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PERFORMANCE OF FORMULATIONS FOR WHITECAPPING IN WAVE PREDICTION MODELS

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ABSTRACT

This paper describes work currently being carried out to examine possible methods to improve the computation of the dissipation by whitecapping in third generation wave prediction models. Such alternatives are needed to avoid unphysical dissipation behavior in the case of double-peaked wave spectra. First, an overview is given of the problems associated with the formulation for whitecapping that is now widely used in wave prediction models. Second, a summary is given of existing suggestions to improve the whitecapping formulation. Third, a number of examples are given with the new formulations to illustrate the potential improvements.

INTRODUCTION

Third generation wave prediction models have been successfully applied on the oceans for some time (Cox and Swail, 2001). In recent years such models have been increasingly applied in coastal areas. This presents greater demands on the wave prediction models not only because better source terms have to be developed for shallow water effects (e.g. wave breaking on depth and three wave interactions) but also because the geometry and bathymetry is more complicated. A typical example is the situation with incoming distantly generated long period swell in combination with a local wind sea generated over a short fetch. This can lead to the occurrence of spectral forms that would not be encountered on the ocean. Formulations that work adequately for application on the ocean do not necessarily work adequately with these spectral forms.

One such formulation is that for dissipation by whitecapping, as it is implemented in the WAM model (WAMDI, 1998) and the SWAN wave model (Booij et al. 1999). Hurdle (1998) discovered that when SWAN is applied in partly sheltered areas, the prediction of the local wave growth due to wind is significantly overestimated. A detailed analysis showed that the presence of small amounts of long period wave energy in the sheltered areas suppresses the dissipation by whitecapping in the model for the wind sea part. Field and laboratory observations of the effect of swell on the growth of wind sea are too few to draw firm conclusions. However, the few observations that are available (cf. Phillips and Banner, 1974; Donelan, 1987; Mitsuyasu and Kusaba, 1993)) suggest that if swell has any effect. it is to suppress the growth due to wind rather than to enhance it.

Wave growth due to wind is a subtle balance between energy input at high frequencies due to wind friction, transfer of energy to lower and higher frequencies by non-linear four-wave interactions (quadruplets) and dissipation by whitecapping. Errors in any one of these source terms can lead to significant changes in the predicted wave growth. The whitecapping problem in situations with multi-peaked spectra may also be important for the prediction of the spectral wave period, since the overestimation of the wave growth is partly caused by too little dissipation at high frequencies.

Several alternative methods suggested by various authors to compute the dissipation by whitecapping are considered in the following pages. These include a formulation suggested by Donelan (1999) and methods suggested by Holthuijsen and Booij (2000) and Tolman and Chalikov (1996) In addition other mechanisms by which swell can influence the growth of wind waves will be discussed.

To be applicable, the formulations must satisfy at least the following:

- The effect of adding small amounts of low frequency energy to the wave spectrum enhances whitecapping dissipation at higher frequencies.;

- It should be possible to reproduce parametric formulations for wave growth in idealized situations equally well as with the current formulation applied in the WAM model and in the SWAN model.

The work so far carried out to examine the performance according to these criteria is described. Because the work is still being carried out not all of the ideas presented in this paper have yet been fully tested.

Detailed attention is also paid to the steepness spectrum in this paper. Although, the description of the steepness spectrum is trivial, the authors would argue that its physical meaning is often neglected when the spectral form, in general, and whitecapping, in particular, are being considered. Little attention seems to be paid to the fact that the integral of the steepness spectrum is unbounded for the standard form applied for the spectral tail. This is obviously unrealistic since the integral of the steepness spectrum is a measure of the average surface slope and this is clearly not infinite. It is of course reasonable to consider that for those parts of the spectral tail dominated by quadruplet interactions the spectral density decreases according to the -4th power of the frequency. However, this behavior will change with increasing frequency as whitecapping and surface tension play an increasingly important role.

The authors would argue that the root cause of the current problems with the formulation for whitecapping is that the assumed form of the spectral tail is unrealistic. This makes it necessary to compute the wave steepness based on the wave height and an average wave period with all the associated disadvantages. The authors wish to argue for the application of a realistic spectral tail and the computation of the wave steepness based on the steepness spectrum.

