Physics of "Saturation-Based" Dissipation Functions Proposed for Wave Forecast Models

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ABSTRACT

The dissipation term is one of the three most important source functions of the radiative transfer equation employed by all spectral wave models to predict the wave spectrum. In this paper, the issue of physics of such dissipation functions is discussed. It is argued that the physics presently utilized in the models do not adequately describe currently known features of the wave dissipation process, and the dissipation functions, to a great extent, remain a residual tuning term in spite of important experimental progress in wave breaking studies. A recently suggested "saturation-based" dissipation function and its connections with the experimental physics are analyzed in detail.

1. Introduction

The authors of this note are a reviewer and an author of the paper by van der Westhuysen et al. (2007), which is dedicated to an implementation of a new dissipation function in the Simulating Waves Nearshore (SWAN) wave model. The form of this function was initially based on the dissipation term suggested by Alves and Banner (2003, hereafter AB03), but eventually had to be significantly modified. In the course of the discussion, the reviewer and the author formulated a set of comments to the AB03 approach that are presented here.

The topic of the note, however, is broader than a mere criticism of physics employed by AB03 dissipation. Here, we would like to raise an issue important for wave modeling: the physics of the dissipation term presently utilized in wave forecast models are not adequate and do not properly describe currently known features of the wave dissipation process.

The dissipation term S_{ds} is one of the three most important source functions of the radiative transfer equation employed by all spectral wave models to predict wave spectrum F:

$$\frac{dF}{dt} = S_{in} + S_{nl} + S_{ds} + \cdots, \tag{1}$$

where the two other sources of wind input S_{in} and resonant nonlinear four-wave interactions S_{nl} are also explicitly mentioned. All the source terms, as well as the spectrum itself, are functions of wavenumber $\mathbf{k}$, frequency ω, time t, and spatial coordinate $\mathbf{x}$.

Since the major, if not dominant part of S_{ds} is attributed to energy losses due to wave breaking, and the breaking has been regarded as a poorly understood and basically unknown phenomenon, formulations of the term have always been loosely based on physics and served as a residual tuning "knob." The tradition originated with Komen et al. (1984) and has persisted throughout more than 20 years. Such significant attempts to improve the S_{ds} parameterization as Polnikov (1991), Banner and Young (1994), Tolman and Cha-

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likov (1996), AB03, among others, rest firmly within this tradition. While highlighting some serious limitations of this approach, the most recent attempts by van der Westhuysen et al. (2007) and Ardhuin et al. (2007) are still, to an extent, based on the residual tuning.

At present, when modeling Eq. (1), there is almost no flexibility in formulating S_{nl} and some limited flexibility in formulating S_{in}. By contrast, functions to represent S_{ds} can be chosen rather arbitrarily and are used in models without much objection from the wave modeling community. There is no consistency and sometimes even little similarity between the terms of Komen et al. (1984), Polnikov (1991), Tolman and Chalikov (1996), and AB03, all of which are incorporated in models and used to forecast the waves, alongside some standard terms for S_{in} and S_{nl}.

The latter two are based on more or less defined physics, but how is physics placed in the S_{ds} formulations? Obviously, all the formulations refer to some physics, but theoretical and experimental guidance had been very uncertain in the past.

Existing theories of the wave-breaking dissipation, both their advantages and shortcomings, were analyzed in detail by Donelan and Yuan (1994), Young and Babanin (2006), the WISE Group (2007), and the analysis will not be repeated here. In short, the set of theoretical models provide the dissipation functions that, if expressed in terms of the wave spectrum, that is,

$$S_{ds} \sim F^m, \tag{2}$$

range from $m = 1$ to $m = 5$. At the 2007 Waves In Shallow Environments (WISE) meeting in Lorne, Australia, V. E. Zakharov, A. I. Dyachenko, and A. O. Prokofiev (2007, personal communication) suggested a new theoretical formulation that, if converted into a spectral representation of (2) type, even gives $m = 8$.

It is fair to mention that, in spite of such a broad choice of the theoretical models, it is the theory by Hasselmann (1974) that is most frequently referred to in S_{ds} formulations. From the very beginning, however (i.e., Komen et al. 1984), this theory was employed only conditionally—that is, speculative properties and parameters were added to meet tuning needs. Over the years, this term has undergone a significant number of similarly speculative alterations and additions, a review of which is available in appendix A of Ardhuin et al. (2007).

Contrary to the theory of dissipation, recent experimental advances in wave dissipation studies have brought about much more certainty regarding the behavior of S_{ds}. In our view, the notion that the dissipation function is a great unknown and that any formulation that helps to satisfy the energy balance is considered legitimate, is no longer satisfactory. Over the past decade, many physical features of the dissipation performance were discovered experimentally and described. Among them, the threshold behavior of wave breaking (Banner et al. 2000; Babanin et al. 2001; Banner et al. 2002), the cumulative effect of wave dissipation at smaller scales and therefore two-phase behavior of the dissipation (Donelan 2001; Babanin and Young 2005; Manasseh et al. 2006; Young and Babanin 2006), quasi-singular behavior of the dissipation in the middle wavelength range (Hwang and Wang 2004), and alteration of wave breaking/dissipation at strong wind forcing (Babanin and Young 2005).

