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DETERMINATION OF WAVE ENERGY POTENTIAL OF BLACK SEA

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This study aims to assess wave energy potential and its long-term spatial and temporal characteristics in the Black Sea within the TUBITAK research project (Akpınar et al., 2015). With this purpose, a wave model (SWAN model version 41.01 driven by the CFSR winds) over the entire Black Sea was constructed. The model was calibrated using buoy data from 1996 at three offshore locations (Gelendzhik, Hopa, and Sinop) obtained within NATO TU-WAVES Project. The calibrated model was also validated using buoy data unused in calibration at five locations (Gelendzhik, Hopa, Gloria, Filyos, and Karaburun). Using this model a database including many of integral wave parameters (such as H_{m0}, T_{m-10} etc.) was produced. Long-term variability of wave energy in the Black Sea basin over a period of 31 years was determined. Finally, hot-spot areas for harvesting wave energy in the Black Sea were identified.

Keywords: SWAN, Wind-wave modelling, Wave Energy Potential, Black Sea

INTRODUCTION

Wave energy is a resource which has the highest marine energy density available in seas. Also, worldwide it is considered as an attractive alternative source of renewable energy, both from reducing CO_2 emissions as well as from independence of external sources. Therefore, assessment of its potential in sea areas is considered to be of great importance all over the world and the number of studies in this field increases rapidly. For the Black Sea, however, only a limited amount of studies has been carried out so far, providing only a crude estimate of its wave energy potential. In view of increasing computational resources and improved wind wave models we have carried out a study to accurately assess the wave energy potential for the Black Sea (Akpınar et al., 2016).

This paper summarizes the work done to assess this energy potential and its spatial and temporal characteristics in the Black Sea within the TUBITAK research project (Akpınar et al., 2015). For this purpose, the third-generation numerical wave hindcast model SWAN has been applied. Within the study, firstly, a SWAN wave model for the entire Black Sea was established. Secondly, we optimized the whitecapping coefficient in the physical settings of the SWAN model for the Black Sea by calibrating source term settings for deep water. Calibration and validation of the SWAN model was carried out with buoy measurements at six buoy locations (Hopa, Gelendzhik, Gloria, Sinop, Filyos, and Karaburun) (Figure 1). Thirdly, a 31-year long-term simulation was performed using the SWAN model and driven by hourly CFSR wind fields. This resulted in a huge data base of wind and wave parameters at a grid covering the entire Black Sea. Lastly, this database was analysed to obtain the spatial and seasonal variations of the wave energy potential of the Black Sea. This information is required to identify hot-spot areas to determine optimal locations for Wave Energy Converters (WEC).

SWAN MODEL

SWAN is a third-generation wave model for obtaining realistic estimates of wave parameters in coastal areas, lakes and estuaries from given wind, bottom and current conditions. However, SWAN can be used on any scale relevant for wind-generated surface gravity waves. The model is based on the wave action balance equation with sources and sinks. The source/sink terms (S_{tot}) represent all physical processes which generate, dissipate, or redistribute wave energy. They are defined for wave variance density spectra $E(\sigma, \theta)$ as a function of frequency σ and direction θ. In shallow water, six processes contribute to S_{tot}. These terms denote, respectively, wave growth by the wind, nonlinear transfer of wave energy through three-wave and four-wave interactions and wave decay due to whitecapping, bottom friction and depth-induced wave breaking. Transfer of wind energy to the waves is described with a resonance mechanism (Phillips, 1957) and a feed-back mechanism (Miles, 1957). Based on the two wave growth mechanisms, wave growth due to wind commonly described as the sum of linear and exponential growth term of a wave component:

$$S_{inp}\left(\sigma,\theta\right) = A + B\,E(\sigma,\theta) \qquad (1)$$

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in which A and B depend on wave frequency and direction, and wind speed and direction. The effects of currents are accounted for by using the apparent local wind speed and direction. The expression for the term A is due to Cavaleri and Malanotte-Rizzoli (1981) with a filter to avoid growth at frequencies lower than the Pierson-Moskowitz frequency (Tolman, 1992). Two optional expressions for the coefficient B are used in the SWAN model. The first is taken from an early version of the WAM Cycle 3 model (the WAMDI group, 1988). It is due to Snyder et al. (1981), rescaled in terms of friction velocity U_* by Komen et al. (1984). The second expression for B in SWAN is taken from the WAM Cycle 4 model (Komen et al., 1994). It is due to Janssen (1991a) and it accounts explicitly for the interaction between the wind and the waves by considering atmospheric boundary layer effects and the roughness length of the sea surface. The corresponding set of equations is solved (as in the WAM model) with the iterative procedure of Mastenbroek et al. (1993).