NOMENCLATURE

C_{wc}	coefficient of scaling for whitecapping
$E(\omega)$	energy density spectrum (m^2/Hz)
E_{tot}	total wave variance (m^2)
g	acceleration due to gravity (m/s^2)
H_{m0}	significant wave height (m)
H_s	significant wave height (m)
k	wave number (1/m)
$\hat{k}$	mean wave number (1/m)
s	wave steepness
$\hat{s}$	mean wave steepness
$\hat{s}_{PM}$	mean wave steepness for PM-spectrum
$S_{st}(\omega)$	steepness spectrum
S_{wc}	source function for whitecapping
t	time (s)
T_p	peak period (s)
U_A	effective wind speed (m/s)
x	location (m)
Y	realization spectral density spectrum (m^2/Hz)
$\Delta\omega$	spectral bandwidth (radians)
η	surface elevation (m)
θ	direction (radians)
ω	radian frequency
ω_m	mean radian frequency

THE WHITECAPPING PROBLEM

The formulation for dissipation by whitecapping as implemented in most numerical models is based on pulse-based description of Hasselmann (1974, as adapted by Komen et al., 1984). It is given by:

$$S_{wc}(\omega,\theta) = -C_{wc}\hat{\omega}\frac{k}{\hat{k}}\left(\frac{\hat{s}}{\hat{s}_{PM}}\right)^2 E(\omega,\theta) \qquad (1)$$

where $\hat{\omega}$ and $\hat{k}$ are a mean frequency and a mean wave number, and where $\hat{s}$ is a mean wave steepness, and C_{wc} a scaling parameter. The parameter $\hat{s}_{PM}$ is the mean wave steepness for a Pierson-Moskowitz spectrum ($\hat{s}^2{}_{PM} = 3.02\times10^{-3}$). In many third generation models, the average wave steepness is computed from the energy based significant wave height and some average wave frequency $\hat{s} \propto \hat{\omega}^2 H_{m0}$. In finite depth the mean steepness is defined as:

$$\hat{s} \propto \tilde{k}\sqrt{E_{tot}} \qquad (2)$$

with E_{tot} the total wave variance.

An undesired characteristic of this formulation is that the addition of small amounts of low frequency energy to the wave spectrum can have a large influence of the average wave period and thus significantly decrease the computed wave steepness. In this way, the low frequency energy has a large influence on a process that is occurring in the high frequency part of the spectrum. This behavior is illustrated in Figure 1, which shows the source term for whitecapping for a uni-modal wave spectrum and one for a double peaked spectrum with a small swell peak. It is clear that when a small amount of swell energy is added to a wind sea, the computed average wave number decreases and the computed steepness decreases.

This reduction in wave steepness is sometimes so significant that dissipation by whitecapping becomes an order of magnitude smaller leading to excessive growth in the wave energy at high frequencies. This behavior with the SWAN model is reported by various authors (see e.g. Hurdle (1998), Holthuijsen et al. (2001)). The case reported by Hurdle is illustrated in Figure 2 in which the wind speed was 20 m/s and the incoming swell had a peak period of 6 s and a significant wave height of 0.1 m. As can be seen, wave growth is enhanced when some swell is present. This experiment shows that the simplified definition of steepness applied in the pulse-based model for whitecapping allows the presence of swell to accelerate the wave growth due to wind - the opposite of the effect expected from field observations.

An improved formulation may implicitly lead to suppression of wave growth by the presence of swell (e.g. because the addition of swell energy increases the computed wave steepness). Several authors have already carried out work into promising alternative formulations, e.g. Ris et al. (1999) and Holthuijsen et al. (2001).

