RECENT DEVELOPEMENTS IN PHYSICAL PARAMETERIZATIONS USED IN VAG AND WAM WAVE MODELS

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ABSTRACT

New formulations of the physical processes involved in the wave evolution have been introduced recently in the VAG and WAM models. The results have been tested during an intercomparison study of three ocean wave models (VAG, WAM and WAVEWATCH III) with moored buoy data. The intercomparison study has allowed the identification of potential improvements.

In order to reduce the imbalance between the input and dissipation source terms, a new physics package has been implemented in the VAG model. The new physics is obtained with a linear combination of the VAG linear input term, the WAM exponential input term and the WAM dissipation source term. The parameterization of the non-linear interactions are kept as in the original VAG model. It is well known that it is difficult to deal with complex seas or rapidly evolving waves in the second generation models. This is related to the fact that, in the second generation models, the non-linear interactions between the wave components are only parameterized. These non-linear interactions are solved explicitly in the third generation wave models. For this reason, the intercomparison study has shown better skills of WAM and WAVEWATCH III models for high swell conditions. The new physics introduced in the VAG model has reduced significantly the underestimation of the high swell.

A modern wind-over-waves coupling theory (WOWC) has been developed in the last years. This theory includes a physical model for short waves, based on the energy balance equation, and accounts for stress due to the separation of the airflow from short and dominant waves and also for the wave-induced stress. A new parameterization of the surface stress (sea drag), based on this theory, has been introduced and tested in the WAM cycle 4 model. The parameterization accounts for the wind speed, wave age and finite bottom dependencies of the surface stress. Also, new formulations of wind input and dissipation due to the wave breaking, based on the new understanding of physics of the processes, have been tested during the intercomparison study. The new formulations of sea drag and wind input and dissipation source terms, introduced in the WAM model, resulted in a better prediction of significant wave height in many cases and reductions in the bias and root mean square error of this parameter.

KEY WORDS: ocean wave, windsea, swell, wave modelling, wave physics parameterization, buoy data.

1. Introduction

The developement in the measurement technics in the last twenty years has led to improvements in the theories describing the processes involved in the wave evolution.

In 2001, a new physical parameterization has been introduced in the second generation wave model VAG (Guillaume, 1987), developed and operationally used at Meteo-France. The new physics is obtained by combining the VAG source terms with the source terms used in the third generation wave model WAM (WAMDI Group, 1988), which is in operational use at European Centrum for Medium Range Weather Forecast (ECMWF). This new physical parameterization has been proposed by Fradon (1997) and Fradon et al. (1999), in order to improve the performance of the VAG second generation wave model. The introduction of the new physics rezulted in a better balance of the source terms in the energy budget computation and a better agreement of the VAG wave growth and decay curves with the WMO curves (WMO, 1998).

The air-sea coupling formulation used in the numerical wave model WAM cycle 4 is based on the wind-over-waves coupling theory (WOWC) introduced by Janssen (1989, 1991). A modern WOWC theory was recently developed by Makin et al. (1995), Makin and Kudryavtsev (1999), Kudryavtsev and Makin (1999), Kudryavtsev and Makin (2001) and Makin and Kudryavtsev (2002). This theory includes a physical model for short waves, based on the energy balance equation, and accounts for stress due to the separation of the airflow from short and dominant waves and also for the wave-induced stress. The parameterization of the surface stress (sea drag) is based on this theory and its implementation in the NEDWAM model (the North Sea version of the WAM model) is described in Makin and Stam (2003). The parameterization accounts for the wind speed, wave age and finite bottom dependencies of the surface stress. The sensitivity study presented in Makin and Stam (2003) has shown that the NEDWAM model is not sensitive to the parameterization of the sea drag and, for this reason, new formulations of wind input and dissipation due to the wave breaking, based on the new understanding of physics of the processes, have been implemented.

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In the present study, the new parameterization of the sea drag, as well as the new formulations of wind input and dissipation source terms, have been implemented in the WAM cycle 4 model and tested on a global grid at a spatial resolution of $1^o \times 1^o$. The new physics introduced in VAG and the changes in the WAM model have been tested during an intercomparison study of the performance of three ocean wave models with moored buoy data. For the experiments, two periods of 1 month were selected: one winter month of February 2002 and one summer month of July 2002. Sensitivity experiments with the VAG and WAM models have been carried out using available analysed 10 m wind field from the global operational numerical weather prediction (NWP) models of ECMWF (IFS - Simmons et al., 1989) and Meteo-France (ARPEGE - Courtier et al., 1991). The results were compared against buoy data and results from another numerical wave model WAWEWATCH III (Tolman 2002, 2002f). Improvements in the root mean square (rms) error and scatter index indicated a positive impact of the new physics introduced in the VAG model. Since March 2003 the new physics is operationally used at Meteo-France. The new formulations of sea drag and wind input and dissipation source terms introduced in the WAM model resulted in a better prediction of significant wave height (swh) in many cases and reductions in the bias and rms error of this parameter.

The paper is organized as follows. Section 2 gives a short description of the new physical parameterization introduced in the VAG model. In section 3, the new sea drag and wind input and dissipation source terms formulations introduced in the WAM cycle 4 model are disscused. Section 4 presents the three ocean wave models and buoy data used in this study. Sensitivity experiments with VAG and WAM models and comparison of the results with buoy and model data are included in section 5. Conclusions and perspectives are pointed out in section 6.