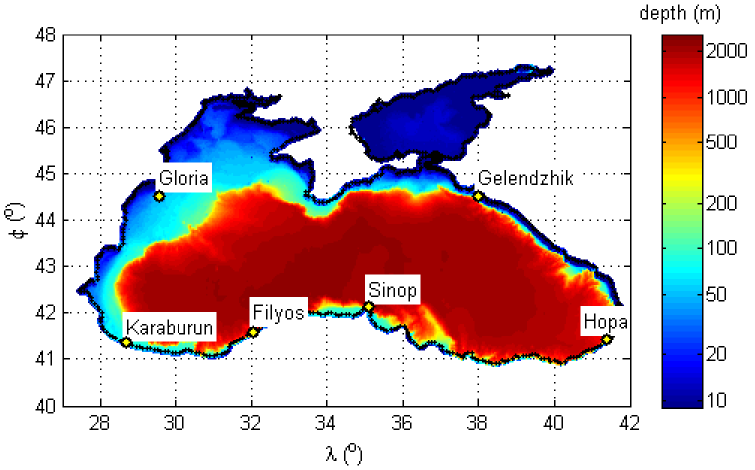


Figure 1. Study area, its bathymetry, and buoy locations

The dissipation term of wave energy is represented by the summation of three different contributions: whitecapping ($S_{ds,w}$), bottom friction and depth-induced breaking. Whitecapping is primarily controlled by the steepness of the waves. In most present day operating third-generation wave models, the whitecapping formulations are based on a pulse-based model (Hasselmann, 1974), as adapted by the WAMDI group (1988):

$$S_{ds,w}(\sigma,\theta) = -\Gamma\,\bar{\sigma}\,\frac{k}{\bar{k}}\,E(\sigma,\theta) \qquad (2)$$

where Γ is a steepness dependent coefficient, k is wave number and $\bar{\sigma}$ and $\bar{k}$ denote a mean frequency and a mean wave number, respectively (cf. the WAMDI group, 1988). Komen et al. (1984) estimated the value of Γ by closing the energy balance of the waves in fully developed conditions. This implies that this value depends on the wind input formulation that is used. Since two expressions are used for the wind input in SWAN, also two values for Γ are used. The first is due to Komen et al. (1984), as in WAM Cycle 3. The second expression is an adaptation of this expression based on Janssen (1991a), as in WAM Cycle 4 (see Janssen, 1991b; Günther et al., 1992).

A number of alternative whitecapping expressions have been proposed to improve the accuracy of SWAN. These range from alternative settings of the Komen et al, (1984) expression, e.g. Rogers et al. (2003), to alternative ways of calculating mean spectral steepness, e.g. Van Vledder and Hurdle (2002). In SWAN, another alternative is presented. This alternative is proposed by Van der Westhuysen et al, (2007) and Van der Westhuysen (2007), based on the whitecapping expression of Alves and Banner (2003). This expression is based on experimental findings that whitecapping dissipation appears to be related to the nonlinear hydrodynamics within wave groups. This yields a dissipation term that primarily depends on quantities that are local in the frequency spectrum, as opposed to ones that are distributed over the spectrum, as in the expression of Komen et al. (1984). However, the final whitecapping expression proposed by Alves and Banner (2003) features additional dependencies on the spectral mean wavenumber and steepness, which is problematic in situations of mixed sea and swell often encountered in the nearshore. Therefore, their whitecapping expression is applied in Van der Westhuysen (2007) without these mean spectral dependencies. This adapted whitecapping expression is used together with a wind input term that is based on that of Yan (1987) (SWAN, 2014).

MODEL SETUP

In this study, the SWAN cycle III version 41.01 model was used to perform the hindcast study. It was run in the third generation and nonstationary mode with a time step equal to 15 min and one iteration per time step, as was found to be sufficient (Akpınar et al., 2012) to accurately predict the wave conditions in the Black Sea. The model domain covers the entire Black Sea, from 27°E to 42°E of longitude and from 40°N to 48°N of latitude shown in Figure 1. The domain was discretized with a regular grid of 225×120 nodes in spherical coordinates with a uniform resolution of 0.067° (1/15°) in each direction. The directional wave energy density spectrum function was discretized using 36 directional bins and 35 frequency bins between 0.04 Hz and 1.0 Hz. The CFSR wind data are used to drive the model as recommended by Van Vledder and Akpınar (2015). The numerical scheme was the slightly dispersive BSBT (first order upwind; Backward in Space, backward in Time) scheme. Details regarding the numerical settings of the SWAN model in the Black Sea can be found in Akpınar et al. (2012).

