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SWAN HINDCAST IN THE BLACK SEA

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A SWAN implementation for the Black Sea area is presented. The advantage of using the SWAN model, both for wave generation and transform, is mainly the simpler procedure of nesting into the initial domain of medium and high resolution areas for further coastal simulations. The reanalysis wind was provided by the project HIPOCAS. Comparisons with WAM (cycle 4) and with data from a buoy located in the North East of the Black Sea basin were also performed. There are two processes that govern the wave generation in SWAN. These are generation by wind and dissipation by whitecapping. Three methods are presently available into the model to account for these processes. The first two are based on the formulations of Komen and Janssen while the third is called the Cumulative Steepness Method. All these formulations were tested and their efficiency will be discussed. Finally some directions for increasing the accuracy of the model results all over the Black Sea as well as the possibility of using SWAN operationally for wave forecast in closed seas will be also pointed.

INTRODUCTION

Although the SWAN model was initially designed for coastal applications that should actually not require a great flexibility in scale, in the last versions its capacities were substantially extended so that now the model can be used on almost any scale. Of course SWAN is less efficient on oceanic scales than WAM. However, as regards the sub oceanic scales, as the medium and small seas are, it seems that is much convenient to use a single model for both wave generation and transformation. The basic scientific philosophy of SWAN is identical to that of WAM (Cycle 3 and 4). SWAN is a third generation wave model and it uses the same formulations for the source terms (although SWAN uses the adapted code for the DIA technique). On the other hand, SWAN contains some additional formulations primarily for shallow water.

This paper presents a calibration of the SWAN model for the Black Sea basin that is compared both with registrations coming from a directional buoy and WAM simulations.

The wind field was provided by the project HIPOCAS "Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe", developed in the framework of the European Program "Energy, Environment and Sustainable Development", which gave the reanalysis wind conditions for 44 years, between 1958 and 2001, (Guedes Soares et al., 2002). For the wave simulations in the Black Sea, described here, the global NCEP reanalysis wind was used as a driver for the regional atmosphere model REMO. The spatial resolution of the wind model output was 0.25° and the time step of one hour.

OPTIONS FOR WAVE GENERATION AND WHITECAPPING DISSIPATION IN SWAN

Transfer of wind energy to the waves is described in SWAN with the resonance mechanism of Phillips (1957) and the feed-back mechanism of Miles (1957). The corresponding source term for these mechanisms is commonly described as the sum of linear and exponential growth:

$$S_{in}(\sigma,\theta) = A + BE(\sigma,\theta) \tag{1}$$

in which *A* describes linear growth and *BE* exponential growth. 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-

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Moskowitz frequency, (Tolman, 1992). Two optional expressions for the coefficient *B* are used in the model. The first is taken from an early version of the WAM model, known as WAM Cycle 3, (the WAMDI group, 1988). It is due to Snyder et al. (1981), rescaled in terms of friction velocity by Komen et al. (1984), and it is currently called the Komen parameterization. The second expression is due to Janssen (1989, 1991) and it is based on the quasi-linear wind-wave theory.

Whitecapping is primarily controlled by the steepness of the waves. In the third generation wave models presently operating (including SWAN) the whitecapping formulations are based on a pulse-based model Hasselmann (1974), as adapted by the WAMDI group (1988), so as to be applicable in finite water depth. This expression is:

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

where $\tilde{\sigma}$ and $\tilde{k}$ denote the mean frequency and the mean wave number, and the coefficient Γ depends on the overall wave steepness

$$\Gamma = \Gamma_{KJ} = C_{ds}\left((1-\delta)+\delta\frac{k}{\tilde{k}}\right)\left(\frac{\tilde{S}}{\tilde{S}_{PM}}\right)^p \tag{3}$$

For δ=0 the expression of Γ reduces to the expression as used by the WAMDI group (1988). The coefficients C_{ds}, δ and p are tuneable coefficients, $\tilde{S}$ is the overall wave steepness and $\tilde{S}_{PM}$ is the value of this parameter for the Pierson-Moskowitz spectrum (= $(3.02\times10^{-3})^{1/2}$). The values of the tunable coefficients C_{ds}, δ and p in the SWAN model have been obtained by Komen et al. (1984) and Janssen (1992) by closing the energy balance of the waves in idealized wave growth conditions (both for growing and fully developed wind seas) for deep water. This implies that coefficients in the steepness dependent coefficient Γ depend on the wind input formulation that is used. Since two different wind input formulations are used in the SWAN model, two sets of coefficients are used. For the Komen parameterization (corresponding to WAM Cycle 3) C_{ds} = 2.36×10^{-5}, δ=0 and p = 4. The tuneable coefficients are in this case C_{ds} and $\tilde{S}^2_{PM}$. In the Janssen parameterization (being assumed also p = 4) C_{ds} = 4.10×10^{-5} and δ=0.5 (as used in the WAM cycle 4). The tuning parameters used in this case are δ and C_{ds1} (default 4.5) which is given by:

$$C_{ds1} = C_{ds}\left(\frac{1}{\tilde{S}_{PM}}\right)^4 \tag{4}$$

An alternative formulation for whitecapping is based on the Cumulative Steepness Method as described in Alkyon *et al.* (2002). With this method dissipation due to whitecapping depends on the steepness of the wave spectrum at and below a particular frequency. It is defined as (directionally dependent):

$$S_{st}(\sigma,\theta) = \int_0^{\sigma}\int_0^{2\pi} k^2\left|\cos(\theta-\theta')\right|^m E(\sigma,\theta)\,d\sigma\,d\theta \tag{5}$$

