Contribution of a new 3rd generation wave model at Météo France

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1 Introduction

Modern numerical wave prediction is based on the description of the sea-state in terms of spectral energy densities and on the numerical solution of a balance equation for the density of Action, ratio of the spectral energy density and the intrinsic frequency. In such a representation when the phases are averaged, only the variance of the wave amplitudes for each propagation direction and frequency is considered. The most advanced models, the so-called third generation or 3G wave models, solve this equation explicitly, without making assumptions about the shape of the energy density spectrum. In the so-called second generation or 2G wave models, only the wind sea part of the wave spectrum is formulated in a definite pattern. Today, most national meteorological services are using 3G models to predict sea state on their area of interest and responsibility. For large areas, at the scale of ocean basins, the models most used are derived from the WAM code (WAMDE group in 1998, Gunther et al., 1992, Komen et al. 1994) or WaveWatchIII (Tolman, 2002a, b).
From these spectral energies densities, a number of synthetic parameters adapted to the needs of marine forecasting can be derived, mainly the significant height, the mean wave direction and period, for any wave partition.

Nevertheless, some studies (Toffoli et al. 2006) suggest that other factors must be taken into account to establish warning criteria for hazardous sea states. Recent progress have been made in understanding some mechanisms responsible for the formation of abnormal waves (Mori and Janssen, 2006, Toffoli et al. 2007) and have led to the definition of new parameters. These parameters are very sensitive to the shape of the spectrum and it is therefore important to model them accurately.

With progress made in the field of wave modeling and in the use of data from space sensors it is now possible to respond satisfactorily to many civilian and military needs. Nevertheless, the scores are not homogeneous with some areas of large biases in the tropics for example, or for high values of significant wave height. Studies have shown (Lefevre et al. 2003) that these biases were mainly related to the formulation of the dissipation used in wave models like WAM (WAMDE, 1988). Based on the work of Alves and Banner (2003), a new formulation of the dissipation term associated with a new input source term has been introduced and tested (Lefevre et al., 2004). Meanwhile, ECMWF introduced a modification in ECWAM in order to improve the dissipation term (Bidlot et al., 2005). While overall scores have improved significantly, large biases still exist in some regions. Recent work on the wave dissipation (ARDHUIN et al., 2008), resulted in a new formulation of the dissipation, thanks to tracking swells by ROS (Radar Aperture Synthesis).

This paper presents an evaluation of various formulations discussed here, through the joint use of in situ data and remote sensed data for the year 2007.

2 Wave modeling

Third-generation wave models are based on a balance equation of the type:

$$\frac{\partial F(f,\theta)}{\partial t} + c_g.\nabla F(f,\theta) + \frac{\partial}{\partial \theta}\left[(c_g.\nabla \theta)F(f,\theta)\right] = S(f,\theta)$$

where Cg denotes the group velocity, F(f, θ), the spectral energy density and S(f, θ) the source terms:

$$S(f,\theta) = S_{in}(f,\theta) + S_{out}(f,\theta) + S_{dis}(f,\theta) + S_{nl}(f,\theta)$$

The first term represents the wind input source term, the second the dissipation due to air friction (negative term), the third term the dissipation due to white capping and the fourth the wave-wave nonlinear interaction term.

2.1 ECWAM

ECWAM is the code implemented at ECMWF (European Center for Weather Forecasting Medium Term), derived from the 3G WAM as a result of an international scientific collaboration (WAMDI, 1988). In this model, the wind input source term reads:

$$S_{in}(f,\theta) = \beta\omega F(f,\theta)$$

with : $\beta = \varepsilon m_\beta \left(\frac{u_*}{c}\right)^2 \cos^2(\theta - \phi), |\theta - \varphi| \langle \pi/2$

where ε is the air and water density ratio, u_* is the friction velocity, θ the propagation direction and φ is the wind direction, m_β is the Miles parameter.