For our wave model computations we have used different formulations for wind growth and whitecapping and calibrated their tuneable C_{ds} parameter. Quadruplet interactions are estimated using the Discrete Interaction Approximation (DIA) by Hasselmann et al. (1985) using $\lambda=0.25$ and $C_{nl4}=3\times10^7$. The JONSWAP bottom friction formulation is used with $C_{fjon}=0.038$ m^2 s^{-3} according to Zijlema et al. (2012). Depth-limited wave breaking is modelled according to the bore-model of Battjes and Janssen (1978) using $\alpha=1$ and $\gamma=0.73$. The triad wave-wave interactions using the Lumped Triad Approximation (LTA) of Eldeberky (1996) in the SWAN were activated (Akpınar et al., 2016).

MODEL CALIBRATION AND VALIDATION

In the calibration, we focused on combinations of the wind and whitecapping source terms, of which the latter is the least known source term in third-generation wave models. Since the SWAN model contains different formulations for wind input and whitecapping, five different combinations defining these two physical processes, as defined below, were formed while other settings were not varied.

Combination 1 (KK): Komen for wind input and Komen for whitecapping
Combination 2 (JK): Janssen for wind input and Komen for whitecapping
Combination 3 (KJ): Komen for wind input and Janssen for whitecapping
Combination 4 (JJ): Janssen for wind input and Janssen for whitecapping
Combination 5 (YW): Yan for wind input and Westhuysen for whitecapping

The performance of these combinations and the effect of the whitecapping coefficients in each combination were systematically examined by varying the whitecapping coefficients (by adding or subtracting 0.5 for Janssen and 0.1e-5 for others) around their default values in SWAN and running the wave model for the year 1996 enabling comparison with measurements. In this way the best model setting was selected as having the min [bias, RMSE, and SI] and max [correlation coefficient (r)] for both wave parameters (H_{m0} and T_{m02}) for data from 1996 at all buoy locations.

These statistical error parameters are computed according to:

$$\text{bias} = \sum_{i=1}^{N} \frac{1}{N}\left(P_i - O_i\right) \tag{3}$$

$$\text{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(P_i - O_i\right)^2\right]^{1/2} \tag{4}$$

$$\text{SI} = \frac{\text{RMSE}}{\overline{O}} \tag{5}$$

$$r = \frac{\sum_{i=1}^{N}\left(\left(P_i - \overline{P}\right)\left(O_i - \overline{O}\right)\right)}{\left[\left(\sum_{i=1}^{N}\left(P_i - \overline{P}\right)^2\right)\left(\sum_{i=1}^{N}\left(O_i - \overline{O}\right)^2\right)\right]^{1/2}} \tag{6}$$

During the calibration process, we first started off with the computational grid covering the entire Black Sea using wave measurements from Hopa, Sinop and Gelendzhik stations collected in 1996. Results of all SWAN runs are summarized in Taylor diagrams generated for H_{m0} and T_{m02} at all buoy locations for data from 1996 (Figure 2). In the Taylor diagrams each-colour represents results for unique combination of source terms. For example, red-coloured dots show performances of model runs for Combination 4. This is shown in the title of each subplot in the Taylor diagrams.

Analysing the results in Figure 2, the best SWAN model setup was determined as the SWAN model with the formulations of Komen et al. (1994) for wind input and Janssen (1991a, 1991b) with C_{ds}=1.5 for whitecapping. It is noted that this value is lower than the default value of C_{ds}=4.5. Error statistic of the best model is presented in Table 1.

