CHAPTER 66

BOTTOM FRICTION DISSIPATION IN THE BELGIAN COASTAL REGIONS

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Abstract

The effect of bottom friction dissipation and of the different formulations used for this term on the wave evolution has been investigated in the Belgian coastal regions. Two eddy viscosity models for the bottom friction dissipation, the Madsen *et al.* (1988) model and Weber's (1991a) model have been implemented in the Cycle 4 version of the third generation WAM model (Günther *et al.*, 1992). The wave conditions for the area of the southern North Sea were hindcasted for the February 1993 storm. The results are compared with buoy data. It is found that the net effect of bottom friction dissipation on the significant wave height hindcast is quite big, in the order of *80%* (of the wave height when the bottom frictiion dissipation is taken into account) along the Belgian coast. Different formulations for the bottom friction dissipation have a quite significant effect on wave evolution in storm conditions. The use of equivalent dissipation coefficients (Luo *et al.*, 1994) results in nearly identical wave hindcasts.

Introduction

Accurate knowledge of wave conditions in coastal areas is very important for the design of harbours or of coastal protection works. Very often these data are not available from measurements and one has to rely on wave models. For example, in Belgium, a wave prediction model is a very useful tool for the navigation of large sea vessels through the shallow entrance channels towards the harbours of Antwerp and Zeebrugge. In general, deep water wave hindcasts are fairly reliable. In shallower areas energy dissipation due to bottom friction can become

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important. The Belgian coastal area is characterised by a sandy bottom and the bottom friction contributes significantly to the energy dissipation. A good representation of this source term is necessary.

In the last decades several different bottom friction dissipation formulations have been developed, including an empirical expression based on the JONSWAP experiment (Hasselmann et al., 1973), two drag-law models (Hasselmann and Collins, 1968; Collins, 1972) and two eddy viscosity models (Madsen et al., 1988; Weber, 1991a). These formulations have widely been used in many operational wave models. The effects of different bottom friction formulations on the energy balance were quantitatively investigated by Luo and Monbaliu (1994). They found that these formulations for the bottom friction source terms result in quite different growth curves for the total energy and the peak frequency for depth-limited wind generated waves. For a water depth of $15m$ and a wind friction velocity of $0.71m/s$ (the corresponding U_{10} equal to $16.5m/s$) a difference as big as 70% for the total energy was reported. Moreover, the required CPU time for different formulations is quite different. The empirical formulation is the simplest one and needs the least amount of computing time. The eddy viscosity model is the most complicated one, and costs the most computing time owing to the extra determination of the friction factor and the bottom friction velocity. Later on Luo *et al.* (1994) proposed the equivalent dissipation coefficients so that different bottom friction dissipation formulations produce the same or nearly the same levels for the total energy and the peak frequency for fetch-limited shallow water conditions.

In this study, the effect of different bottom friction dissipation models on wave evolution in the Belgian coastal regions is investigated. Three different models for the bottom friction dissipation, the empirical expression (Hasselmann *et al.*, 1973) and two eddy viscosity models (Madsen *et al.*, 1988; Weber, 1991a), have been implemented in the Cycle 4 version of the third generation WAM model (Günther *et al.*, 1992). Hindcasts are made for February 1993 in the Belgian coastal area as to study the effect of different bottom friction dissipation formulations on wave evolution and to test the validity of using equivalent coefficients for different formulations in operational circumstances. The results are compared with buoy data at different measurement stations.

THE WAVE MODEL

The wave model used for the present study is the Cycle 4 version of the WAM model (Günther et al., 1992) with a choice for the bottom friction dissipation term. The WAM model is a third generation wave

model which solves the wave transport equation explicitly without any ad hoc assumption on the shape of the wave spectrum. It contains today's knowledge of the physics for the wave evolution of a two dimensional wave spectrum. The basic energy transport equation for a spherical latitude-longitude (ϕ, λ) co-ordinate system , in the absence of currents, can be expressed as,

$$\frac{\partial F}{\partial t}+\frac{1}{\cos\phi}\frac{\partial}{\partial\phi}(c_\phi \cos\phi F)+\frac{\partial}{\partial\lambda}(c_\lambda F)+\frac{\partial}{\partial\omega}(c_\omega F)+\frac{\partial}{\partial\theta}(c_\theta F)=S_{in}+S_{nl}+S_{ds}+S_{bf}$$

