Ocean Modelling 126 (2018) 77–84

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod

Short communication

Parameterizing unresolved obstacles with source terms in wave modeling: A real-world application

Lorenzo Mentaschi[a,*], Georgia Kakoulaki[b], Michalis Vousdoukas[a,c], Evangelos Voukouvalas[d], Luc Feyen[a], Giovanni Besio[e]

[a] European Commission, Joint Research Centre (JRC), Directorate for Space, Security and Migration, via Fermi 2749, 21027 Ispra VA, Italy
[b] Federal University of Pernambuco, Recife, Brazil.
[c] Department of Marine Sciences, University of the Aegean, University hill, 41100, Mitilene, Lesbos, Greece.
[d] Engineering Inegneria Informatica s.p.a, 56 via s. Martino della Battaglia 00185 Rome, Italy
[e] Università di Genova, Dipartimento di Ingegneria Chimica, Civile e Ambientale, via Montallegro 1, 16145 Genova, Italy

ARTICLE INFO

Keywords:
Wave modeling
Subscale modelling
Unresolved obstacles
Wavewatch
UOST
Source term

ABSTRACT

Parameterizing the dissipative effects of small, unresolved coastal features, is fundamental to improve the skills of wave models. The established technique to deal with this problem consists in reducing the amount of energy advected within the propagation scheme, and is currently available only for regular grids. To find a more general approach, Mentaschi et al., 2015b formulated a technique based on source terms, and validated it on synthetic case studies. This technique separates the parameterization of the unresolved features from the energy advection, and can therefore be applied to any numerical scheme and to any type of mesh. Here we developed an open-source library for the estimation of the transparency coefficients needed by this approach, from bathymetric data and for any type of mesh. The spectral wave model WAVEWATCH III was used to show that in a real-world domain, such as the Caribbean Sea, the proposed approach has skills comparable and sometimes better than the established propagation-based technique.

1. Introduction

Unresolved bathymetric and coastal features, such as cliffs, shoals and small islands, are a major source of local error in spectral wave models. Their dissipative effects can be accumulated over long distances and therefore, neglecting them, can compromise the simulation skills on large portions of the domain (Mentaschi et al., 2015a; Tolman, 2003; Tuomi et al., 2014). An established approach to subscale model these dissipative effect consists in attenuating the energy of the waves as they travel through partially obstructed cells, representing the unresolved features by means of transparency coefficients. This attenuation is typically implemented in the numerical scheme that models energy advection (Booij et al., 1999; Hardy et al., 2000; Tolman, 2014,2003). Generally, in this approach only 2 transparency coefficients are considered, for spectral components moving along the 2 axes of the mesh, though for some implementations the directional layout of the unresolved obstacles is considered (Hardy et al., 2000).

The introduction of this technique led to major improvements of the models' skill, but comes with an important drawback: the fact that it is implemented in the propagation scheme till now limited its application to the sole regular grids. This is due to a couple of reasons.

1) In principle, the established approach could be implemented in any numerical scheme based on cell boundary fluxes. However, some of the logics implemented in regular grids for subscale modelling are not immediately applicable to some of the other types of mesh. For example, in finite elements schemes the evolution of the spectral density is estimated in terms of flux convergence into the median dual cells associated with the nodes (Roland, 2008; Tolman, 2014; Zijlema, 2010). In such schemes, understanding the directionality of the reductions related with unresolved obstacles, and how these reductions should be combined, would not be straightforward.
2) Powerful, reliable and freely available tools exist for the automatic estimation of the unresolved obstacles in regular grids (e.g. Chawla and Tolman, 2008). For other types of mesh, like triangular meshes (Roland, 2008; Zijlema, 2010) or Spherical Multi-Cell (SMC) meshes (Li, 2011), these tools should be deeply revised.

These drawbacks impact both model developers (the cost of developing and testing the established technique might be high), and

---

* Corresponding author.
E-mail address: lorenzo.mentaschi@ec.europa.eu (L. Mentaschi).

https://doi.org/10.1016/j.ocemod.2018.04.003
Received 25 November 2017; Received in revised form 6 April 2018; Accepted 16 April 2018

modelers (currently, a parameterization of unresolved obstacles, for meshes other than regular, does not exist).

We further need to say that the meshes of finite elements and SMC schemes are flexible, and in principle allow overcoming the problem of unresolved coastal features by increasing the grid resolution locally. However, this may result in computationally expensive meshes, especially for large scale models. Not to mention the overhead required to elaborate locally highly refined flexible meshes. Therefore, a good first-order parameterization of the effects of unresolved obstacles would be very useful also when using one of these schemes.

A possible solution to this problem is parameterizing the unresolved features with source terms, thus separating the parameterization of the unresolved obstacles from the energy propagation. The Unresolved Obstacles Source Term (UOST) was proposed by Mentaschi et al. (2015b) to this purpose, and models the effects of the subscale features on the cell where they are located, and their shadow on the downstream cells. UOST was tested in a set of ideal case studies, where its skills have been found to be close to the average skills of high resolution models (Mentaschi et al., 2015b).

In this manuscript, we present the first application of UOST to a real-world case (i.e., based on real-world bathymetry and wind data), that was possible only after the development of a software package (hereinafter referenced as alphaBetaLab) for the estimation of the transparency coefficients needed by the source term, from real bathymetric data. We focused our efforts on the Caribbean Sea, an area where the presence of many small islands and cliffs requires parameterization in low resolution models, due to their corresponding large impact on wave dynamics. We examined the performances of UOST on a time frame of 10 years (2000–2009), and compared it to the approach established in WW3 (Chawla and Tolman, 2008; Tolman, 2003).