The wave induced stress τ_w is calculated from the source term S_{in}, following the relationship:

$$\tau_{w_x} = \int_0^{2\pi}\int_0^{\infty} d\vec{k}..\vec{k}S_{in}$$, with $\vec{k}$ wave vector

Knowing τ_w, u_* is then derived from the wind speed at 10m (u10) by iteratively solving an equation linking these quantities (Janssen, 1989), starting from an initial estimate based on wind alone. The value of the roughness length is also computed.

The dissipation term, modified by Bidlot et al. (2005), reads:

$$S_{dis}(f,\theta) = \gamma\langle\omega\rangle\alpha^{2m}\left[(1-a)\left(\frac{k}{\langle k\rangle}\right)^2 + a\left(\frac{k}{\langle k\rangle}\right)^4\right]F(f,\theta)$$

avec $\langle\omega\rangle = \int Fd\omega / \int Fd\omega/\omega$, $\sqrt{\langle k\rangle} = \int Fd\omega / \int Fd\omega/\sqrt{k}$, $\alpha^2 = \langle k\rangle^2 \int Fd\omega$

where γ, a and m are constants to be adjusted. The main change in the dissipation term described above is the definition of the average frequency, which gives more weight to high frequencies. With the readjustment of the parameters a and m, this led to a similar wave growth with or without swell, unlike before when it was too strong in the presence of swell. Similarly, dissipation of the swell was too strong in the presence of wind sea. All the settings used in ECWAM are noted BAJ

2.2 WAM_MA

The formulation of the input source term in ECWAM is based on assumptions of quasi-linearity (Janssen, 1991) where terms of interactions between turbulence and the wave induce flow are neglected. Kudryatsev et al. (1999) and Makin and Kudryatsev (1999) proposed a formula that took into account these interactions with the tension resulting from the air flow separation induced by the waves. We always have $S_{in} = \beta\omega F$

But with : $\beta = \varepsilon m_\beta R\left(\frac{u_*}{c}\right)^2 \cos(\theta-\varphi)\left|\cos(\theta-\varphi)\right|$ if R>0 otherwise $\cos^2$

R is defined by: $R = 1 - m_c\left(\frac{c}{u_{10}}\right)^{n_c}$ m_c, m_β, n_c are constant to be adjusted

R is close to 1 for slow waves and may become negative for very fast waves, typically for the swell. Here, β may be negative for waves faster than the wind or opposing the wind. A limitation is imposed on β (around -100) for very low value of wind speed (u10).
u_* is determined using a formula proposed by Makin (2003), function of the wind sea age.

The dissipation term proposed by Alves and Banner (2003) reads:

$$\gamma_{dis} = -C^b_{dis}\left(\frac{\alpha}{\alpha_{PM}}\right)^m \left(\frac{B(k)}{B_r}\right)^{p/2}\left(\frac{k}{\langle k\rangle}\right)^n$$

where C^b_{dis}, m, p, n et B_r are constant to adjust. α is the mean steepness, α_{PM} is the mean steepness of a fully developed sea and $B(k)$ is the saturation spectrum of *F*(*f*) defined by:
:

$B(k) = \frac{1}{2\pi}F(f)c_g k^3$, with c_g the group velocity.

The dissipation term of the form $S_{dis} = \gamma_{dis}\omega F$ is now a nonlinear function of the spectral energy density because the function γ_{dis} depends on this density.

The exponent p is defined from $B(k)/B_r$: $p = \frac{p_0}{2}\left(1+\tanh\left\{10\left[\left(\frac{B(k)}{B_r}\right)^{1/2}-1\right]\right\}\right)$; $p_o = 6$

When $B(k) > B_r$, we have: : $p = p_o$ and the dissipation is mainly governed by the ratio $B(k)/B_r$. For $B(k) < B_r$, p=0 and the dissipation is no longer governed by the mean wave steepness.

2.3 WW3-SHOM

The formulations described below are those used in the WW3-SHOM code and are described in ARDHUIN et al. (2009).
The wind input source is similar to the one used in ECWAM with a correction of the friction velocity formulation in order to limit energy input in the high frequency part of the spectrum.
A new term is introduced to take into account swell dissipation. Indeed, with formulations such BAJ or MA models tend to overestimate the wave height in the tropics (Figure 1). The mechanism underlying this new formulation is related to the air resistance. Two formulations are proposed based on a Reynolds number (Re), which differentiates the laminar flow of the turbulent flow of air. This Reynolds number depends on the product of values of the significant amplitudes of orbital velocities (u_{orb}) and orbiting displacement (a_{orb}) divided by the kinematic viscosity of air (ν).