where F is the wave energy spectrum, t is the time, ϕ is the latitude, λ is the longitude, ω is the angular frequency, θ is the wave direction measured clockwise from the true north, c_ϕ, c_λ, c_ω and c_θ are the rate of change of the position and propagation direction of a wave packet travelling along a great circle path. The left hand side of the above equation represents the local rate of change of wave energy density, propagation along great circles, shifting of frequency due to time variation in depth (note that currents are not included in this study), and refraction. The right hand side represents all effects of generation and dissipation of the waves. They include wind input S_{in}, whitecapping dissipation S_{ds}, non-linear quadruplet wave-wave interactions S_{nl} and bottom friction dissipation S_{bf}. The detailed description of these source terms, except the bottom friction dissipation, can be found in Günther et al. (1992).

Models for bottom friction dissipation

The wave energy dissipation due to the bottom friction in the wave boundary layer equals the work done by the turbulent bottom stress on the free stream orbital bottom velocity. There are different models to parametrize the bottom stress. The ones implemented in this study ~~is~~ are an empirical expressen, and some variations on the eddy viscosity model, which relates the bottom shear stress to the vertical gradient of the velocity through an eddy viscosity coefficient.

An empirical expression

The simplest form for the bottom friction dissipation was proposed by Hasselmann et al. (1973) who applied the Hasselmann and Collins (1968) theory to measure the decay of swell in the JONSWAP experiment (Hasselmann et al.,1973). It can be expressed as

$$S_{bf}(f,\theta)=-\frac{2c}{g}\frac{k}{\sinh 2kh}F(f,\theta)$$

with $S_{bf}(f,\theta)$ the bottom friction dissipation spectrum, c an empirical coefficient, g the acceleration of gravity, k the wave number, and h the

water depth. In the JONSWAP experiment, the empirical coefficient c was found to vary over two orders of magnitude, with a mean value for c of $0.038m^2s^3$. This empirical dissipation formulation with the mean value for c has been used in wave models by WAMDI (1988) and performed well.

Two eddy viscosity models

Based on the linearized form of the boundary layer equations and a simple eddy viscosity formulation of shear stress, Madsen *et al.* (1988) derived a formulation for bottom friction dissipation

$$S_{bf}(f,\theta) = -f_w u_{br} \frac{k}{\sinh 2kh} F(f,\theta)$$

with

$$u_{br}^2 = 2\iint \frac{\omega^2}{\sinh^2 kh} F(f,\theta) df d\theta$$

where f_w is the friction factor, u_{br} is the representative near bottom velocity, and ω is the angular frequency. The friction factor f_w in the Madsen *et al.* model is a function of the bottom roughness height and parameters characterised by the wave conditions. It can be estimated using the formulation of Jonsson (1966):

$$\frac{1}{4\sqrt{f_w}} + \log_{10}\frac{1}{4\sqrt{f_w}} = m_f + \log_{10}\frac{a_{br}}{K_N}$$

where m_f is a constant. A value of -0.08 for m_f was determined experimentally by Jonsson and Carlsen (1976). The bottom roughness height K_N depends on the flow field and the sediment properties. The near-bottom excursion amplitude a_{br} is formulated as:

$$a_{br}^2 = 2\iint \frac{1}{\sinh^2 kh} F(f,\theta) df d\theta$$

This dissipation formulation was implemented in a parametric windsea model for finite water depths by Graber and Madsen (1988), and in a third-generation model for wind waves in combined wave-current flow by Tolman (1991). Graber and Madsen (1988) incorporated the bottom dissipation using a tuned constant friction factor. Tolman (1991) reported that a constant bottom roughness height ranging between $2cm$ and $5cm$ produced a good agreement between numerical results and measurements for the nondimensional wave height and period.

With a one-layer eddy viscosity model, based on the random turbulent wave boundary layer and using perturbation theory, Weber (1991a) derived another eddy viscosity model, which results in a frequency-dependent representative bottom friction velocity.

$$S_{bf}(f,\theta) = -u_{a*}(T_{\tilde{k}}(\varsigma_0) + \tilde{T}_{\tilde{k}}(\varsigma_0))\frac{k}{\sinh 2kh}F(f,\theta)$$

where u_{a*} is the wave boundary layer friction velocity and can be determined as a function of wave number, wave spectrum, bottom boundary layer thickness and bottom roughness height. $T_{\tilde{k}}$ is a dimensionless function and $\tilde{T}_{\tilde{k}}(\varsigma_0)$ is its complex conjugate. When the bottom roughness height is given, the values for u_{a*}, $T_{\tilde{k}}$ and $\tilde{T}_{\tilde{k}}(\varsigma_0)$ can be worked out iteratively with an initial u_{a*}.