2. The new physics introduced in the VAG model

The source terms used in the original VAG model are described in Guillaume (1987) and Fradon (1997). A previous study performed by Fradon (1997) and Fradon et al. (1999) has shown that the wave growth is significantly faster in VAG than in WAM, as well as the peak frequency decreases faster with time in case of VAG with respect to WAM. WAM gives better agreement with the WMO curves. The decay of the waves is also faster for VAG than for WAM. These large differences between VAG and WAM growth curves are associated with even larger differences in the energy balance. The exponential growth and dissipation terms are above five times higher in WAM than in VAG. In the VAG model, these small terms are compensated by a very large linear term and a large limitation term. Experience showed that the use of a high linear growth term is not very satisfactory. Also, the fact that the limitation term has the same order of magnitude as the other terms contributing to the energy budget can lead to a high sensitivity of the VAG model to the frequency of the wind forcing.

In order to reduce the imbalance between input and dissipation terms, a new physics package has been proposed by Fradon (1997) and Fradon et al. (1999) and implemented in the last version of the VAG model by Stefanescu and Lefevre (2001). The new physics is obtained with a linear combination of the VAG linear wind input term, the WAM exponential wind input term and the WAM dissipation source term, defined by a set of three coefficients (a,b,c). The linear growth term has been kept small compared to the exponential one. The parameterization of the non-linear interactions are kept as in the original VAG model. The total source/sink term used in the new physical parameterization reads:

$$S^{VAG,new} = a \cdot S_{VAG}^{linear\ wind\ input} + b \cdot S_{WAM}^{exponential\ wind\ input} + c \cdot S_{WAM}^{dissipation} + S_{VAG}^{limitation} \tag{1}$$

For the shallow water conditions, an additional bottom friction dissipation term (which has the same formulation in VAG and WAM) is added to the source function.

The experiments performed by Fradon (1997), Fradon et al. (1999) and Stefanescu and Lefevre (2001) showed that the growth curves are more realistic in case of using the new physics. Also, a better balance of the source terms in the energy budget computation is obtained and the strong effect of limitation is diminished.

3. The new sea drag parameterization and wind input and dissipation source terms formulations introduced in the WAM model

A new air-sea coupling formulation has been recently developed by Makin et al. (1995), Makin and Kudryavtsev (1999), Kudryavtsev and Makin (1999), Kudryavtsev and Makin (2001) and Makin and Kudryavtsev (2002). Its implementation and testing in the NEDWAM model is presented in Makin and Stam (2003). The new parameterization is valid only under stationary and spatial homogeneous wind and waves conditions, when the constant-flux layer is established in the marine atmospheric surface boundary layer. It can be applied for both pure windsea and mixed windsea-swell conditions. However, only the windsea part of the wave spectrum is used to calculate the sea drag, while the contribution of swell spectrum is not accounted for. Therefore, the parameterization assumes that the wind waves direction coincides with the wind direction.

The third generation wave model WAM solves explicitly (without any assumptions on the shape of the wave spectrum) the energy balance equation, in which the source function is defined as a superposition of four source terms: wind input, dissipation by wave breaking, bottom friction dissipation and non-linear interactions between the wave components. The source terms of the WAM model cycle 4 are described in WAMDIG (1988), Günther et al. (1992) and Komen et al.(1994).

The sensitivity study presented in Makin and Stam (2003) showed that the NEDWAM model is not sensitive to the parameterization of the sea drag and, for this reason, new formulations of wind input and dissipation due to the wave breaking, based on the new understanding of physics of the processes, were implemented.

The quasi-linear form of the dissipation source term S_{dis} used in the WAM model cycle 4:

$$S_{dis} = \gamma_{dis} \omega F \tag{2}$$

is defined in terms of the integrated spectral steepness, as proposed by Hasselmann (1974). The dissipation rate γ_{dis} reads:

$$\gamma_{dis} = -C_{dis} \frac{\langle \omega \rangle}{\omega} (\frac{\alpha}{\alpha_{PM}})^2 \frac{k}{2\langle k \rangle} (1 + \frac{k}{\langle k \rangle}) \tag{3}$$

where k is the wavenumber, $\alpha_{PM} = 4.57 \times 10^{-3}$ is the Pierson-Moskowitz steepness for a fully developed sea, $\alpha = E\langle k\rangle^2$ is the squared average steepness of the spectrum and $C_{dis} = 9.4 \times 10^{-5}$ is a dimensionless constant. E represents the total wave variance, while $\langle\omega\rangle$ and $\langle k\rangle$ are the mean angular frequency and mean wavenumber.

Formulation (3) gives a dissipation rate at the spectral peak that is too low during young windsea growth and too strong for old windseas (Banner and Young 1994, Makin and Stam 2003). It is based on the average wave steepness, which is not appropriate for mixed windsea-swell situations.

