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Scaling depth-induced wave-breaking in two-dimensional spectral wave models

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ABSTRACT

Wave breaking in shallow water is still poorly understood and needs to be better parameterized in 2D spectral wave models. Significant wave heights over horizontal bathymetries are typically under-predicted in locally generated wave conditions and over-predicted in non-locally generated conditions. A joint scaling dependent on both local bottom slope and normalized wave number is presented and is shown to resolve these issues. Compared to the 12 wave breaking parameterizations considered in this study, this joint scaling demonstrates significant improvements, up to ~50% error reduction, over 1D horizontal bathymetries for both locally and non-locally generated waves. In order to account for the inherent differences between uni-directional (1D) and directionally spread (2D) wave conditions, an extension of the wave breaking dissipation models is presented. By including the effects of wave directionality, rms-errors for the significant wave height are reduced for the best performing parameterizations in conditions with strong directional spreading. With this extension, our joint scaling improves modeling skill for significant wave heights over a verification data set of 11 different 1D laboratory bathymetries, 3 shallow lakes and 4 coastal sites. The corresponding averaged normalized rms-error for significant wave height in the 2D cases varied between 8% and 27%. In comparison, using the default setting with a constant scaling, as used in most presently operating 2D spectral wave models, gave equivalent errors between 15% and 38%.

1. Introduction

Predicting breaking waves in shallow water under complex 2D bathymetry and current conditions is important for understanding the natural development of oceanic islands and coastal regions, the design and management of man-made coastal structures, and risk assessment. Such waves usually dissipate in a relatively narrow 1D surf zone fringing the coast. However, occasionally a surf zone may occur suddenly and with catastrophic effect over a large 2D region when low-lying land, an island or a reef is inundated in a severe storm. Waves have been shown to be vitally important in understanding processes such as sediment re-suspension and transport in estuaries (e.g. Green and Coco, 2014) and the exchanges between the nearshore and inner shelf (Lentz et al., 2008). Furthermore, the increase in the need for interdisciplinary research to understand these complex processes has led to an increased use of coupling phase-averaging wave models to flow and circulation models (e.g. Dietrich et al., 2013).

Phase-averaged spectral wave models are widely used to describe the sea-state with waves described with a 2D energy spectrum, defined at each location and moment in time as the distribution of wave energy over frequency and direction of the constituent wave components (Phillips, 1977; WAMDI, 1988; Holthuijsen, 2007). Within the limitations of stationary Gaussian processes, a variety of statistical wave parameters can be estimated from the spectrum such as the significant wave height, defined as the mean wave height of the one-third highest waves (Longuet-Higgins, 1952). The most advanced of these models are the so-called third-generation wave models where the non-linear quadruplet wave–wave interactions are explicitly represented, permitting a development of the wave spectrum that is unrestrained by a priori assumptions. This is in contrast to first- and second-generation wave models where quadruplet interactions are not represented or are represented by simple parameterizations (Komen et al., 1994). This difference allows third-generation wave models to freely develop the spectrum in arbitrary 2D conditions of wind, currents and bathymetry as the spectral shape is not enforced a priori (Holthuijsen, 2007). We conform to this

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commonly accepted practice despite the fact that such models still typically use parametric expressions for the remaining wave processes e.g. white capping and wind input. Operational models of this type are WAM (WAMDI group, 1988; Komen et al., 1994; Monbaliu et al., 2000), WAVEWATCH III (Tolman, 1990a, 2009; Tolman and Chalikov, 1996), TOMAWAC (Benoit et al., 1996), SWAN (Booij et al., 1999; Ris et al., 1999; Zijlema, 2010), MIKE21SW (Sørensen et al., 2004), CREST (Ardhuin et al., 2001) and WWM (Roland et al., 2006; Roland, 2009).

The default parameterization for depth-induced wave breaking dissipation, used in most of these models, is one based on an analogy of the dissipation in a 1D bore (Lamb, 1932; Stoker, 1957; LeMéhauté, 1962) introduced by Battjes and Janssen (1978). It combines the dissipation of a single breaking wave with a Rayleigh distribution for random wave heights. From this, three dissipation models were developed: Battjes and Janssen (1978), Thornton and Guza (1983) and Baldock et al. (1998). They are subsequently referred to as the BJ78, TG83 and B98 models. The essential difference is how they represent the statistics of the breaking waves (see Fig. 1; top panel).

Battjes and Janssen (1978) truncate the distribution of the wave heights at an upper limit given by the maximum possible wave height for a given depth $H = H_{max}$ where they assume a delta function in the distribution (with a surface area equal to the probability of exceeding $H = H_{max}$ if the complete Rayleigh distribution would apply). As shown in Fig. 1(A), this delta function represents the assumption that all breaking waves have the same wave height H_{max}. A reduced breaking criterion of Miche (1944) is then used to scale the dissipation with a fixed ratio of the maximum possible wave height H_{max} and the local depth d, denoted as $\gamma_{BJ} = H_{max}/d$. Battjes and Janssen (1978) used $\gamma_{BJ} = 0.8$ in their computations, but most third-generation models use $\gamma_{BJ} = 0.73$, a value averaged from the more extensive data set of Battjes and Stive (1985, their Table 1). For convenience, we subsequently refer to this parameterization for dissipation and γ-scaling as the BJ model.

