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New drag formulation in NEDWAM

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1 Introduction

The dynamical air-sea coupling was introduced into the WAM Cycle 4 model and is based on a wind-over-waves coupling (WOWC) theory by Janssen (1989, 1991). It was criticized by Doortmont and Makin (2000) who clearly showed the deficiency both in physical formulation of WOWC and it's numerical implementation. A modern self-consistent wind-over-waves coupling 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). The 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, as well as the wave-induced stress. A new parameterization of the surface stress (sea drag) is based on this recent theory (Makin, 2003). The parameterization accounts for the wind speed, wave age and finite bottom dependencies of the surface stress. The parameterization was checked against the wind-over-waves model results and several field data sets obtained in a wide range of the wind speed and wave age. A good agreement was obtained, and it was concluded that the parameterization could be used for practical purposes in the operational environment for ocean-state and atmospheric models.

Here the parameterization is implemented in the NEDWAM model (the North Sea version of the WAM model). A sensitivity study has shown that the NEDWAM model is not sensitive to the parameterization of the sea drag, a result obtained earlier by Doortmont and Makin (2000). New formulations of two source terms in the balance equation of the wave spectral density, namely wind input and dissipation due to breaking, based on new understanding of physics of the processes were implemented. That allowed significant reduction in the bias of the significant wave height and the mean period, but not in the standard deviation.

2 New drag formulation

2.1 Parameterization

Ideas on which the parameterization was built, its detailed description, and discussions can be found in Makin (2003). Here a short description and some additional explanation of the parameterization is given.

First, it is noted that the parameterization (and the WOWC model) 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. The parameterization (and the WOWC model) can be formally applied for pure wind sea and mixed wind sea - swell (Guo Larsen et al., 2003). However, the possible impact of swell on the drag is not accounted for by the model and the parameterization. Only the wind wave part of the wave spectrum is used to calculate the drag. It means that the parameterization presume that the direction of the wind coincides with the direction of wind-waves.

The parameterization is based on the resistance law, which relates the surface stress (sea drag) to the properties of the surface. Being written in terms of the drag coefficient CD_{10} it reads:

$$CD_{10} \equiv \frac{u_*^2}{u_{10}^2} = \tau^t + \tau_d^s, \tag{1}$$

where u_* is the friction velocity and u_{10} is the wind speed at 10 m height. The dimensionless stress supported by the viscous stress, by the wave-induced stress and the separation stress from short waves is

$$\tau^t = \frac{\kappa^2}{\ln^2 \frac{10}{z_0^t}}. \tag{2}$$

It is parameterized through the Charnock-type relation for the local roughness parameter z_0^t

$$z_0^t = 0.1\frac{\nu}{u_*} + (0.0075 + f_{u_{10}})\frac{u_*^2}{g}, \tag{3}$$

where the fitting function $f_{u_{10}}$ (which carries no physical basis)

$$f_{u_{10}} = 0.02\max[0, \tanh(0.075u_{10} - 0.75)] \tag{4}$$

is introduced to account for the separation stress supported by short waves (described by the WOWC model explicitly). The second term on the right-hand-side of (1), τ_d^s is the dimensionless stress supported by the airflow separation from the dominant waves (waves at the spectral peak of the wave spectrum). It has the form

$$\tau_d^s = 0.08 \frac{u_r^2}{u_{10}^2} \exp\left(-\frac{\varepsilon_T^2}{\varepsilon_d^2}\right), \qquad (5)$$

where u_r

$$u_r = \max\left[0, u(\frac{\lambda_p}{4\pi}) - c_p\right] \qquad (6)$$

is the reference wind speed that is the difference of the wind speed at height $z = \lambda_p/4\pi$ (λ_p is the wavelength at the spectral peak) and the wave phase speed at the spectral peak c_p. For typical wind-sea conditions the wind speed $u(\lambda_p/4\pi)$ is close to u_{10} so that $\tau_d^s \sim (1 - c_p/u_{10})^2$. Parameter c_p/u_{10} is called the wave age parameter. For young seas $c_p/u_{10} < 1$ and increases to 1 as the sea develops. It means that the separation stress τ_d^s decreases with increasing wave age. In terms of the drag coefficient it means that younger seas support more sea drag than an old fully developed sea.