A new spectral dissipation source term, based on the local wave steepness and strongly non-linear dependent of the wave spectrum, has been suggested by Alves and Banner (2003). This new formulation improves the prediction of wave evolution from young to old seas, in accordance with field observations. Alves and Banner (2003) proposed the following expression for the dissipation rate:

$$\gamma_{dis} = -C_{dis}^{b}(\frac{\alpha}{\alpha_{PM}})^m(\frac{B(k)}{B_r})^{p/2}(\frac{k}{\langle k\rangle})^n \tag{4}$$

where C_{dis}^{b}, m, p, n and B_r are constants (to be adjusted for the new balance), and $B(k)$ is the saturation wave spectrum related to the wave density spectrum $F(f)$ by:

$$B(k) = \frac{1}{2\pi}F(f)c_g k^3 \tag{5}$$

where c_g is the group velocity.

The dissipation source function $S_{dis} = \gamma_{dis}\omega F$ is now non-linear with respect to F, as the spectrum $B(k)$ (or $F(f)$) enters directly in the dissipation rate.

The parameterization of the wind input used in WAM model cycle 4 is based on the quasi-laminar critical layer model of the airflow developed by Miles (1957, 1959). Kudryavtsev et al. (1999) showed that the applicability of the quasi-laminar model in the description of the airflow dynamics is very limited. Usually, the wind input source function S_{in} is written as follows:

$$S_{in} = \beta\omega F \tag{6}$$

where β is the growth rate parameter. Makin et al. (1999) suggested an alternative formulation for the growth rate parameter:

$$\beta = \frac{\rho_a}{\rho_w}m_\beta R(\frac{u_*}{c})^2\cos(\theta-\theta_w)|\cos(\theta-\theta_w)| \tag{7}$$

where ρ_a and ρ_w are the density of air and water and m_β is a constant. Function R is defined by:

$$R = 1 - m_c(\frac{c}{u_{10}})^{n_c} \tag{8}$$

R has values close to 1 for slowly moving waves and negative values for fast moving waves. Notice, that the wind input source term will be negative for fast moving waves or (and) waves traveling in the oposite direction relative to wind direction.

The new balance was tuned for the NEDWAM model in the North Sea region, for shallow water conditions, yielding the following constants: C_{dis}^{b}=2.5×10^{-5}, $B_r = 4\times10^{-3}$, $m = 2$, $p = 6$ and $n = 1$ for the dissipation source term and $m_\beta = 0.045$, $m_c = 0.3$ and $n_c = 5$ for the wind input source term. The proportionality coefficient for the bottom friction source term S_{bot} was tuned to twice the original value (from 0.076 to 0.152), without changing the bottom friction source term formulation.

4. Description of the models and buoy data

Results from three ocean wave models are presented in this study: the second generation model VAG (Guillaume, 1987), developed at Meteo-France, the third generation wave model WAM (WAMDI Group, 1988), and the WAWEWATCH III (also refered as WW3) wave model (Tolman 1997, 1999a), which is a third generation model developed at NOAA/NCEP. For the experiments, two periods of 1 month were selected: one winter month of February 2002 and one summer month of July 2002. Sensitivity experiments with different configurations of VAG and WAM models have been carried out during this study.

The analysed 10 m wind field from the operational NWP models of ECMWF (IFS) and Meteo-France (ARPEGE TROPIQUE) were used as input for all wave models. The spatial resolution of the wind field was $1^o \times 1^o$ for IFS model and $1.5^o \times 1.5^o$ for ARPEGE TROPIQUE model. A coupling frequency of 6h was used for all wave models. The Sea Surface Temperature (SST), used in the wave models every 6h, in order to obtain the ice sea mask, is the analysis of the assimilation cycle of the NWP model ARPEGE TROPIQUE, taken at a spatial resolution of $1.5^o \times 1.5^o$.

All wave models were run on a global grid with a spatial resolution of $1^o \times 1^o$. The main characteristics of VAG, WAM (with different configurations) and WW3 are presented in Table 1.

The buoy data consist of wind speed and direction, swh and mean (only for the buoys located in the West coast of European continent) or peak wave period. Buoy peak period can not be compared with model mean period, but it is usefull to distinguish which kind of waves occur (windsea, swell or mixed windsea-swell). The buoy measurements are averaged and are available at a 6h interval. The wind speed and direction at the buoy location are adjusted to the 10 m level. Data from 30 moored buoys were used in this study. Only 2 buoys (44011 and 63111) are located in shallow water regions, while the rest of them are located in deep water regions. The 30 buoys are located in four main regions: West coast of European continent, East coast of the North American continent, West coast of the North American continent and the area around the Hawaiian Islands. The five digit WMO buoy identificator has been used to distinguish between the 30 buoys.

Model	Wave physics	Spectral discretization	Time steps	Source terms
VAG1	deep water	22 frequencies 18 directions	propagation: 900s source terms integration: 900s	original physics
VAG2	deep water	22 frequencies 18 directions	propagation: 900s source terms integration: 900s	new physics a=0.1, b=0.7, c=0.5
VAG3	deep water	22 frequencies 18 directions	propagation: 900s source terms integration: 900s	new physics a=0.1, b=0.8, c=0.5
WW3	deep water	25 frequencies 24 directions	global: max 3600s propagation: max 1300s source terms integration: min 300s	Tolman and Chalikov
WAM dw	deep water	25 frequencies 18 directions	propagation: 600s source terms integration: 600s	sea drag: WAM 4.0 input: WAM 4.0 dissipation: WAM 4.0
WAM sw	shallow water	25 frequencies 18 directions	propagation: 600s source terms integration: 600s	sea drag: WAM 4.0 input: WAM 4.0 dissipation: WAM 4.0
WAM_MM	shallow water	25 frequencies 18 directions	propagation: 600s source terms integration: 600s	sea drag: Makin input: Makin dissipation: Makin
WAM_M3	shallow water	25 frequencies 18 directions	propagation: 600s source terms integration: 600s	sea drag: Makin input: Makin dissipation: WAM 3.0
WAM_M4	shallow water	25 frequencies 18 directions	propagation: 600s source terms integration: 600s	sea drag: Makin input: Makin dissipation: WAM 4.0

