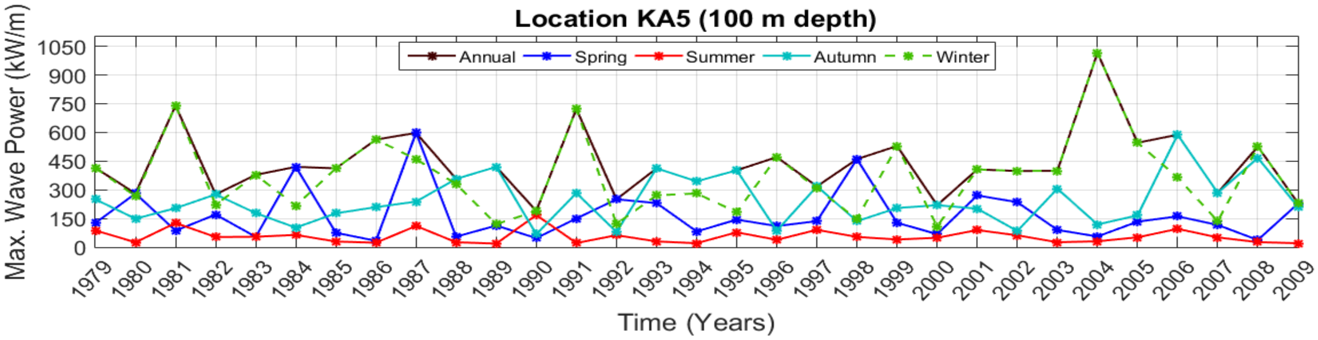

Fig. 6. The annual and seasonal changes of maximum theoretical wave power at location KA5 (100 m depth).

In Table 3, site KA5 (100 m depth) reports an average annual median of 0.8 m with a maximum of 12.8 m wave height and the mean annual median theoretical wave power of this site is 1.2 kW/m with a maximum of 1015 kW/m in the long-term 31-year wave hindcast which present it as the most energetic location in the area. The seasonal statistics of the analysis in Table 4 also show KA5 as the best choice for the extraction of wave energy in the interest area. The mean seasonal wave power potential at location KA5 is the highest for winter with three peak values in 1981, 1991, and 2001, with the two lowest values in 1989 and 2000 along the long-term 31-year period in Fig. 5. Summer presents the lowest wave power potential. The annual and winter maximum values of wave power potential report the highest values in 2004 and the lowest value in 1990 (Fig. 6).

4 Conclusion

The development of renewable energy plays a vital role in a country. Therefore, in order to contribute to the development of renewable energies, all local resources need to be evaluated in detail. Wave energy is one of the uncovered energy treasures that can make a significant positive change in electrical power. Currently, the potential of uncovered wave energy in Turkish coastlines of the Black Sea is not investigated enough. Thus, in order to enhance the light on convertible wave power in the south-western coasts of the Black Sea, a 31 year (1979-2009) wave power resource assessment was presented in this research work. An appropriate nearshore numerical model was used in a three-level (Coarse grid, Fine grid, and high-resolution Sub-grid) nested layered mode to hindcast the ocean waves' energy resource levels. The study investigated the theoretical wave power, annual variations of wave power, and the power roses, which shows the direction of force by the use of statistical indices, which can interpret the available power resources and their variations clearly. In SWAN analysis coarse mesh gives the vital information as input to fine mesh and the fine mesh gives the inputs to the finest grid (sub-domain), and the nested high-resolution sub-domain provides the important wave parameters like significant wave height (H_s), T_{m-02} mean wave period, T_{m-10} wave energy period, etc. for all the study area spatially and interested locations. The results show that the wave energy resource in the study area is high, and the potential locations can be considered for extracting wave electrical power. For example, the average annual theoretical wave power at location KA5 (Depth 100 m, Land distance 40 km) is 8.3 kW/m while the mean significant wave height is 1.14m, and the maximum significant wave height is changing between 6 - 13 m.

The wave resource of the study area can be considered significant and can be studied in detail on the applicability of wave energy resource applications. Medium range scaled wave energy converters, which are based on significant wave height and wave period of a long term examination of the resource, can deliver reliable electrical power, can be adapted to the area.

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