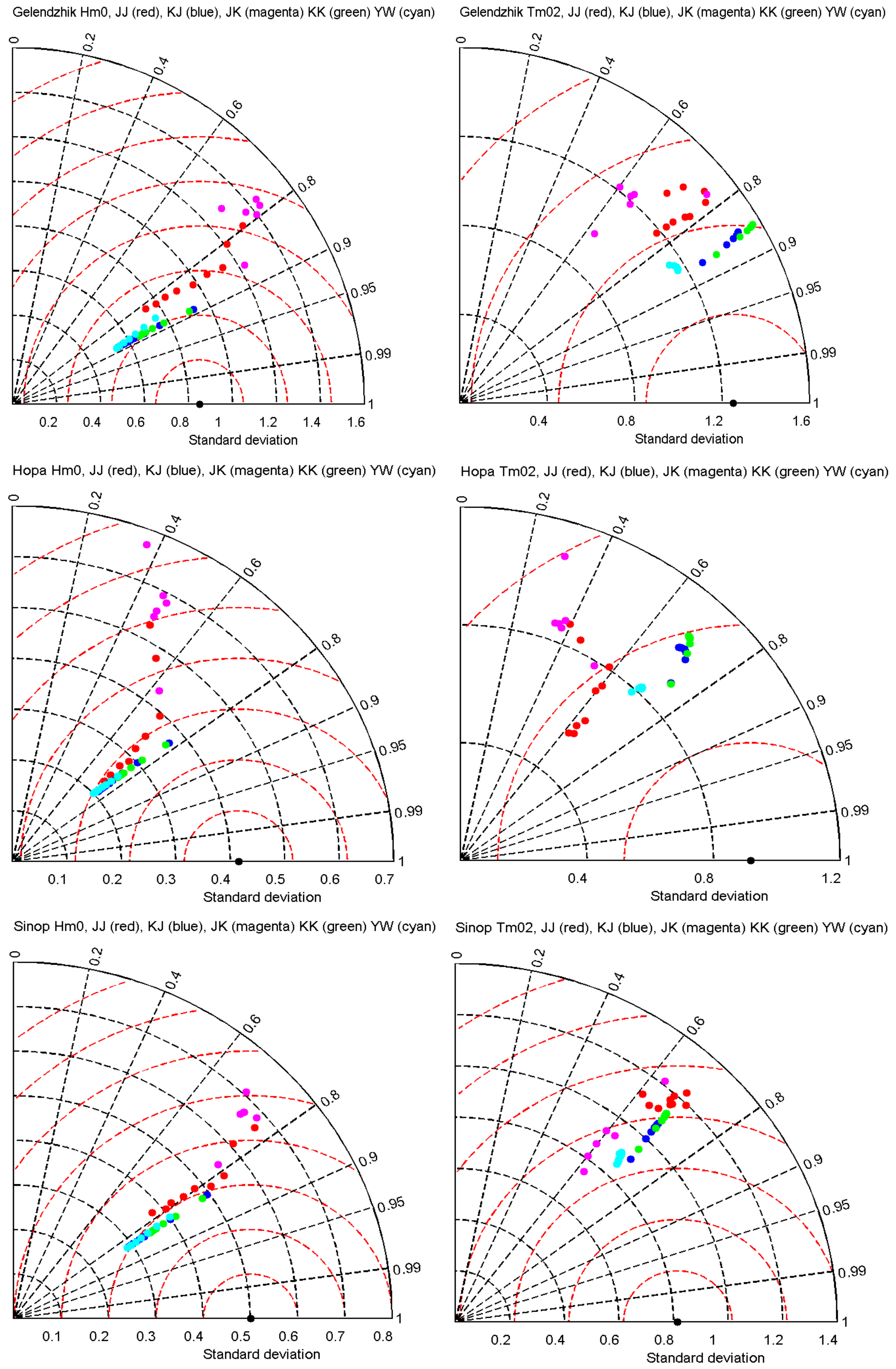
Table 1. Error statistic of the best model in calibration stage

Location	Parameter	n	x_{mean}	y_{mean}	R	bias	RMSE	SI
Gelendzhik	H_{m0}	1924	1.06	0.98	0.88	0.08	0.41	0.38
	T_{m02}	1924	3.99	3.66	0.86	0.33	0.79	0.20
Hopa	H_{m0}	3093	0.58	0.57	0.84	0.01	0.28	0.49
	T_{m02}	3093	4.01	3.39	0.81	0.62	0.95	0.24
Sinop	H_{m0}	2416	0.80	0.78	0.85	0.02	0.26	0.33
	T_{m02}	2416	3.79	3.81	0.72	-0.02	0.69	0.18

After the calibration, it is seen that SWAN model performance improved by 11.6% for H_{m0} and 3.3% for T_{m02} on average at three locations in comparison with those using the default SWAN model settings. Verification was done using wave measurements from Hopa, Gelendzhik, Filyos, Karaburun and Gloria not used in the determination of the best model settings. Error statistics of the best model in the validation stage is summarized in Table 2. More details for calibration and validation progresses can be found in Akpınar et al. (2016).