Table 1: The main characteristics of the wave models used in this study

5. Sensitivity and intercomparison study

a. Experiments made with different configurations of VAG and WAM models

The VAG model was run using the original physics (VAG1 configuration) and the new physics with two sets of coefficients (VAG2 and VAG3 configurations, as described in Table 1).

The modifications for the VAG2 and VAG3 wave models concerned only wind input and dissipation source terms, but not the non-linear interactions source term. The VAG wave model belongs to the class of the second generation wave models and uses a simple parameterization of the non-linear transfer. This parameterization works satisfactory for the locally-generated wind-sea, but have defects in mixed windsea-swell situations. The weakness of the approach is most pronounced in case of strong and rapidly varying winds. The new physics associated to the set of coefficients used in the VAG2 configuration has reduced significantly the underestimation of the high swells. Figure 1 shows about 1m improvement in swh in case of VAG3 and 0.5m in case of VAG2 for the swell situation occured at buoy 62029 between 23 and 25 February 2002. For the swell situation occured between 5-7 February 2002, VAG2 improves with about 1m the prediction of the swh.

The overestimation of the swh by VAG1 model for windsea situations (probably due to the strong effect of the linear wind input term) has been reduced by the use of the new physics in VAG2 and VAG3. This situation is well ilustrated in figure 2, which presents the swh time series for the buoy 44142 located in a fetch limited area on the East coast of the North American continent.

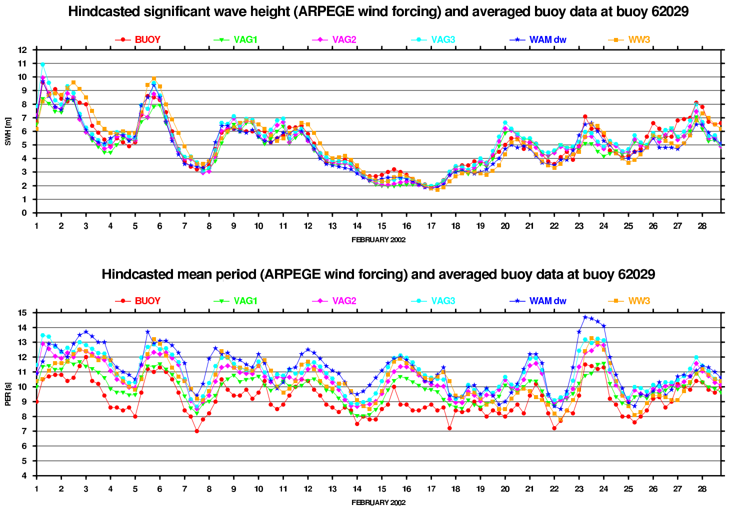

Figure 1: Time series of swh and mean period at buoy 62029 for February 2002

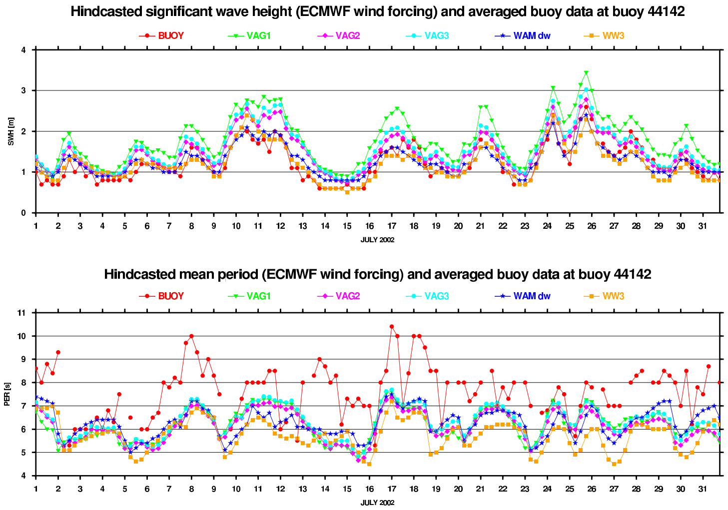

Figure 2: Time series of swh and mean (for the models) or peak (for the buoy) period at buoy 44142 for July 2002

Different configurations of the WAM model were considered in our sensitivity study, depending on the wind input and dissipation formulations and the value of some coefficients ($cb = \rho_w/\rho_a m_\beta R$, used in the wind input source term, and p used in the dissipation term):

- $WAM\_MMcb-20p6$ with $cb = max(-20, cb)$ and $p = 6$;
- $WAM\_MMcb-20p0$ with $cb = max(-20, cb)$ and $p = 0$;
- $WAM\_MMcb-100p6$ with $cb = max(-100, cb)$ and $p = 6$;
- $WAM\_MMcb-20p0t6$ with $cb = max(-20, cb)$ and p defined as a function of the ratio $B(k)/B_r$, as proposed by Alves and Banner (2003):

$$p = \frac{p_0}{2} + \frac{p_0}{2}\tanh\{10[(\frac{B(k)}{B_r})^{1/2} - 1]\} \tag{9}$$

with p_0 a constant set up numerically to 6.