This formulation was implemented in a regional third generation WAM model for the Texel storm hindcast case, and a value of $4cm$ for the bottom roughness height was selected according to the flow conditions in the southern North Sea (Weber, 1991b). Because of the better prediction of the significant wave height for that storm it was suggested that the eddy viscosity formulation with a bottom roughness height of $4cm$ is to be preferred upon the empirical JONSWAP expression with the mean value for c of $0.038\ m^2s^{-3}$.

In fact, the study of Luo and Monbaliu (1994) and Luo et al. (1994) showed that the bottom roughness height of $4cm$ in Weber's formulation is not equivalent to the mean value for c of $0.038\ m^2s^{-3}$ of the empirical JONSWAP expression in terms of the resulting total energy and peak frequency growth curve levels for an idealised fetch-limited shallow water case. In order to produce the same or nearly the same growth curves levels, a c value of $0.067m^2s^{-3}$ for the empirical JONSWAP formulation is equivalent to the bottom roughness height of 4cm. A bottom roughness height of $0.69cm$ in the Weber model and a bottom roughness height of $0.35cm$ in the Madsen et al. model are equivalent to the mean value $0.038\ m^2s^{-3}$ for c of the empirical JONSWAP expression.

Model Area

The model implementation was made on two grids. In order to intercept swell generated far away, but which may travel to the Belgian coast, a coarse grid was used. A fine grid was used to cover the southern North Sea, including the Belgian coastal area, with a spatial resolution of $10km \times 10km$. This grid is nested in the coarse grid with a resolution of $50km \times 50km$ covering the whole North Sea from $48^\circ N$ to $70^\circ N$ latitude and $7^\circ W$ to $12^\circ E$ longitude. We used a stereographic projection for the grid description running the model with the Cartesian co-ordinate option. Fig. 1 shows the fine grid model bathymetry and also the indication of the two Belgian buoy stations: A2-buoy (A2B) and Westhinder (WEH). It is

clear that the water depths are quite limited and vary from less than $5m$ to about $47m$ in this area. The water depth at A2B is about $8m$ and at WEH it is about $25m$.

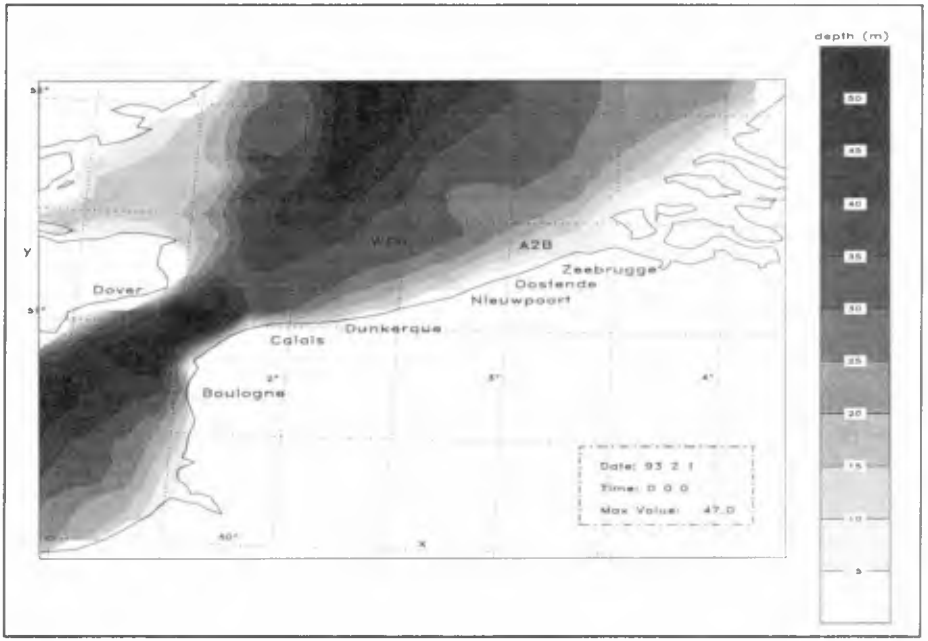


Fig. 1 The bathymetry of the southern North sea and locations of two Belgian buoy stations.