ALTERNATIVE FORMULATIONS

Three alternative formulations for dissipation by whitecapping are being considered:

- The cumulative steepness method. This method was first implemented by Cecchi (Ris et. al, 1999) following suggestions by Donelan (1999) and Booij (private communication), that the dissipation by whitecapping at a particular frequency should depend on the steepness of the wave spectrum at and below that frequency. This means that the relative dissipation increases with frequency because the cumulative steepness also increases with frequency. This is physically plausible. It seems unlikely that what happens at higher frequencies can have much influence on the dissipation of the energy at a particular frequency whereas the slope in the water surface associated with lower frequencies should be expected to have a significant influence. (This is analogous to a car in a hilly area. The acceleration of a car rolling down a hill (analogous to whitecapping) is influenced only by surface fluctuations on a length scale longer than the car, analogous to the cumulative steepness). The physical mechanism behind the cumulative steepness method is that of surface straining, in which shorter waves riding on top of longer waves are modulated causing enhanced dissipation where the shorter waves are steepened. Booij also added local wave steepness in his method.

  The method also has the considerable practical advantage that the shape of the tail of the spectrum need not be considered - it will result from the use of the formulation without being required by it.
- The extended Komen method. Ris et al. (1999) developed this method and Holthuijsen and Booij (2000) extended and tested it. In this method, the dissipation by whitecapping for a particular frequency depends only on parameters computed from the energy spectrum at frequencies above that frequency. The formulation behaves as expected in the presence of swell (whitecapping in the wind sea part of the spectrum) and therefore may be considered a considerable improvement. An example of an application of this method to a field case is given below. Furthermore, it is unlikely to require extensive re-calibration of the model, since it should give very similar results to the previous formulation for situations with single peaked spectra.
- The Tolman and Chalikov (1996) method. In this method it is considered that the dissipation mechanism above the spectral peak frequency are different from those below the peak frequency. Below the peak frequency the dissipation is described using an analogy with dissipation of wave energy due to oceanic turbulence. They obtained a diagnostic parameterization for the high frequency dissipation by assuming a quasi-steady balance of source terms in the corresponding regime.

The authors do not favour the modified Komen method since the dissipation at a particular frequency depends on the steepness at frequencies higher than that being considered. Furthermore, since the questions discussed in the previous section over the form of the tail of the spectrum are unresolved, the steepness still has to be computed based on an average wave number and the corresponding spectral energy.

There are various ways to improve the existing Komen method, the cumulative steepness method and the extended Komen method. The existing method and the extended Komen method could both be improved by changing the weighting used to compute the average wave number to put more emphasis on higher frequencies and less on the lower frequencies.

The cumulative steepness method as implemented by Cecchi, may be improved in a number of ways:

- Remove the dependency of the formulation on the local steepness;
- Add directional dependence;
- Add terms to describe the change in the wind input in the presence of swell.

The formulation would give less dissipation at low frequencies than the presently implemented pulse model. This would have the additional advantage of helping to solve the problem of too much swell dissipation as observed by Rogers et al., (2000).

In the present study, the accent is not on the dissipation at low frequencies. However, if it transpires that the modeling of the wave growth is improved by the implementation of the method but that the dissipation at low frequencies leads to unrealistic model response, the addition of the term given by Tolman and Chalikov (1995) will be considered.

THE STEEPNESS SPECTRUM

We can derive the steepness spectrum for a frequency spectrum by considering a realization of the energy spectrum. The surface elevation η, is given by:

$$\eta = \sum Y(\omega_i) e^{i(kx - \omega_i t)} \tag{3}$$

Where the expected value of $Y(\omega)$ is $\sqrt{E(\omega)\Delta\omega}$ and $E(\omega)$ is the spectral density at frequency ω. The surface slope is then given by:

$$s = d\eta / dx = d / dx\left\{\sum Y(\omega_i)\cdot e^{i(kx-w_i t)}\right\} \quad (4)$$

Then

$$s = \sum ikY(\omega_i)\cdot e^{i(kx-\omega_i t)} \quad (5)$$

Analogously it can be shown that the expected value of spectral density of steepness spectrum is given by:

$$S(\omega) = k^2 E(\omega) \quad (6)$$

In deep water, the wave number, k, is proportional to ω^2. This means that the expected value of the surface slope is only defined for wave spectra in which the tail reduces faster than with ω^{-5}.