Table 2. Error statistic of the best model in validation stage

Location	Parameter	R	bias	RMSE	SI
Filyos	H_{m0}	0.74	0.13	0.42	0.68
	T_p	0.62	0.37	1.21	0.22
Karaburun	H_{m0}	0.84	0.02	0.29	0.38
Hopa	H_{m0}	0.85	0.07	0.33	0.50
	T_{m02}	0.77	0.47	0.96	0.24
Gelendzhik	H_{m0}	0.88	0.12	0.41	0.43
	T_{m02}	0.86	0.40	0.83	0.22
Gloria	H_{m0}	0.85	0.38	0.67	0.51
	T_p	0.39	-0.28	1.63	0.34



Gelendzhik Hm0, JJ (red), KJ (blue), JK (magenta) KK (green) YW (cyan)

Gelendzhik Tm02, JJ (red), KJ (blue), JK (magenta) KK (green) YW (cyan)

Hopa Hm0, JJ (red), KJ (blue), JK (magenta) KK (green) YW (cyan)

Hopa Tm02, JJ (red), KJ (blue), JK (magenta) KK (green) YW (cyan)

Sinop Hm0, JJ (red), KJ (blue), JK (magenta) KK (green) YW (cyan)

Sinop Tm02, JJ (red), KJ (blue), JK (magenta) KK (green) YW (cyan)

Figure 2. Taylor diagrams showing model performances in calibration progress

WAVE ENERGY POTENTIAL

In order to determine hot spots areas on the Black Sea for wave energy, the calibrated and validated SWAN model was run for a period of 31 years from 1979-2009. As a result, mean annual wave energy flux based on spectral wave height (H_{m0}) and spectral energy period (T_e) for all data, each season, and month on the whole Black Sea (Figures 3 and 4) were computed based on the equation below:

$$\text{mean } P_w = \text{mean}\left(0.486 \times \left(H_{m0}^2\right)_i \times \left(T_e\right)_i\right) \tag{5}$$

where *i* represents time step in our model runs. The arrows in these figures represent the mean direction of wave energy flux.