It reads: $S_{out},(f,\theta) = -1.2\varepsilon\left\{2k\sqrt{2\nu\omega}\right\}F(f,\theta)$ pour $R_e < 10^5$ et,

$S_{out}(f,\theta) = -\varepsilon\left\{16 f_e \omega^2 u_{orb}/g\right\}F(f,\theta)$ pour $R_e > 10^5$

where $f_e = 0.7 f_{e,GM} + [0.015 - 0.018\cos(\theta-\varphi)]u_* / u_{orb}$, is adjusted on the basis of observations (ARDHUIN et al. 2008b). fe, GM is the friction factor.

The dissipation term due to wave breaking is partly inspired by the work of Banner and Young (2004), based on the use of the saturation spectrum. It is however different from the term introduced by Alves and Banner (2003), because the breaking is here set as a threshold function. In Alves and Banner (2003), the dissipation rate for a spectral component depends on the difference between the spectrum and a saturation threshold. To take into account the damping of small waves caused by larger waves, a cumulative term ($S_{ds,c}$) was introduced (Filipot et al. 2008). The dissipation term due to whitecaping is written in the form of an isotropic term and a non isotropic one. This last term allows to adjust the directional spreading using data from directional buoys. We have:

$$S_{ds}(f,\theta) = \omega C_{ds}\left\{0.25\left[\max\left\{\frac{B(f)}{B_r}-1,0\right\}\right]^2 + 0.75\left[\max\left\{\frac{B'(f,\theta)}{B_r}-1,0\right\}\right]^2\right\}F(f,\theta) + S_{ds,c}(f,\theta)$$

with $S_{ds,c},(f,\theta) = -c_3 F(f,\theta)\int_0^{0.7f}\int_0^{2\pi}\frac{56.3}{\pi}.\max\left\{\sqrt{B(f',\theta')}-\sqrt{B_r},0\right\}\frac{\Delta C}{C_g'}.d\theta' df'$

$$B'(f,\theta) = 2\pi\int_{\theta-80^\circ}^{\theta+80^\circ} k^3\cos^2(\theta-\theta')F(f,\theta').C_g d\theta'$$

$$B(f,\theta) = \max\{B'(f,\theta), \theta \in [0,2\pi[\}, \quad B_r = 0.0009$$

$$S_{ds,c}(f,\theta) = -c_3 F(f,\theta) \int_0^{0.7f} \int_0^{2\pi} \frac{56.3}{\pi} \max\left\{\sqrt{B(f',\theta')} - \sqrt{B_r}, 0\right\} \frac{\Delta C}{C_g'} .d\theta' df'$$

C_{ds}, c_3 are constants to adjust. Many tests have been carried out to find the coefficients that minimize the errors. The results for versions 337 and 405 are presented here.

2.4 MFWAM

The MFWAM model is derived from ECWAM code, and is suitable for vector parallel supercomputer. It has been enriched with formulations for the dissipation developed in the WW3-SHOM code.

3 Verification et discussion

The verification of the models and various formulations has been largely accomplished through observations of reference that combine the significant wave heights from the three altimeters onboard JASON, ENVISAT and GFO satellites . Simulations were carried out from global versions of the wave models with regular grids of resolution 0 .5 ° x 0.5 ° and using the same bathymetry and ice masks. Winds from the same model analyses were used for the simulations (6 hourly winds). The simulations were performed for the year 2007. Maps of biases and root mean squared errors are shown in Figures 1 and 2.