Kitaigorodskii (1983) analyzed the expected form of the spectral tail for an inertial sub-range of frequencies. He considered an idealized situation in which energy is input at the low frequency end of the spectrum and, in the equilibrium situation, is transferred at a constant (independent of frequency) rate to higher frequencies. Because the transfer rate for a given spectral density is higher at higher frequencies, the spectral density has to decrease with frequency correspondingly. On this basis, the spectral tail must decrease according to ω^{-4} in the inertial sub-range of frequencies. This is known as Kolmogoroff type equilibrium. Kitaigorodskii goes on to argue that this sub-range must be roughly:

$$\omega_m < \omega < \frac{30g}{U_A} \quad (7)$$

where ω_m is the peak frequency and U_A the effective wind speed.

Kitaigorodskii gives a further restriction on the upper limit of the inertial sub-range based on consideration of whitecapping. This upper limit is given in terms of gravity and the rate of energy transfer through the spectrum. He goes on to consider the form of the spectral tail above this limit but below the range where surface tension and viscosity play a role. In this range, whitecapping determines the upper limit to the spectral density. He expresses this following Phillips (1958) as instability that occurs when the downward acceleration in the wave exceeds gravity. This leads to a form of the spectral tail that decreases according to ω^{-5} This is known as Phillips type equilibrium.

Subsequently, Kitaigorodskii, tried to find measured data to confirm the transition between the two forms for the spectral tail. He concluded, based on limited data, that the transition frequency is given by:

$$\tilde{\omega}_g = \frac{U_A \omega_g}{g} = 1.5 - 3.3 \quad (8)$$

This means that for higher wind speeds the transition occurs at a lower frequency as would be expected, since the spectral tail is more saturated.

In private communication from Kahma (2001), he estimates the transition frequency to capillary waves is about 13 Hz. At this frequency the spectral tail will decrease more rapidly than with Phillips type equilibrium.

As an example, a spectrum is considered for the fully arisen sea corresponding to a wind speed, U_A, of 12.5 m/s (Bft. 6 - whitecapping begins to play a role at Bft. 4). According to the SPM (1984), the corresponding values for H_s and T_P are about 6 m and 13 s for a fully grown sea state. For these values ω_g is 1.88 rad/s. Figure 3 shows the form of the corresponding spectrum and Figure 4 of the related steepness spectrum with the adapted spectral form for the tail. The transition to the Phillips equilibrium form (ω^{-5} tail) is at 0.3 Hz. It can be seen that the energy spectrum is well past its peak at this frequency. However, the steepness spectrum is at its peak. When considering wave steepness it is therefore highly important to model the spectral tail properly. Also shown in Figure 3 is the spectrum corresponding to young wind waves with the same wind speed and a small component of added swell. This spectrum has a tail with Kolmogorov type equilibrium (ω^{-4} tail). The steepness spectrum is roughly constant above 1 Hz, which intuitively seems rather unrealistic. The swell is just distinguishable in the energy spectrum but cannot be seen at all in the steepness spectrum. However, the effect on the steepness computed according to the pulse theory of Hasselmann is significant - a reduction from a steepness of 8.2% to 6.9%. The explanation for this is the method to compute the mean wave number, which places more weight on the lower frequencies than on higher frequencies

Theory of the equilibrium spectral form suggests that in the high frequency tail of the spectrum within some range of the peak frequency, the spectral density must decay with the fourth or fifth power of the frequency, ω. Traditionally, it has been assumed that that this form for the tail of the spectrum continues beyond this range. However, this would mean that the spectral definition of wave steepness is unbounded. Therefore the spectral definition of wave steepness has been considered not to be usable. The authors, however, prefer to contend that this implies that the assumed form of the high frequency spectral tail is unrealistic.

THE CUMULATIVE STEEPNESS METHOD

Using the above concept the cumulative steepness wave method can be is defined as:

$$S_{st}(\omega) = \int_0^{\omega} k^2 E(\omega) d\omega \tag{9}$$

and the new whitecapping source is given by:

$$S_{wc}^{st}(\omega,\theta) = -C_{wc}^{st} S_{st}(\omega) E(\omega,\theta) \tag{10}$$

with C_{wc}^{st} a tunable coefficient.