- $WAM\_M3cb-20$ with $cb = max(-20, cb)$;
- $WAM\_M4cb-20$ with $cb = max(-20, cb)$.

Makin and Stam (2003) proposed $cb = max(-20, cb)$ and a constant value for p, namely 6. First experiment with $WAM\_MMcb-20p6$ configuration showed that the swell dissipation is too small in this case (see figure 3 for buoy 46005 located in the West coast of the North American continent region, for which periods with swell situations are pointed out by the high peak period measured at the buoy).

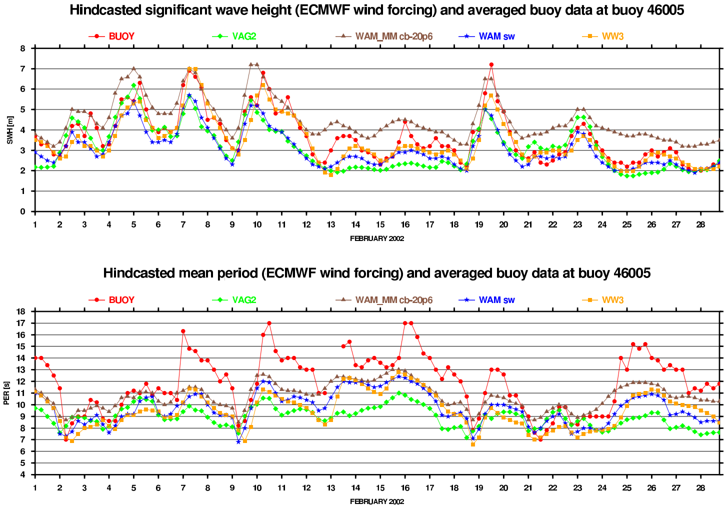

Figure 3: Time series of swh and mean (for the models) or peak (for the buoy) period at buoy 46005 for February 2002

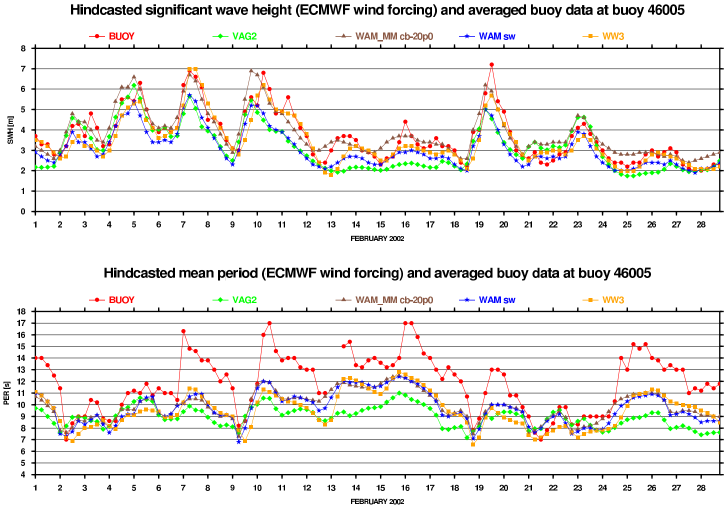

Figure 4: Time series of swh and mean (for the models) or peak (for the buoy) period at buoy 46005 for February 2002