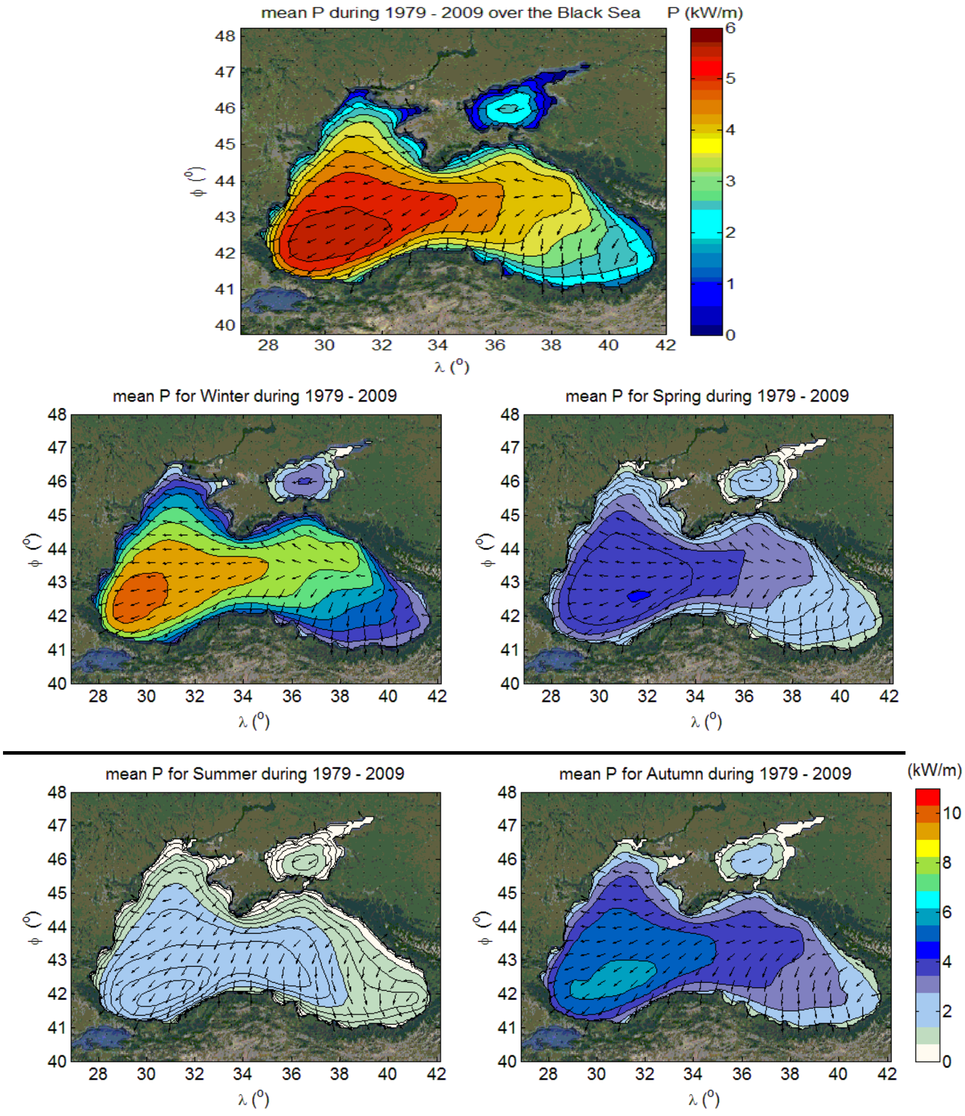


Figure 3. Mean annual and seasonal wave energy flux predicted by the SWAN model over the period 1979 - 2009 in the Black Sea

Mean wave energy fluxes over the Black Sea are found as maximum in the offshore coasts of Bulgaria, and Istanbul and Kırklareli provinces of Turkey (about 5 kW/m). Areas of secondary importance are found along Romania's Constanta coast and Turkey's coasts from Sinop to Sakarya. The eastern Black Sea is exposed to low energetic waves with an average wave energy flux of 2 kW/m. The spatial patterns of seasonal average wave power (Figure 3) are very similar to the averages based on all years but their levels are slightly different. The winter months of December, January and February, have the largest contribution to the annual average wave power potential with a maximum of up to 10.5 kW/m. Winter is followed by autumn that includes September, October and November with a maximum of 6.3 kW/m. Followed by the autumn season is spring in the months of March, April and May with a maximum value of 4.5 kW/m. Summer shows the least amount of wave energy flux with a maximum value of 2.3 kW/m. As seen, there is quite a large difference between the highest average wave energy flux value in summer and that of winter in the Black Sea. This indicates how much the potential wave power varies per season.