The other parameters that enter (5) are: $\varepsilon_d = H_s k_p/2$ is the dominant wave steepness, H_s is the dominant significant wave height obtained as an integral around the spectral peak of the wind-wave spectrum, and $k_p = 2\pi/\lambda_p$ is the peak wavenumber, $\varepsilon_T = 0.24$ is a threshold level constant. Both parameters H_s and k_p could be obtained from a wave model, measurements, or empirical relations, e.g., as a function of fetch. (In the mixed wind-wave - swell seas characterized by a double spectral peak only the wind-wave part of the spectra should be taken to obtain H_s and k_p). It is a common practice that the peak frequency $\omega_p$rather than the peak wavenumber is known/measured. These are related via the dispersion relation

$$\omega_p^2 = g k_p \tanh(k_p d) \qquad (7)$$

where d is the water depth. The phase speed $c_p = \omega_p/k_p$.

From (5) $\tau_d^s \sim \exp(-\varepsilon_T^2/\varepsilon_d^2)$. For a wind sea characterized by a small steepness ε_d the negative exponent goes to zero and so does the separation stress. The younger seas are steeper than the old sea and thus support more sea drag. It is important to notice that the absolute value of the significant wave height H_s does not define the stress, the steepness does that.

Dominant waves propagating from the deep into the shallow water start feeling the bottom and become shorter in the wavelength (the frequency is conserved). According to (7) waves in a shallow water increase the peak wavenumber k_p, so that they become steeper and support more sea drag.

Given the wind speed u_{10}, the significant wave height of the wind sea H_s, the peak wavenumber of the wind sea k_p and the depth d, equation (1) is solved by iterations to obtain the friction velocity u_*.

Knowing the friction velocity results can be presented in terms of the drag coefficient $CD_{10} = (u_*/u_{10})^2$, or, assuming the logarithmic wind profile

$$u_{10} = \frac{u_*}{\kappa} \ln \frac{10}{z_0}, \tag{8}$$

in terms of the roughness parameter z_0

$$z_0 = 10 \exp(-\frac{\kappa u_{10}}{u_*}), \tag{9}$$

or in terms of the dimensionless Charnock parameter z_*

$$z_* = z_0 \frac{g}{u_*^2}. \tag{10}$$

All these representations are equivalent.

2.2 Implementation in the WAM model

Given the wind speed at 10 m height u_{10} the WAM model calculates the evolution of a two-dimensional, in frequency and direction, ocean wave spectrum in space and time by solving the energy transport equation, (e.g., Komen et al., 1994)

$$\frac{dF}{dt} + \frac{\partial}{\partial \phi}\left(\dot{\phi} F\right) + \frac{\partial}{\partial \lambda}\left(\dot{\lambda} F\right) + \frac{\partial}{\partial \theta}\left(\dot{\theta} F\right) = S, \tag{11}$$

where $F = F(f, \theta; \boldsymbol{x}, t)$ represents the spectral density for waves with frequency f (the angular frequency $\omega = 2\pi f$) and direction of propagation θ at location $\boldsymbol{x} = (\phi, \lambda)$ and at time t. The source term S is a function of $f, \theta, \boldsymbol{x}, t$ and F itself, and it is defined by a superposition of four source terms,

$$S = S_{\text{in}} + S_{\text{dis}} + S_{\text{bot}} + S_{\text{nl}}, \tag{12}$$

where S_{in} is the wind input, S_{dis} is the dissipation by wave breaking, S_{bot} is the bottom dissipation and S_{nl} is the non-linear wave-wave interaction source term. The momentum exchange between the air and the sea is incorporated in the wind input source function S_{in}.

For a given time in each grid point the integral wave parameters necessary for the new parameterization are calculated by the following procedure using the standard WAM subroutines. First, the wave spectrum is separated into pure wind sea and swell part. Swell is defined by the WAM model as waves satisfying the following condition

$$\frac{28 u_*}{c} \cos(\theta - \theta_w) < 0.83,$$

where c is the phase speed of the wave component f, and θ_w is the wind direction. The rest of the spectrum is considered as pure wind sea wave spectrum $F^w(f, \theta)$. The significant wave height for the pure wind sea is calculated from

$$H_s = 4\sqrt{\int_0^{f_m}\int_0^{2\pi} F^w(f,\theta)d\theta df}, \qquad (13)$$

the peak frequency f_p ($\omega_p = 2\pi f_p$)corresponds to the maximum in $F^w(f,\theta)$, and f_m is the maximum prognostic frequency bin (in the NEDWAM $f_m = 0.4117$ Hz.