Directional effects are included in this method by considering the physical process of the straining mechanism. This states that short waves propagating on top of larger waves are compressed on the forward face of the longer waves and stretched at the backward face. The compressed waves become steeper, resulting in enhanced dissipation. It is assumed that this process does not act when the waves propagate at an angle of 90°, but it does again when the waves have opposing directions of propagation. A simple way to account for this dependence is to introduce a cos-term over the directional difference. This leads to the following form of the directionally dependent cumulative steepness method:

$$S_{st}(\omega,\theta) = \int_0^{\omega}\int_0^{2\pi} k^2 \left|\cos(\theta-\theta')\right| E(\omega,\theta') d\omega d\theta' \tag{11}$$

The potential capabilities of the cumulative steepness method are illustrated in Figure 5 for a uni-modal and bi-modal spectrum. The upper part of the figure shows the variation of the density of a uni-modal and a bi-modal energy spectrum. The lower part of the figure shows the corresponding cumulative wave steepness as a function of frequency.

The whitecapping source function based on the cumulative steepness method was computed for a uni-modal and a bi-modal spectrum and is shown in Figure 6. The upper panel shows the wave spectra. The middle panel shows a comparison between the computed source term for a uni-modal spectrum using the Komen formulation and the cumulative steepness method. The lower panel shows a comparison of these two formulations for a double peaked spectrum. The addition of a swell peak slightly increases the cumulative wave steepness. The results clearly show that the cumulative steepness method behaves according to physical expectations.

The wave growth has also been simulated using both formulations for an idealized situation with restricted fetch. The formulations were implemented in a spectral wave model that applies the same integration method applied in WAM. The results of this are shown in Figure 7. This figure shows the wave growth predicted using both formulations for a situation beginning with a swell wave with height 0.1 m and peak period 6 s and for a situation beginning with no waves. Also shown is the theoretical growth in the wave height according to Kahma and Calkoen (1992) The results indicate that the cumulative steepness method agrees reasonably well with growth curve of Kahma and Calkoen (1992) but that the Komen method tends to overestimate wave growth at this short fetch. However, these differences are in part related to the tuning of the model. Of more interest is that accelerated wave growth due to the presence of the swell can be seen for the Komen method but not for the cumulative steepness method.

FIELD CASE

Bottema and Beyer (2001) show a comparison between measurements and results of SWAN computations for various locations in the IJsselmeer. An overview of these locations is given in Figure 8. In the right panel of Figure 4 of Bottema and Beyer (2001) a double peaked spectrum is shown for location FL25. The situation is from May 28, 2001 and refers to a wind speed of 19 m/s and a wind direction of 257°N. The spectrum consists of low frequency waves coming from the North and high frequency waves coming from the west south west. From this figure it is evident that the wind sea peak is overestimated. The overestimation might be due to the above identified ‘whitecapping’ problem or due to the use of an incorrect wind speed, which is probably too high in the computation. As noted in Bottema and Beyer (2001) a uniform wind speed has been used in the SWAN calculation and differences in the roughness of land land-sea might affect the wind speeds just offshore. They estimate that the actual wind speed could be up to 15% lower than used in the computation.

To check whether over-estimation may be explained by the aforementioned ‘whitecapping problem’ an analysis was made of the capabilities of the extended Komen (EKOM) formulation as implemented in the special SWAN version 32.10 (Ris et al., 1999).

A number of runs, each with different settings. were made and the results were compared with the standard Komen whitecapping setting. Figure 9 shows the result of the run with the best agreement with measurements for station FL25. The figure clearly shows that the modified whitecapping formulation is able to improve the prediction of the wind-sea peak at station FL25. However, some tuning was applied to obtain this result. This implies that the if the extended Komen formulation is to be made generally applicable, tuning using a range of field cases will probably be required. Further analyses are needed to determine the role of the spatial varying offshore wind speed.

DISCUSSION

The present study has shown that the whitecapping formulation of Komen et al. (1984) as applied in many wave prediction models underestimates the dissipation of the wind sea part in the case a swell is present. This unwanted behavior has been recognized by various authors (e.g. Hurdle, 1998; Holthuijsen and Booij, 2000).