In this expression the coefficient *m* controls the directional dependence. It is expected that this coefficient will be about 1 if the straining mechanism is dominant; *m* is more than 10 if other mechanism play a role (e.g. instability that occurs when vertical acceleration in the waves becomes greater than gravity). Default in SWAN is *m* = 2. The new whitecapping source term is given by:

$$S^{st}_{wc}(\sigma,\theta) = -C^{st}_{wc}S_{st}(\sigma,\theta)E(\sigma,\theta) \tag{6}$$

with C^{st}_{wc} a tuneable coefficient (with the default value 0.5).

MODEL PARAMETERIZATION AND COMPUTATIONAL STRATEGIES

The area considered has the origin with the coordinates (27.5, 41.0) and the lengths in x-direction (longitude) 14° and in y-direction (latitude) 6°, covering both the Black Sea and the Sea of Azov. Because in that region 1° in longitude has about 85 km while in latitude about 110 km the maps were scaled adequately (figure 1). In the geographical space the computational grid was chosen identical with the bathymetric grid and has 176 points in x direction and 76 points in y direction, with Δx=Δy=0.08°. In the space direction-frequency were assumed 24 directions and 30 frequencies.

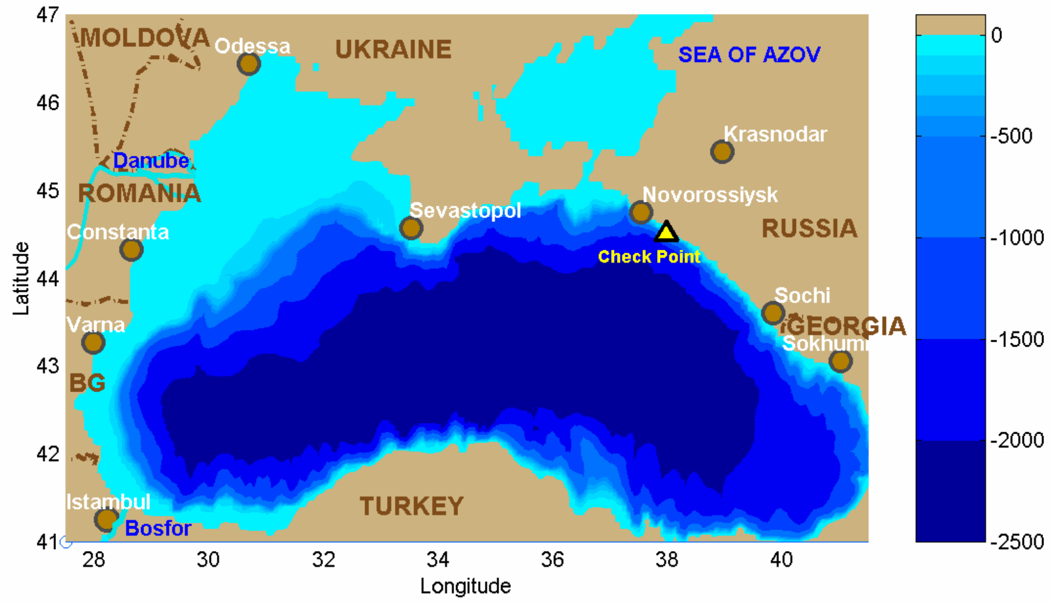


Figure 1

The bathymetric map for the Black Sea area and the localization of the check point

Three different simulations were made using the three parameterizations for wind growing and dissipation by whitecapping available into the model, as discussed in the previous paragraph, respectively Komen, Janssen and CSM. However the values of the tuneable coefficients were found too large for the Black Sea conditions and after various calibrations these coefficients were set as follows: for Komen formulation $C_{ds} = 1.2\times10^{-5}$; for Janssen formulation Cds1 = 1.1 and for CSM $C_{wc}^{st} = 0.1$. This reduces the dissipation by whitecapping and increases the wave height fields. For the other physical processes the default parameterizations were used, that is the triad wave-wave interactions were deactivated and for the quadruplet wave-wave interactions use was made of the fully explicit computations of the nonlinear transfer with DIA (Discrete Interaction Approximation) per sweep. The computations were performed in the non stationary mode with a 20 min time step and the number of iterations was set from 1 which is the default value to 4 increasing in this way the numerical accuracy reached until the model passes to another time step. Simulations were performed for the period 1st November 1996 – 6th February 1997.