Hindcast Study

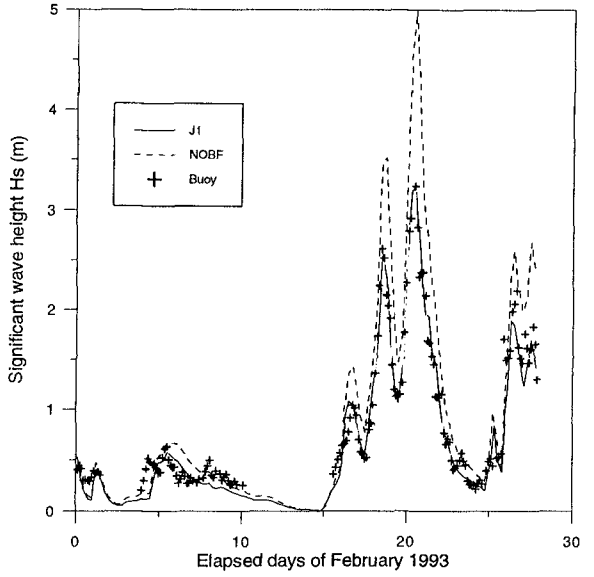
One month period running from the 1st to the 28th of February 1993 is hindcasted by the WAM model. From the 19 to the 21 February, there happened a strong storm in the southern North Sea. The model wind was provided by the United Kingdom Meteorological Office (UKMO) in GRIB (GRIdded Binary) and decoded by the Management Unit of the North Sea Mathematical Models (M.U.M.M.). These winds were compared with ERS-1 satellite data and with buoy data. The comparison showed that the wind forcing used to drive the wave model is of good quality (Ovidio *et al.*, 1994).

Effect of bottom friction dissipation

In order to see the effect of the net bottom friction dissipation on the wave evolution, this term was simply switched on and off in the model. Runs were carried out, and they are denoted by J1 when the empirical JONSWAP expression ($c=0.038m^2s^{-3}$) was used as bottom

friction formulation and by NOBF for cases when no bottom friction dissipation term was used. Figures 2 (a) and (b) show the hindcasted significant wave heights from the runs J1 and NOBF and the wave buoy measurements at A2B and WEH, respectively. The maximum net effect of the bottom friction dissipation on the hindcasted H_s values is in the order of *53%* (of the wave height from the J1 run) at A2B and only *12%* at WEH.

(a)



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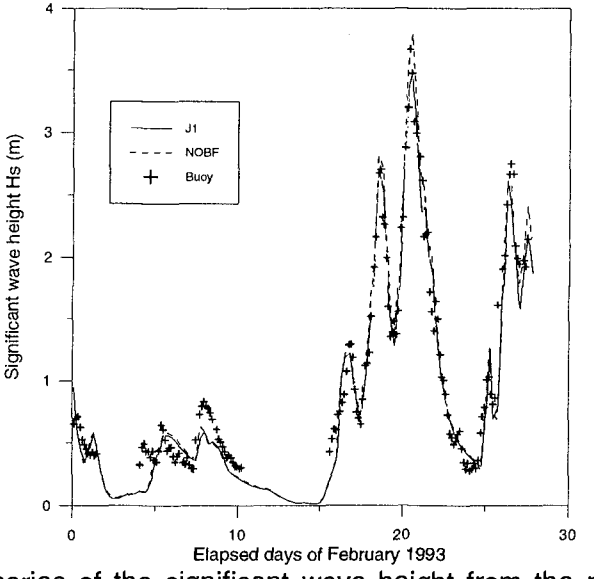


Fig. 2 Time series of the significant wave height from the runs J1 and NOBF and observations: (a) at A2 Buoy (A2B); (b) at Westhinder (WEH).

A2B is located in water with a depth of about $8m$, i.e. at a much shallower position than WEH where the water depth is about $25m$. At A2B, the model results agree very well with the observations when the bottom friction dissipation is included.

A global view of the net effect of the bottom friction dissipation on the significant wave height hindcast in the southern North Sea is displayed in Fig. 3 on February 21, 1993 at 12h GMT. Fig. 4 shows the prediction of the wave height from the run J1 (empirical formulation) to calculate the bottom friction dissipation in the model. It is clear that the bottom friction dissipation has to some extent an effect on the wave evolution in the whole southern North Sea. The effect is particularly strong in front of the Belgian and Dutch coast and in the south-east coastal area of the United Kingdom. Differences for the significant wave height prediction in the storm conditions can be as large as 80% (of the wave height from the J1 run) along the Belgian coast.