How are these physics, which are by no means tentative reasoning but definite field observations, included in S_{ds} terms? In WAVEWATCH, two-phase behavior of the dissipations term is accommodated [although the assumed physics of Tolman and Chalikov (1996) are different to those in the experiments by Babanin and Young (2005)]. Van der Westhuysen et al. (2007), in their SWAN model simulations, incorporated threshold limitations and a wind-forcing dependence for the dissipation function. Overall, however, most models lack these new insights into the physics of wave breaking. Since there appears to be great confusion in this regard, we point out that, for example, the analytical model of Hasselmann (1974) is neither in contrast nor in support of the aforementioned threshold behavior; it is unrelated to it. It predicts the behavior of the whitecapping dissipation provided whitecaps already exist on the forward face of the wave, that is, what happens if the waves are above the steepness/spectral threshold and are already breaking.

These observed features need to be accommodated in modern dissipation terms; otherwise, the models do not reflect the correct physics and do not describe the reality adequately. It is fast becoming clear that, without incorporating these new features, the models cannot properly forecast complex or nonstandard circumstances. Ardhuin et al. (2007) showed one such situation: wave growth in the presence of swell and over slanting fetches. The most apparent nonstandard circumstances where failure of the standard-tuned terms is to be expected are extreme wind wave conditions, which are also of utmost interest from practical points of view. As mentioned above, the dissipation function is altered under such conditions, and so is the wind input (e.g., Donelan et al. 2006; Stiassnie et al. 2007; Babanin et al. 2007a). No amount of good tuning and statistical fitting, as opposed to employing correct physics, will be able to extrapolate source terms tuned to standard conditions into such extreme situations.

The incorporation of these new dissipation features, however, is more complex than a mere replacing of one dissipation term with another. For example, if a cumulative integral is added to the breaking dissipation term (as proposed by Young and Babanin 2006), then local-in-wavenumber-space balance can no longer be satisfied and reformulations and adjustments of the wind input function and perhaps of the entire model will also be required. It is no surprise, therefore, that no model has tried to incorporate the cumulative effect so far.

The AB paper was the first significant effort to produce a new S_{ds} formulation that would incorporate some of the recent experimental advances mentioned above. We believe that this is a most positive step, and that is why it requires more serious attention. It has already been followed by a number of similar attempts, and therefore it needs a thorough revision at this stage in order to check agreement of its claims with the referred experimentally observed physics for the benefit of future research on implementing this physics into numerical models.

As will be shown, the term proposed by AB03 still lacks consistency of approach, particularly if compared with the ways of implementing the physics in S_{in} and S_{nl}. In this regard, it is hardly different to other formulations of the dissipation term based on tuning rather than physics. The main topics are twofold: the relation of the AB03 term to wave groups and the role of the threshold/switch B_r [Eq. (5) below]. The discussion of the links between S_{ds} and wave groups in section 2 is academic rather than practical, as it concerns the physical principles underlying the approach of AB03. As pointed out by our reviewer 2, "the discussion of physics (of wave groups) in AB03 has no connection with the model design." However, the discussion of the switch B_r in section 3 is important for practical applications, as we believe that the statements that this form of the dissipation term is based on a threshold behavior of wave breaking appears to be mistaken.

2. Links between AB03 dissipation and wave group modulation

The links between AB03 dissipation and wave group modulation were postulated in the AB03 abstract and mentioned throughout the paper, but all experimental evidences provided for such links seem to be circumstantial. For example, it is pointed out that a connection between wave groups and wave breaking was observed in experiments (e.g., Donelan et al. 1972; Rapp and Melville 1990) or was revealed in numerical simulations of wave groups (e.g., Dold and Peregrine 1986). While that is certainly true, real causes of wave breaking in natural conditions remain unknown. For instance, a recent experimental study by Babanin et al. (2007b) has shown that steep monochromatic wave trains, with no initial group structure, inevitably start to break within a few dozens of wave periods. Amplitude modulation within such an initially uniform train also develops, but it appears to be controlled by the initial steepness rather than being a free property. Therefore, it is not necessarily true that any form of wave-breaking dissipation is defined by the group structure of wave field, and this link needs to be supported explicitly in every particular case.

Discussion of the reasons for the wave breaking is beyond our scope here, but the issue of free/bound wave grouping is of principal importance for spectral wave modeling. If the modulation was independent of the steepness and depended on behavior of arbitrary wave groups, such physics could not be unambiguously employed in spectral models because information about free wave groups is unavailable from the spectrum, apart from the spectral peak. If this is not the case and the spectral density alone, at least in the first approximation, can define both the breaking threshold and the wave modulations, then such physics can be employed in spectral models to describe wave-breaking dissipation. Here we would like to analyze connections of the AB03 dissipation with wave group properties, regardless whether the wave groups are indeed responsible for wave breaking.

AB03 refer to the experimental paper by Banner et al. (2000) as a starting point where a thresholdlike behavior of the breaking was first found and was associated with the nonlinear wave group modulation. We would like to point out, however, that in Banner et al. this association was assumed rather than verified.

Banner et al. (2000) dealt with dominant waves, and the breaking probability of such waves was expressed as a function of the spectral peak steepness. It was argued that, since the breaking is happening most likely because of the wave groups, then the spectral peak steepness should be used for such dependence rather than the total spectral steepness. The reason for that was due to the fact shown, for example, by Longuet-Higgins (1984) that the width of the spectral peak determines the properties of dominant wave groups. In Banner et al. (2000), however, no connection between the breaking probability and the width of the spectrum was attempted. The width was fixed at $\pm 30\%$ of the peak frequency, and mean steepness within this band was considered. Therefore, the logic was reversed: it is not that the breaking behavior was shown to depend on the wave groups, but this dependence was assumed in order to choose the spectral band to calculate the steepness.