PRELIMINARY VALIDATION RESULTS

As checkpoint a directional buoy was used located into the north-east part of the Black Sea basin (37.98E, 44.51N). At that site the water depth is of 85m and the distance to shore is of about 7 kilometres. The direct comparisons with the buoy (for the considered period) in terms of significant wave height, peak period and mean wave direction are presented in the figures bellow. Thus in figure 2 are given the results for Komen parameterization versus the buoy measurements, while in figures 3 and 4 those provided by Janssen parameterization and respectively the Cumulative Steepness Method compared with the same buoy registrations. Some discontinuities in the curves describing the buoy data reflect some gaps that were encountered in the measured data field. For all the three parameterizations the direct comparison shows in general good results in terms of significant wave height and peak period and some differences for the mean wave directions although even in this case the main tendencies were correctly described by the model. There were not relevant differences in the computational time of the three methods tested. The SWAN version used was the current one (SWAN40.41) which is faster than the previous versions mainly because of the new method implemented for the DIA approximation in the quadruplet computations.

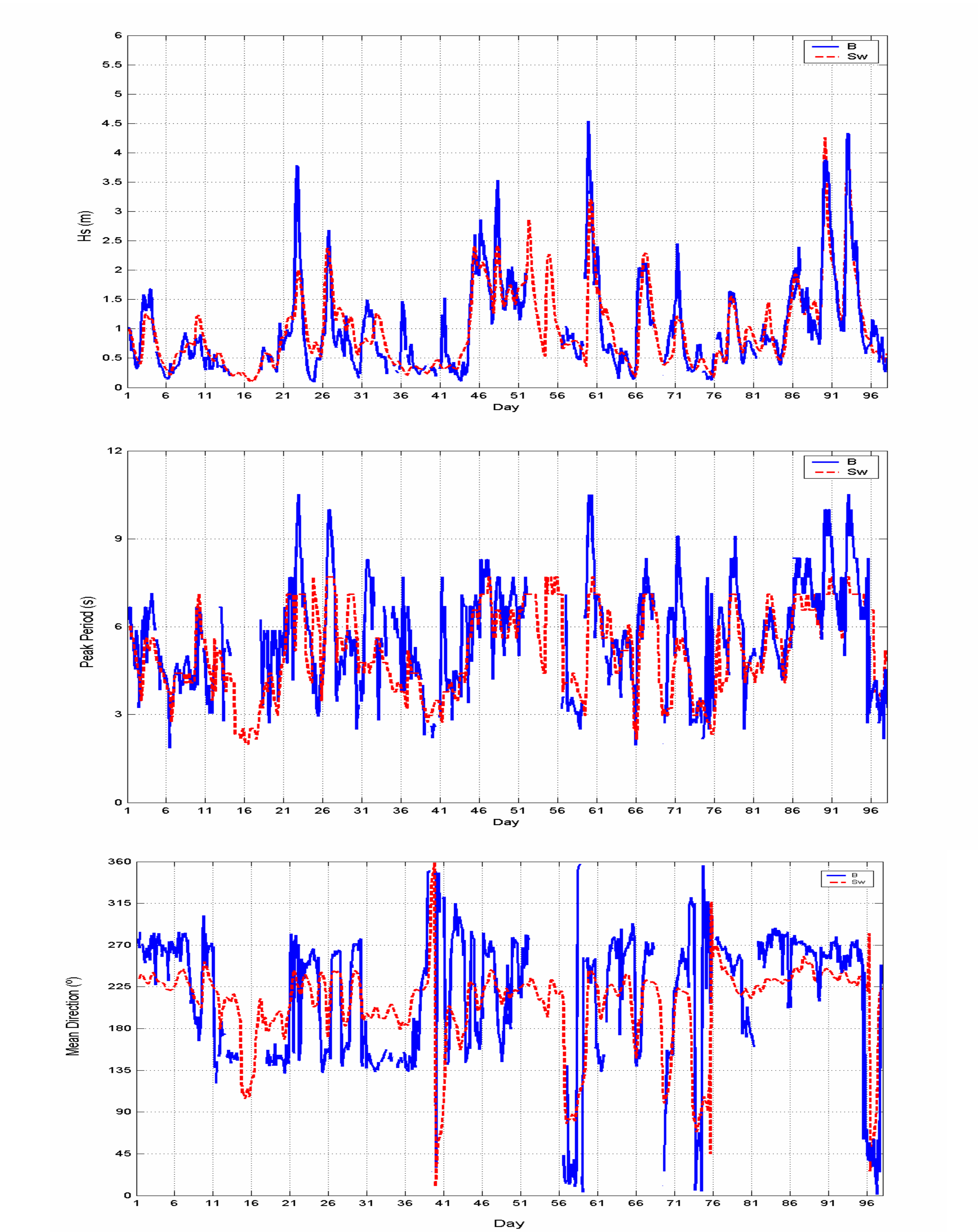


Figure 2

Comparison buoy – SWAN (Komen parameterization), Hs, Tp and Mean direction

(1996.11.01h00-1997.02.06h00– 660 valid data points)