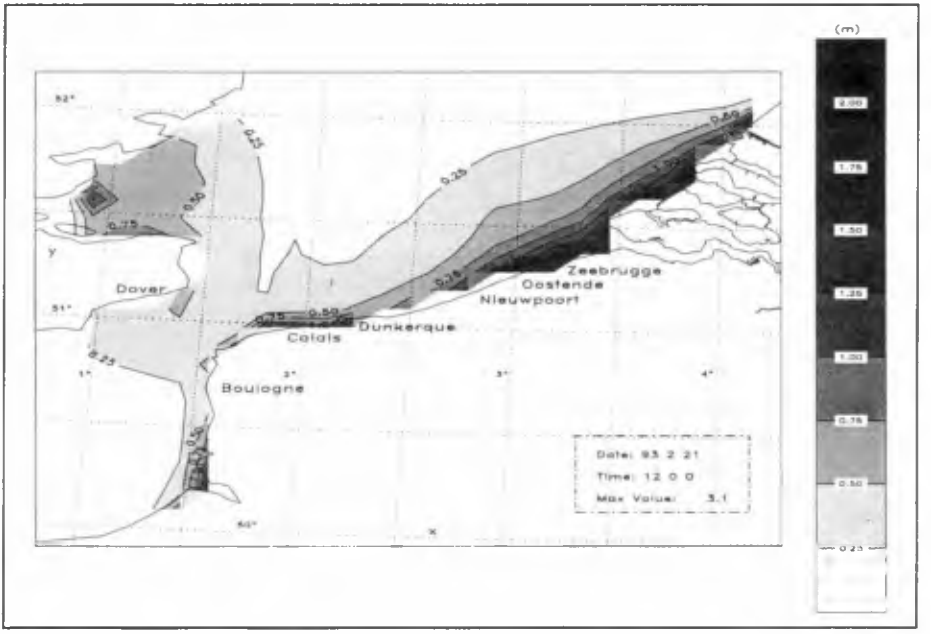


Fig. 3 The net effect of the bottom dissipation on the significant wave height hindcast at 12h GMT 21 February 1993

Effect of different formulations

Runs were also carried out with the two eddy viscosity models implemented for this study. They are denoted by M1 for the Madsen et al. (1988) model and W1 for Weber's model (1991a). The bottom roughness