Meanwhile, it is logical to consider the peak steepness rather than the total steepness in any scenario if the dominant waves are investigated, regardless of the role of wave groups. Therefore, the fact that the breaking probability of dominant waves depends on the excess steepness of these waves above some steepness threshold may or may not in fact be directly determined by the wave groups. According to this dependence, if the waves initially form no groups at all, but are steep enough, they will still break. This is in agreement with the results of Babanin et al. (2007b) mentioned above.

Although it may look circumstantial in Banner et al. (2000), the connection between the wave groups and the breaking was further degraded on the way to the dissipation function suggested in AB03. As the next step, the saturation rather than steepness was introduced as a spectral parameter to define breaking rates in Banner et al. (2002). While in Banner et al. (2000) the breaking threshold was established for the dominant waves only, in Banner et al. (2002) a thresholdlike behavior was demonstrated across the spectrum in terms of the saturation. In our view, the link with the groupiness has further faded away at this stage as there is no obvious or proven connection between the saturation, even if it is averaged over some frequency band and the wave groups of respective scales. In Banner et al. (2002), conclusions about the link between the breaking and the groupiness were made by analogy: the threshold behavior is established in both cases; in the first case it was due to the groups (Banner et al. 2000), hence it is due to the groups in the second case also (Banner et al. 2002).

Thus, even before the last step to the AB03 dissipation, such a sequence of assumptions already looks very vague, but any links between wave goups and breaking appear to be lost in the subsequent transition to the new "threshold" behavior employed in AB03. This new threshold function is different to the experimental threshold functions found in Banner et al. (2000) and even in Banner et al. (2002), both physically and mathematically, as will be demonstrated below. Still, the connection of the breaking (dissipation) within wave groups is postulated. In retrospect, the connection now looks as follows: 1) in Banner et al. (2000), the groups were assumed responsible for the breaking, and therefore the average steepness of dominant waves of ±30% of the peak frequency was chosen to characterize the breaking (which, in fact, still may or may not be defined by the groups); 2) since such steepness demonstrated a threshold behavior and the saturation spectrum also demonstrated a threshold behavior, the saturation was assumed to be linked with the groups in Banner et al. (2002); 3) in AB03, the threshold behavior was not utilized but saturation was and, since in Banner et al. (2002) it was assumed to be linked with the groups, it was assumed so in AB03.

Having said all the above, we would like to emphasize that we do not intend to state that the wave groups and the wave breaking are not connected. Most likely they are, although the extent of importance and degree of precedence of groupiness in causing the breaking onset is not clear to us. Links between the AB03 dissipation and the groups, however, do not appear to be substantiated with a reasonable degree of certainty. This is an important issue that, we believe, needs to be highlighted. Otherwise, if the wave modulation is accepted as the default mechanism that defines the breaking process without a need for substantiation in every particular case, the dissipation research efforts may concentrate on studies of the modulation process. However, before the role of the groups is proved and clarified, other avenues for the dissipation mechanisms, that is, those not necessarily connected to the groups, need to also be extensively investigated.

3. The wave breaking threshold

The issue of the wave breaking threshold is much more important in our discussion of the AB03 approach, compared to the issue of AB03 dissipation links with the wave groups above. In AB03, the wave group influence on breaking was postulated to be imperative, but whether it is imperative or not has a little effect on the dissipation function form where no group properties appear to be directly employed.

It is not so with the wave breaking threshold. This threshold is stated to be directly utilized in the AB03 dissipation function, both qualitatively and quantitatively, and we disagree with this statement.

In Banner et al. (2000) and its companion paper of Babanin et al. (2001), it was found that the dominant waves, if they are below some spectral steepness $\varepsilon_{\mathrm{th}}$, do not break. If they are above, they do, and the breaking probability b_T depends quadratically on the excess of the steepness over the threshold value:

$$b_T \sim \begin{cases} (\varepsilon - \varepsilon_{\mathrm{th}})^2, & \varepsilon \geq \varepsilon_{\mathrm{th}} \\ 0, & \varepsilon < \varepsilon_{\mathrm{th}}. \end{cases} \tag{3}$$

In AB03, if we translate their dissipation function into a breaking rate dependence, (3) is replaced with

$$b_T \sim (\varepsilon/\varepsilon_{\mathrm{th}})^n. \tag{4}$$

This is a different function mathematically and it has a different physical sense.

The first function can qualitatively translate into the

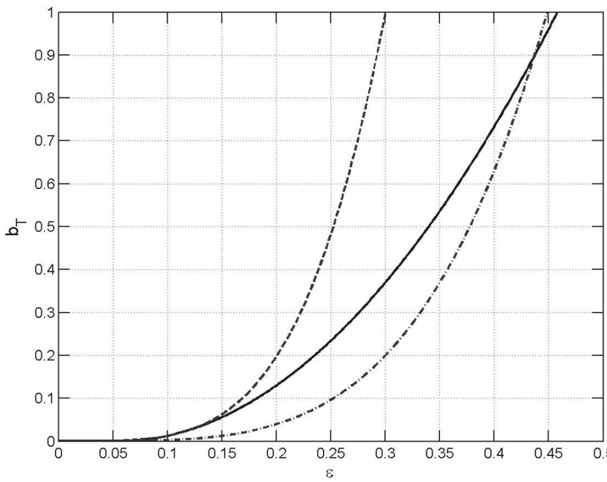

FIG. 1. Comparisons of dependencies (3) and (4), where the solid line is the (3)-like dependence of Babanin et al. (2001, Fig. 13). If (4) is tuned to reproduce typical breaking rates (i.e., $b_T \sim$ 5%, dotted line), it fails for larger rates and vice versa (dash–dotted line).