In literature a number of solutions to this problem have been proposed, all of which aim to neutralize these unwanted effects of swell on the dissipation of the higher frequencies. The modified Komen method as proposed by Holthuijsen and Booij (2000) is probably able resolve the overestimation of the wind sea peak for the IJsselmeer case.

From a physical point of view the cumulative steepness method is more elegant because it has a better physical basis than the previous method. Still, there are a number of problems to be resolved. One is to find the proper decay of the spectral tail, the dissipation of the swell and precise directional effects. Numerical growth curve experiments and comparisons with field measurements are planned to resolve these problems.

The whitecapping problem is part of the general problem of swell-sea interaction under wind-driven conditions. Sea and swell waves can interact in many other ways. If the sea and swell peak are close to one another they may exchange energy by non-linear quadruplet wave-wave interactions (e.g. Masson, 1993). Swells may also influence the wind-profile and surface drag above the sea-surface and affect indirectly the growth of the wind-sea. In this respect one should be very careful when using results obtained in wind-flumes where the wind profile might be affected by rigid lid effects and the omission of the 2-d effects that occur in nature. Therefore, field measurements of wave growth in the presence of swell are needed to calibrate and validate the new formulations for whitecapping dissipation.

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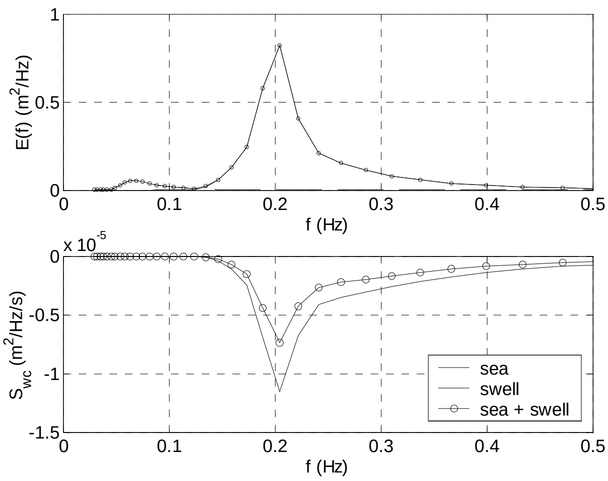

Figure 1: Source function for whitecapping for a uni-modal wind-sea spectrum, a swell spectrum and the sum of both spectra.

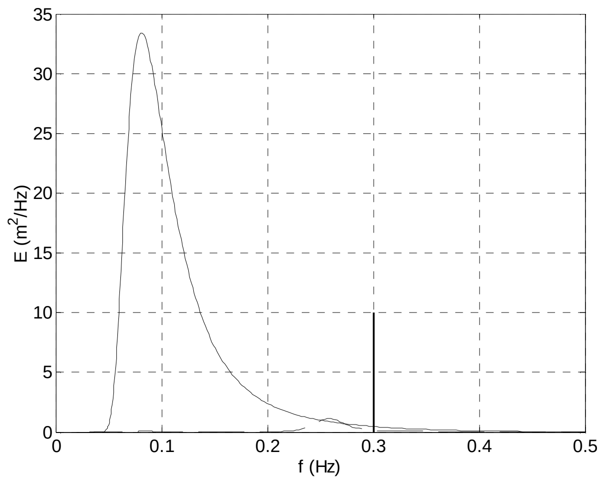

Figure 3: Fully developed wave spectrum (H_s=10 m, T_p=13 s) and a young wind wave spectrum (H_s=1m, T_p=3.9s) with added swell (H_s=0.25m, Tp=12s).

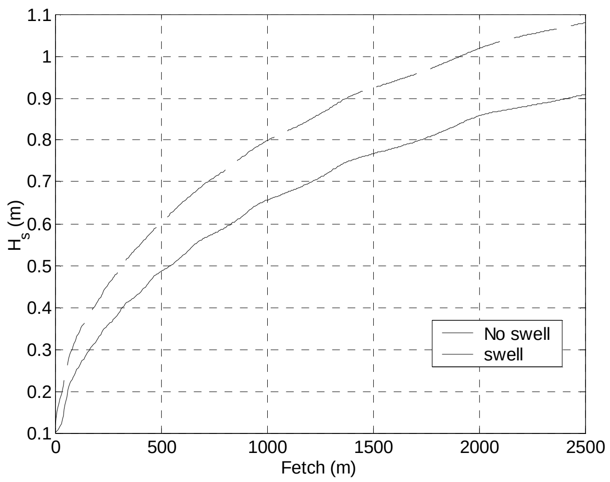

Figure 2: Example of wave growth in a sheltered area with and without the presence of a small incoming swell.