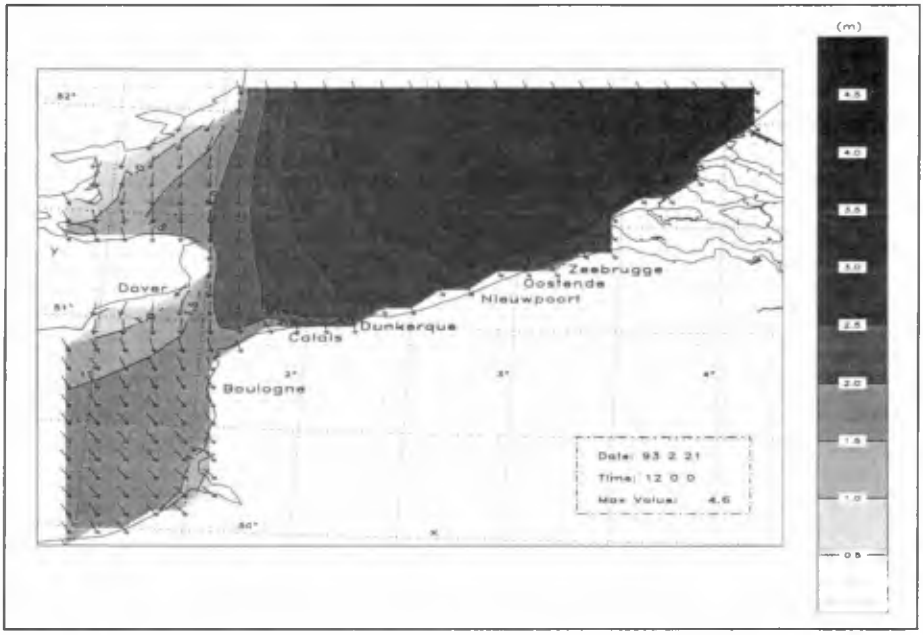


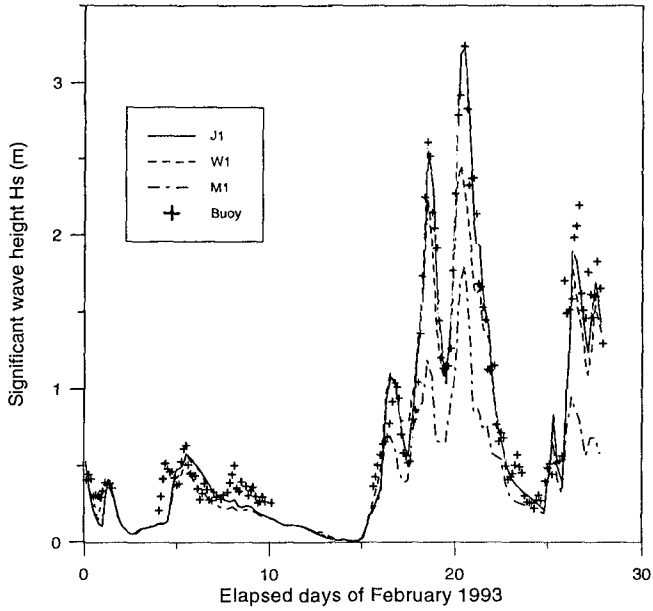
Fig. 4 The significant wave height predicted by the WAM Cycle 4 with the empirical formulation for bottom friction dissipation at 12h GMT 21 February 1993.

height in these two runs was kept the same as the original value (K_n=4cm) suggested by Weber (1991b) for the southern North sea areas. In Fig. 5 (a) and (b) the hindcasted results for the significant wave height from the runs J1, M1 and W1 are displayed with the measured data for stations A2B and WEH, respectively. The resultant effect on the hindcasted Hs values of using different bottom friction dissipation models with their original coefficients can be as big as *47%* for station A2B and *15%* for station WEH. The J1 run with the empirical formulation predicts significant wave height very close to the buoy measurement.The eddy viscosity model from Madsen et al. (1988, denoted by M1) underestimates the H_s value with about *1.5m* (*47%* of the J1 H_s peak value in storm conditions) at A2B. The W1 run with Weber's (1991a,) model also underestimates the H_s with about *1.0m* (*30%* of the J1 H_s peak value in storm conditions). Both eddy viscosity models with the bottom roughness height at *4cm* predict too much bottom friction dissipation for this storm.

A global view at 12h GMT February 21, 1993 of the significant wave height difference between the run J1 with the empirical bottom friction dissipation formulation and the run M1 with the Madsen model is shown in Fig. 6. The maximum difference for the significant wave height

was found in front of the Belgian coast zone, in the order of *1.5m* (about *47%* of the significant wave height from the J1 run).

(a)



(b)

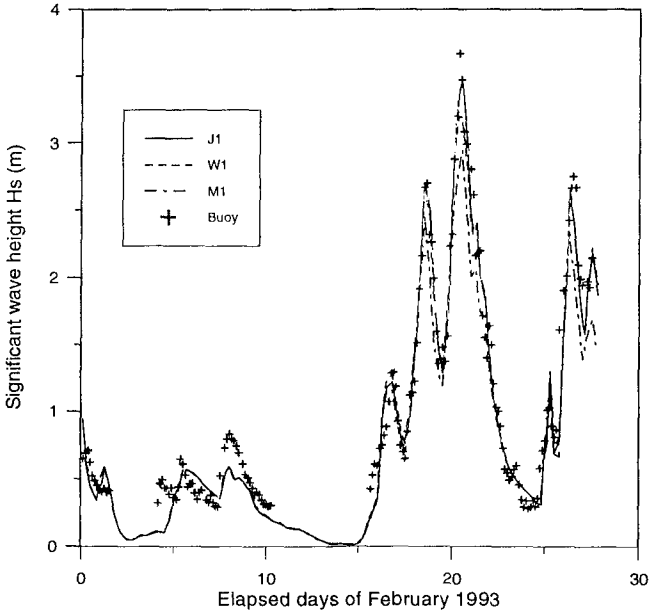


Fig. 5 Time series of significant wave height using three different bottom friction formulations for February 1993: (a) A2B; (b) WEH.