second if $\varepsilon \gg \varepsilon_{\text{th}}$ (the threshold would have to be disregarded then), but not if $\varepsilon \sim \varepsilon_{\text{th}}$. The latter, however, is the case for real seas with typical breaking rates at moderate winds in deep water conditions being of the order of $b_T \sim 5\%$ (e.g., Babanin et al. 2001, Fig. 13). In Banner et al. (2000), maximal ratio observed was $\varepsilon/\varepsilon_{\text{th}} \sim 2$, and in Babanin et al. (2001) where extreme breaking rates (up to 60%) were investigated the maximal ratio was $\varepsilon/\varepsilon_{\text{th}} \sim 2.5$. The absolute majority of wave fields are well below these maxima. Therefore, dependences (3) and (4) are essentially different functions; they cannot substitute for one another and produce the same results at all circumstances. As illustrated in Fig. 1, if dependence (4) is tuned to give correct values of b_T for typical breaking rates (i.e., $b_T \sim 5\%$), it will fail at large breaking rates, and vice versa. The principle difference, obviously, will have place at $\varepsilon < \varepsilon_{\text{th}}$ where no breaking occurs according to (3), but breaking rates would only approach zero if $\varepsilon \to 0$ in (4).

Therefore, introducing ε_{th} in (4) does not appear to relate to the threshold found in Banner et al. (2000, 2002) and in order to avoid confusion we will henceforth call it a "switch" rather than a threshold in accordance with the role it plays in the AB03 dissipation. We mention that the importance of the difference between the formulations (3) and (4) has already been recognized, and one of the AB03 authors in a recent paper by Banner and Morison (2006) suggested a dissipation function with a (3)-like threshold. The Banner and Morison dissipation expression, however, is significantly different from AB03 in a number of physical aspects and will not be discussed further.

a. The AB03 dissipation function

From this discussion of the breaking dependencies, we now turn to the AB dissipation function directly. For our purposes, its general form can be rewritten as

$$S_{\text{ds}} = aF(B/B_r)^n,$$

where

$$n = \begin{cases} 4-5, & B > B_r \\ 0, & B \le B_r. \end{cases} \tag{5}$$

Here $B(\omega) = \omega^5 F(\omega)/2g^2$ is the nondimensional saturation spectrum, B_r is the switch constant, and all the weighting and other factors are put into the coefficient a for simplicity. In AB03 formulation, exponent n depends on B and is switched to zero if $B(\omega) < B_r$.

Since B_r is a constant, then in terms of the spectrum F formulation, (5) can be rewritten as

$$S_{\text{ds}} \sim \begin{cases} bF^{n+1}, & B > B_r \\ cF, & B \le B_r. \end{cases} \tag{6}$$

Thus, the main functional connection of S_{ds} with the wave spectrum in (5) is not different to customary power-law forms (2) of the dissipation functions. Those functions do not have any breaking threshold implemented and depend linearly or nonlinearly on the wave spectrum directly, just like S_{ds} in (6). The main difference is the switch that changes the exponent and pre-exponents b and c at $B = B_r$. That is, the dissipation function from being very strongly nonlinear (e.g., in the test case BYM1 of AB03, which we have chosen for further comparison, $S_{\text{ds}} \sim F^4$ if $B > B_r$) switches to the usual linear function of the wave spectrum $S_{\text{ds}} \sim F$ if $B < B_r$. The switch employed in AB03 is somewhat smoothed in order to prevent numeric instabilities [i.e., Eq. (6) in AB03], but the smoothing obviously does not change its physical meaning of the nonlinear-to-linear switch.

As stated above with respect to the links between the groups and the wave breaking, here we are not trying to state that such form of the dissipation function is incorrect. In fact, it works very well in many aspects in the AB03 numerical tests. What we are trying to point out is that such behavior of the dissipation does not follow from experiments, does not employ the experimentally observed threshold behavior of the wave breaking, and at this stage it is an assumption that does not rely on independent support.

b. Quantitative value of the switch

AB03 state that B_r is a breaking threshold below which no breaking occurs, but some dissipation persists as a linear function of the wave spectrum, due to some background reasons. We will talk about this background dissipation in the discussion section, but here we would like to discuss the quantitative value employed for B_r in AB03.

AB03 chose to determine the magnitude of B_r numerically, and this magnitude varies between their different numerical tests. Such an approach seems inconsistent as a conclusion about the universal saturation value had been made in Banner et al. (2002), published before, and thus the experimental data on B_r were available. From Fig. 4 in Banner et al. (2002), for example, it can be seen that the value of $B_r = 4.25 \times 10^{-3}$ chosen for the numerical test case BYM1 in AB03 is not the breaking threshold, but rather corresponds to some 5% breaking rates, typical for moderate wind conditions, and the threshold in terms of the saturation spectrum is, in fact, 2–3 times lower. If, however, for consistency with Banner at al. (2000), the experimental data are plotted in terms of $\sqrt{B} \sim \varepsilon$, then a fit to the Banner et al. (2002) data produces a threshold close to $B_r = 5 \times 10^{-4}$ (Babanin and Young 2005) (i.e., some 6 or more times lower compared to the values utilized in AB03). In any case, it is significantly lower than the values of B_r employed in AB03. Thus, regardless of its physical and mathematical meaning, the B_r switch is also quantitatively not the breaking threshold, and this brings us to the question of how the AB03 dissipation actually works.

c. *Physics of the AB03 dissipation term*

While issues of the groupiness and breaking threshold are important from the point of view of physics employed by the models, as far as the wave forecast is concerned the above discussion is a matter of interpretation. In other words, if the parameters n and B_r are recognized as tuning knobs rather than physical properties, the AB03 dissipation term still works and, under a certain set of conditions, is able to reproduce integral and some spectral features of wave evolution well. However, some practical, rather than physical, reservations then draw our attention.