In Section 2 a brief summary of UOST is given. Section 3 describes the simulations carried out in this study and the methodology used for validation and comparison. In Section 4, the model skill in the Caribbean sea is presented and discussed. Conclusions are finally drawn in Section 5.

2. Parameterizing unresolved features with source terms

The UOST/alphaBetaLab approach relies on the hypothesis that any mesh can be considered as a set of polygons, called cells, and that a spectral wave model estimates the average value of the unknowns in each cell. The definition of cell depends on the numerical scheme. In regular grids, the cells are all the rectangles that form when the domain is subdivided with a regular lattice. In triangular meshes, the nodes are the reference points of the median dual cells. In SMC meshes, cells are rectangular, as in regular grids, and their size and position depend on the resolution of the local lattice.

Given a cell (let us call it A, Fig. 1 ab) UOST estimates, for each spectral component, the effect of a) the unresolved features located in A (Local Dissipation, LD); b) the unresolved features located upstream of A, and projecting their shadow on A (Shadow Effect, SE). For the estimation of SE, an upstream polygon A' is defined for each cell/spectral component, as the intersection between the joint cells neighboring A (cells B, C and D in Fig. 1 a,b), and the flux upstream of A.

For each cell or upstream polygon, and for each spectral component, two different transparency coefficients are estimated. 1) The overall transparency coefficient α: a value of 1 for this coefficient indicates a cell (or upstream polygon) completely free of unresolved obstacles, while $\alpha = 0$ indicates a totally obstructed cell/upstream polygon. 2) A layout-dependent transparency β, defined as the average transparency of cell sections starting from the cell upstream side. Values close to 1 represent a polygon free of obstacles, or with obstacles all located close to the downstream side. Values close to 0 indicate that the polygon is totally obstructed, and the obstacles are all located close to the upstream side of the polygon. The values of α and β are such that always $\beta \geq \alpha$. The LD and SE components of the source term can be written as (Mentaschi et al., 2015b)

$$\left.\frac{\partial F}{\partial t}\right|_{LD}(\mathbf{x},\mathbf{k}) = -\frac{1-\beta_l}{\beta_l}\frac{c_g}{\Delta L}F \tag{1}$$

$$\left.\frac{\partial F}{\partial t}\right|_{SE}(\mathbf{x},\mathbf{k}) = -\left(\frac{\beta_u}{\alpha_u} - 1\right)\frac{c_g}{\Delta L}F\ , \tag{2}$$

where F is the spectral density, $\mathbf{x}$ is the position of the cell in space, $\mathbf{k}$ is the wave vector of the spectral component, c_g is the group velocity, ΔL is the path length of the spectral component in the cell. The subscripts l and u of α and β indicate that these coefficients can be referred, respectively, to the cell and to the upstream polygon. We need to mention, that theoretically a formulation based on source terms, such as UOST, is unable to model total blocking. However, we notice that the LD and SE contributions diverge in case of total blocking, virtually providing infinite dissipation. In practice a high limit is imposed to the maximum allowed dissipation, able to dump almost completely the energy. For a more detailed discussion of **1** and **2** the reader is referred to Mentaschi et al. (2015b).

The estimation of the transparency coefficients from a real bathymetry is a major challenge in the parameterization of unresolved obstacles, and the reason for the development of automation software such as Gridgen (Chawla and Tolman, 2008). The package alphaBetaLab comes as a logical generalization of Gridgen, and automates the estimation of the upstream polygon and of the coefficients α_l, β_l, α_u, β_u, without making any assumption on the geometrical nature of the cells, other than considering them as free polygons. This involves, that it can be applied to any type of mesh, including unstructured finite elements and SMC meshes. We need to mention that while UOST would be able to modulate the energy dissipation with the spectral frequency, only the direction is currently considered in alphaBetaLab. Given a polygon alphaBetaLab estimates the transparency coefficient α as a function of the cross section σ of the unresolved obstacles for each directional bin (Fig. 1 c,d):

$$\alpha(\mathbf{x},\mathbf{k}) = 1 - \sigma(\mathbf{x},\mathbf{k})\ . \tag{3}$$

The coefficient β is estimated slicing the cell into $\mathrm{N_s}$ subsections starting from the upstream side, along the direction of each propagating spectral component (i.e. the sides of the slices are normal to the propagation direction), the last slice being equal to the whole polygon. In the case shown in **1** c, where the algorithm is illustrated for $\mathrm{N_s} = 4$ and for a spectral component propagating along the x axis for a rectangular cell, the first slice would span from $\mathrm{x_0}$ to $\mathrm{x_1}$, the last from $\mathrm{x_0}$ to $\mathrm{x_4}$. The coefficient β is then estimated as the average α of all the slices. In the present study $\mathrm{N_s} = 8$ slices have been considered for each directional bin. For more details about the definition and the estimation of β, the reader is referred to Mentaschi et al. (2015b). For cells intersecting large land bodies for more than 10% of their surface, α and β are set to 1 (no unresolved obstacles), because there UOST would conflict with the resolved part of wave sheltering and shallow water dynamics.

We need to underline, that both UOST and Gridgen do not provide full subscale modelling, but only a parameterization of the energy dissipation due to unresolved obstacles. Full subscale modelling would require also a parameterization of refraction, reflection, as well as shallow water dynamics (Mentaschi et al., 2015b).

2.1. *Time resolution*

In spectral models adopting the fractional steps method (Yanenko, 1971), setting a source-term time step (i.e. the time step of application of the source terms) much larger than the critical Courant-Friedrichs-Lewy (CFL) time step (i.e. the time required for the fastest spectral component to cross a specific cell) can lead to inaccuracies, especially if the wave climate and wind forcing change significantly in the length scale of one cell (Tolman, 2014, Appendix B1); this can happen, for example, in extreme conditions. In the case of subscale