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Part II. Sea waves forecasting and hindcasting

KEY WORDS: *Wave modeling. Wave energy balance equation. Numerical wave models. VAGBUL, WAM, WAVEWATCH III. Sea state forecast. Hindcast. Black Sea. Satellite altimeter data. Verification.*

Basic concepts of a wave modelling

The figure 2.1 presents the most important elements of a wave modelling.

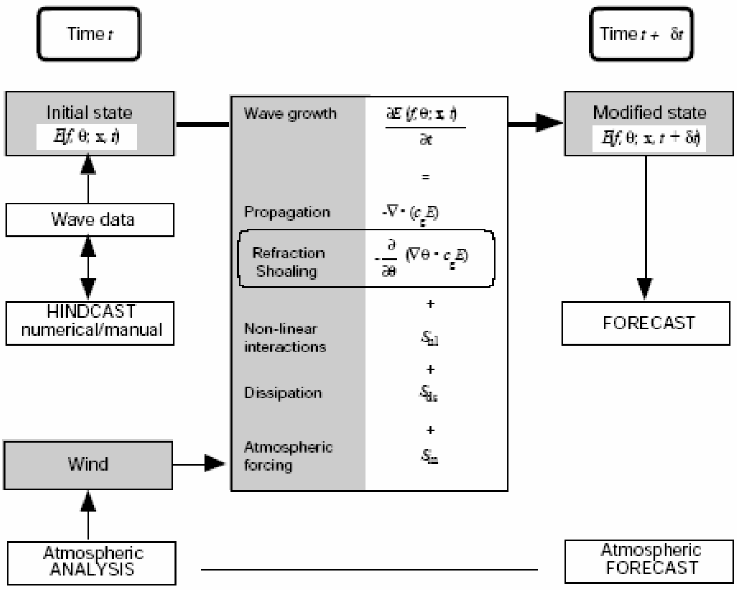

Fig.2.1.The elements of wave modelling (adopted from the WMO Guide, 1998).

Spectral energy-balance equation.

Various techniques have been used to forecast waves. The earliest attempts were based on empirical relationships between wave height and wavelength and wind speed, duration, and fetch. The development of the wave spectrum allowed evolution of individual wave components with frequency f traveling in direction θ of the directional wave spectrum. The most used descriptor of the wave field is the energy-density spectrum $E(f, \theta)$. From this spectrum, we can deduce most of the parameters expected of an operational wave model, namely: the significant wave height, the frequency spectrum, the peak frequency, the primary wave direction, any secondary wave directions, the zero-crossing period, etc. The wave spectrum can be predicted using winds calculated from a numerical weather prediction models (NWP).

The general formulation for wave numerical models based on the elements in Fig.2.1 involves the spectral energy-balance equation, which describes the development of the surface gravity wave field in time and space:

$$\frac{\partial E}{\partial t} + \nabla \bullet \left(c_g E \right) = S = S_{in} + S_{nl} + S_{ds} \qquad (2.1)$$

where: $E=E(f,\theta, x, t)$ is the two-dimensional wave spectrum depending on frequency f, and direction of propagation θ, x is spacing in the two horizontal directions and t is time.

$c_g = c_g(f,\theta)$ is the deep-water group velocity;

S is the net source function, consisting of three terms:

***S*in**: energy input by the wind;

***S*nl**: non-linear energy transfer by wave-wave interactions;

***S*ds**: dissipation.

This form of the equation (2.1) is valid for **deep water** with no refraction and no significant currents.

The essence of wave modeling is to solve the energy balance equation written down in Equation 2.1. This first requires the definition of starting values for the wave energy, or initial conditions which in turn requires definition of the source terms on the right hand side of Equation 2.1 and a method for solving changes as time progresses.

The wave-forecasting models now used by meteorological agencies throughout the world are based on integrations of equation (2.1) using many individual wave components (The SWAMP Group 1985; The WAMDI Group, 1988; Komen *et al*., 1994, Lavrenov, 2003). The forecasts follow individual components of the wave spectrum in space and time, allowing each component to grow or decay depending on local winds, and allowing wave components to interact according to Hasselmann's (Hasselman, 1985) theory. Typically the sea is represented by 300 components: 25 wavelengths going in 12 directions (30°). Each component is allowed to propagate from grid point to grid point, growing with the wind or decaying in time, all the while interacting with other waves in the spectrum. To reduce computing time, the models use a nested grid of points: the grid has a high density of points in storms and near coasts and a low density in other regions.

First, second and third generation wave models.

Wave models compute the wave spectrum by numerical integration of Equation 2.1 over a geographical region. The models may differ in several respects, e.g.: the representation of the spectrum, the assumed forms of *S*in and *S*ds, the representation of *S*nl and whether the integration is carried out in natural characteristic coordinates along individual rays or in terms of a discretized advection operator in a grid-point system common to all wave components. Wave numerical models may differ in the propagation schemes used and in the manner in which they deal with shallow water effects and the influence of ocean currents on wave evolution. A classification of wave models into first, second and third generation wave models is used, which takes into account the method of handling the non-linear source term Snl:

- First generation models do not have an explicit Snl term. Non-linear energy transfers are implicitly expressed through the Sin and Sds terms;
- Second generation models handle the Snl term by parametric methods, for example by applying a reference spectrum (for example the JONSWAP or the Pierson-Moskowitz spectrum) to reorganize the energy (after wave growth and dissipation) over the frequencies;
- Third generation models calculate the non-linear energy transfers explicitly, although it is necessary to make both analytic and numerical approximations to expedite the calculations.

Results from many of the operational first and second generation models were intercompared in the SWAMP (1985) study. The main difference between the second and third generation wave models is that in the latter the wave energy-balance equation is solved without constraints on the shape of the wave spectrum; this is achieved by attempting to make an accurate calculation of the Snl term. The efficient computation of the non-linear source term together with more powerful computers made it possible to develop third generation spectral wave prediction models (e.g. the WAM model, WAMDI Group, 1988, Komen et al., 1994).

Initial conditions.

It is rare that we have a flat sea to work from, or that we have measurements, which completely characterize the sea state at any one time. For the numerical wave models, the usual course of action is to start from a flat sea and "spin up" the model with the winds from a period of several days prior to the period of interest. We then have a hindcast derived for the initial time. For operational models this has to be done only once, since it is usual to store this hindcast and progressively update it as part of each model run.

Wind forcing.

Perhaps the most important element in wave modelling is the motion of the atmosphere above the sea surface. The only input of energy to the sea surface over the time-scales we are considering comes from the wind. Transfer of energy to the wave field is achieved through the surface stress applied by the wind, which varies roughly as the square of the wind speed. Thus, an error in wind specification can lead to a large error in the wave energy and subsequently in parameters such as significant wave height. A wind history (analyses) or forecasts from the Numerical Weather Prediction (NWP) models are used for the atmospheric forcing of the numerical wave models. For more details see the module Black Sea meteorology.

Wind input.

The rate at which energy is fed into the wave field is designated by ***S*in**. This wind input term, ***S*in**, is generally accepted as having the form:

$$S_{\text{in}} = A(f,\theta) + B(f,\theta)\, E(f,\theta)$$

$A(f,\theta)$ is the resonant interaction between waves and turbulent pressure patterns in the air suggested by Phillips (1957), whereas the second term on the right hand side represents the feedback between growing waves and induced turbulent pressure patterns as suggested by Miles (1957). In most applications, the Miles-type term rapidly exceeds the Phillips-type term. According to Snyder et al. (1981), the Miles term has the form:

$$B(f,\theta)=\max\left[0,\mathrm{K}_1\frac{\rho_{\mathrm{a}}}{\rho_{\mathrm{w}}}\left(\mathrm{K}_2\frac{U_5}{g}f\cos(\theta-\psi)-1\right)2\pi f\right].$$

where :

ρ_a and ρ_w ; are the densities of air and water, respectively; K1 and K2 are constants; ψ is the direction of the wind; and $U5$ is the wind speed at 5 m.