3 Experimental set up

The numerical experiments are performed for a time period of October 1, 2000 until January 31, 2001. The period is characterized by a large variability in the weather with the occurrence of several severe storms, mild storms and very calm weather. The combination of stormy and quiet weather is necessary to create representative results of a wave model performance.

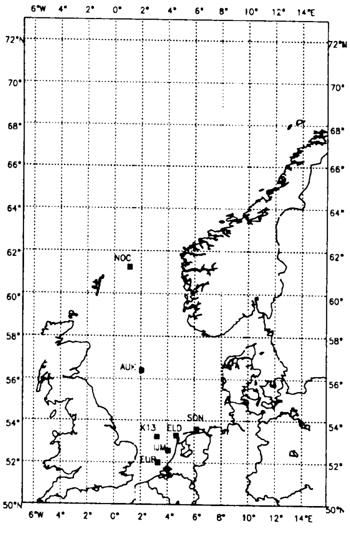

Figure 1: Location of observation stations NOC, AUK, K13, EURO, IJM and ELD in the North Sea.

All NEDWAM runs made in this study are performed on a 'coarse-grid' NEDWAM version previously used in operational forecast at KNMI. The NEDWAM area covers the part of the North Sea running from 50.67°N to 70.00°N and from 7.50°W to 16.50°E. This area is gridded by a spacing of 1/3 degree in the latitudinal direction and 1/2 degree in the longitudinal direction (the grid size is about 32 km). The model is driven by the wind at 10 meter height supplied by the atmosphere model HIRLAM with the resolution of 1/2 degree in both latitudinal and longitudinal directions, the grid size is about 55 km. The NEDWAM model output of the performed hindcast runs was archived every 3 hours.

Results of the intercomparison between modelled and observed wave parameters are presented for the significant wave height and mean period in terms of the bias (BIAS), standard deviation (SD), root-mean-square (RMS) and index of agreement (IOA). The definitions are standard. A negative bias means that the model underestimates the observations. The estimates are based on model results and observations from six stations AUK (56.2°N, 2.0°E), depth 77 m, EURO (52.0°N, 3.2°E), depth 30 m, K13 (53.1°N, 3.1°E), depth 28 m, NOC (61.1°N, 1.1°E), depth 161 m, ELD (53.2°N, 4.4°E), depth 28 m, and IJM (52.3°N, 4.0°E), depth 24 m, which are Wavec buoys located near (oil-)platforms producing three-hourly wave observations. Reliable and fairly complete wave observation sets were available for these stations. The location of stations is shown in Figure 1.

4 Sensitivity study

The sensitivity study consists of two hindcast runs made for the period of 1-31 October 2000. October was characterized by a large variability in weather conditions. The wind speed ranges from 0 to 25 m/s. One run is performed with original NEDWAM. The second run was performed with the new parameterization of the sea drag as it is presented above. Notice, that only the drag formulation was changed in the NEDWAM. All model parameters remained the same and no parameter tuning was performed. Results are presented in Table 1 and 2 for the significant wave height and the mean period. These two parameters are defined through the full wave spectrum, thus including possible swell. Wind statistics for this period is given in Table 3. The wind statistics show that the HIRLAM model persistently underestimates the measured wind speed with a bias in the range of 0.05 to 1.50 m depending on the station. The standard deviation is fairly constant for all stations and is around 1.60 m/s.

The original NEDWAM underestimates the wave height in the range of 0.12 to 1.24 m depending on a station. The standard deviation is fairly constant and is around 0.30 m. The run with the new drag parameterization shows that the magnitude of the bias is increased on 0.06 m for all station as compared to the original, the standard deviation remains the same.

The new parameterization has no impact on the mean period. This study shows that the NEDWAM is rather conservative to the formulation of the sea drag. In fact the same result was obtained earlier by the parameter tuning study by Doortmont and Makin (2000). A fact that the new parameterization, based on the advanced physics and carefully tested in a wide range of exter-