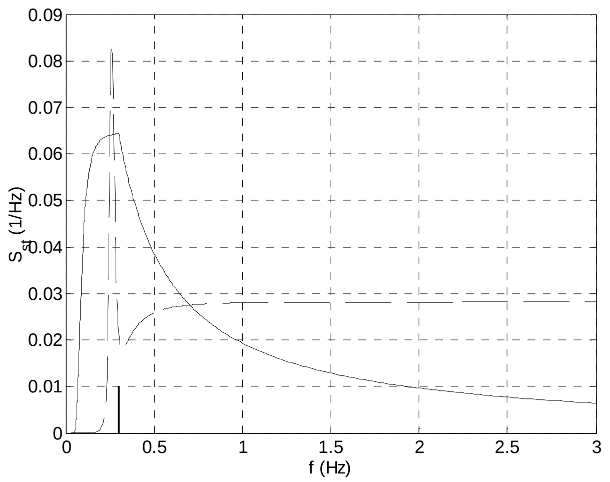

Figure 4: Steepness spectrum for wave spectra as shown in Figure 3.

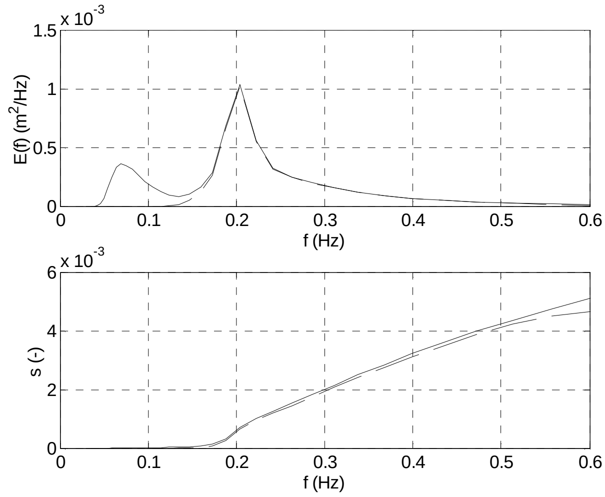

Figure 5: Variation of integral wave steepness for a uni-modal and bi-modal wave spectrum.