First, the dissipation function proportional to the wave spectrum to the power of 4 or 5 is strongly nonlinear. Not only is there no experimental evidence for such strong dissipation across the spectrum, but this function is also very different from the dissipation terms presently employed in spectral wave models. Most of these terms are linear or quasi-linear functions of the wave spectrum.

Second, the wind input functions used in AB03 are the regular source functions of Snyder et al. (1981) and

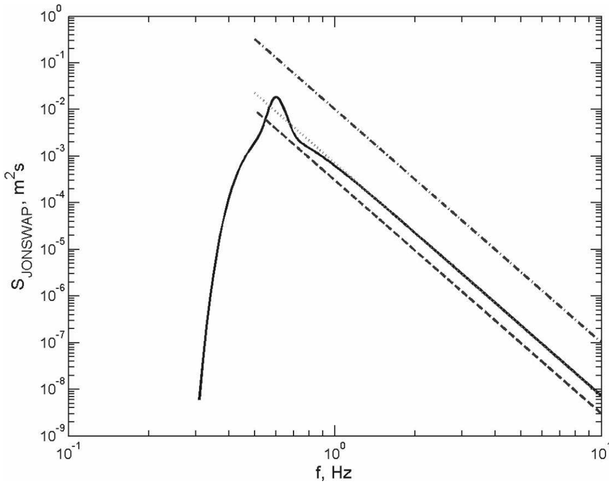

FIG. 2. Illustration of the JONSWAP spectrum with peak enhancement of $\gamma = 7$ chosen for clarity (solid line): zero breaking saturation level (dashed line), 5% breaking level (dotted line), and 100% breaking level (dash–dotted line). The breaking limits are drawn qualitatively for illustration purposes only and must not be used for estimates.

Yan (1987). These input terms are routinely utilized in wave models to balance the linear-in-spectrum dissipation and, therefore, it was not immediately clear how they could balance such a strongly nonlinear dissipation and produce similar growth rates. This scaling mismatch was pointed out and quantified by van der Westhuysen et al. (2007).

It appears that AB03 term works as some quasi-linear rather than strongly nonlinear function of the spectrum in order to satisfy the balance and that the B_r switch helps to achieve this balance. In this regard, it is principally important that this switch does not actually have magnitude close to the breaking threshold; otherwise, it would not be possible to reproduce the experimental growth curves with such a dissipation term.

Figure 2 illustrates how, in our view, the AB03 term works. This view was subsequently verified by means of numerical simulations of the wave spectrum evolution, as will be described below. In Fig. 2, the JONSWAP spectrum parameterization (solid line) and arbitrary breaking limits are used for illustration purposes, but real spectra and breaking threshold exhibit similar behavior (e.g., Babanin and Young 2005).

The dashed line indicates the zero-breaking saturation limit, and the dash–dotted line is the ultimate spectral limit in the saturation terms (i.e., the spectral density cannot physically reach over this limit because steepness of waves will be such that all waves will be breaking; e.g., Babanin et al. 2007b). If the spectral density drops below the dashed level, there will be no breaking in the wave field but, unless the waves are swell or forced by very light winds, they normally do exhibit some breaking. Therefore, wave spectra exist between these two lines. The dotted line indicates the B_r value chosen in AB03.

As mentioned above, at typical moderate deep water conditions breaking rates are of the order of a few percent (e.g., Babanin et al. 2001, their Fig. 13). AB03 apparently chose a value for their B_r switch such that it corresponds to a breaking rate of around 4%–5% rather than to the actual breaking threshold (see section 3b).

Now, if the spectrum is above the B_r dotted line, it is quenched by the very strong AB03 dissipation, which is proportional to the spectrum to the power of 4 or 5. This takes place until the spectrum is reduced to below the B_r line. Once it is, it corresponds to the typical 5% breaking wave field, and the switch now turns the dissipation into a typical linear function of the wave spectrum, Eq. (5). If such a spectrum is now kept under the 5% breaking saturation line and allowed to evolve under the quasi-linear-in-spectrum dissipation and input, it obviously should exhibit growth curves typical for moderate wind wave conditions, which it does as seen from the AB03 numerical simulations.

If the switch B_r was chosen to equal the breaking threshold values observed in the field, the nonlinear option of the AB03 dissipation would reduce the spectra below this threshold, and the resulting spectra and wave growth curves would be too low. If, on the other hand, the switch B_r was selected to be higher and corresponded to breaking rates greater than 5%, the growth curves would lie too high compared to the observations, as such spectra are rarely observed. This simple reasoning explains why, when AB03 chose to determine the magnitude of B_r numerically on the basis of the growth curves rather than experimentally, they obtained a B_r value corresponding to the 5% breaking rate rather than to the threshold.

Thus, B_r in the AB03 dissipation is not the breaking threshold and is not even some bottom limit for the spectrum (i.e., if the spectrum drops below this limit, the waves do not break). Instead, it is the top limit. By means of this upper limit and the nonlinear-dissipation switch, the spectrum in numerical simulations is held below it, values of the variance are always reasonable, and the growth curves are reproduced correctly. Effectively, it is a "soft" lid: the spectrum is allowed to rise above the lid, but is then quenched back, with the relaxation time to the below-the-lid spectrum determined by the parameter n in Eq. (5).