H_s [m]	1-31 October 2000					
	NOC	AUK	K13	IJM	EUR	ELD
	BIAS					
$NEDWAM_{original}$	−1.24	−0.49	−0.40	−0.29	−0.34	−0.12
$NEDWAM_{sensitivity}$	−1.28	−0.55	−0.47	−0.36	−0.41	−0.18
$NEDWAM_{new\ balance}$	−0.55	−0.01	−0.16	−0.10	−0.16	0.10
	SD					
$NEDWAM_{original}$	0.44	0.33	0.28	0.26	0.30	0.37
$NEDWAM_{sensitivity}$	0.44	0.35	0.29	0.26	0.29	0.38
$NEDWAM_{new\ balance}$	0.42	0.31	0.26	0.24	0.26	0.30
	RMS					
$NEDWAM_{original}$	1.31	0.59	0.48	0.39	0.45	0.38
$NEDWAM_{sensitivity}$	1.35	0.65	0.55	0.44	0.50	0.41
$NEDWAM_{new\ balance}$	0.69	0.31	0.30	0.26	0.31	0.32
	IOA					
$NEDWAM_{original}$	0.72	0.93	0.95	0.97	0.95	0.97
$NEDWAM_{sensitivity}$	0.70	0.91	0.93	0.95	0.93	0.96
$NEDWAM_{new\ balance}$	0.90	0.98	0.98	0.98	0.97	0.98

Table 1: *Bias, standard deviation (SD), root-mean-square (RMS) and index of agreement (IOA) of the modelling error of H_s obtained by the original NEDWAM model, NEDWAM model with a new drag parameterization (sensitivity study), and NEDWAM model with a new drag parameterization and a new balance at each station for the time period 1-31 October 2000.*

T [s]	1-31 October 2000					
	NOC	AUK	K13	IJM	EUR	ELD
	BIAS					
$NEDWAM_{original}$	−2.4	−0.8	−0.5	−0.5	−0.4	−0.4
$NEDWAM_{sensitivity}$	−2.3	−0.8	−0.5	−0.5	−0.4	−0.4
$NEDWAM_{new\ balance}$	−1.9	−0.5	−0.3	−0.2	−0.2	−0.2
	SD					
$NEDWAM_{original}$	1.1	0.5	0.4	0.5	0.5	0.6
$NEDWAM_{sensitivity}$	1.1	0.5	0.4	0.6	0.5	0.6
$NEDWAM_{new\ balance}$	1.1	0.5	0.4	0.5	0.5	0.5
	RMS					
$NEDWAM_{original}$	2.6	1.0	0.6	0.7	0.7	0.7
$NEDWAM_{sensitivity}$	2.6	1.0	0.7	0.7	0.7	0.7
$NEDWAM_{new\ balance}$	2.2	0.7	0.5	0.5	0.5	0.5
	IOA					
$NEDWAM_{original}$	0.48	0.83	0.93	0.91	0.91	0.91
$NEDWAM_{sensitivity}$	0.49	0.82	0.92	0.91	0.91	0.91
$NEDWAM_{new\ balance}$	0.54	0.88	0.95	0.94	0.93	0.94

Table 2: *Bias, standard deviation (SD), root-mean-square (RMS) and index of agreement (IOA) of the modelling error of the mean period T obtained by the original NEDWAM model, NEDWAM model with a new drag parameterization (sensitivity study), and NEDWAM model with a new drag parameterization and a new balance at each station for the time period 1-31 October 2000.*

U_{10} [m/s]	1-31 October 2000					
	NOC	AUK	K13	IJM	EUR	ELD
	BIAS					
HIRLAM	−1.43	−0.05	−0.55	−0.30	−1.06	−0.08
	SD					
HIRLAM	1.58	1.64	1.41	1.70	1.58	1.72
	RMS					
HIRLAM	2.13	1.65	1.51	1.73	1.90	1.72
	IOA					
HIRLAM	0.91	0.96	0.97	0.96	0.95	0.96

Table 3: *Bias, standard deviation (SD), root-mean-square (RMS) and index of agreement of the modelling error of U_{10} obtained by HIRLAM (55 km) model, at each station for the time period 1 October 2000 - 31 January 2001.*

nal wind and waves parameters, produces increased bias is not surprising: the parameterization enters the balance (12), which was tuned with the original formulation in it. So, the possible uncertainties (mistakes) of the original sea drag formulation are simply incorporated/compensated in/by different source terms of the balance.

The new parameterization is verified against several field data sets. A good comparison obtained allows to consider this parameterization as a 'truth'. Thus no parameters will be changed further in the parameterization. There are two possible ways to proceed. One is a parameter tuning based on original WAM source terms. Such study was performed by Makin and Stam (2001, unpublished). They showed that the bias can be improved but on expense of introducing an artificial function in the dissipation formulation, which is of course not desirable. The other way is to introduce alternative source functions, which are consistent with new physics underlying the new drag formulation, and to retune the new balance.