Results from the BAJ formulation (Bidlot et al., 2005) shows a significant overestimation of wave height in the tropics and a slight underestimation in the middle latitudes, an area of significant wave generation. These biases were more important in the previous version of WAM (WAM_C4), which had motivated the introduction of new formulations for input and energy dissipation (Lefevre et al, 2003, 2004). This version was called WAM_MA and has been compared to C4-WAM, WW3, using as reference data buoy observations. WAM_MA best scores were found for WAM_MA in terms of RMSE, especially for high values of Hs. Nevertheless, the comparisons made in this study with data from altimeters (Figure 1) show areas of very negative way, such as in the equatorial Atlantic and the Indian Ocean, and west to Australia. The overall scores are also generally worse than WW3_BAJ or ECWAM.

However, with the 337and 405 settings, errors and biases are significantly reduced in comparison with BAJ setting, as used in MFWAM, everywhere (except in the moderate southern latitudes). In particular, the addition of a dissipation term for the swell has reduced the overestimation in the inter-tropical zone while correcting the underestimation in areas of high wave generation. However, the 405 version with the best overall scores has a significant negative bias, larger to others in the range of the high values of Hs. The 437 version allows a better prediction of extreme events with an overall score below the 405 version but higher than WW3-BAJ (Figure 3).

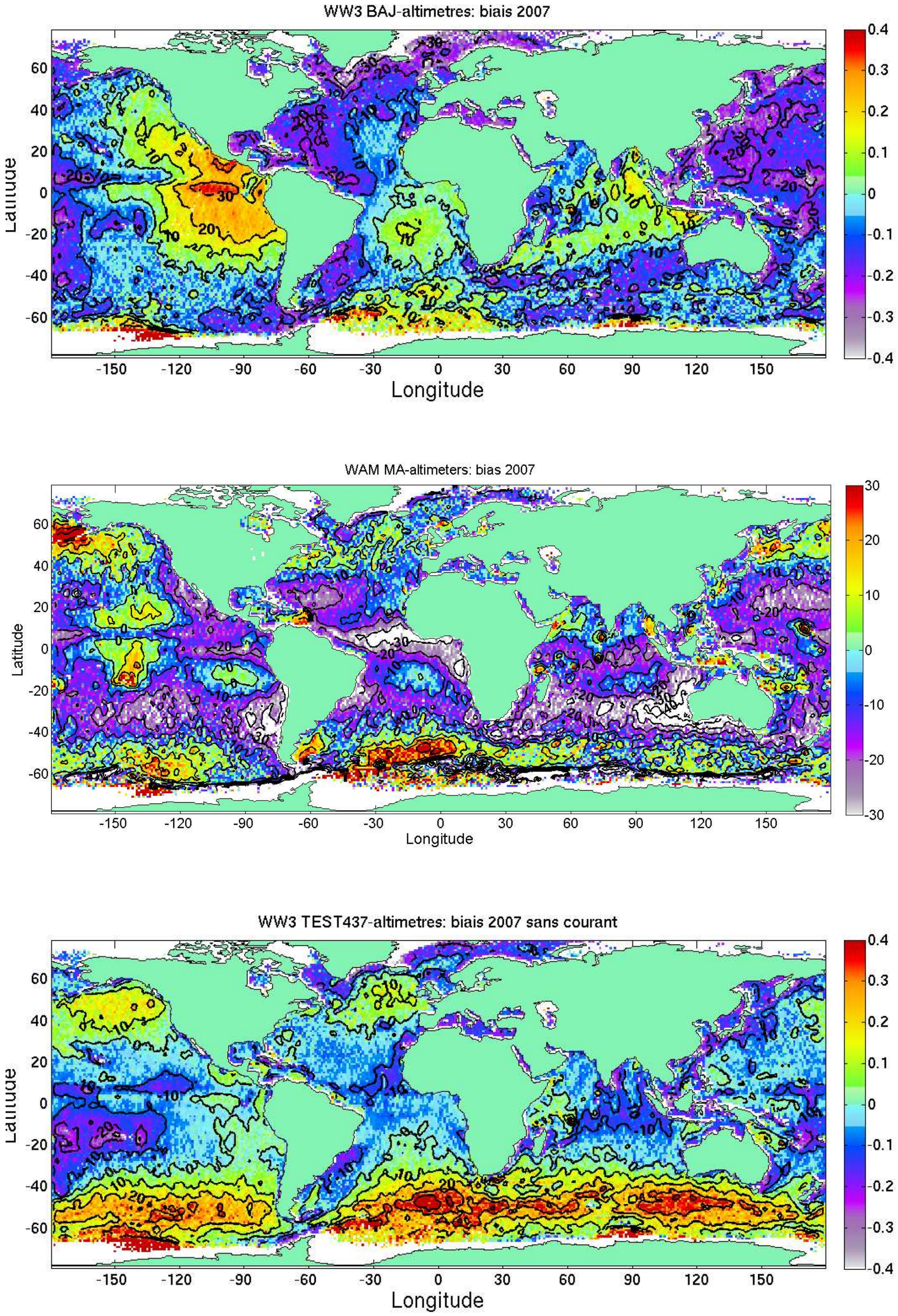

FIG. 1. Map of model biases (in m for WW3 and cm for WAM cm) with the ECMWF parameterization (top), the setting of Makin and Alves (Middle) and the setting of version 437 (bottom) The reference observations combine the significant wave heights from the three altimeters JASON, GFO and ENVISAT