Dissipation

The term ***S*ds** describes the rate at which energy is lost from the wave field. In deep water, this is mainly through wave breaking (whitecaps). More details about the form of the term **Sds** are given in (Komen, 1994, Lavrenov, 2003).

Non-linear interactions

Generally speaking, any strong non-linearities in the wave field and its evolution are accounted for in the dissipation terms. Input and dissipation terms can be regarded as complementary to those linear and weakly non-linear aspects of the wave field, which we are able to describe dynamically. Into this category fall the propagation of surface waves and the redistribution of energy within the wave spectrum due to weak, non-linear interactions between wave components, which is designated as a source term, ***S*nl**. The non-linear interactions are discussed in details in (Hasselmann and Hasselmann (1985)).

The source term *S*nl can be handled exactly but the requirement on computing power is great. In third generation models, the non-linear interactions between wave components are indeed computed explicitly by use of special integration techniques and with the aid of simplifications introduced by Hasselmann (Hasselmann et al., 1985). Even with these simplifications powerful computers are required to produce real-time wave forecasts. Therefore many second generation models are still in operational use. In second generation numerical wave models, the nonlinear interaction is parameterized or treated in a simplified way.

The effect of the term, *S*nl, is briefly described in (Sea Waves, Part I) as follows: in the dominant region of the spectrum near the peak, the wind input is greater than the dissipation. The excess energy is transferred by the non-linear interactions towards higher and lower frequencies. At the higher frequencies the energy is dissipated, whereas the transfer to lower frequencies leads to growth of new wave components on the forward (left) side of the spectrum. This results in migration of the spectral peak towards lower frequencies. The non-linear wave-wave interactions preserve the spectral shape and can be calculated exactly.

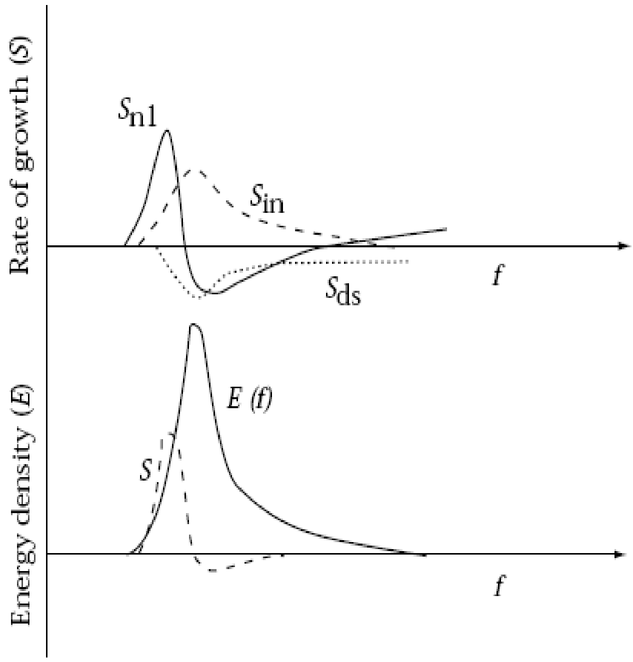

Fig.2.2. Structure of spectral energy growth. The lower curves are the frequency spectrum *E(f)* and the total growth curve S. The upper curves show the components $S_{in,}$ S_{ds} and $S_{nl.}$ (after WMO Guide, 1998).

Propagation.

Wave energy propagates not at the velocity of the waves or wave crests (which is the phase velocity: the speed at which the phase is constant) but at the group velocity (see Sea waves, part I). In wave modelling we are dealing with descriptors such as the energy density and so it is the group velocity, which is important.

The propagative effects of water waves are quantified by noting that the local rate of change of energy is equal to the net rate of flow of energy to or from that locality, i.e. the divergence of energy-density flux. The practical problem encountered in computer modelling is to find a numerical scheme for calculating this. In manual models, propagation is only considered outside the generation area and attention is focused on the dispersion and spreading of waves as they propagate.

Propagation affects the growth of waves through the balance between energy leaving a locality and that entering it. In a numerical model it is the propagation of wave energy, which enables fetch-limited growth to be modelled. Energy levels over land are zero and so downwind of a coast there is no upstream input of wave energy. Hence energy input from the atmosphere is propagated away, keeping total energy levels near the coast low.

Discrete-grid methods

The energy balance, Equation 2.1, is often solved numerically using finite difference schemes on a discrete grid. $\Delta \boldsymbol{x}i$ (i = 1, 2) is the grid spacing in the two horizontal directions. Equation 2.1 may take such a form as:

$$\begin{aligned} E(\boldsymbol{x}, t+\Delta t) &= E(\boldsymbol{x}, t) \\ &\quad - \Delta t \sum_{i=1}^{2} \left[\frac{\left(c_{g_i} E\right)_{x_i} - \left(c_{g_i} E\right)_{x_i - \Delta x_i}}{\Delta x_i} \right] \\ &\quad + \Delta t\, S(\boldsymbol{x}, t) \end{aligned} \qquad (2.2)$$

where

Δt is the time-step; E and S are functions of wavenumber ($\boldsymbol{k}$), or frequency and direction (f,θ). Using the spectral representation $E = E(f, \theta)$, we have energy density as an array of frequency direction bins (f,θ). The above approach collects a continuum of wave components travelling at slightly different group velocities into a single frequency bin, i.e. it uses a single frequency and direction to characterize each component. Due to the dispersive character of ocean waves (see Sea waves, part I), the area of a bin containing components within (Δf, $\Delta\theta$) should increase with time as the waves propagate away from the origin; the wave energy in this bin will spread out over an arc of width $\Delta\theta$ and stretch out depending on the range of group velocities. In the finite difference approach, all components propagate at the mean group velocity of the bin, so that eventually the components separate as they propagate across the model's ocean. This is called the "sprinkler" effect as it resembles the pattern of droplets from a garden sprinkler. It should be stressed that this is only an artifice of the method of modelling. All discrete-grid models in the inventory suffer from the sprinkler effect, although usually the smoothing effect of continual generation diminishes the potential ill effects, or it is smoothed over as a result of numerical error (numerical diffusion). There are many finite difference schemes in use: from first-order schemes, which use only adjacent grid points to work out the energy gradient, to fourth-order schemes, which use five consecutive points. The choice of time-step, Δt, depends on the grid spacing, $\Delta \boldsymbol{x}$, as for numerical stability the distance moved in a time-step must be less than one grid space. The Coutant-Friderik-Levy parameter of the numerical stability is:

$$c_g \frac{\Delta t}{\Delta x} \le 1 . \qquad (2.3)$$

where c_g is the group velocity, Δt is the time step and Δx is the grid step.

The discrete-grid models calculate the complete $E(f, \theta)$ spectrum at all sea points of the grid at each time-step.

The wave models for the deep water account for growth of waves due to wind input, dissipation of energy by breaking waves (white capping), and transfer of energy between spectral components by non-linear interactions. Wave energy is advected from one grid point to the next at the group velocity.

