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Nonlinear saturation-based whitecapping dissipation in SWAN for deep and shallow water

André J. van der Westhuysen *, Marcel Zijlema, Jurjen A. Battjes

Environmental Fluid Mechanics Section, Faculty of Civil Engineering and Geosciences, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, The Netherlands

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Abstract

This study investigates the effectiveness of a revised whitecapping source term in the spectral wind wave model SWAN (Simulating WAves Nearshore) that is local in frequency space, nonlinear with respect to the variance density and weakly dependent on the wave age. It is investigated whether this alternative whitecapping expression is able to correct the tendency towards underprediction of period measures that has been identified in the default SWAN model. This whitecapping expression is combined with an alternative wind input source term that is more accurate for young waves than the default expression. The shallow water source terms of bottom friction, depth-induced breaking and triad interaction are left unaltered. It is demonstrated that this alternative source term combination yields improved agreement with fetch- and depth-limited growth curves. Moreover, it is shown, by means of a field case over a shelf sea, that the investigated model corrects the erroneous overprediction of wind-sea energy displayed by the default model under combined swell-sea conditions. For a selection of field cases recorded at two shallow lakes, the investigated model generally improves the agreement with observed spectra and integral parameters. The improvement is most notable in the prediction of period measures.

Keywords: SWAN; Whitecapping dissipation; Wind–wave spectra; Wave period; Combined wind-sea and swell

1. Introduction

The spectral wind wave model SWAN (Booij et al., 1999) is a widely used tool for the computation of wave fields over shelf seas, in coastal areas and shallow lakes. The accurate estimation of wave statistics by such models is important to various engineering applications in these environments. SWAN computes the evolution of wave action density N using the action balance equation (Booij et al., 1999):

$$\frac{\partial N}{\partial t}+\nabla_{x,y}\cdot[(\vec{c}_{\mathrm{g}}+\vec{U})N]+\frac{\partial}{\partial\theta}(c_\theta N)+\frac{\partial}{\partial\sigma}(c_\sigma N)=\frac{S_{\mathrm{tot}}}{\sigma} \quad (1)$$

with

$$S_{\mathrm{tot}}=S_{\mathrm{in}}+S_{\mathrm{wc}}+S_{\mathrm{nl4}}+S_{\mathrm{bot}}+S_{\mathrm{brk}}+S_{\mathrm{nl3}}. \quad (2)$$

The terms on the left-hand side represent, respectively, the change of wave action in time, the propagation of wave action in geographical space (with $\vec{c}_{\mathrm{g}}$ the wave group velocity vector and $\vec{U}$ the ambient current), depth- and current-induced refraction (with propagation velocity c_θ in directional space θ) and the shifting of the radian frequency σ due to variations in mean current and depth (with the propagation velocity c_σ). The right-hand side represents processes that generate, dissipate or redistribute wave energy. In deep water, three source terms are used: the transfer of energy from the wind to the waves, S_{in}; the dissipation of wave energy due to whitecapping, S_{wc}; and the nonlinear transfer of wave energy due to quadruplet (four-wave) interaction, S_{nl4}. In shallow water, dissipation due to bottom friction, S_{bot}, depth-induced breaking, S_{brk}, and nonlinear triad (three-wave) interaction, S_{nl3}, are additionally accounted for.

The application of SWAN to a range of field situations has shown that significant wave height tends to be well predicted, but that period measures are typically somewhat underestimated (e.g. Bottema et al., 2003; Rogers et al., 2003). The

* Corresponding author. Tel.: +31 15 278 3255; fax: +31 15 278 4842.
E-mail address: A.J.vanderWesthuysen@tudelft.nl (A.J. van der Westhuysen).

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underprediction of period measures is related to the following: for pure wind-sea, the energy density at lower frequencies is typically underpredicted, whereas energy levels in the tail are generally overpredicted. These leave both the peak and mean periods underpredicted. In combined swell-sea situations, SWAN predicts higher dissipation of swell in the presence of wind-sea than without it, whereas the wind-sea part of the spectrum experiences reduced dissipation in the model due to the presence of the swell, leading to accelerated wave growth (Hurdle, 1998; Holthuijsen and Booij, 2000). This behaviour is at odds with the observations in the field and the laboratory, for example Donelan (1987), which suggests that the presence of low-frequency waves may actually reduce the growth of the wind-sea part of the spectrum, while the swell energy is not dissipated.