5 New balance

Two source terms in the wave density balance equations (12) will be altered, namely dissipation due to wave breaking and wind input source terms. The alternative formulations are based on recently developed physics that reflects the significant progress in the knowledge made during last decades. It is noted that the original WAM is based on physics reflecting the knowledge of 80th and even earlier years and does not correspond to the current understanding of the processes involved in wave development and evolution.

5.1 Dissipation due to wave breaking

The commonly used quasi-linear form of the dissipation source term $S_{\text{dis}} = \gamma_{\text{dis}}\omega F$, proposed by Hasselmann (1974), is defined in terms of the integrated spectral steepness as used in the WAM model (Komen et al., 1994):

$$\gamma_{\text{dis}} = -C_{\text{dis}}\frac{\langle\omega\rangle}{\omega}\left(\frac{\alpha}{\alpha_{\text{PM}}}\right)^2\frac{k}{2\langle k\rangle}\left(1+\frac{k}{\langle k\rangle}\right):$$

where k is the wave number, $\alpha_{\text{PM}} = 4.57\times10^{-3}$ is the Pierson-Moskowitz steepness for a fully developed sea and $\alpha = E\langle k\rangle^2$ is the squared average steepness of the spectrum. Dimensionless constant $C_{\text{dis}} = 9.4\times10^{-5}$ determines the overall strength of S_{dis}. The total wave variance E is defined by

$$E = \int_0^\infty\int_0^{2\pi} F(f,\theta)d\theta df, \tag{14}$$

and the mean angular frequency and mean wave number are defined, respectively, by

$$\langle\omega\rangle = E\left(\int_0^\infty\int_0^{2\pi} F(f,\theta)\omega^{-1}d\theta df\right)^{-1}, \quad \langle k\rangle = E\left(\int_0^\infty\int_0^{2\pi} F(f,\theta)k^{-1/2}d\theta df\right)^{-2}. \tag{15}$$

This formulation results in the dissipation rate at the spectral peak that is too low during young wind sea growth and too strong for old wind seas, and does not reproduce correctly field observations (Banner and Young, 1994). At the time the quasi-linear model was formulated, the underlying role of wave groupiness, and hence the spectral bandwidth, in the breaking onset was not recognized. Thus the limiting narrow band spectral arguments that have been advanced to preclude a nonlinear dependence of the dissipation source term on the spectrum are no longer considered to be valid. A new spectral dissipation source term is based on a threshold behavior of the local wave steepness (Banner et al., 2000). This formulation seeks to embody the nonlinear wave group modulation that underlies wave breaking, and results in a strongly nonlinear dependence of the dissipation source term on the wave spectrum. That improves the prediction of wave evolution from young to old seas consistent with field observations (Alves and Banner, 2002; Alves et al., 2002). Another short-coming of the currently used Komen et al. (1994) dissipation formulation is its (numerical) sensitivity on the occurrence of low frequency peaks when applied in mixed sea-swell situations. This leads to a decrease of the average wave steepness and an unphysical reduction of wind-sea dissipation, leading to artificially enhanced growth of the wind sea. A similar problem occurs for the swell dissipation. A small amount of wind sea energy increases the average wave steepness, thereby increasing the dissipation of swell waves. Both effects lead to an underprediction of wave period measures. Therefore the concept of using the mean wave steepness should be revised. Alves and Banner (2002), Alves et al. (2002) suggested the following general formulation of the dissipation rate

$$\gamma_{\rm dis} = -C^{\rm b}_{\rm dis}\left(\frac{\alpha}{\alpha_{\rm PM}}\right)^m \left(\frac{B(k)}{B_r}\right)^{p/2} \left(\frac{k}{\langle k\rangle}\right)^n, \tag{16}$$

where $C^{\rm b}_{\rm dis}$, m, p, n and B_r are constants (to be tuned in the new balance), and $B(k)$ is the saturation wave spectrum related to the wave density spectrum $F(f)$ by

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

and c_g is the group velocity

$$c_g = \frac{1}{2}c\left(1 + \frac{2kd}{\sinh(2kd)}\right).$$

Notice, that because the spectrum $B(k)$ (or $F(f)$) enters directly the dissipation rate (16), the dissipation source function $S_{\text{dis}} = \gamma_{\text{dis}}\omega F$ is now nonlinear with respect to F.