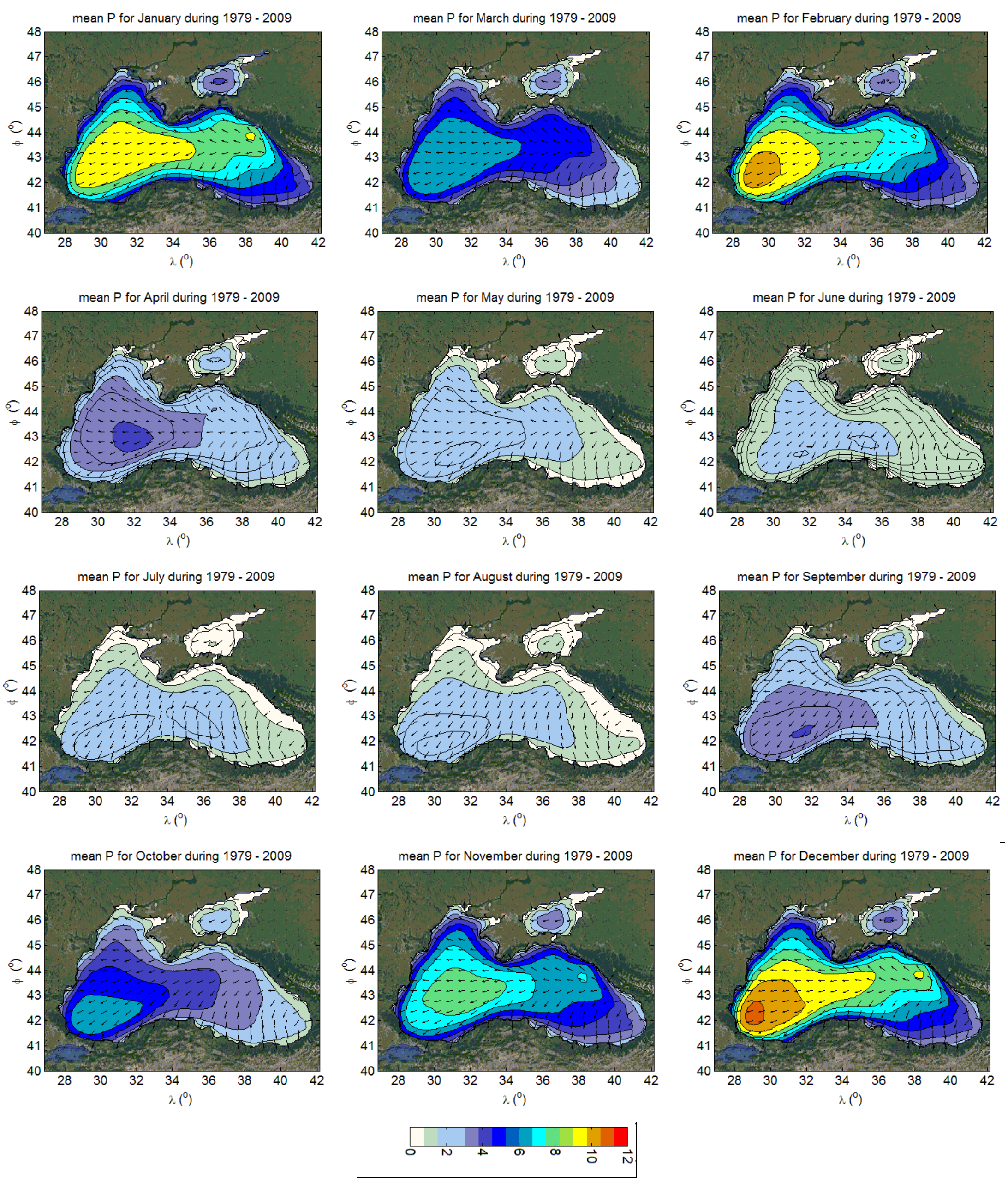


Figure 4. Mean monthly wave energy flux (kW/m) predicted by the SWAN model over the period 1979 - 2009 in the Black Sea.

CONCLUSIONS

In this study we obtained the results below:

- ✓The best SWAN setting was obtained for Combination 3 (KJ) where the SWAN model was applied with the formulations of Komen et al. (1994) for wind input and Janssen (1991a, 1991b) with C_{ds}=1.5 for whitecapping.
- ✓Tuning of SWAN model resulted in lower values of the whitecapping coefficient than the default setting.
- ✓ The highest values of wave energy potential occur in the south-western region of the Black Sea and they decrease towards north-western and eastern parts of the basin.
- ✓ Hot spot areas are offshore areas of Bulgaria and Istanbul and Kırklareli provinces of Turkey having an annually averaged wave energy potential of about 5 kW/m in the south western part of the Black Sea.
- ✓ The winter months (December, January, and February) have the highest wave energy flux.
- ✓There is a larger seasonal variation in wave energy potential in the Black Sea.

Having determined the hot spot areas in the Black Sea, our future studies will be focused on improving the SWAN model results by applying for higher resolution nested sub-grids in the south-western parts of the Black Sea. Here, shallow water effects will play a larger role in determining the wave energy potential. The final aim of our studies is to create a detailed database of wave conditions and related wave energy potential that can be used by third parties to develop WEC farms in the Black Sea. Finally, in due time we plan to include recent wave model developments in the parameterization of physical processes.

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REFERENCES

Akpınar, A., G.Ph. Van Vledder, M.İ. Kömürcü, and M. Özger, 2012. Evaluation of the numerical wave model (SWAN) for wave simulation in the Black Sea. *Continental Shelf Research*, 50–51, 80–99.

Akpınar, A., S. Bekiroğlu, G.Ph. Van Vledder, B. Bingölbali, and H. Jafali, 2015. Temporal and Spatial Analysis of Wave Energy Potential along the Southern-west Coasts of the Black Sea. Project number: 214M436, TUBITAK Project.

Akpınar, A., B. Bingölbali, and G.Ph. Van Vledder, 2016. Wind and wave characteristics in the Black Sea based on the SWAN model forced with the CFSR winds, *Ocean Engineering*, 126, 276-298.

Alves, J.H.G.M., and M.L. Banner, 2003. Performance of a saturation-based dissipation-rate source term in modelling the fetch-limited evolution of wind waves, *Journal of Physical Oceanography*, 33, 1274-1298.

Battjes, J.A., and J.P.F.M. Janssen, 1978. Energy loss and set-up due to breaking of random waves, *Proceedings of the 16th International Conference on Coastal Engineering*, ASCE, 569–587.