It is interesting to point out that real waves may or may not behave like this. There are no wave growth curves obtained at extreme conditions in the field available but, once they are and if they are similar to those for moderate conditions, then the dissipation may be indeed quenching the spectrum nonlinearly until it is reduced to the 5% breaking level. There is, in fact, experimental evidence that the equilibrium level of wave frequency spectra depends on the wind forcing only if the forcing is low and it remains constant if the forcing is high (e.g., Babanin and Soloviev 1998).

These speculations, however, are beyond our scope here. What should be mentioned here is that, from a modeling perspective, the soft lid employed by AB03 is an effective way to achieve a set growth curves, but such behavior of the dissipation is not based on current proven experimental knowledge. Instead, such a formulation of the dissipation function still lacks known experimental facts, that is, the threshold behavior of the wave breaking. Besides, our interpretation of the AB03 switch as an upper limit for the spectrum, below which normal wave-breaking activity persists, rather than the breaking threshold, below which "the breaking-wave contribution to S_{dsl} should become negligible," is basically opposite to that suggested in AB03.

4. Numerical simulations with AB03 dissipation

Numerical tests were conducted to verify the reasoning and understanding outlined in section 3. The SWAN model was used to run case BYM1 of AB03, which combines the wind input of Yan (1987) with the AB03 whitecapping setting $C_{\mathrm{ds}} = 9.25 \times 10^{-3}$, $m = 1$, $n = 2$, $B_r = 4.25 \times 10^{-3}$, and $p_0 = 6$ [see AB03, p.1290 for details, note that n in this paragraph has a different meaning than the exponent n employed in Eq. (5) of this paper which in this equation is equal $n = p_0/2$].

A moderate wind speed $U_{10} = 10$ m s^{-1}, equal to $u_* = 0.38$ m s^{-1} in SWAN, was used. To speed up the computations, discrete interaction approximation (DIA) instead of an exact qaudruplet expression was employed as the nonlinear term since for the comparison purposes such difference should not be relevant. The only parameter varied in our simulation was $p_0 = 2n$ [i.e., the nonlinearity measure, the exponent of Eq. (5)].

a. Test 1

In this test, two values of p_0 were employed: first, the AB03 value of $p_0 = 6$ (i.e., $S_{\mathrm{dsl}} \sim F^4$), which was then increased by a factor of 10 to $p_0 = 60$ (i.e., unreasonably massive nonlinearity of $S_{\mathrm{ds}} \sim F^{31}$ was introduced).

Figure 3 shows the spectra at the beginning (dimensionless fetch $X^* = 7 \times 10^4$), the middle ($X^* = 7 \times 10^5$), and somewhat beyond the Kahma and Calkoen