5.2 Wind input

The parameterization of the wind input that is currently used in NEDWAM (details see Komen et al., 1994) is based on a physical mechanism (so-called the quasi-laminar critical layer model of the airflow) developed in late 50th by Miles (1957, 1959). Belcher and Hunt (1993) wrote a revolutionary paper introducing the rapid distortion theory of turbulence in the description of the turbulent airflow above waves. They suggested the non-separated sheltering mechanism of the wave growth and argued that the Miles' mechanism is inappropriate in description of the wave growth (also, Belcher and Hunt, 1998). Numerical studies by Mastenbroek (1996), Mastenbroek et al. (1996) based on full nonlinear Reynolds equations with the 2nd order turbulent stress closure demonstrated no effects of the critical layer directly. Kudryavtsev et al. (2000) developed scaling arguments and showed that the applicability of the quasi-laminar model in the description of the airflow dynamics is very limited. Above mentioned brought a necessity for a revision of the wind input term in the WAM model. As usual we write

$$S_{\text{in}} = \beta\omega F, \tag{17}$$

where β is the growth rate parameter. Here, the alternative formulation for the growth rate parameter is based on the parameterization suggested by Makin and Kudryavtsev (1999)

$$\beta = \frac{\rho_a}{\rho_w} m_\beta R \Big(\frac{u_*}{c}\Big)^2 \cos(\theta - \theta_w)|\cos(\theta - \theta_w)|, \tag{18}$$

where m_β is a constant, ρ_a and ρ_w are the density of air and water, and function R is defined by

$$R = 1 - m_c\left(\frac{c}{u_{10}}\right)^{n_c}, \tag{19}$$

yielding $R \sim 1$ for slowly moving waves $c \ll u_{10}$, while $R \to 0$ for fast moving waves $c > u_{10}$ with constants $m_c < 1$ and $n_c > 1$ (to be tuned in the new balance). In fact (18) is the extended relation by Plant (1982). This original relation is valid only for slow moving waves. Introduction of function R extended its validity to fast moving waves, which are of primarily interest for the WAM model.

5.3 Tuning parameters

The new balance was tuned on the period 1-31 October 2000 to yield the following constants.

In the dissipation source term (16): $C^{\mathrm{b}}_{\mathrm{dis}} = 2.5 \cdot 10^{-5}$, $B_r = 4 \cdot 10^{-3}$, $m = 2$, $p = 6$, and $n = 1$.

In the wind input source term (18) and (19): $m_\beta = 0.045$, $m_c = 0.3$, $n_c = 5$.

Additionally, without changing the functional relation for the bottom dissipation source term S_{bot} its proportionality coefficient was tuned to twice the original value, from 0.076 to 0.152.

Results are presented in Table 1 and 2. A significant reduction in the bias of the significant wave height is obtained. The magnitude is decreased to two-three times as compared to the original NEDWAM run. There is also persistent reduction of the standard deviation but a very marginal one: few centimeters only. The improvement in the r.m.s. and the index of agreement is due to the improvement in the bias.

There is some improvement in the bias of the mean period. In fact for the coastal stations the magnitude goes twice down. In absolute value that is only 0.2÷0.3 seconds. The standard deviation remains the same.

5.4 Control run

Finally the control run is done for the period 1 November 2000 - 31 January 2001.

H_s [m]	1 November 2000 - 31 January 2001					
	NOC	AUK	K13	IJM	EUR	ELD
			BIAS			
$NEDWAM_{original}$	−1.22	−0.53	−0.37	−0.21	−0.26	−0.15
$NEDWAM_{new\ balance}$	−0.47	+0.01	−0.09	−0.01	−0.08	+0.10
			SD			
$NEDWAM_{original}$	0.50	0.36	0.27	0.26	0.27	0.27
$NEDWAM_{new\ balance}$	0.54	0.38	0.28	0.26	0.26	0.26
			RMS			
$NEDWAM_{original}$	1.32	0.64	0.45	0.34	0.38	0.31
$NEDWAM_{new\ balance}$	0.72	0.38	0.31	0.26	0.27	0.28
			IOA			
$NEDWAM_{original}$	0.79	0.92	0.93	0.95	0.93	0.96
$NEDWAM_{new\ balance}$	0.93	0.97	0.97	0.97	0.96	0.97