Operational numerical wave models

National Meteorological Services of many maritime countries now operationally use numerical wave models, which provide detailed sea-state information at given locations. Often this information is modeled in the form of two-dimensional (frequency-direction) spectra. The two-dimensional spectrum, which is the basic output of all spectral wave models, is not by itself of great operational interest; however, many wave products which can be derived from this spectrum are of varying operational utility depending upon the type of coastal and offshore activity.

Significant wave height may be regarded as the most useful sea-state parameter. As defined earlier (see Sea Waves, part I), the significant wave height describes the sea state in a statistical sense and is therefore of universal interest to most offshore and coastal activities. The significant wave height can be easily calculated from the two-dimensional spectrum, using a simple formula. Besides significant wave height, two other parameters, which are of operational interest, are the peak period (or, in some applications, the zero up/down crossing period) and the direction in which waves are moving. It should be noted that the convention of wave direction from wave models varies (i.e. "from which" direction or "to which" direction), whereas measured data are invariably presented as the direction "from which" waves travel, consistent with the meteorological convention for wind direction.

A practical advice:

In order to prepare an accurate sea state forecast (hindcast) for the Black Sea one must to choose an **appropriate numerical wave** model and determine:

- the bathimetry of the Black sea (in order to prepare a sea-land mask)
- the wind fields (prognostic or historical) over the area of interest (wave model atmospheric forcing)
- the computer capacity (workstation or power PC under the operation system LINUX)

Operational system for the numerical real time wave forecasting at NIMH-BAS.

The considerable increase in requirements for Black Sea forecasts has led to the development of the numerical wave forecasting system at the National Institute of Meteorology and Hydrology of the Bulgarian Academy of Sciences (NIMH-BAS). The operational system was created by a team of scientists from NIMH-BAS in collaboration with the meteorological office of France Meteo-France.

The numerical wave model VAGBUL has been in operational use in the Department of Weather and Marine Forecasts at NIMH-BAS since January 1997. This is the METEO-FRANCE VAG wave model (named after the French word for ocean wave 'vague') [Guillaume, 1990], implemented and adopted for the Black Sea (Kortcheva A, 1996). VAGBUL is run operationally for the whole basin of the Black Sea. The model can be used both as a deep water and as a shallow water model. In addition to the VAGBUL wave model, Since 2002 NIMH-BAS has also operated the third generation wave models WAVEWWATCH III (version 2,22) and WAM (cycle 4). All wave models include some shallow-water physics, namely bottom friction, refraction and shoaling.

The short description of the wave models VAGBUL, WAM and WW3 used at NIMH-BAS for the wave forecast for the Black Sea area is given below.

VAGBUL

The VAG model, operational at the French Met Service (*Guillaume 1987, Fradon 2000*) is a second generation coupled discrete model. Numerical wave model VAGBUL has been formulated in terms of the basic transport equation for two-dimensional wave spectrum. The evolution of the two-dimensional ocean wave spectrum E(f,θ,φ,λ,t) with respect to the frequency f and the direction θ as a function of the latitude φ and the longitude λ on a spherical earth is governed by the transport equation:

$$\frac{\partial E}{\partial t} + \frac{1}{\cos\varphi}\frac{\partial}{\partial\varphi}\left(\frac{d\varphi}{dt}\cdot\cos\varphi\cdot E\right) + \frac{\partial}{\partial\lambda}\left(\frac{d\lambda}{dt}E\right) + \frac{\partial}{\partial\theta}\left(\frac{d\theta}{dt}E\right) = S \qquad (2.4)$$

where: S is the net source function describing the wind input Sin, Sds is the surface dissipation, Snl is the non-linear interaction term and Sbf is the bottom friction.

The left-hand side of the energy balance equation (2.4) represents the propagation of the wind waves, i.e., the advection The first term of is presents the local variation of the E, terms 2 and.3 are present the latitude longitude propagation and term 4 the change of the wave direction by propagation to the spherical geometry.

$$\frac{d\varphi}{dt} = c_g \, R^{-1} \cos\theta \qquad (2.5)$$

$$\frac{d\lambda}{dt} = c_g \sin\theta (R\cos\varphi)^{-1} \qquad (2.6)$$

$$\frac{d\theta}{dt} = c_g \sin\theta \tan\varphi R^{-1} + \frac{1}{kR}\frac{\partial\omega}{\partial h}(\sin\theta \frac{\partial h}{\partial\varphi} - \frac{\cos\theta}{\cos\varphi}\frac{\partial h}{\partial\lambda}) \qquad (2.7)$$

where g is the acceleration of gravity

R is the radius of the earth

h is the depth

k is the wavenumber

$$\omega = (gk \tanh kh)^{1/2} \qquad (2.8)$$

The great circle refraction term for the deep water was augmented to include the refraction due to the variations of the water depth (Phillips,1977) - the second term in (2.4). The infinite group velocity c_g for the deep water was replaced by the corresponding expression for finite depth h:

$$c_g = \frac{c}{2}\left(1 + \frac{2kh}{\sinh(2kh)}\right) \qquad (2.9)$$

where c is the phase velocity

$$c = \sqrt{\frac{g}{k} \operatorname{th}(kh)} \qquad (2.10)$$

the source functions :

$$\frac{\partial E}{\partial t} = S = S_{in} + S_{ds} + S_{nl} + S_{bf} \qquad (2.11)$$

An important aspect of the wave model is its modular structure. Namely, two main tasks: integration for the advection term and for the source term are isolated. A first order “upstream" propagation scheme was implemented for the integration of the advection term. For the integration of the source term, a first order explicit scheme was implemented.

The input source terms related to the wind speed used in the VAG model consist of a linear growth term representing the Phillips mechanism (*Phillips 1957*) and an exponential growth term representing the Miles mechanism (*Miles 1957*). The dissipation due to the wave breaking is described in *Golding (1983*). An additional bottom friction term is taken into account for shallow water conditions. The non-linear interactions between the wave components are parameterized. In the first step, the part of the wave spectrum corresponding to the wind-sea is selected and the total energy of this domain is limited (if necessary) to the total energy of the Pierson-Moskowitz spectrum (*Pierson and Moskowitz,1964*) corresponding to the fully developed spectrum associated with the specified wind speed. The limitation allows the solving of the problem of imbalances between growth and dissipation terms. In the second step, the wind-sea part of the spectrum is reshaped into a JONSWAP spectrum (*Hasselman et al. 1973*) with a cosine square distribution on each side of the wind direction in such a way that the total energy of the wave spectrum is conserved.

WAM

The WAM (*WAMDI Group 1988*) wave model is one of the best-tested wave models in the world. It has been distributed among over 50 research groups for forecasting on global and regional scales. WAM is operational at the European Centrum for Medium Range Weather Forecast (ECMWF). The wave model WAM solves explicitly (without any assumptions on the shape of the wave spectrum) the same energy balance equation used in the VAG model, but with additional non linear inter-actions terms. The physical part of the WAM model differs quite appreciably from that of the original VAG model. The WAM source/sink term does not take into account the linear growth and for this reason the spectrum is initialised with a low energy JONSWAP spectrum. The source/sink term used in the WAM model includes: an exponential growth term, given by Miles (*Miles 1957*), which takes into account the theory of Janssen (*Janssen 1991*) for the wind-wave coupling, a dissipation term (*Komen et al. 1994)* and an explicit term for computation of the non-linear interactions between the wave components (*Hasselmann et al. 1985)*. The source terms and propagation are computed with different methods and time steps. The source terms integration is done with an implicit integration scheme, while the propagation scheme is a first order upwind flux scheme.