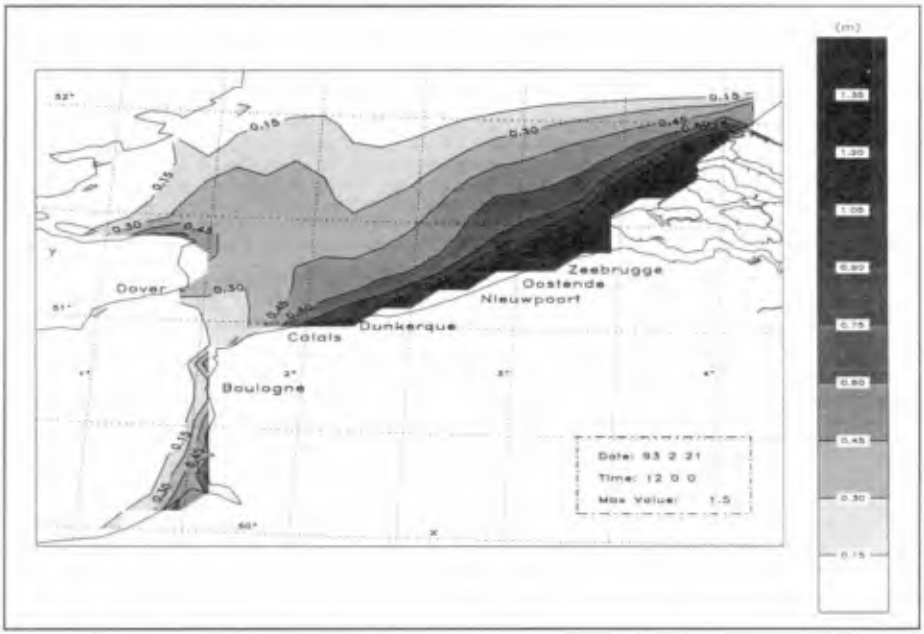


Fig. 6 The significant wave height difference between J1 and m1 runs at 12h GMT 21 February 1993.

Test of Equivalent Coefficients

As we discussed in the introduction, the study of Luo *et al.* (1994) proposed to use equivalent dissipation coefficients for different models of bottom friction dissipation in order to produce the same or nearly the same fetch-limited growth curves levels. For example, a bottom roughness height of $0.69cm$ in the Weber model and a bottom roughness height of $0.35cm$ in the Madsen et al. model are equivalent to the mean value of c of $0.038\ m^2s^{-3}$ in the empirical JONSWAP expression. The questioned remained whether these so-called equivalent dissipation coefficients are still valid for the real circumstances. These equivalent coefficients were tested for the February 1993 storm. Different model runs were carried out with the equivalent coefficients, denoted by M2 for the Madsen model with a bottom roughness height of $0.35cm$, and W2 for Weber's model with a bottom roughness height of $0.69cm$.

Figures 7 (a) and (b) show time series of the significant wave height for the runs J1, M2 and W2 for the stations A2B and WEH, respectively. The obtained H_s values from the different bottom friction dissipation models with equivalent coefficients are nearly identical, and very close to the wave observations. A global view of the significant wave height difference at 12h GMT 21st of February 1993 between the

empirical formulation and the eddy viscosity Madsen et al. model but using equivalent dissipation coefficients is presented in Fig. 8. Compared with Fig. 6, it is found that the wave height difference resulting from