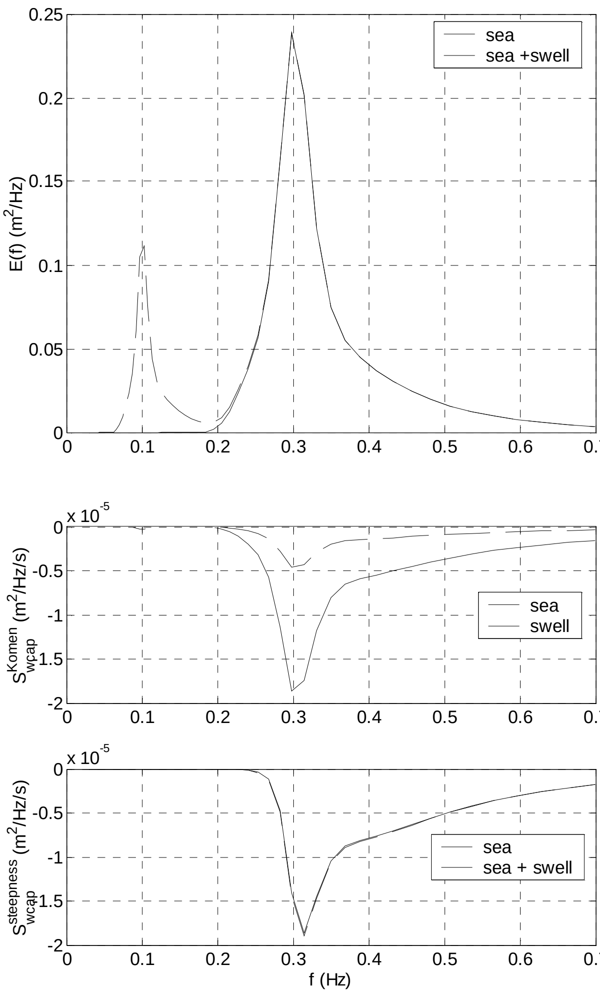

Figure 6: Whitecapping source function. Upper panel wave spectra, middle panel Komen whitecapping source function, lower panel cumulative wave steepness source function.

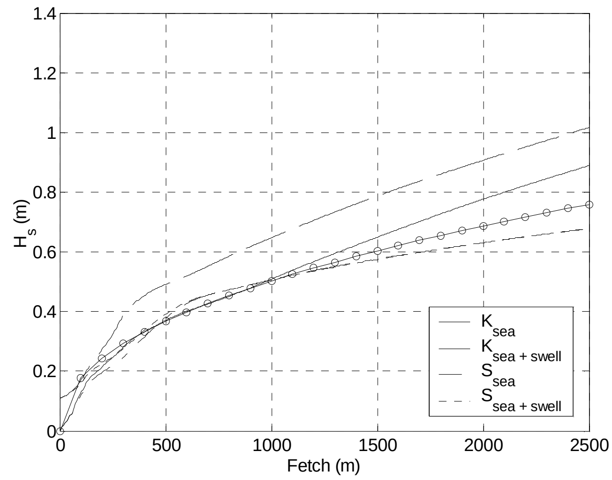

Figure 7: Wave growth in a sheltered area with and without the presence of a small incoming swell with Hs=0.1 m and Tp=6 s, for a wind wind speed of 20 m. The white-capping source term is computed with the standard Komen method (K) and the cumulative steepness method (S). The theorerical line of Kahma and Calkoen is shown with the dots.

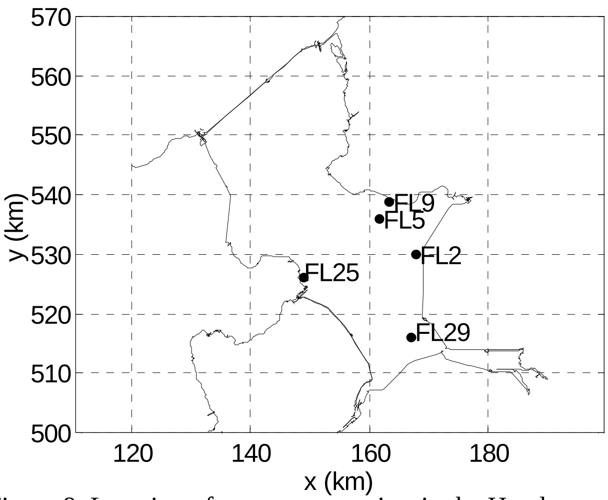

Figure 8: Location of measurement sites in the IJsselmeer.

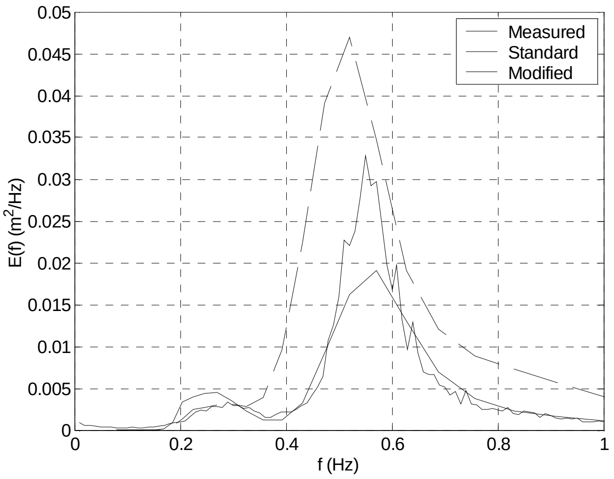

Figure 9: Measured wave spectrum, and computed wave spectrum using standard and modified whitecapping formulation.