A comprehensive description of the WAM model, its physical basis, its formulation and its various applications are given in (Komen et al., 1994) and on the web sites of the European Centre for Medium-range Weather Forecasts (ECMWF):

http://www.ecmwf.int/research/ifsdocs/WAVES/Chap6_Software8.html

http://www.ecmwf.int/newsevents/training/rcourse_notes/NUMERICAL_METHODS/WAVE_MODEL/Wave_model1.html

WAVEWATCH III (WW3)

WW3 (Tolman H, 2002a, 2002b) is a third generation wave model developed at NOAA/NCEP. WW3 differs from its previous versions (WW1 and WW2) for the governing equations, the models structure, the numerical methods and physical parameterisations. In WW3, new input source terms have been introduced. Only the terms for the nonlinear interaction are similar to WAM.

WW3 solves the **spectral action density balance** equation for wave number-direction spectra $N(k, \theta, \lambda, \varphi, t)$:

$$\frac{\partial N}{\partial t} + \frac{1}{\cos\phi}\frac{\partial}{\partial\phi}\dot{\phi}\, N\cos\theta + \frac{\partial}{\partial\lambda}\dot{\lambda}\, N + \frac{\partial}{\partial\theta}\dot{\theta}_g\, N = \frac{S}{\sigma}, \qquad (2.12)$$

For mode details about WW3 model description see NOAA/NCEP web site:

http://polar.ncep.noaa.gov/waves/wavewatch/wavewatch.html

(Documentation and source code of the WW3 wave model is available for free).

Numerical aspects of the wave models, implemented for the Black Sea.

Initialization.

The initial state is the 24 hours forecast of the wave spectrum from the previous day.

Horizontal resolution.

The numerical models VAGBUL, WAM and WW3 were implemented on a spherical grid cover the area of the Black Sea from 40°N to 47°N and from 27°E to 42°E on a regular latitude-longitude grid. The grid resolution is 0.25°x0.25° latitude-longitude grid.

The NIMH-BAS is testing an improved wave forecast with 0.833° x 0.833° ° latitude-longitude grid.

Spectral discretization.

For VAGBUL, 22 frequencies logarithmically spaced from 0.040 Hz to 0.296 Hz, at the intervals of Df/f = 0.1, and 18 directions (constant increments).

The spectral discretization of WW3 and WAM is with 25 frequencies ranging from 0.042 Hz to 0.41 Hz, at intervals equal to VAG, and 24 directions (constant increments).

Input data.

All numerical wave models have been driven by 10 m wind fields provided by the ARPEGE NWP model (see module **"Black Sea meteorology").** The wind fields are available every 6 hours on a regular latitude-longitude grid with a 0.5°x0.5° mesh size. A bilinear interpolation scheme is used to collocated the 10m winds with the fine mesh grid of the wave model.

Output data.

Wave model output products are available every 6 hours up to 48 hours from 00.00 and 12.00 UTC. Wave energy two-dimensional spectra are post-processed to provide output fields of the following variables:

Significant wave height
Wave direction
10m Wind speed
10m Wind direction
Mean period
Peak period
Swell wave height
Wind wave height
Mean Swell direction
Mean Swell period

The model results are available for NIMH-Varna via Internet and used for the issue of storm warnings in case of strong winds over the Black Sea area.

http://weather.bg/ani-valnenie/k.php

In addition, directional wave spectrum output charts for selected locations in the western part of the Black Sea are available. (WWW3 wave model) The wave spectra are displayed in polar diagrams.

Computer resources.

The current versions of the VAGBUL, WAM and WW3 wave models in NIMH-BAS have been implemented on a power PC (Intel compiler) under the Linux Operating System. The old versions were implemented on the SUN Workstation ARDA (Fujitsu compiler). But the use of a power PC is more efficient (effective).

<u>Examples of typical output from the operational wave models.</u>

The main output from the wave models is a wave chart depicting contours of significant wave height and arrows showing mean wave direction. A typical output fields from the wave models VAGBUL and WW3 are given in Fig.2.3, 2.4 and 2.6. Fig.2.5 presents the wind field from ARPEGE NWP model for the same situation.

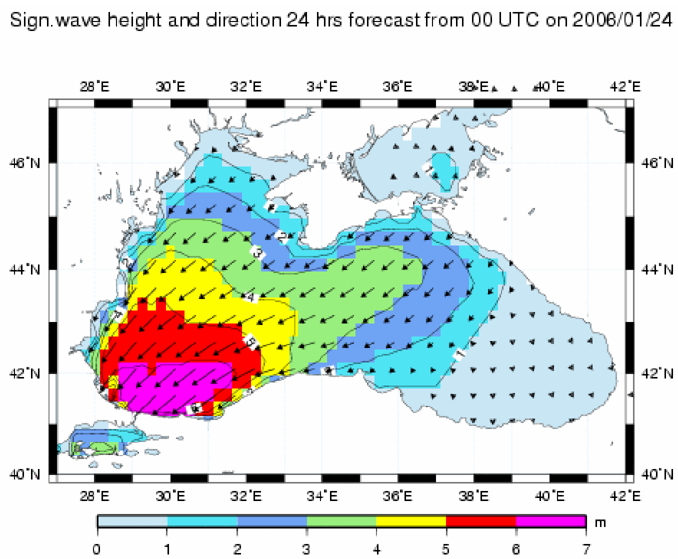

Fig. 2.3.   Field of significant wave height and mean wave direction (VAGBUL, NIMH-BAS) (Dimitrova M, Kortcheva A, 2006).

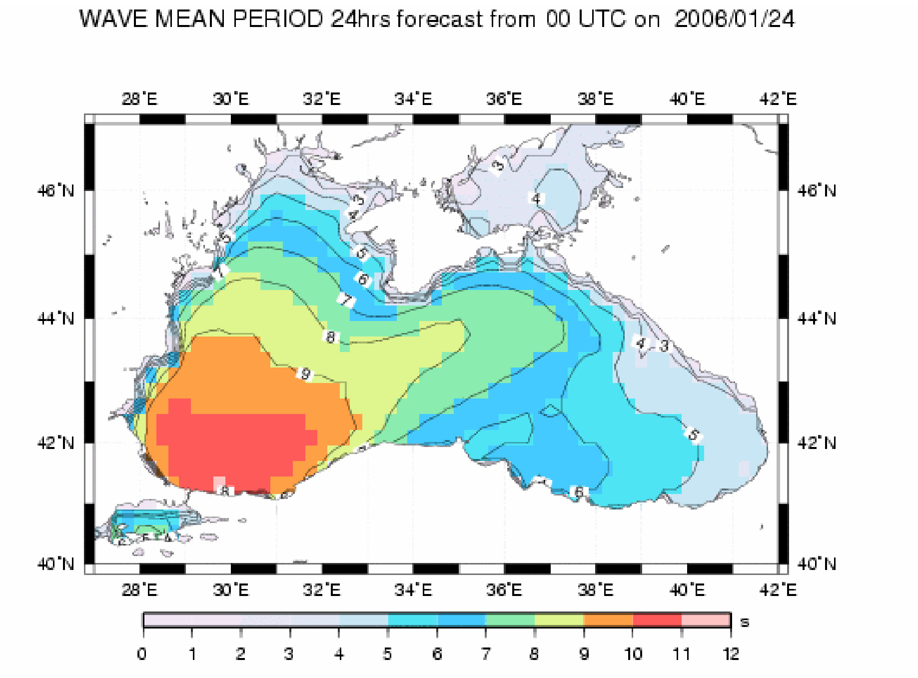

Fig. 2.4. Mean wave period (VAGBUL, NIMH-BAS) (Dimitrova M, Kortcheva A, 2006)