Thornton and Guza (1983, Fig. 1B) suggest, on the basis of their field observations, using a Rayleigh distribution for the breaking waves shifted to higher wave heights instead. This is achieved through the use of a weighting function with a scaling coefficient $M_{TG} = (H_{rms}/\gamma_{TG}d)^n$ where $n = 2$ and $\gamma_{TG} = H_{rms,max}/d$ is the ratio of the maximum possible root-mean-square wave height to depth.

Baldock et al. (1998, Fig. 1C) also suggest using a Rayleigh distribution but truncated at a lower limit of $H_b = \gamma_B d$ (the minimum breaker height) to represent the breaking wave height distribution. Their expression for dissipation is subsequently corrected by Janssen (2006), Janssen and Battjes (2007) and Alsina and Baldock (2007). An overview of variable parameterizations for

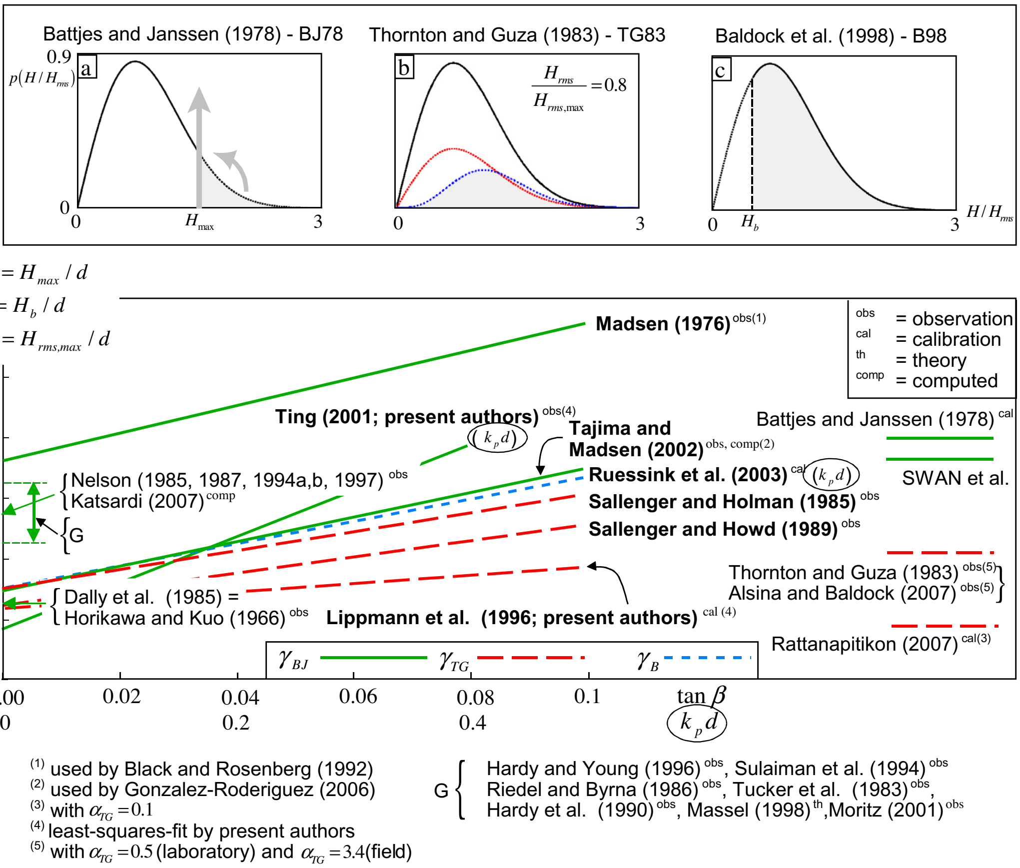

Fig. 1. The parameterization of depth-induced wave breaking. The top panels illustrate the representation of the breaking waves with the Rayleigh probability density function (in black) for the (a) Battjes and Janssen (1978; BJ), (b) Thornton and Guza (1983; TG) and (c) Baldock et al. (1998; B) dissipation models. The delta function used in BJ78 is represented by a vertical arrow in (a). Both expressions of Thornton and Guza (1983, their Eqs. (20) and (21)) are shown in (b) as the red and blue lines respectively for $H_{rms}/\gamma_{TG}d = 0.8$. The lower panel presents the ratio of critical wave height over depth, which is used to scale the dissipation models, as a function of bottom slope $\tan\beta$ or normalized wave number $k_p d$. The seven varying scalings considered in this study are labeled in bold type. All expressions are based on direct observations of individual waves except when indicated otherwise (see inset). All expressions have been derived for irregular waves (or have been used for irregular waves as indicated). The values of γ at $\tan\beta = 0$ from reference group G cluster between 0.45 and 0.65. Constant values are indicated at the right-hand side of the diagram with horizontal lines. The commonly used value $\gamma_{BJ} = 0.73$ in third-generation models (indicated with SWAN et al.) has been added as reference. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)