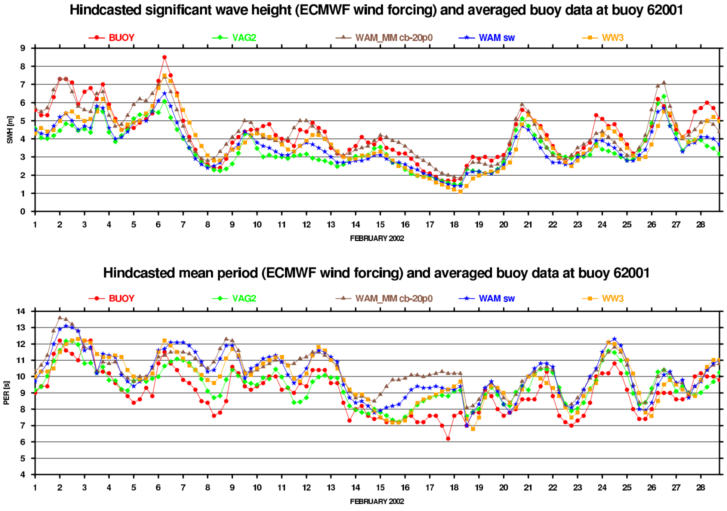

Figure 5: Time series of swh and mean period at buoy 62001 for February 2002

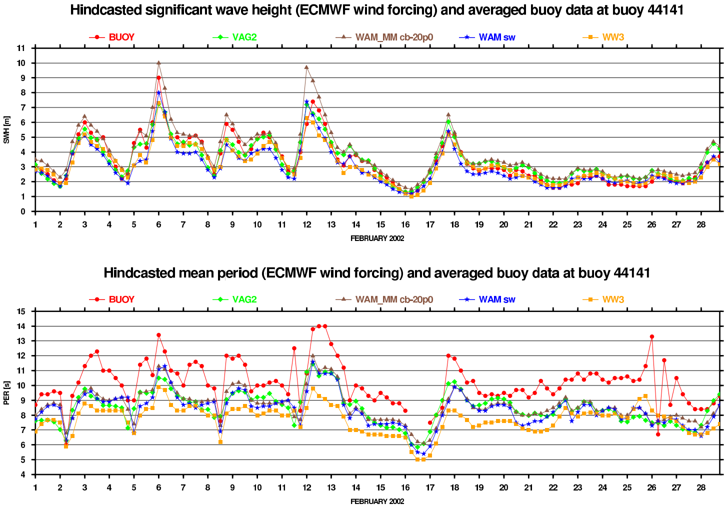

Figure 6: Time series of swh and mean (for the models) or peak (for the buoy) period at buoy 44141 for February 2002

For this reason, additional experiments with the new sea drag and wind input formulations, but with dissipation taken from WAM cycle 3 or WAM cycle 4, were performed. For these experiments cb was set to $max(-20, cb)$. The experiments made with $WAM\_M4cb-20$ showed swh values close to those obtained with the WAM cycle 4 model. If we set up the parameter p to 0, than the dissipation source term described by (2) and (4) will differ from the WAM cycle 3 dissipation source term only by the use of angular frequency ω instead of the mean angular frequency $\langle\omega\rangle$. This should lead to a smaller dissipation of swell and a stronger dissipation of windsea by $WAM\_MMcb-20p0$, compared to $WAM\_M3cb-20$. The experiments showed that the results obtained with $WAM\_MMcb-20p0$ are rather close to that ones obtained in case of $WAM\_M3cb-20$. Therefore, $p=0$ works well for swell dissipation.

Also, Alves and Banner (2003) suggested that $[B(k)/B_r]^{p/2}$ should approach assimptotically to 1 in case of spectral components with reduced local steepness, like swell. By setting $p=0$ we satisfy this condition and the results presented in figures 4 and 5 show a better description of swell dissipation in this case. Figure 6 shows the swh for windsea situations occured at buoy 44141 (this buoy is located in a fetch limited area). For this buoy, a significant overestimation of the swh peaks occurs in case of setting $p=0$. For waves with big local steepness ($B(k)/B_r>1$), a constant value for p (set up to 6 in our experiments) is more appropriate.

In case of $WAM\_MMcb-100p6$, the results are very good for windsea situations (see figure 7), but the swell dissipation is to strong (not shown) . Therefore, it appears that it is not appropriate to use a constant value for p in case of mixed windsea-swell situations.

Alves and Banner (2003) suggested to define p as in expression (9). In this case, p is equal to 0 for waves with a reduced local steepness (swells) and it takes a constant value p_0 (in our case p_0 is set to 6) for waves with a big local steepness (windseas). The experiments made with $WAM\_MMcb-20p0t6$ configuration showed that the improvements in swell dissipation are still kept (see figures 8 and 9), while the overestimation of the windsea peaks is removed (figure 10).

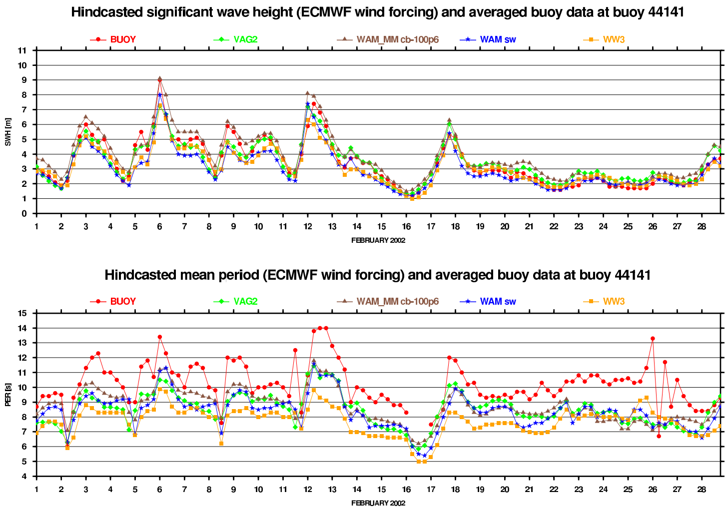

Figure 7: Time series of swh and mean (for the models) or peak (for the buoy) period at buoy 44141 for February 2002

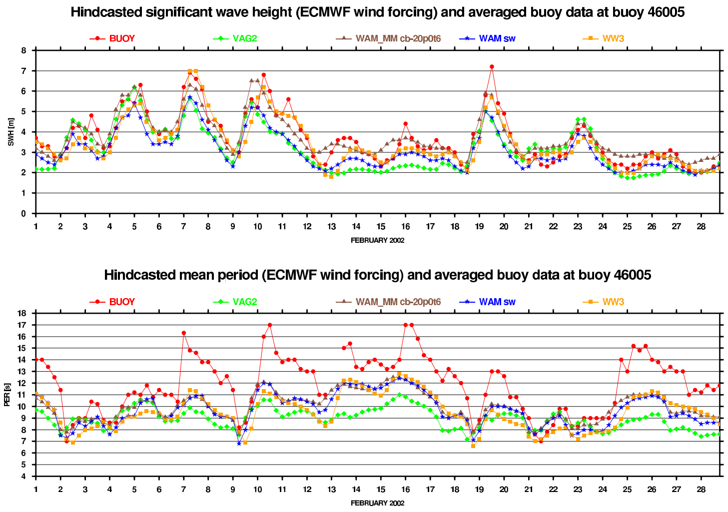

Figure 8: Time series of swh and mean (for the models) or peak (for the buoy) period at buoy 46005 for February 2002