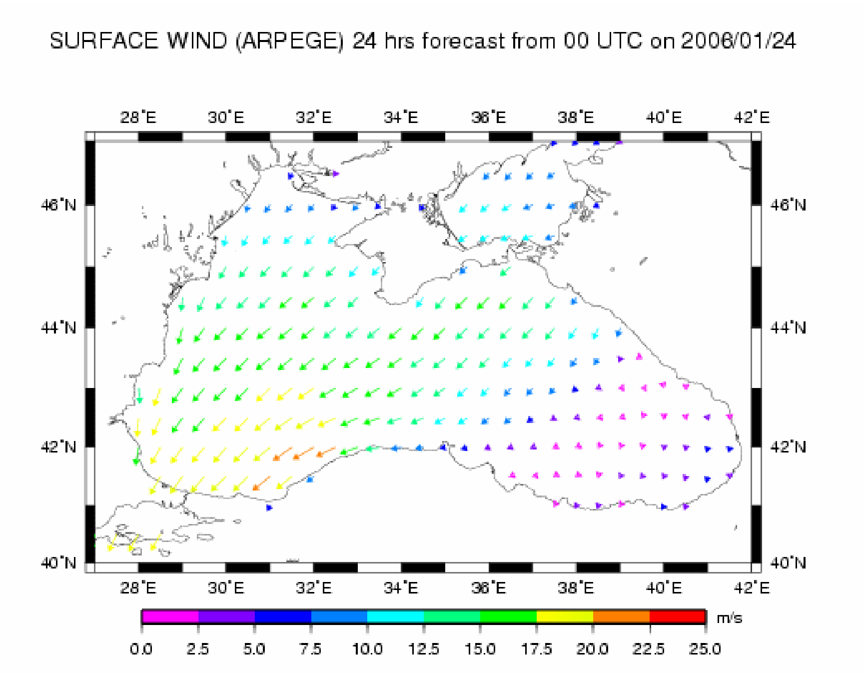

Fig. 2.5. Wind field from ARPEGE (NIMH-BAS) (Dimitrova M, Kortcheva A, 2006)

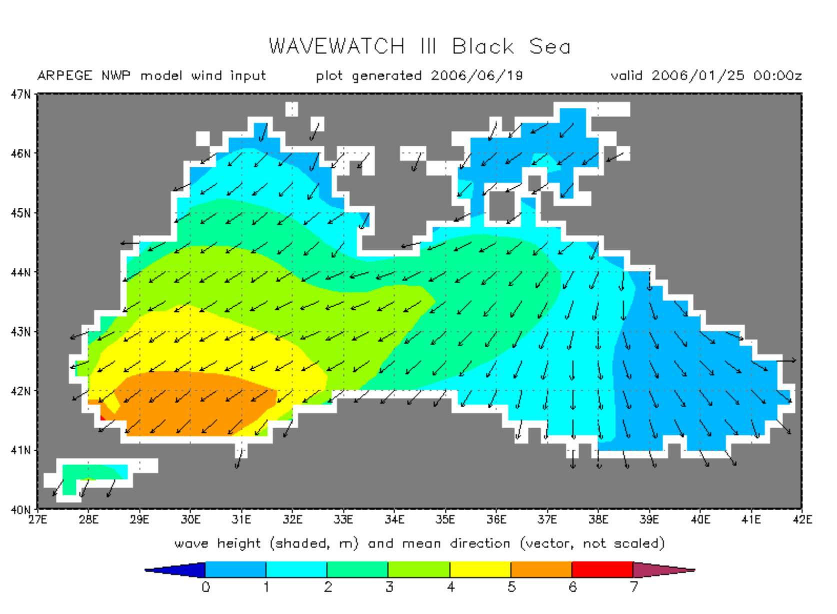

Fig. 2.6. Significant wave height and mean wave direction (WW3 -NIMH-BAS) (Dimitrova M, Kortcheva A, 2006)

Output from WW3 wave model produced by NIMH's Sea Modeling Group for 25/01/ 2006 Contours are significant wave-height in meters, arrows give mean direction of waves propagation.

Wave data: observed, measured and hindcast.

Knowledge of the sea state and the sea surface winds is of great importance for the validation of the results from the wave models. Wave data are often required by meteorologists for real time operational use and also for climatological purposes. Three types of wave data that are available, namely, observed, measured and hindcast.

Visual observations

A traditional source of wave information has been from so-called ships of opportunity. Given the lack of surface based measurements of waves on the open ocean, the coverage offered by merchant shipping has been utilized in the WMO Voluntary Observing Ship (VOS) Programme. The participating ships report weather information including visual observations of waves. Many of the observations are reported in real time as part of the routine meteorological reports which are circulated internationally on the Global Telecommunication System. These reports use the WMO SHIP code (see the Manual on codes, WMO, 1995). Visual observations by VOS of wind speed and direction, significant wave height, wave period, and wave direction (wind sea and swell) have always been of great importance, and will continue to be important. However by their nature these observations are subjective, and whilst useful in assessing marine forecast products - since the ships themselves may be receiving routing advice, the data are not sufficiently precise to permit assimilation or direct application in numerical wave models

Unfortunately there is no VOS in the Black Sea area.

Measured wave data.

Instrumented observations of wave height and wave period are available from a network of moored buoys operated by offshore oil industry. Various methods are available for measuring the directional wave spectra at sea, on offshore installations and at the coast. The most common systems for routine data collection are various types of wave buoys, which are still the major source of data in deep water, away from offshore platforms Buoy data are usually inappropriate for extreme analysis due to short record lengths. Buoy data are particularly useful for validating (or calibrating) numerical models and remote sensing algorithms, verification and predictive model tuning (calibration).

The majority of instrumented wave observations provide one-dimensional, i.e. frequency spectrum data. Freely available (i.e. non-proprietary) directional wave spectrum measurements, i.e. 2-D, which would correspond to the output of modern wind wave models, are extremely scarce. However the network of buoys in the Black Sea is too sparse.

Instrumental observations of wave height and period in the Black Sea area are very rare.

Satellite wave data.

Altimeter data.

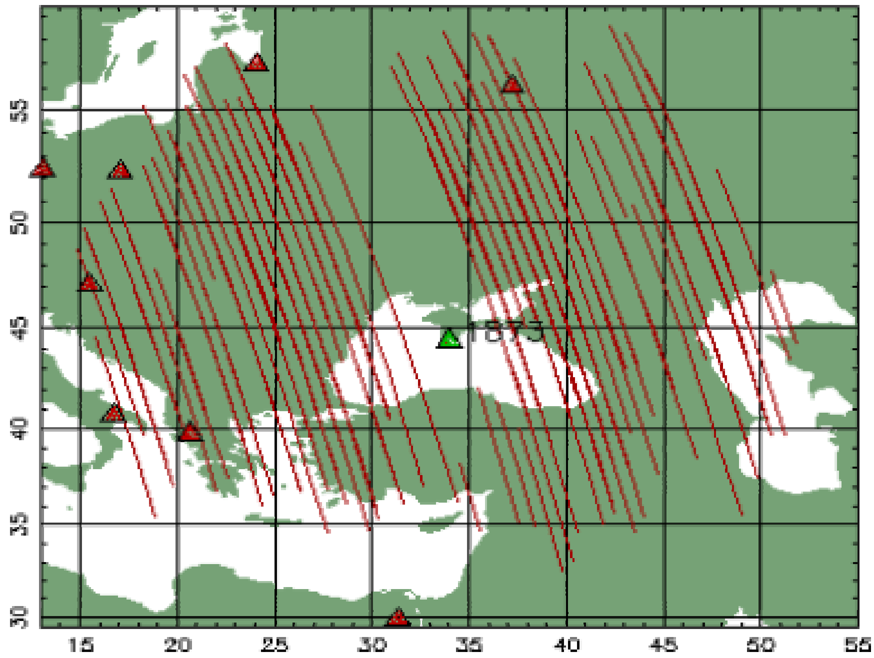

Fig. 2.7. The tracks of the ERS-2 altimeter.