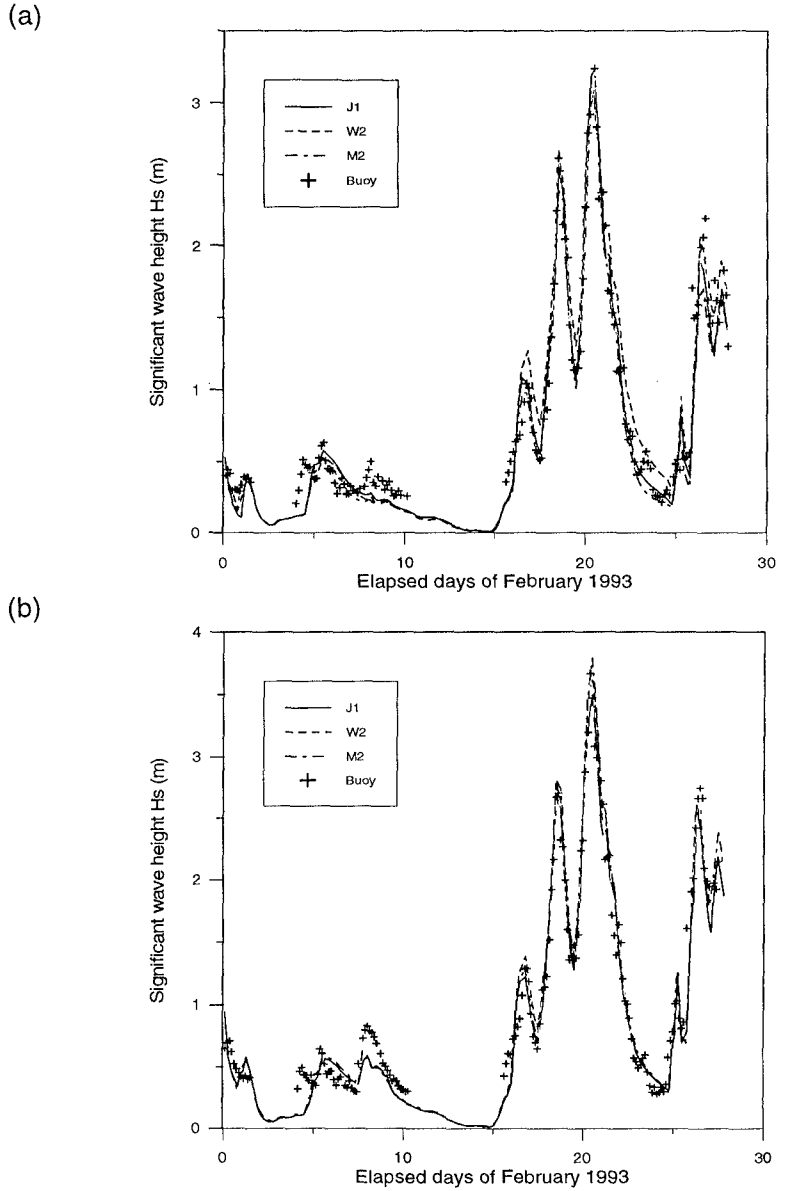


Fig. 7 Time series of significant wave height from three different bottom friction formulations with the equivalent dissipation coefficients for the February 1993: (a) A2B; (b) WEH.

different bottom friction formulations has been dramatically reduced (from more than *1.5m* to only *0.2m*) along the Belgian coast .

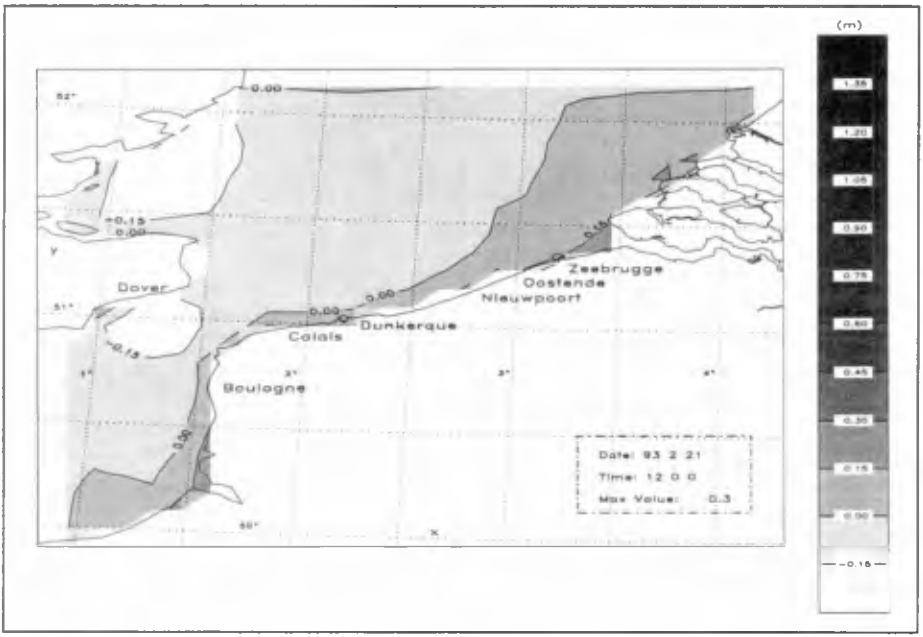


Fig. 8 The significant wave height difference between J1 and M2 runs at 12h GMT 21 February 1993.

Conclusions

A wave hindcast in the Belgian coastal region was made by using the 3G WAM Cycle 4 with three different bottom dissipation models. The results were intercompared and also compared to buoy data. It is found that the net effect of bottom friction dissipation on the significant wave height hindcast is quite big, in the order of *80%* along the Belgian coast. The hindcasted wave conditions are sensitive to the use (including the choice of coefficient) of the bottom friction dissipation model, specially in storm conditions. The use of equivalent dissipation coefficients results in the same or nearly the same effect on the wave evolution and improves wave hindcast results.

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