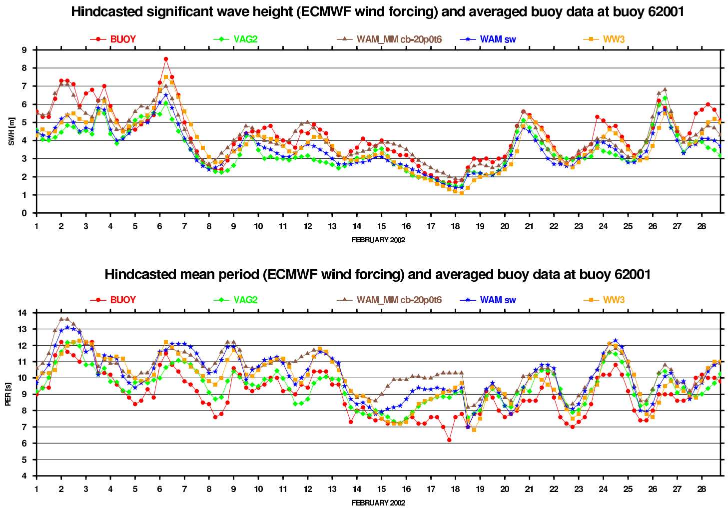

Figure 9: Time series of swh and mean period at buoy 62001 for February 2002

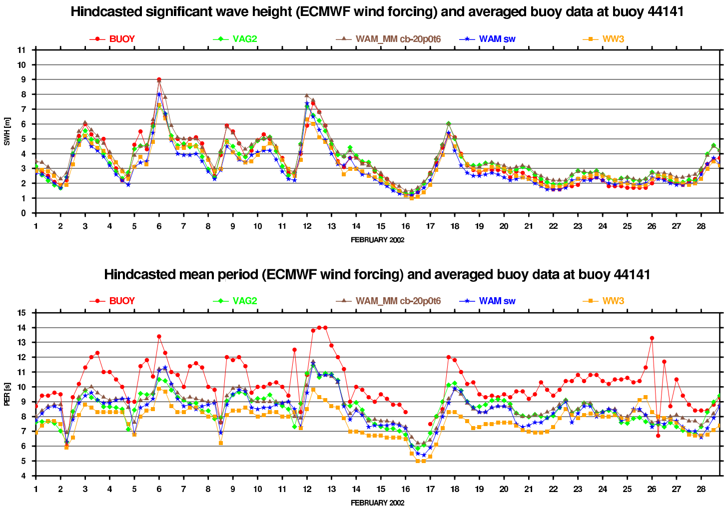

Figure 10: Time series of swh and mean (for the models) or peak (for the buoy) period at buoy 44141 for February 2002

b. *Global statistics for the models used in the intercomparison study*

As regard to the analysed wind speeds used for the hindcast study, the ECMWF winds are much better compared to the winds produced by NWP model ARPEGE TROPIQUE. A possible explanation of this could be the fact that the ECMWF center is performing variational assimilation of the 10 m wind speed, while Meteo-France not. Further, only statistics for experiments performed with the ECMWF wind field is presented. The quality of the analysed wind speed of ECMWF is good for both February and July periods (see tables 2 and 4). Scatter diagrams (not shown) and symmetric slopes (tables 2 and 4) indicate a small overestimation of the ECMWF wind speed.

The improvements of VAG swh due to the use of the new physics are clear. For February, rms error and symmetric slope show an advantage for VAG3 compared to VAG2, but the scatter index is slightly better for VAG2 (see table 2). Also, we have to note that the time series showed increased overestimation of VAG3 in some situations, compared to VAG2. Statistics for July (table 4) indicate better values for VAG2 configuration. When computing statistics for the total period (February + July), the VAG2 swh shows the best quality between all VAG configurations (not shown).

From table 3 it can be seen that for February $WAM\_MMcb - 20p0t6$ swh has the best quality between all WAM configurations. Comparing $WAM\_MMcb - 20p0t6$ statistics with statistics computed for shallow water run of WAM cycle 4 ($WAMsw$), there is a clear improvement of rms error, scatter index and symmetric slope. For July, rms error and symmetric slope is better for $WAM\_MMcb - 100p6$ configuration (comparing to the other WAM configurations). Only scatter index is slightly better for $WAM\_MMcb - 20p0t6$ configuration (see table 5). Time series also showed better agreement of $WAM\_MMcb - 100p6$ swh with buoy data. The $WAM\_MMcb - 20p0t6$ swh is overestimated for July. For the total period (February + July), the $WAM\_MMcb - 20p0t6$ configuration appears to have the best quality between all WAM configurations (not shown).

Comparing the three wave models statistics (VAG and WAM with different configurations and WW3), we can see that for February $WAM\_MMcb - 20p0t6$ swh has the best quality (it is better even than WW3 swh), while for July WW3 swh has better quality than $WAM\_MMcb - 20p0t6$ swh and comparable quality with $WAM\_MMcb - 100p6$ swh.