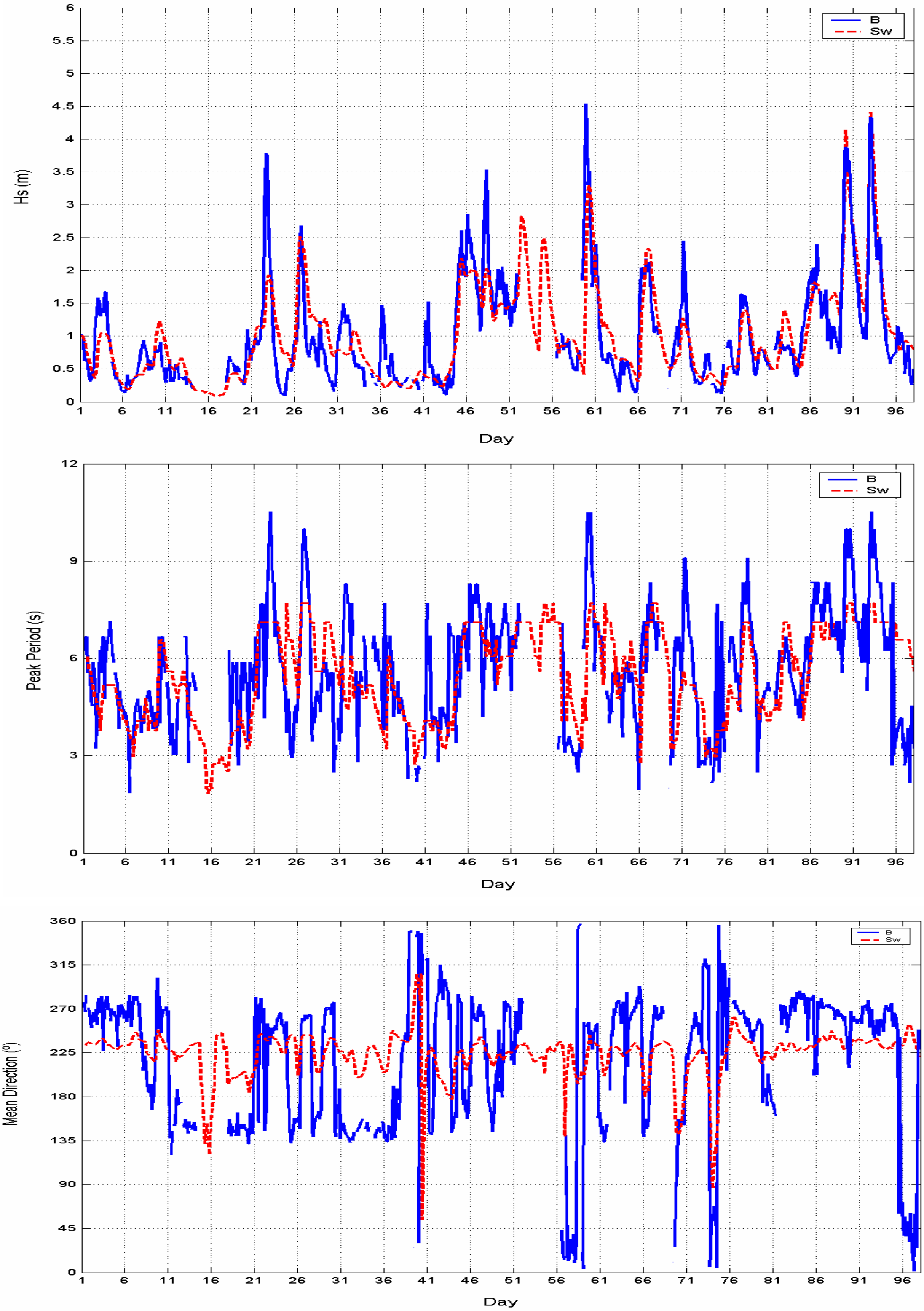


Figure 3
Comparison buoy – SWAN (Janssen parameterization), Hs, Tp and Mean direction
(1996.11.01h00-1997.02.06h00– 660 valid data points)