Cavaleri, L., and P. Malanotte-Rizzoli, 1981. Wind wave prediction in shallow water: Theory and applications. *Journal of Geophysical Research*, 86, C11, 10961-10973.

Eldeberky, Y. 1996. Nonlinear transformation of wave spectra in the nearshore zone, Ph.D. Thesis, Delft University of Technology, the Netherlands.

Günther, H., S. Hasselmann, and P.A.E.M. Janssen, 1992. The WAM model Cycle 4 (revised version), Deutsch. Klim. Rechenzentrum, Techn. Rep. No. 4, Hamburg, Germany.

Hasselmann, K., 1974. On the spectral dissipation of ocean waves due to whitecapping, *Boundary-layer Meteorology*, 6, 1-2, 107-127.

Hasselmann, S., K. Hasselmann, J.H. Allender, and T.P. Barnett, 1985. Computations and parameterizations of the linear energy transfer in a gravity wave spectrum, (part II): parameterizations of the nonlinear transfer for application in wave models, *Journal of Physical Oceanography*, 15 (11), 1378–1391.

Janssen, P.A.E.M. 1991a. Quasi-linear theory of wind-wave generation applied to wave forecasting, *Journal of Physical Oceanography*, 21, 1631-1642.

Janssen, P.A.E.M. 1991b. Consequences of the effect of surface gravity waves on the mean air flow, Int. Union of Theor. and Appl. Mech. (IUTAM), Sydney, Australia, 193-198.

Komen, G.J., S. Hasselmann, and K. Hasselmann, 1984. On the existence of a fully developed wind-sea spectrum, *Journal of Physical Oceanography,* 14, 1271-1285.

Komen, G.J., L. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmann, and P.A.E.M. Janssen, 1994. Dynamics and modelling of ocean waves. Cambridge University Press. 554.

Mastenbroek, C., G. Burgers, and P.A.E.M. Janssen, 1993. The dynamical coupling of a wave model in a storm surge model through the atmospheric boundary layer, *Journal of Physical Oceanography*, 23, 1856-1866.

Miles, J.W. 1957. On the generation of surface waves by shear flows. *Journal of Fluid Mechanics*, 3, 185−204.

Phillips, O.M. 1957. On the generation of waves by turbulent wind, *Journal of Fluid Mechanics*, 2, 417−445.

Rogers, W.E., P.A. Hwang, and D.W. Wang, 2003. Investigation of wave growth and decay in the SWAN model: three regional-scale applications, *Journal of Physical Oceanography*, 33, 366-389.

Snyder, R.L., F.W. Dobson, J.A. Elliott, and R.B. Long, 1981. Array measurement of atmospheric pressure fluctuations above surface gravity waves, *Journal of Fluid Mechanics*, 102, 1-59.

SWAN Team. 2014. SWAN user manual. SWAN Cycle III version 40.91, Delft University of Technology, p. 123.

Tolman, H.J. 1992. Effects of numerics on the physics in a third-generation wind wave model, *Journal of Physical Oceanography*, 22, 10, 1095-1111.

Van der Westhuysen, A.J., 2007. Advances in the spectral modelling of wind waves in the nearshore, Ph.D. thesis, Delft University of Technology, Department of Civil Engineering, The Netherlands.

Van der Westhuysen, A.J., M. Zijlema, and J.A. Battjes, 2007. Nonlinear saturation based whitecapping dissipation in SWAN for deep and shallow water, *Coastal Engineering*, 54, 151-170.

Van Vledder, G. Ph., and D.P. Hurdle, 2002. Performance of formulations for whitecapping in wave prediction models, *Proceedings of 21st International Conference on Offshore Mechanics and Arctic Engineering*, OMAE2002-28146, 155-163.

Van Vledder, G.Ph., and A. Akpınar, 2015. Wave model predictions in the Black Sea: sensitivity to wind fields. *Applied Ocean Research*, 53, 161-178.

WAMDI group, 1988. The WAM model − a third generation ocean wave prediction model, *Journal of Physical Oceanography*, 18, 1775−1810.

Yan, L. 1987. An improved wind input source term for third generation ocean wave modelling, Scientific report WR-No 87-8, De Bilt, The Netherlands.

Zijlema, M., G.Ph. Van Vledder, and L.H. Holthuijsen, 2012. Bottom friction and wind drag for wave models. *Coastal Engineering*, 65, 19–26.