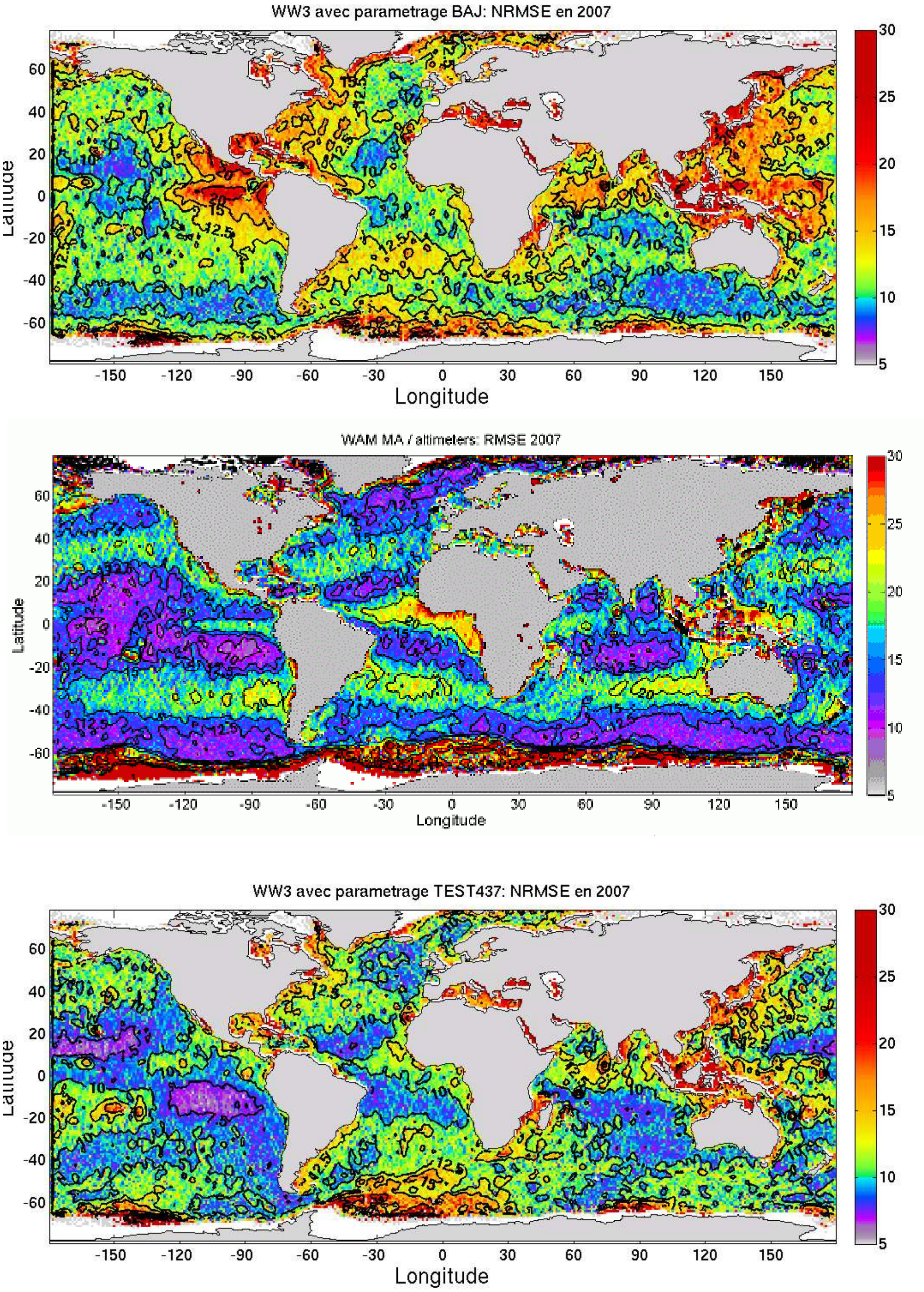

FIG. 2. Same as figure 1 but for the NRMSE in percents.

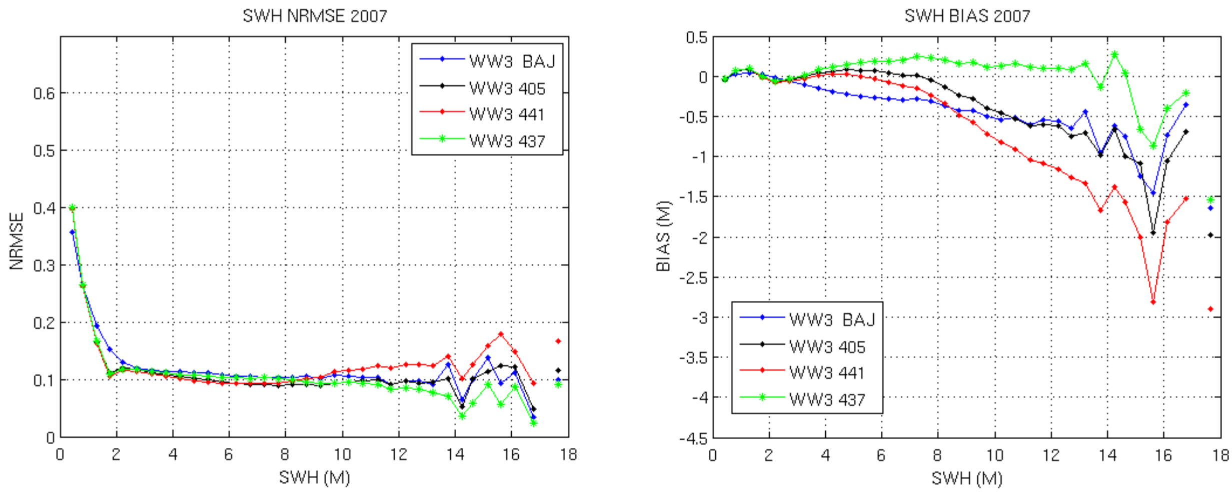

FIG 3. Curves of Normalized RMSE in percents and of biases (in meters) related to the significant wave height for WW3_SHOM (ARDHUIN et al., 2009), for the settings BAJ, 405, 441 and 437. The reference observations combine the significant wave heights from the three altimeters JASON, GFO and ENVISAT

4 Conclusion et perspectives

The new parameterizations proposed by ARDHUIN et al. (2009) can improve the overall scores compared to the formulations used in ECWAM (BAJ), reducing biases in both the areas of wave generation and in areas where the swell is dominant. In particular, the addition of a term for the swell dissipation has corrected the underestimation in terms of wave height in areas of high wave generation and the overestimation in the inter-tropical zone. However, only the 437 can significantly reduce the negative bias for high values of Hs, while the 405 version is more accurate for more moderate values. Further adjustments can be made, especially in cases of extreme winds (case of cyclones) and scores can be improved through the assimilation of new data, such as ASAR spectra (level 2) and ENVISAT heights waves from the Jason-2 altimeter. In September 2009, the ECWAM code has been modified with the introduction of a new term for the swell dissipation based on the Rapid Distorsion Theory (Janssen and Bidlot, 2009), with significant improvements.

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