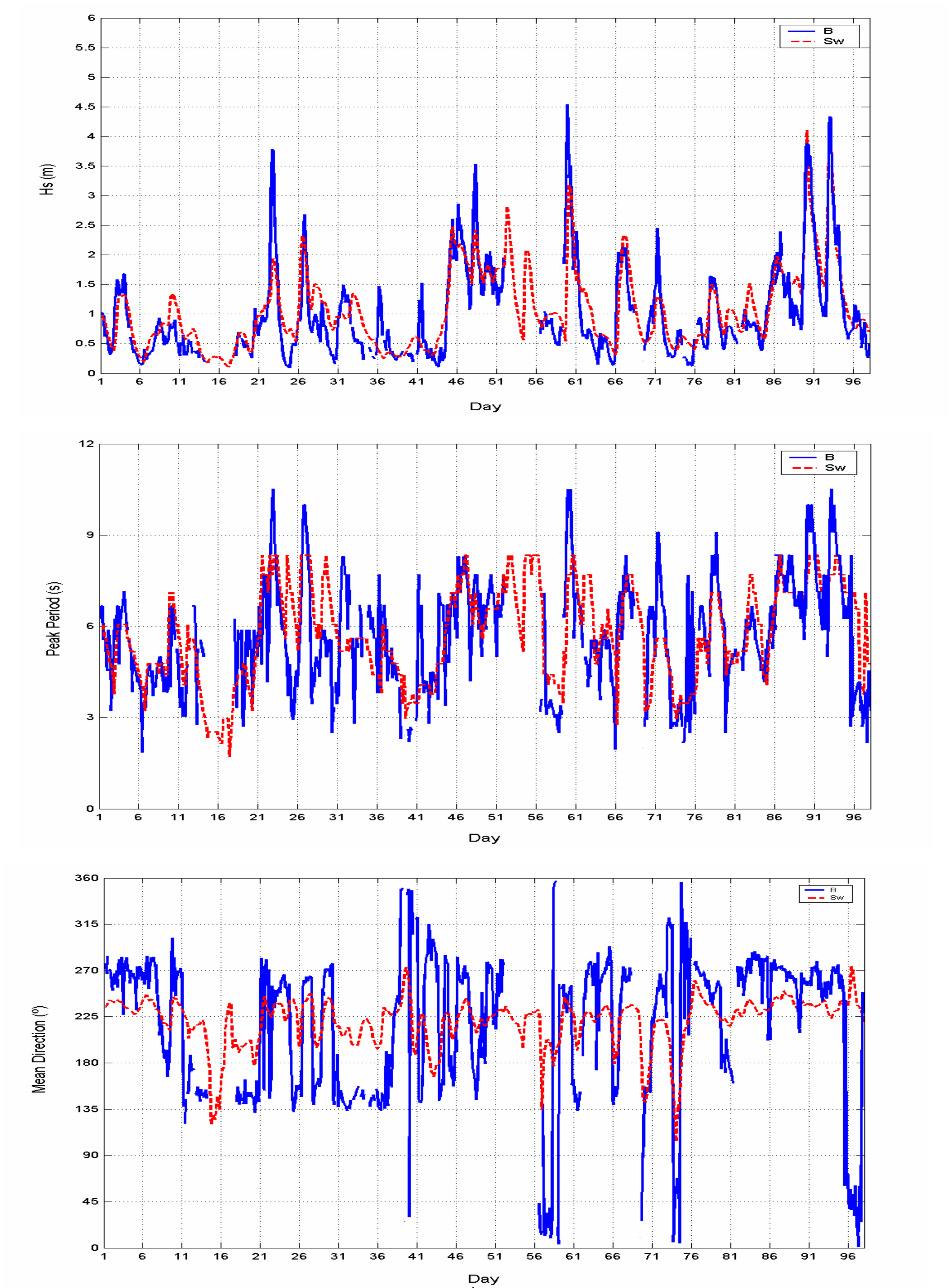


Figure 4

Comparison buoy – SWAN (CSM parameterization), Hs, Tp and Mean direction

(1996.11.01h00-1997.02.06h00– 660 valid data points)

SPATIAL REPRESENTATIONS

One of the highest energetic peaks encountered in the period analysed was at the end of January (1997.01.29h03). In figure 5 the significant wave height fields, are presented the wave and the wind vectors for this case, while in figure 6 the peak periods and the group velocity vectors for the same case.

