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Parameterization of unresolved obstacles in wave modelling: A source term approach

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ABSTRACT

In the present work we introduce two source terms for the parameterization of energy dissipation due to unresolved obstacles in spectral wave models. The proposed approach differs from the classical one based on spatial propagation schemes because it provides a local representation of phenomena such as unresolved wave energy dissipation. This source term-based approach presents the advantage of decoupling unresolved obstacles parameterization from the spatial propagation scheme, allowing not to reformulate, reimplement and revalidate the parameterization of unresolved obstacles for each propagation scheme. Furthermore it opens the way to parameterizations of other unresolved sheltering effects like rotation and redistribution of wave energy over frequencies. Proposed source terms estimate respectively local energy dissipation and shadow effect due to unresolved obstacles. Source terms validation through synthetic case studies has been carried out, showing their ability in reproducing wave dynamics comparable to those of high resolution models. The analysis of high resolution stationary wave simulations may help to better diagnose and study the effects of unresolved obstacles, providing estimations of transparency coefficients for each spectral component and allowing to understand and model unresolved effects of rotation and redistribution of wave energy over frequencies.

1. Introduction

Unresolved obstacles (small islands, cliffs, shoals ...) are a main source of local error in spectral wave modelling (Tolman, 2001; 2002; 2014). In presence of a coast with complex bathymetry local errors can accumulate and affect vast portions of the domain (e.g. Hardy and Young, 1996; Ponce de León and C., 2005; Tuomi et al., 2014; Mentaschi et al., 2015). An established approach to solve this issue has been proposed by Booij et al. (1999) and implemented in SWAN® model (Holthuijsen et al., 2001) and in WAVEWATCH III® model (hereinafter referred to as WWIII, Tolman, 2014, 2003; Chawla and Tolman, 2008). This approach consists in correcting energy fluxes estimated by the spatial propagation scheme on the basis of transparency coefficients of obstructed cells. A similar approach has been implemented by Hardy et al. (2000) in WAM model, introducing transparency coefficients modulated as functions of spectral component direction, though Chawla and Tolman (2008) showed that transparency coefficients defined per main grid axis are accurate enough in most cases.

This approach improves significantly wave model performances, but at the same time its use leads to some drawbacks. Sheltering due to unresolved obstacles is mainly a local effect, hence a local parameterization by a source term may be a good alternative to a description in the propagation scheme. In the approach described by Tolman (2003) a cell transparency coefficient α is applied partly to reduce the ingoing energy flux at the upstream border, partly to reduce the outgoing flux at the downstream border, using a rule completely independent from the layout of the unresolved obstacles inside the cell. As a result the estimated net energy flux throughout the cell is correct; however, the resulting average energy is not always rigorously represented. Imposing different values for upstream and downstream transparencies may help to overcome this issue, but the physical meaning of upstream and downstream transparency is not always straightforward. Drawbacks of representing local effects

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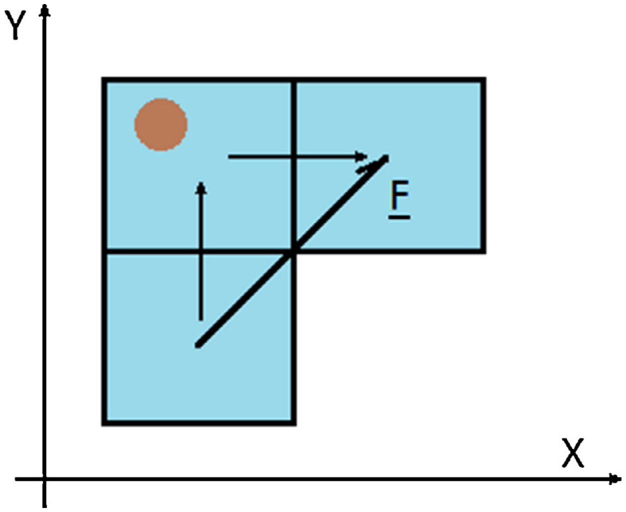

Fig. 1. Propagation scheme drawback: the energy flux for an oblique spectral component is reduced by an obstacle (the brown spot) that is not on the real path of the energy. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in the propagation scheme are also possible in regular grids where the flux is decomposed and propagated separately to *y* and *x* directions. An example is illustrated in Fig. 1. Here energy travels from the bottom-left cell to the top-right cell, and should not encounter any obstacle on its path. However, as a result of flux decomposition in y and x directions, system behaves as if top-left obstruction (the brown dot in the figure) was on energy path.