The unsatisfactory model performance described above is found both in deep and shallow water situations and could therefore be the combined result of deficiencies in both deep and shallow water source terms. However, we will focus our attention here on the deep water terms. In default mode, SWAN uses the wind input and whitecapping expressions of Komen et al. (1984), with wind input based on Snyder et al. (1981) and whitecapping based on Hasselmann (1974), together with the Discrete Interaction Approximation (DIA) for quadruplet interaction (Hasselmann and Hasselmann, 1985). Of these three, the wind input based on Snyder et al. (1981) is the best-established experimentally, at least for light winds over fairly mature wind-sea. Quadruplet interaction, although difficult to measure experimentally, is well-established theoretically for homogeneous, random-phase wave fields. Van der Westhuysen et al. (2005) demonstrate that the peak period underprediction by SWAN is partly due to the use of the DIA, which is an approximation of the complete set of quadruplet interactions described by Hasselmann (1962). In comparison, there is much uncertainty concerning the physical mechanism of whitecapping in deep and shallow water and hence the appropriate form for its source term. The expressions available for whitecapping are therefore mostly speculative. The model errors described above can readily be related to the whitecapping formulation of Komen et al. (1984): it has been found that the erroneous model behaviour in the presence of swell is caused by the expression's dependence on the mean spectral wavenumber and steepness (Hurdle, 1998), and that the overprediction of energy levels in the tail appears to be caused by insufficient dissipation in this spectral region (Rogers et al., 2003).

A number of modifications to the whitecapping expression have been proposed in the literature to improve the simulation results of SWAN. A first group of modifications considers pure wind-sea conditions: Booij et al. (1999) apply a rescaled version of the Komen et al. (1984) whitecapping formulation in combination with the wind input expression of Janssen (1991) (the so-called WAM Cycle 4 physics, see Komen et al., 1994). They find, however, that this source term combination produces less accurate predictions of significant wave height and peak period than the default model. Rogers et al. (2003) alter the weighting of the relative wavenumber factor in the Komen et al. (1984) whitecapping formulation, by which the distribution of dissipation over frequency is changed. This compensates for the peak period underprediction caused by the DIA, in addition to increasing dissipation in the tail region. Within the observation range of Kahma and Calkoen (1992) this leads to improved period measures, but unfortunately wave energy is overestimated as a result (Fig. 1).

The second group of modifications considers combined swell-sea situations: Holthuijsen and Booij (2000) suggest that the dependence of wind-sea dissipation on swell in the Komen et al. (1984) expression be removed by making the dissipation at a particular frequency a function of the mean wavenumber and steepness of only the frequencies higher than itself. This method succeeds in removing the dependence of wind-sea dissipation on swell, but does not appear to be based on any physical considerations. Furthermore, this method retains the problem of enhanced dissipation of swell in the presence of wind-sea. Hurdle and Van Vledder (2004) propose an opposite approach (the so-called Cumulative Steepness Method, CSM), where dissipation at a particular frequency depends on the cumulative steepness of all spectral components *up to* the frequency considered, rather than on the mean values of wavenumber and steepness. This approach is based on the principle of surface straining, by which shorter waves are steepened by their superposition on longer waves, thus inducing breaking. Hurdle and Van Vledder demonstrate that their dissipation source term successfully decouples the growth of wind-sea from the presence of low-energy swell, but their model variant does not reproduce fetch-limited growth curves for pure wind-sea very well (Fig. 1). Rogers et al. (2003) propose to disallow the dissipation of swell energy, so that the dissipation of swell in

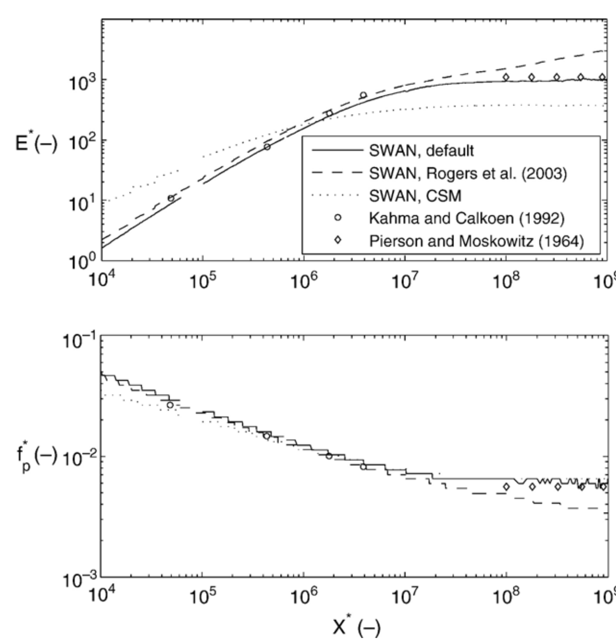

Fig. 1. Comparison of the deep water, fetch-limited growth curves produced using Komen et al. (1984) source terms (default model) with those produced using the Rogers et al. (2003) and CSM alternatives for whitecapping. In all cases the DIA is used for quadruplet interaction. Results for $U_{10}=10$ m/s, presented in terms of dimensionless energy $E^*=g^2E_{tot}/u_*^4$ and peak frequency $f_p^*=f_p u_*/g$ as functions of dimensionless fetch $X^*=gX/u_*^2$, with friction velocity u_* calculated using Wu (1982).