Model	ECMWF	VAG1 dw	VAG2 dw	VAG3 dw	WAM dw	WW3 dw
No. of entries	2010	2490	2490	2490	2490	2490
Buoy mean	8.8660	3.6928	3.6928	3.6928	3.6928	3.6928
Bias	0.6087	-0.0752	-0.2585	-0.0471	-0.4557	-0.2440
Rms error	1.7357	0.7737	0.7357	0.7042	0.7353	0.6733
Scatter index	0.1833	0.2085	0.1865	0.1903	0.1563	0.1699
Symmetric slope	1.0763	0.9594	0.9204	0.9777	0.8707	0.9398

Table 2: Wind speed and swh statistics for February 2002

Model	WAM sw	WAM_MM sw (cb-20 p6)	WAM_MM sw (cb-20 p0)	WAM_MM sw (cb-100 p6)	WAM_MM sw (cb-20 p0t6)	WAM_M3 sw (cb-20 p0)	WAM_M4 sw (cb-20 p0)
No. of entries	2490	2490	2490	2490	2490	2490	2490
Buoy mean	3.6928	3.6928	3.6928	3.6928	3.6928	3.6928	3.6928
Bias	-0.4842	0.7930	0.3156	0.0932	0.1603	0.2997	-0.4871
Rms error	0.7517	0.9930	0.6518	0.6418	0.5703	0.6463	0.7498
Scatter index	0.1557	0.1618	0.1544	0.1720	0.1482	0.1551	0.1544
Symmetric slope	0.8651	1.1764	1.0746	1.0272	1.0281	1.0747	0.8670

Table 3: Swh statistics for February 2002

Model	ECMWF	VAG1 dw	VAG2 dw	VAG3 dw	WAM dw	WW3 dw
No. of entries	2398	3316	3316	3316	3316	3316
Buoy mean	6.1878	1.6761	1.6761	1.6761	1.6761	1.6761
Bias	0.1214	0.1670	0.0776	0.1736	-0.0192	-0.0739
Rms error	1.0760	0.4133	0.3573	0.4003	0.3418	0.3069
Scatter index	0.1728	0.2256	0.2081	0.2152	0.2036	0.1777
Symmetric slope	1.0212	1.0812	1.0246	1.0795	0.9661	0.9575

Table 4: Wind speed and swh statistics for July 2002

Model	WAM sw	WAM_MM sw (cb-20 p6)	WAM_MM sw (cb-20 p0)	WAM_MM sw (cb-100 p6)	WAM_MM sw (cb-20 p0t6)	WAM_M3 sw (cb-20 p0)	WAM_M4 sw (cb-20 p0)
No. of entries	3316	3316	3316	3316	3316	3316	3316
Buoy mean	1.6761	1.6761	1.6761	1.6761	1.6761	1.6761	1.6761
Bias	-0.0471	0.8061	0.3286	0.0824	0.2989	0.2591	-0.1060
Rms error	0.3345	0.8920	0.4535	0.3254	0.4323	0.3898	0.3127
Scatter index	0.1976	0.2279	0.1865	0.1878	0.1863	0.1737	0.1755
Symmetric slope	0.9507	1.4322	1.1693	1.0492	1.1503	1.1319	0.9201

Table 5: Swh statistics for July 2002

6. Conclusions and perspectives

A new physical parameterization has been introduced in the second generation wave model VAG, in order to improve the balance of the source terms in the energy budget computation and the wave growth and decay. Three versions of the VAG model (VAG1 with the original physics and VAG2 and VAG3 with the new physics for two sets of coefficients) have been investigated during February and July 2002, together with the performance of the third generation wave models WAM and WW3. We can indicate a positive impact of the new physics. In general, the improvements in rms error and scatter index are greater for VAG2. The new physical parameterization works very well for the locally-generated windsea. The new physics brought some improvements in prediction of swh for mixed windsea-swell situations or rapidly evolving waves, but it still underestimate the swh in such situations.

Since March 2003 the new physics is operationally used at Meteo-France and it will be also introduced in the operational versions of the VAG model integrated for the Black Sea area in Romania and Bulgaria.

A new parameterization of the sea drag as well as new formulations of wind input and dissipation source terms have been inplemented in the WAM cycle 4 model and tested on a global grid. Different configurations of the WAM model have been investigated, depending on the wind input and dissipation formulations and the value of some coefficients used in the wind input and dissipation source terms. Improvements in swell dissipation have been found for $WAM\_MMcb-20p0$ and $WAM\_MMcb-20p0t6$ configurations. The new formulations of sea drag and wind input and dissipation source terms introduced in the WAM model resulted in a better prediction of swh in many cases and reductions in bias and rms error of this parameter. The global statistics computed for February 2002 showed the best quality for $WAM\_MMcb-20p0t6$ configuration, compared to the other configurations of WAM and also VAG and WW3 models. For July 2002, $WAM\_MMcb-100p6$ and WW3 gave the best prediction of swh, while $WAM\_MMcb-20p0t6$ overestimated the values of of this parameter.

The results obtained with the new physical parameterizations introduced in WAM are very encouraging. Further experiments can be done in order to adjust the coefficients for a better balance of the new physical parameterizations.

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