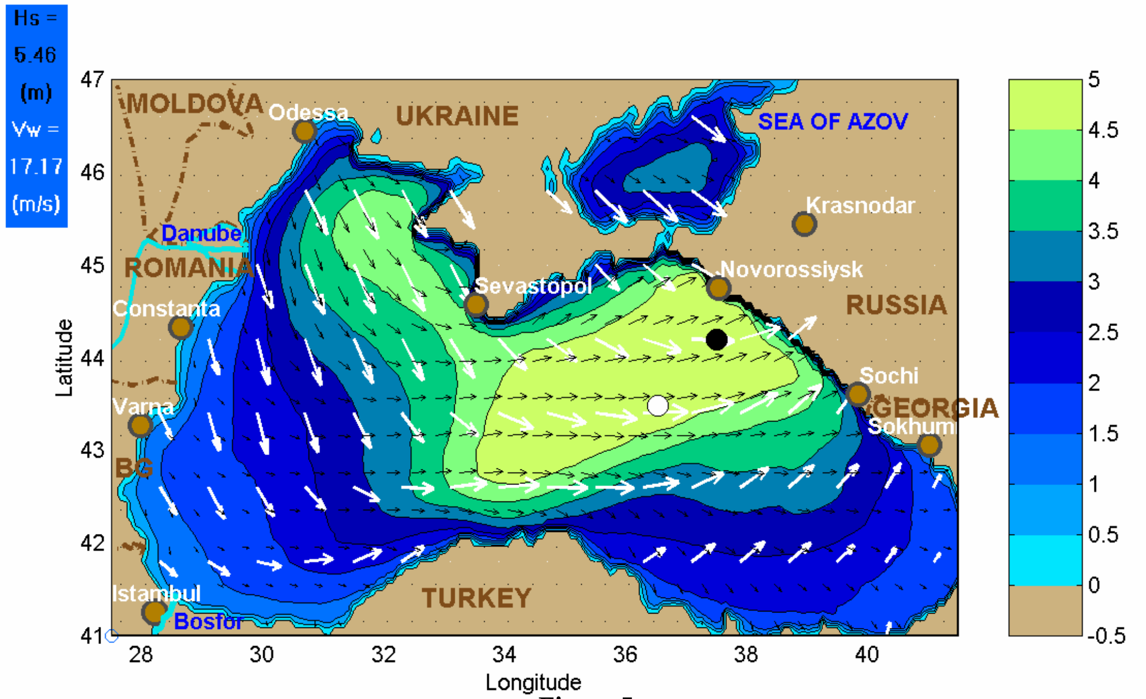


Figure 5

Hs fields, wave vectors (black arrows) and wind vectors (white arrows) for the local energetic peak of 1997.01.29h03

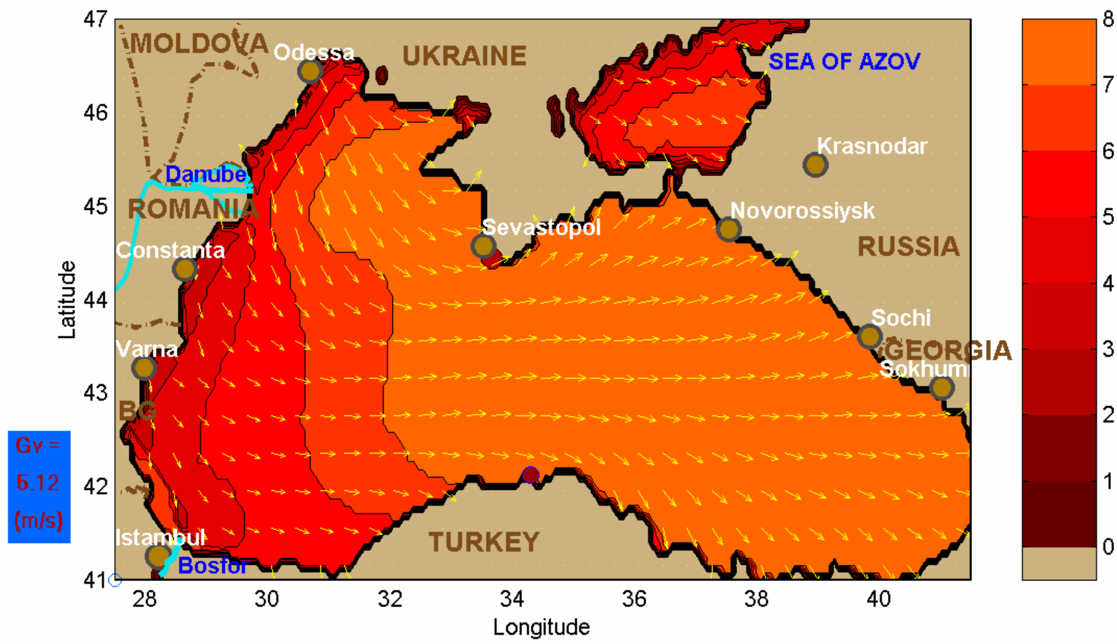


Figure 6

Tp fields, group velocity vectors (yellow arrows) for the local energetic peak of 1997.01.29h03

The storm at the end of January is in some sense typical for the Black Sea area, it starts in the eastern part of the basin and after little time it is propagated into the western side where the intensity is higher and the storm usually reaches its apex, and can be encountered waves with significant wave heights even greater than seven meters. Figure 7 presents the significant wave height fields, the wave and the wind vectors for the global energetic peak corresponding to this storm, which occurs about 15 hours after the local peak illustrated in figures 5 and 6.