Classical wind and wave data over the oceans are mainly from buoys. Development of remote sensing techniques during the last twenty years is changing this situation significantly. Satellite borne altimeters that are presently able to measure significant wave height, along track and continuously over many years, at a rate of sampling of about one earth resolution every 100 min, with an accuracy of the same order than buoy measurement accuracy. Through the launch of ocean observing satellites, such as ERS-1, ERS-2, POSEIDON and TOPEX-POSEIDON, JASON 1 and ENVISAT wave modellers are now receiving detailed data on a global, continuous basis. Over the past twenty years there has been a continuous interplay between ocean wave forecasting and altimeter data resulting in improvements in both.

Satellite wave data with global coverage are now available from various sources. Raw data from each of these missions can be obtained from the responsible space agencies.

Fast delivery data (FDP) from the satellites are also available in near-real time via the Global Telecommunication System (GTS).

High-level altimeter wave data (sorted, quality controlled and corrected) can be provided from the GEOSAT, Topex/Poseidon and ERS-1/2 missions by the AVISO (Archiving Validation Interpretation of Satellite data in Oceanography) centre in Toulouse.

http://www.aviso.oceanobs.com/

Satellite synthetic aperture radar (SAR)

SAR sensors record microwave radar backscatter in order to identify patterns of surface roughness. SAR can operate in two modes: Image Mode and Wave Mode. Wave Mode operation of the SAR provides 5 km x 6 km images at intervals of 200 km along track. This product provides the SAR wave power spectra in polar coordinates. Because the data rate is relatively low, onboard data storage is possible, and there is a global sampling of wave spectra, but the SAR data are collected along the satellite orbit and are therefore only sporadically available at any fixed location.

For more details see:

http://www.aviso.oceanobs.com/

Hindcast wave data

A wave model in operational use will usually be forced by **forecast winds** to produce wave **forecasts.** However, the model may also be driven by **historical** winds pertaining to past events, such as storm situations in the Black Sea. In such cases the wave field generated by the wave model is called the **hindcast** wave field. Wave hindcasting is a non-real-time application of numerical wave models, which has become an important marine application in many national weather services.

The purpose of a wave hindcast is to generate wave data that will help describe the temporal and spatial distribution of important wave parameters. The existing network of wave observing buoys in the Black Sea is very limited. Consequently, a meaningful wave climatology describing temporal and spatial distribution of wave parameters cannot be developed solely from the buoy data.

VAGBUL, WW3 and WAM wave models have been used in the hindcast mode to create wave databases and related wave climatologies for the Black Sea. The wave hindcast can be used also to simulate wave fields associated with intense storms that particularly affect the western part of the Black Sea. A similar study for the storms in the Black Sea is in progress at the NIMH-BAS and is expected to be completed shortly (Dimitrova M, Kortcheva A, 2006).

Most recent wave climatologies, especially regional climatologies, are based on hindcast data (Kortcheva A, 1994; Cherneva, Z., N. Valchev, 2002; Özhan, E., S. Abdalla, N. Yilmaz, 2003, N. Valchev, 2005). More details on the wave climatology and its applications can be found in (WMO Guide, 1998).

The quality of hindcast data (or at least its credibility) can be improved by validating the results against available in situ measurements or satellite altimeter Hs data (for instance, this is currently being carried out at the NIMH-BAS (V.Galabov, 2005)- Fig. 2.10-2.14.

Verification of operational wave models

Because ocean wave models being used in operational mode, appropriate verification of a wave model against observed wind and wave data is necessary and important. The performance of a wave model must be continually assessed to determine its strengths and weaknesses so that it can be improved through adjustment or modifications. It is also necessary to develop sufficient confidence in the model products for operational use. There are a number of levels of model testing and verification. In wave model development a number of idealized test cases are usually modelled. The basic output of spectral wave models is the two-dimensional wave spectrum and a suitable test would be to use the model to simulate the evolution of a wave spectrum with fetch or duration for stationary uniform wind fields. Data from field experiments, such as the JONSWAP experiment (see Sea Waves Part I), can be used to assess the model's performance.

Ideally, a model would be verified by comparisons with measured directional wave spectra. However, such measurements are relatively uncommon and there are problems with interpreting the results of comparisons of individual directional wave spectra. For these reasons, model validation studies are usually performed in a statistical sense using all available data, and are based on comparisons of derived parameters.

Since the wind field that drives the model is intimately related to the model wave field, most evaluation studies also include verification of wind speed and direction. An important requirement for evaluation of a wave model is the availability of reliable sea-state measurements and related weather data. Most of the evaluation have used buoy data for wind and wave measurements and have occasionally used analysed weather maps for additional wind information. More recently, satellite altimeter data have been used to validate wave model results.

Several statistical parameters are calculated and analysed the magnitude and variation of these parameters to determine the skill of an operational wave model.

Among the parameters that are most commonly used are:

- The mean error (ME) or bias;
- The root-mean-square error (RMSE);
- The Scatter Index (SI) defined as the ratio of RMSE to the mean observed value of the parameter; and
- r, the sample linear correlation coefficient between the model and the observed value.

At most Meteorological Services, the initial verification of operational wave model is performed during the implementation phase and the verification statistics are updated periodically so as to monitor the model's performance.