Table 4: *Bias, standard deviation (SD), root-mean-square (RMS) and index of agreement (IOA) of the modelling error of H_s obtained by the original NEDWAM model, and NEDWAM model with a new drag parameterization and a new balance at each station for the time period 1 November 2000 - 31 January 2001.*

T [s]	1 November 2000 - 31 January 2001					
	NOC	AUK	K13	IJM	EUR	ELD
	BIAS					
$NEDWAM_{original}$	-2.0	-0.9	-0.4	-0.3	-0.2	-0.4
$NEDWAM_{new\ balance}$	-1.5	-0.4	-0.2	-0.2	-0.1	-0.2
	SD					
$NEDWAM_{original}$	1.5	0.9	0.7	0.6	0.5	0.7
$NEDWAM_{new\ balance}$	1.5	0.9	0.7	0.7	0.5	0.7
	RMS					
$NEDWAM_{original}$	2.5	1.3	0.8	0.7	0.6	0.8
$NEDWAM_{new\ balance}$	2.1	1.0	0.8	0.7	0.5	0.7
	IOA					
$NEDWAM_{original}$	0.46	0.76	0.83	0.87	0.89	0.85
$NEDWAM_{new\ balance}$	0.50	0.82	0.82	0.84	0.90	0.83

Table 5: *Bias, standard deviation (SD), root-mean-square (RMS) and index of agreement (IOA) of the modelling error of the mean period T obtained by the original NEDWAM model, and NEDWAM model with a new drag parameterization and a new balance at each station for the time period 1 November 2000 - 31 January 2001.*

U_{10} [m/s]	1 November 2000 - 31 January 2001					
	NOC	AUK	K13	IJM	EUR	ELD
	BIAS					
HIRLAM	-1.02	$+0.01$	-0.52	-0.24	-0.83	$+0.08$
	SD					
HIRLAM	1.49	1.44	1.33	1.57	1.54	1.68
	RMS					
HIRLAM	1.80	1.44	1.43	1.59	1.75	1.69
	IOA					
HIRLAM	0.96	0.97	0.97	0.95	0.94	0.94

Table 6: *Bias, standard deviation (SD), root-mean-square (RMS) and index of agreement of the modelling error of U_{10} obtained by HIRLAM (55 km) model, at each station for the time period 1 November 2000 - 31 January 2001.*

The wind statistics shown in Table 6 do not differ much from that obtained for October 2000, Table 3.

The significant wave height statistics presented in Table 4 show a considerable reduction in the bias as compared to the original NEDWAM run. The reduction in the bias was obtained also in the tuning parameter study by Makin and Stam (2001, unpublished). There to reduce the bias an artificial (having no physical grounds) function was introduced in the dissipation source term. In the present study the considerable reduction is achieved by introduction of the new formulation of the sea drag together with new formulations of dissipation and wind input source functions. The standard deviation is not improved as compared to original run.

The same conclusion is valid for the mean period statistics: there is a reduction in a bias up to 0.5 sec and no improvement in the standard deviation.

6 Conclusions

A new parameterization of the sea drag based on the advanced wind-over-waves coupling theory and carefully tested against several field data sets is introduced in NEDWAM. The sensitivity study showed that the current version of NEDWAM is not sensitive to the sea drag formulation. With the new drag formulation errors in the wave parameters statistics remain in fact the same. That implicates that other sources of errors in NEDWAM are responsible. The most probable sources are: the quality of the driving wind fields on one hand, deficiencies in the physical formulation of the source terms, and their numerical implementation on the other hand.

Two new formulations for the wind input and dissipation due to wave breaking source functions are introduced in NEDWAM. New formulations are based on the present-day understanding of the processes, which govern the waves development and evolution. After tuning the new balance a control run is made on independent data. A considerable reduction in the bias of the significant wave height and mean period is obtained for all station. However, the errors in the standard deviation are not reduced.

There seems to be a correspondence between the underestimation of the wind speed and the wave height taken at each concrete station, which would explain the observed errors in the bias. Errors in the standard deviation of the wave parameters could be also caused by errors in the wind. Additionally, it is a known fact that NEDWAM is not capable to reproduce correctly swell in the northern part of the North Sea (open sea NOC station). That could be a reason of large errors in wave parameters. Another suspected source of errors is the known deficiencies in the formulation of the nonlinear source term and in the numerical implementation of the propagation scheme. The discussion of these problems is out of the scope of the present study.

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