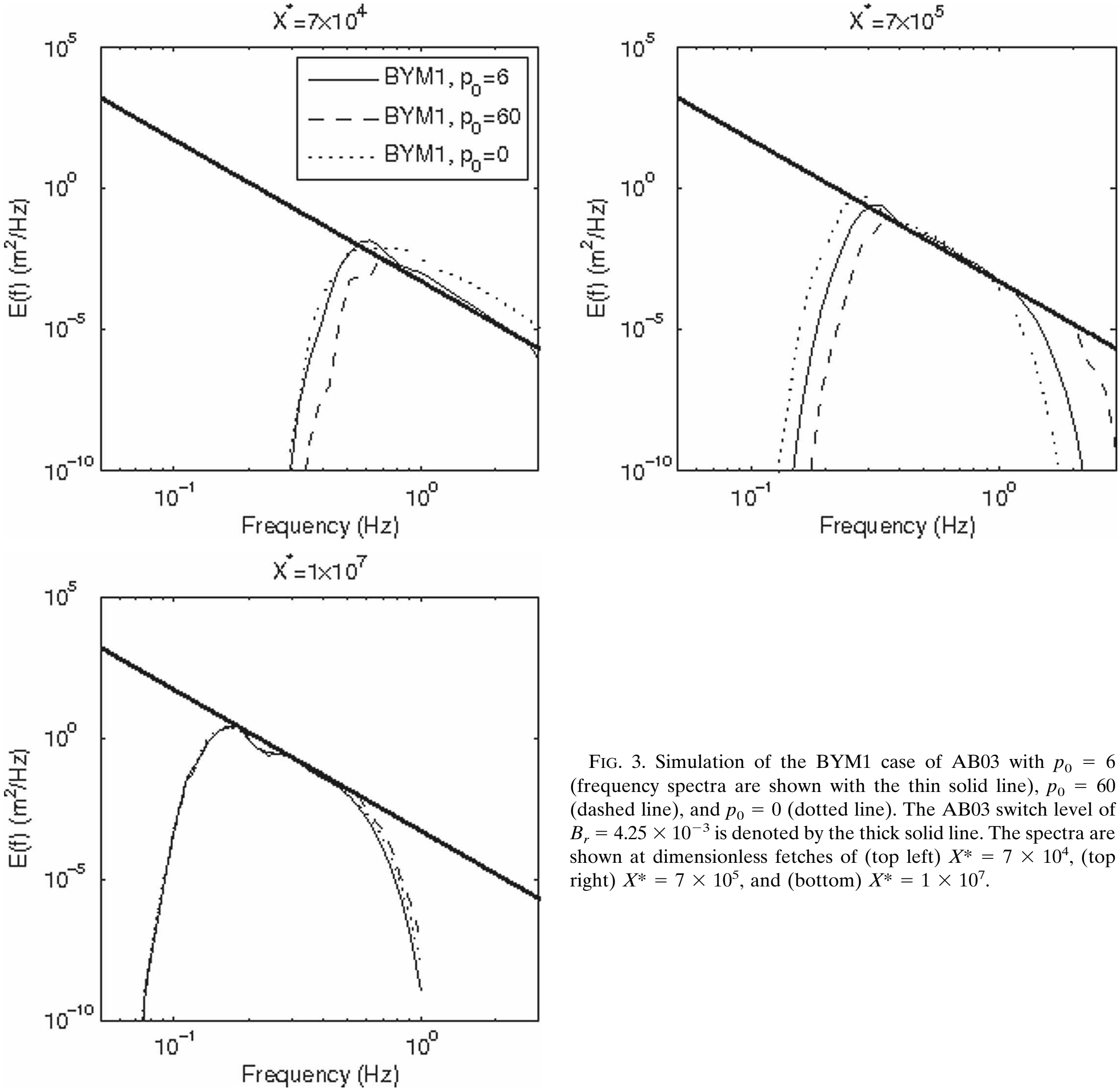

FIG. 3. Simulation of the BYM1 case of AB03 with $p_0 = 6$ (frequency spectra are shown with the thin solid line), $p_0 = 60$ (dashed line), and $p_0 = 0$ (dotted line). The AB03 switch level of $B_r = 4.25 \times 10^{-3}$ is denoted by the thick solid line. The spectra are shown at dimensionless fetches of (top left) $X^* = 7 \times 10^4$, (top right) $X^* = 7 \times 10^5$, and (bottom) $X^* = 1 \times 10^7$.

(1992) fetch range ($X^* = 1 \times 10^7$). Also plotted is the AB03 switch level (thick solid line), computed with

$$B(k) = B_r = \frac{1}{2\pi} c_g k^3 F(f), \tag{7}$$

where k is wavenumber, c_g is group velocity, and $B_r = 4.25 \times 10^{-3}$.

As seen in the figure, the influence of the massive increase of p_0 on the spectra is, indeed, what we predicted. With the setting BYM1 ($p_0 = 6$, solid-line spectra), the high frequency flank of the spectra lies on the switch level (cf. with the illustration in Fig. 2). At the highest frequencies, the spectral tail decays strongly. Increasing p_0 to 60 (dashed-line spectra) does not affect this result essentially, confirming our prediction that the nonlinear option of the AB03 dissipation only exists to make the spectrum dissipate down to the level of B_r. The two dissipation settings, with $p_0 = 6$ and $p_0 = 60$, therefore, prove to be essentially equivalent. Below the B_r switch, the linear dissipation in both cases has a quite strong dependence on wavenumber, hence the strong decay of the high-frequency tail.

In Fig. 4, integral dependencies of dimensionless energy and peak frequency versus fetch are shown. These graphs correspond to Fig. 9 in AB03. The huge increase in p_0 has almost no effect on peak frequency. There is

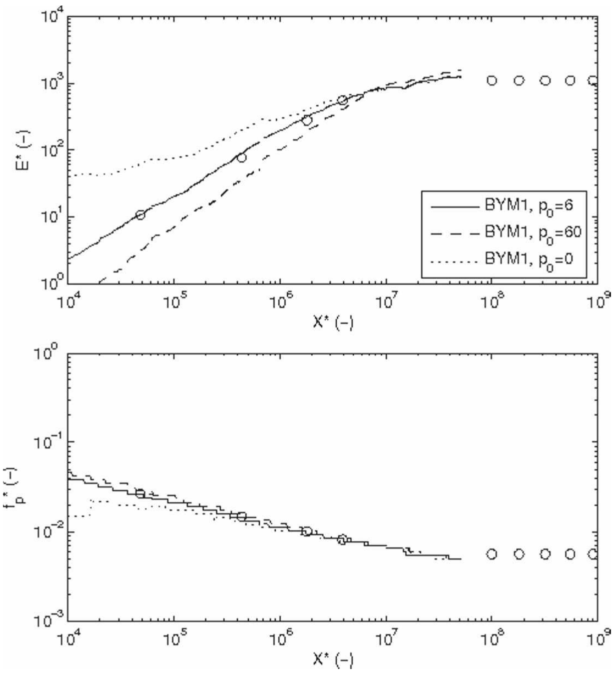

FIG. 4. Simulating the BYM1 case of AB03 with p_0 = 6 (solid line), p_0 = 60 (dashed line), and p_0 = 0 (dotted line): (top) dimensionless energy and (bottom) peak frequency vs dimensionless fetch.

a clear influence on the growth curve of dimensionless energy, although perhaps not as much as one would expect when increasing the exponent 10 times. These differences can be anticipated at earlier stages of wave development and are due to interplay between the AB03 nonlinear dissipation option and the spectral peak (see Figs. 2 and 3). For younger waves, the peak enhancement over the rest of the spectrum is much greater (e.g., Babanin and Soloviev 1998) and, therefore, differences in the time of relaxation of peak spectral densities to the B_r level become essential. Since peak waves contain most of wave energy, the two energy growth curves deviate, but the deviation vanishes as the peak enhancement becomes less pronounced.

b. Test 2

This test was intended to simulate alterations opposite to those of test 1. Two values of p_0 were employed: first, the AB03 value of $p_0 = 6$ (i.e., $S_{\text{ds}} \sim F^4$), which was then replaced with $p_0 = 0$; that is, the $(B/B_r)^n$ factor is excluded and the dissipation is set linear $S_{\text{ds}} \sim F$ from the very beginning.