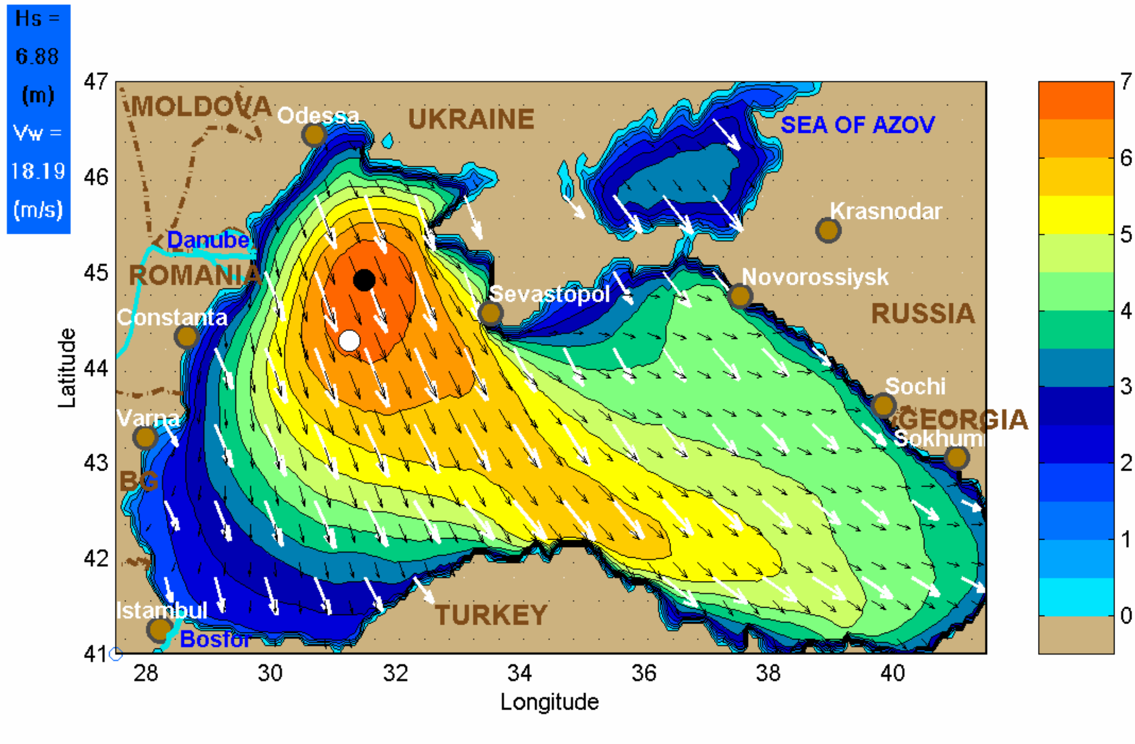


Figure 7
Hs fields, wave vectors (black arrows) and wind vectors (white arrows) for the global energetic peak of 1997.01.29h03

STATISTICAL RESULTS

Usually the error statistics assumes the estimation of some parameters like: mean values, bias, RMSE (root-mean-square-error), SI (scatter index) and *r* (correlation coefficient also called Pearson's product momentum correlation). If X_i represent the measured values, Y_i the simulated values and *n* the number of observations the up mentioned parameters can be defined with the relationships:

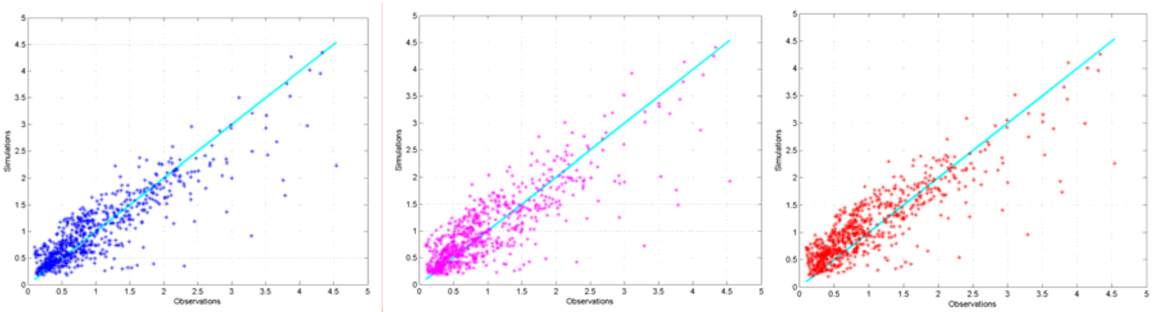
$$X_{med} = \tilde{X} = \frac{\sum_{i=1}^{n} X_i}{n} \qquad Bias = \frac{\sum_{i=1}^{n}(X_i - Y_i)}{n} \qquad RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{n}} \tag{7}$$

$$SI = \frac{RMSE}{\tilde{X}} \qquad r = \frac{\sum_{i=1}^{n}\left(X_i - \tilde{X}\right)\left(Y_i - \tilde{Y}\right)^2}{\left(\sum_{i=1}^{n}\left(X_i - \tilde{X}\right)^2 \sum_{i=1}^{n}\left(Y_i - \tilde{Y}\right)^2\right)^{\frac{1}{2}}} \tag{8}$$

Table 1 presents the statistical results concerning the period in analysis (between 1st November 1996 and 6th February 1997) for the SWAN model simulations using for wind growing and dissipation by whitecapping the parameterizations of Komen, Janssen and CSM. Due to the gaps existent into the measured data field, as well as some uncertainty concerning the wind field for a period of a few days in the middle of December 1996, the total number of data points compared was of 660. Figure 8 presents the scatter plots for the significant wave height corresponding to the three parameterizations.

n=660	X_{med}	Y_{med}	Bias	RMSE	SI	r	
Hs (m)	1.005	1.013	-0.008	0.386	0.384	0.871	**K**
Tp (s)	5.62	5.25	0.369	1.42	0.253	0.651	**O**
Dir (°)	216.1	207.5	8.58	53.5	0.3	0.47	**M**
Hs (m)	1.005	1.026	-0.022	0.432	0.430	0.837	**J**
Tp (s)	5.62	5.52	0.1	1.516	0.270	0.562	**N**
Dir (°)	216.1	224.5	-8.4	68.1	0.315	0.33	**S**
Hs (m)	1.005	1.104	-0.099	0.407	0.405	0.865	**C**
Tp (s)	5.62	5.82	-0.197	1.43	0.255	0.629	**S**
Dir (°)	216.1	221.1	-5.83	66.65	0.308	0.403	**M**

Table 1
Wave statistics (1996.11.01h00-1997.02.06h00), 660 data points.