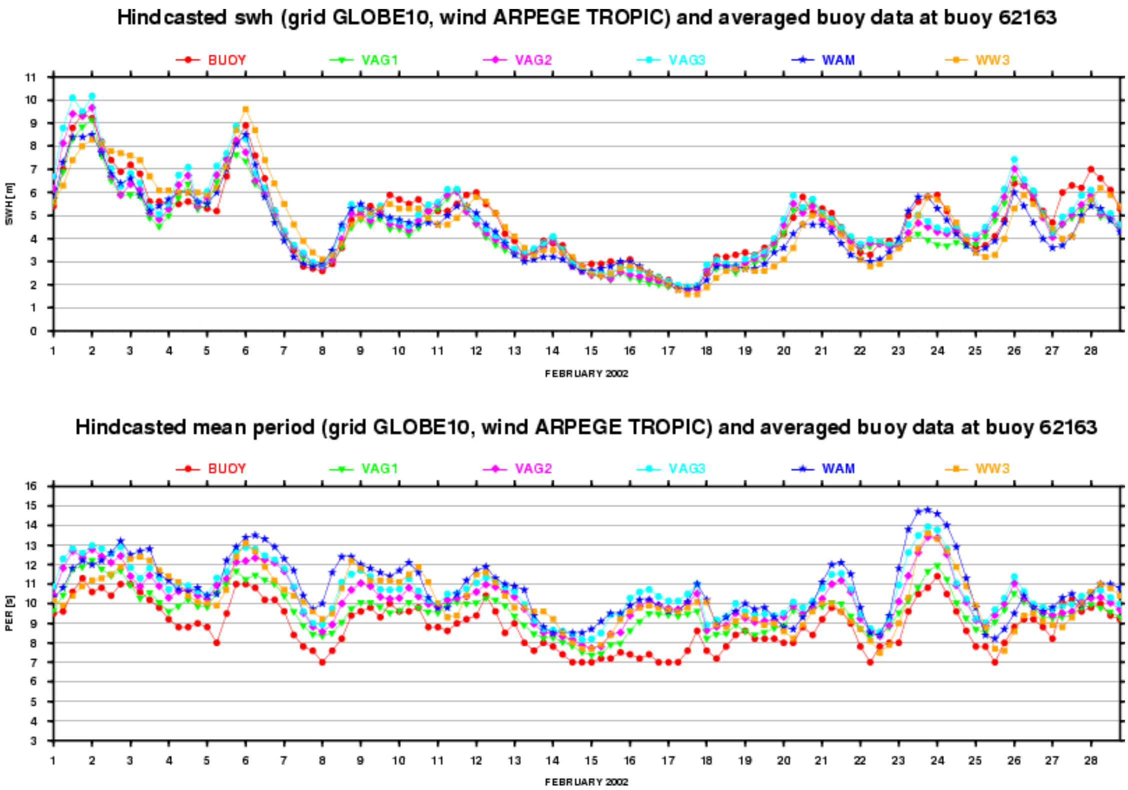

Fig. 2.8. The time series of SWH (top panel) and mean wave period (bottom panel) from VAG, WAM and WW3 models and buoy data at location of buoy 62163 during February 2002. (Lefevre, Kortcheva, Stefanescu, 2003).

A comparison of the performance between the second-generation VAG model and the two third-generation WAM and WW3 wave models with buoy data was done in Meteo-France (Lefevre, Kortcheva, Stefanescu, 2003). These models were run with the same wind fields. The example of the time series of SWH from all models and the buoy data are presented on Fig. 2.8 for the period of one month. The statistical results (Lefevre, et al, 2003) show that VAG and WAM results are in general in a good agreement with the observations, but also that WW3 results are a little better than these of WAM and VAG

The wave model evaluation for the Black Sea has relied for lack of the conventional wave data from buoys and weather ships. Recent advances in satellite technology have created the possibility to utilise remotely sensed wave and wind data for the validation of wave and weather prediction models. For example, for the Black Sea the VAGBUL, WW3 and WAM wave models were validated using altimeter data from the TOPEX/POSEIDON, ERS1/2 (A. Kortcheva, 1998), and ENVISAT satellites

(V.Galabov,2005). Fig.2.9. shows the results of a comparison between significant wave heights (SWH) obtained from the wave model and altimeter-derived SWH from the second European Sensing Satellite (ERS-2) during a storm situation in the Black Sea. The discrete spectral VAG model was used for issuing wave hindcast for the Black Sea. A total number of 687 collocated data points were selected over the period of 1992 –1998. The overall statistics for SWH obtained from the VAGBUL forced by ARPEGE wind : the mean error - 0.11 m , the standard deviation error - 0.51 m, RMSE - 0.53 m and the scatter index - 0.29. SWH (mean) from the VAGBUL - 1.88m and ERS2 SWH - 1.76 m.

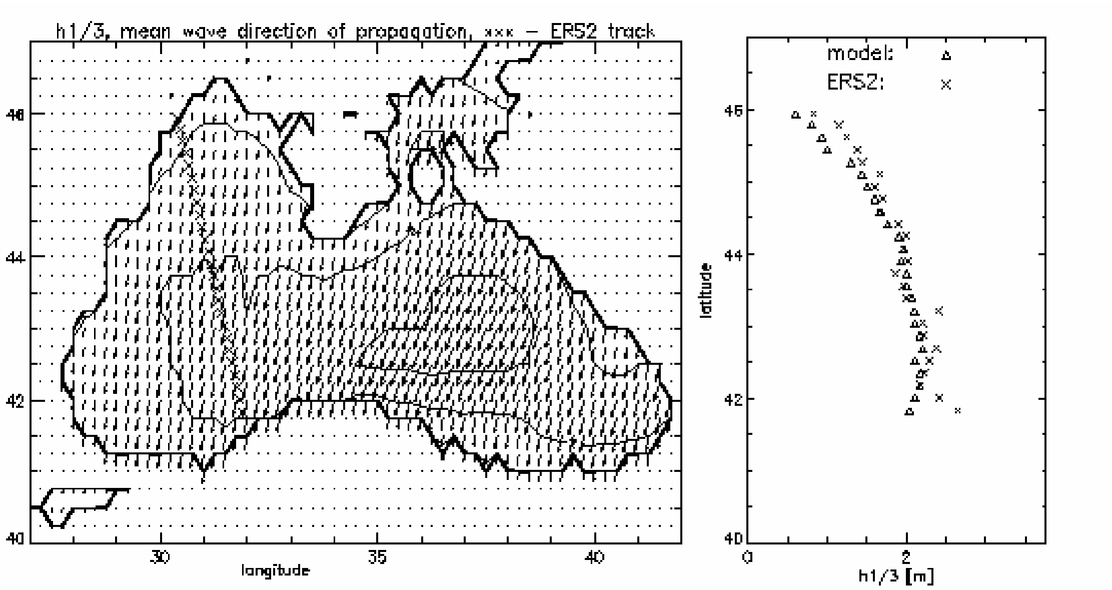

Fig. 2.9. Comparison of modeled by VAGBUL SWH and ERS-2 altimeter data during the storm in the Black Sea on 23 December 1996 at 12.00 UTC (A. Kortcheva, 1998).

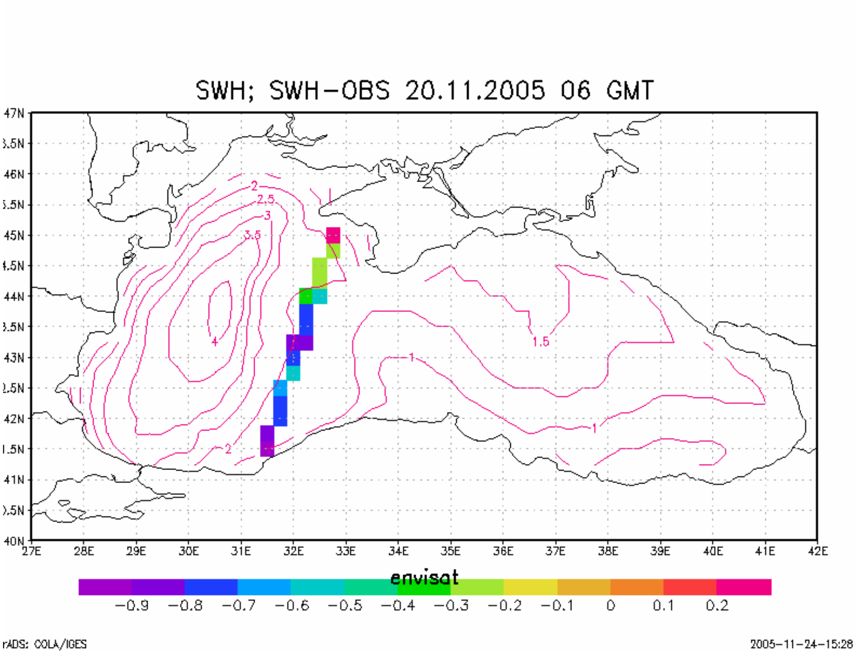

Fig.2.10. Visualization of the difference: hindcasted Significant Wave Height (SWH) by the VAGBUL wave model minus the observed SWH by the radar altimeter abroad the satellite ENVISAT (Galabov V, 2005).