Comparisons are shown in Figs. 3 and 4 with the linear-dissipation spectra denoted by the dotted line. We should make one comment first: at least some part of the strong overestimation of the dimensionless wave energy and peak period (including a jump) at very short fetches is due to low frequency components that are insufficiently dissipated at advanced stages of growth, subsequently get transported to propagation directions countering the wind by quadruplets, and end up "polluting" very young spectra upwind. In SWAN, this typically happens when whitecapping dissipation is too weak.

In Fig. 3, one can see that removing the nonlinear AB03 option only affected spectra at the earliest stages. At these stages, with standard wind input, not only the peak, but the entire spectrum needs nonlinear quenching in order to stay within the 5% breaking limit. Keeping in mind the comment in the previous paragraph, this fact is reflected by the top subplot in Fig. 4 where the dimensionless energy at early stages is now exaggerated. We must emphasize that this result also supports our earlier conjecture that the role of the nonlinear option of the AB03 dissipation is to reduce the spectrum to the 5% breaking limit and to keep it there in order to reproduce standard growth rates.

5. Discussion

The results presented above raise the question whether the AB03 framework can still be usefully applied in wave models. Van der Westhuysen et al. (2007) implemented a dissipation expression based on AB03 in the SWAN wave model. The form of this function was initially based on the dissipation term suggested by AB03, but eventually had to be significantly modified in order to employ observed values of the breaking threshold and to achieve dimensional consistency with the wind input. As a result, the new dissipation function is based on different physics to that postulated in AB03, even though it utilizes the saturation spectrum.

We furthermore mention a number of issues related to a more general topic of modeling the spectral dissipation. First, we point out that the "saturation-based dissipation" term used to designate the AB03 dissipation is ambiguous and even somewhat misleading and, in our view, has to be avoided. The saturation spectrum (Phillips 1958, 1984) has been routinely used in nonlinear parameterizations of the spectral dissipation so as to observe a proper dimension. That is, the Donelan (2001) term that incorporates the cumulative dissipation effect, the van der Westhuysen et al. (2007) term that accommodates the breaking threshold, and the AB03 term that does not include the cumulative effect or breaking threshold, but introduces the soft lid, are all saturation based. These dissipation formulations are very different and imply different physics, often incompatible, and the saturation spectrum has little to do with their performance. What unifies these terms is not the saturation, but the fact that all are either nonlinear or quasi-nonlinear (plus the cumulative term in the case of Donelan 2001).

Another suggestion is to separate different dissipation mechanisms into different dissipation terms that are added rather than multiplied together. Traditionally, as also done in AB03, mainly because of poor knowledge of the physic of wave dissipation, a single term S_{ds} was employed in the radiative transfer equation (1) to parameterize all the processes of wave attenuation together. For example, in the AB03 formulation, which was intended to reflect the breaking-threshold behavior, the dissipation was not actually set to zero when this threshold was reached. It was then attributed to some other than breaking background processes, but effectively the same term was used, which led to much confusion. In reality, the wave attenuation consists of many physical processes, independent or interdependent and, in our view, should be best described as

$$S_{\mathrm{ds}} = S_{\mathrm{br}} + S_{\mathrm{turb}} + S_{\mathrm{visc}} + S_{\mathrm{wind}} + \cdots, \qquad (8)$$

where S_{br} is dissipation due to breaking, S_{turb} is due to turbulent viscosity, S_{visc} is due to molecular viscosity, S_{wind} is due to the interaction of waves with adverse winds, etc. This way, each dissipation term may have a different formulation as dictated by relevant physics, and any one of them may turn to zero as necessary while the wave evolution and the wave energy dissipation will still proceed.

Despite the fact that present wave forecast models, with their speculative dissipation terms but well-tuned balance, are capable of forecasting main wave characteristics generally well, they obviously fail in nonstandard circumstances (i.e., Ardhuin et al. 2007). Therefore, employment of correct physics of all wave dynamics processes, including the dissipation is very important. This can become particularly relevant in extreme, or any other, situations that deviate from standard-tuned conditions.

6. Conclusions

In this note, the issue of physics of dissipation functions employed in wave forecast models is discussed. These functions have been "tuning knobs" of wave models for decades and, to a great extent, remain a residual tuning term in spite of important experimental progress in wave breaking studies in recent years. The newly found physics of wave breaking and dissipation still have to find their way into wave model parameterizations.

The AB03 paper (Alves and Banner 2003) attempted to utilize newly found features of wave breaking (i.e., a breaking threshold). As such, it is an important step toward an adequate description of wave field dynamics and has been followed by a number of similar studies. Given the significance of the step and the attention that it has attracted, the AB03 dissipation term is thoroughly analyzed here.

It is argued thatassociation of this dissipation formulation with the process of nonlinear group evolution is not well substantiated, but most importantly the statement that this form of the dissipation term is based on a threshold behavior of wave breaking appears to be mistaken.

The formulation does not consistently employ experimentally observed threshold dependencies, nor does it use experimentally obtained values for the threshold. On the contrary, the magnitude of the dimensionless switch B_r appears to correspond to the spectra that certainly comprise breaking waves, and these waves break at, typical for moderate conditions, a rate of some 5%.

As a result, the meaning of the B_r switch turns out to be to an extent opposite to the AB03 interpretation. That is, the switch does not signify a breaking threshold, that is, a lower spectral limit below which no breaking occurs, but rather an upper limit allowed by the formulation itself. Subsequently, the dissipation function, being postulated as strongly nonlinear, works as quasi-linear. The role of the nonlinear option is mainly limited to quenching the spectrum toward a limit if it happens to exceed the switch level; below this level, conventional spectral evolution, controlled by linear dissipation and input, takes place and thus regular growth rates are well reproduced.

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