KOM **JNS** **CSM**

Figure 8
Hs scatter plots, (1996.11.01h00-1997.02.06h00), 660 data points.
(X axis – observations at the buoy, Y axis – SWAN simulations)

DISCUSSIONS

Table 1 shows that the parameterization that gave better results for all the three wave parameters compared (Hs, Tp and Dir) is that using the Komen formulation. In this case all the indicators (RMSE, SI and r) have better values. Moreover this was the parameterization for which the smallest relative modification of the tuneable coefficient was necessary. From the same table it can be noticed that the Cumulative Steepness Method which is in experimental phase in SWAN seems also to give promising results.

The results were also compared with those provided by the WAM model for the same period at the end of 1996 and the beginning of 1997 that used exactly the same wind data field, Vlachev et al. (2004). It has to be noticed that the SWAN results are superior to that provided by WAM and published in the work for any of the SWAN parameterization considered. Referring to the RMSE the values obtained were for Hs: 0.53, for Tp: 1.74 and for Dir: 92.7, which means higher root mean square errors at least regarding the significant wave height and the mean direction. The scatter indexes obtained were: 0.68 for Hs, 0.34 for Tp and 0.46 for Dir, which means also that the results of SWAN are better. Finally the computed correlation coefficients were for Hs: 0.73, for Tp: 0.55 and 0.36 for Dir. This means also better correlations with the measured data as concerns the SWAN results in comparison with WAM.

Differences between wave model simulations and measurements can be generated due to various factors, most frequent being: differences between wind fields used for calculations from the real, inaccurate measurements and errors due to the choices of some parameters in the wave model (the default options being not always the most appropriate for a specific area). Lopatoukhin et al. (2004) provided some interesting information concerning the wind and wave climate of the seas around Russia including the Caspian and Black Seas. Thus as regards the NCEP reanalysis wind the best correspondence is in the North (Barents Sea where the correlation was of about 0.9). However it seems also that this correlation decreases somehow when moving to the south direction. In the same work some results were presented concerning simulations with the SWAN model (version 40.31) in the Caspian Sea. The simulations were made only using the Komen parameterization and were tested various values for the coefficients C_{ds} and $\tilde{S}^2_{PM}$ (from the default values 2.36×10^{-5} and 3.02×10^{-3} till the values 1.86×10^{-5} and 3.62×10^{-3}), being followed actually the same path for calibrating the model as in the present work.

However two additional simulations were finally performed considering the Komen parameterization. The first one included 36 directions instead of 24, reducing in this way the step in the directional space from 15° to 10°. The results of the statistical parameters were sensibly the same. In the second simulation both parameters in the Komen parameterization were modified, being used the values: $C_{ds} = 1.36\times10^{-5}$ and $\tilde{S}^2_{PM} = 3.62\times10^{-3}$.

FINAL CONSIDERATIONS

The SWAN implementation in the Black Sea was validated with good results for the eastern part of the basin. The next step should be a cross validation in order to check the model results in some other points located especially on the western coast of the sea where actually the storms are usually stronger.
Besides the wind generation and whitecapping dissipation there are two other directions that can influence the accuracy of the SWAN results in deep water and that it worth to be explored in the future work for a full calibration of the model in the Black Sea area. These are the options in the parameterizations for quadruplets and those to counteract the so called Garden-Sprinkler effect in the propagation scheme.

The quadruplet wave-wave interactions which dominate the evolution of the spectrum in deep water are parameterized in various ways in SWAN. The most common method uses the Discrete Interaction Approximation (DIA) of Hasselmann et al. (1985). This DIA has been found to be quite successful in describing the essential features of a developing wave spectrum. A full computation of the quadruplet wave-wave interactions is extremely time consuming and not convenient in any operational wave model. Nevertheless, the current version of SWAN (40.41) has two options to compute the Boltzmann integral in an exact manner. The first approach is the so-called FD-RIAM technique while the second approach is the exact method bearing the name Xnl which is also enable to capture the frequency shift and the spectral shape changes as water depth decreases. For the numerical computations of the wave propagation SWAN uses an implicit upwind scheme. Usually, the numerical diffusion of the numerical scheme (S&L) is so small that the so-called garden-sprinkler effect (GSE) may show up if propagation over very large distances is considered (as in the present case). This means that a continuous swell field disintegrates into a set of discrete fields due to the discrete description of the spectrum. It can be counteracted by a diffusion term that has been explicitly added to the numerical scheme. Its value depends on the spectral resolution and the propagation time of the waves (the wave age). Tuning these parameters it is expected to find the most appropriate computational scheme that will balance the numerical accuracy of the model results with the computing time.

Finally it can be concluded that the SWAN model becomes a viable option as a generation model for making operational forecast in the Black Sea area as well as in other seas with medium size. Since the diffraction was also included into SWAN (in a phase-decoupled approximation) a single model can be now used in these cases for wave generation, transformation and up to the local scales.

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