Another drawback of using approaches based on the propagation scheme is that the sheltering effects of unresolved features involve not only energy dissipation, but also rotation of spectral components and redistribution of energy over frequencies due to unresolved refraction/diffraction. Since propagation scheme propagates separately each spectral component it would be difficult to model through it transformations of the whole spectrum such as rotations. Conversely in an approach based on a source term the whole propagated spectrum is available, allowing parameterization of rotations and redistribution of wave energy over frequencies as a future development.

The introduction of propagation schemes allowing unstructured grids with varying resolution like finite elements propagation scheme (Roland, 2008), or spherical multiple-cell propagation scheme (Li, 2012), partially overcomes the problem of unresolved obstacles, but it is not always computationally convenient to increase resolution in proximity of all the obstacles existing in the domain.

In this study we introduce a new source term approach to parameterize the energy dissipation due to unresolved obstacles on the basis of transparency coefficients estimated for each obstructed cell/spectral component. The first source term models the average local dissipation (LD), while a second source term models the shadow effect (SE) of an obstructed cell towards the downstream cells.

The present manuscript is organized as follows: the LD-SE scheme is formulated in Sections 2.1, 2.2 and 2.3 and the performances of the source terms couple are assessed in Section 3 on the basis of simple theoretical cases. Discussion of the obtained results is presented in Section 4 and some final conclusions are drawn in Section 5.

2. The local dissipation and shadow effect scheme (LD-SE)

As mentioned above unresolved obstacles can involve different effects, ranging from energy dissipation to spectral components rotation and redistribution of wave energy over frequencies due to unresolved refraction-diffraction effects. In the following sub-sections the description of the source terms formulation for local dissipation and shadow effect due to unresolved obstacles will be presented.

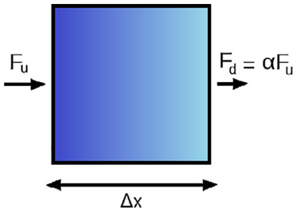

Fig. 2. $1 - \alpha$ source term.

2.1. The local dissipation (LD) source term

Following previous works about the parameterization of unresolved obstacles (e.g. the already cited Booij et al., 1999; Hardy et al., 2000; Holthuijsen et al., 2001; Tolman, 2003; Chawla and Tolman, 2008), this formulation relies on the concept of transparency coefficient α of an obstructed cell. Let us consider a cell and a spectral component directed in the *x* direction, as represented in Fig. 2. In stationary conditions and under the hypotheses of null wind wave growth and null resolved dissipation the coefficient of transparency α of the cell is defined as the ratio between the spectral energy density exiting the cell (F_d, where the suffix *d* stands for downstream) and the spectral energy density entering the cell (F_u, where the suffix stands for upstream)

$$\alpha = F_d / F_u. \tag{1}$$

The energy loss rate of the cell is proportional to the attenuation coefficient $(1 - \alpha)$ and to the distance covered by the mode in a time unit. Hence the dissipation rate by unit length is given by

$$\left.\frac{\partial F}{\partial t}\right|_{\alpha} = -(1 - \alpha)\frac{c_g}{\Delta x}F_u, \tag{2}$$

where Δx is the *x* span of the cell. Since a spectral wave model does not estimate the upstream energy density F_u, expression (2) must be expressed in terms of the average energy *F* of the cell. If the dissipation is constant across the cell, the average spectral density *F* of the cell is given by the average between F_u and F_d

$$F = \frac{F_u + F_d}{2} = \frac{1 + \alpha}{2}F_u. \tag{3}$$

Using expression (3) to eliminate F_u from (2) we obtain the $1 - \alpha$ source term

$$\left.\frac{\partial F}{\partial t}\right|_{\alpha} = -2\frac{1 - \alpha}{1 + \alpha}\frac{c_g}{\Delta x}F. \tag{4}$$

Source term given by expression (4) describes local dissipation using the sole overall transparency coefficient of the cell. However using a single α coefficient for each spectral component is not enough to estimate accurately the average energy loss of the cell. Let us consider for example a situation where all the unresolved obstacles are concentrated in the downstream half of the cell, and the first half of the cell is not involved in the energy dissipation. The use of the $1 - \alpha$ source term, which models an energy dissipation continuously distributed throughout the cell, leads to an underestimation of the cell average energy. An analogous argument for the opposite situation of unresolved obstacles concentrated in the upstream half of the cell leads to the conclusion that in this case the $1 - \alpha$ source term tends to overestimate the average energy.

A more accurate estimate of the cell average energy may be achieved subdividing the cell in two halves and considering a transparency coefficient for each half. Fig. 3 illustrates the new configuration. We consider a spectral component directed in the *x* direction. The transparency coefficients α_1 and α_2 are associated to the two