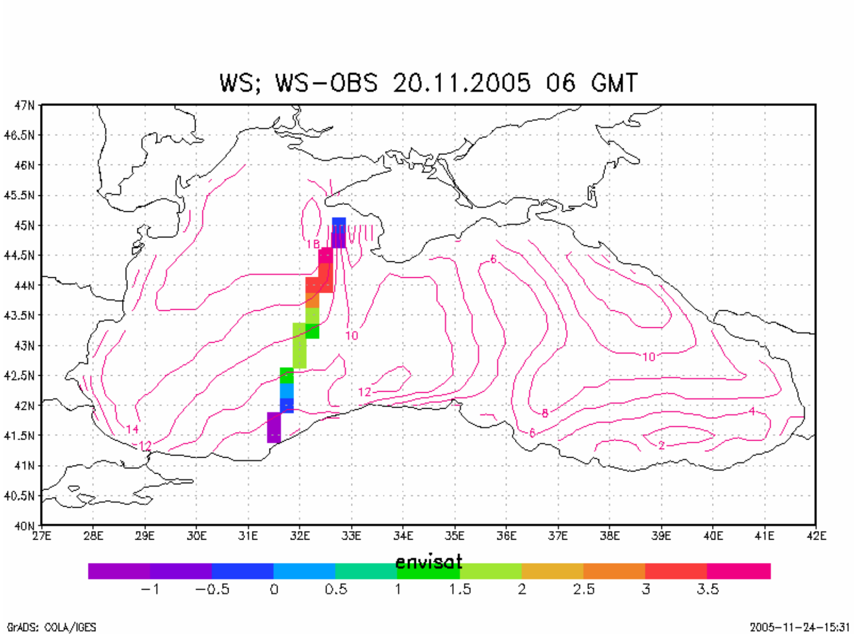

Fig.2.11. Visualization of the difference: 10m. wind speed from the ARPEGE NWP model minus the observed wind speed by the radar altimeter abroad the satellite ENVISAT (Galabov V, 2005).

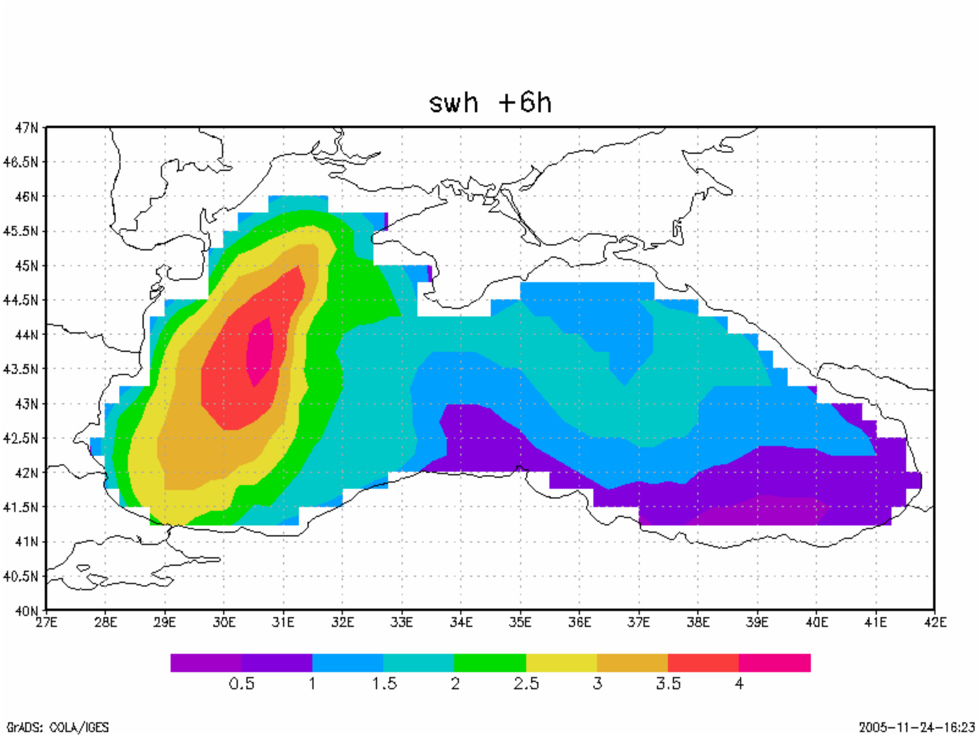

Fig.2.12. Field of SWH on 20/11/2005 at 06.00 GMT- VAGBUL wave model (Galabov V, 2005)

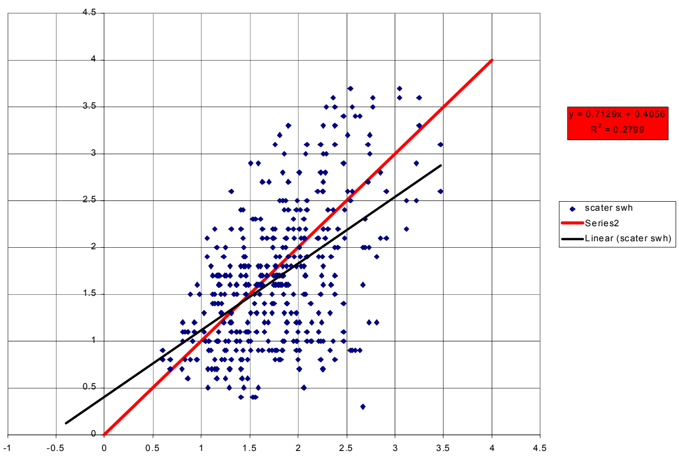

Fig. 2.13. Scatter plot for SWH from VAGBUL wave model against ENVISAT altimeter wave data (Galabov V, 2005)

Bias=-0.10
Standard deviation= 0.64
RMSE=0.65
Scatter Index=0.36
Symmetric Slope=0.98

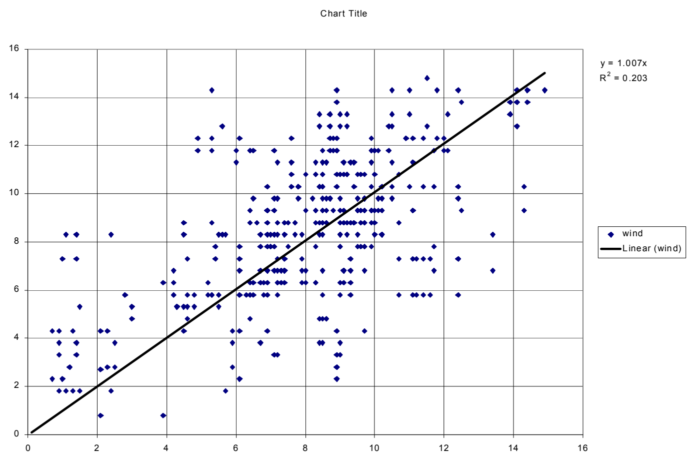

Fig. 2.14. Scatter plot for the 10m. wind speed from ARPEGE NWP model against ENVISAT altimeter wind data (Galobov V, 2005)

Bias=0.45
Standard deviation=2.66
RMSE=2.70
Scatter Index=0.33
Symmetric Slope=1.06

Figure 2.13 shows the scatter plot for SWH as well as several statistical parameters: the bias, RMSE, standard deviation, symmetric slope and scatter index. Fig 2.14 shows similar scatter plot for the 10m.wind speed from ARPEGE NWP model. Still it is too early to comment such results (even if the statistics don't look very good the cases are not enough to make any general conclusions) but this is the base of the technology which we will use in our future project and we hope that in this way we will reach our goals.

The main problems are to put this system in the operational practice and to evaluate enough cases, which is not quite easy because the area of the Black Sea is relatively small and often we don't have a satellite tracks crossing the storm areas.