Ocean Modelling 103 (2016) 118–132

Contents lists available at ScienceDirect

Ocean Modelling

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

Virtual Special Issue
Ocean Surface Waves

On the modeling of wave-enhanced turbulence nearshore

Saeed Moghimi[a,*], Jim Thomson[b], Tuba Özkan-Haller[a], Lars Umlauf[c], Seth Zippel[b]

[a] College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, USA
[b] Applied Physics Laboratory, University of Washington, Seattle, USA
[c] Department of Physical Oceanography, Leibniz Institute for Baltic Sea Research, Warnemünde, Germany

ARTICLE INFO

Article history:
Received 17 February 2015
Revised 9 September 2015
Accepted 1 November 2015
Available online 10 November 2015

Keywords:
Turbulence modeling
Wave modeling
Turbulence dissipation rate
One-dimensional vertical
Wave–current interaction
Wave–ocean energy exchange

ABSTRACT

A high resolution k–ω two-equation turbulence closure model, including surface wave forcing was employed to fully resolve turbulence dissipation rate profiles close to the ocean surface. Model results were compared with observations from Surface Wave Instrument Floats with Tracking (SWIFTs) in the nearshore region at New River Inlet, North Carolina USA, in June 2012. A sensitivity analysis for different physical parameters and wave and turbulence formulations was performed. The flux of turbulent kinetic energy (TKE) prescribed by wave dissipation from a numerical wave model was compared with the conventional prescription using the wind friction velocity. A surface roughness length of 0.6 times the significant wave height was proposed, and the flux of TKE was applied at a distance below the mean sea surface that is half of this roughness length. The wave enhanced layer had a total depth that is almost three times the significant wave height. In this layer the non-dimensionalized Terray scaling with power of −1.8 (instead of −2) was applicable.

1. Introduction

Growing interest in fully coupled three-dimensional (3D) atmosphere–wave–ocean modeling systems motivates improvements to parameterizations and coupling between model components. Debate continues on whether momentum exchange between surface waves and the ocean circulation should be treated as a vortex force or radiation stress (Mellor, 2003; McWilliams et al., 2004; Ardhuin et al., 2008; Aiki and Greatbatch, 2014; Mellor, 2015). Similarly in recent years, the treatment of energy exchange between waves and ocean has been the subject of several research activities. A recent modeling study by Gerbi et al. (2013) shows the effects of white-capping dissipation on a river plume during an upwelling favorable wind condition using a three-dimensional coastal ocean model. Carniel et al. (2009) compare two-equation turbulence closure models to investigate the effects of surface wave breaking on surface drifter trajectory in the Adriatic Sea. However, in both of these studies, the effects of the momentum exchange between waves and ocean were not included.

Most modeling studies on surface wave breaking effects on turbulence and mixing quantities were conducted using a one-dimensional vertical (1DV) water column model following Craig and Banner (1994). They suggest a turbulent kinetic energy (TKE) balance between diffusion and dissipation, where the surface flux of TKE (associated with breaking waves) is prescribed as proportional to the surface wind friction velocity cubed (e.g. Burchard, 2001; Umlauf and Burchard, 2003; Umlauf et al., 2003; Kantha and Clayson, 2004). Rascle et al. (2013) utilized a 1DV Mellor and Yamada (1982) turbulence model to compare three different methods for simulating turbulence induced by surface breaking waves.

Most of the research on wave breaking turbulence and water column mixing are focused on the deep ocean and lakes. There have been some attempts to investigate these phenomenon in nearshore regions (3 [m] < depth < 10 [m]), surf-zones and shallow estuaries (e.g. Feddersen and Trowbridge, 2005; Feddersen, 2012b; Grasso et al., 2012; Jones and Monismith, 2008b). Feddersen and Trowbridge (2005) present a 1DV model, including a two-equation k–ϵ turbulence closure model, to study the effects of wave breaking turbulence on the mean circulation and turbulence quantities inside the surf-zone. Feddersen et al. (2007) extend their previous investigation from the surf-zone to the nearshore (outer surf-zone) region (depth > 3 [m]). They use bottom mounted turbulence measurements to show that, to correctly estimate the vertical distribution of the TKE

* Corresponding author. Tel.: +1 541 737 3402; fax: +1 541 737 2064.
E-mail address: moghimi@coas.oregonstate.edu, moghimis@gmail.com (S. Moghimi).

http://dx.doi.org/10.1016/j.ocemod.2015.11.004
1463-5003/

dissipation rate according to Terray et al. (1996), a greater surface flux of energy is needed compared to the open ocean.

In this study, we used nearshore measurements of surface TKE dissipation rates from Surface Wave Instrument Floats with Tracking (SWIFT) buoys (Thomson, 2012) to investigate energy transfer from breaking waves to the ocean water column in the vicinity of a tidal inlet. Drawing on the modeling studies in similarly complex nearshore settings (e.g. Newberger and Allen, 2007; Kumar et al., 2012), we utilized coupled wave and circulation models to characterize the spatial variability of the wave and circulation field at the site. The wave and circulation models are coupled in a rudimentary fashion such that the effects of the tidal circulation on the wave kinematics and dynamics are included, resulting in a reasonable view of spatially varying wave field. Using this representation of the wave field, we then focused our attention on the effects of wave motions on water column turbulence properties. For this purpose we locally employed a high resolution, two-equation turbulence model of the ocean water column (with several hundred vertical layers) to fully resolve the TKE dissipation rate close to the water surface. We performed a wide range of sensitivity analyses to gain insight into the different physical parameters involved in the modeling procedure (e.g. surface roughness). Traditionally, following Craig and Banner (1994), the wind friction velocity is used in prescribing the surface boundary flux of TKE. However, it may be more reasonable to use the wave dissipation computed directly by a wave model instead of an approximation based on wind friction velocity. In this study, we compared two widely used methods for computing these wave related quantities and discussed their impact on the calculation of a TKE dissipation rate.

The structure of this paper is as follows. In Section 2, a brief description of the momentum and energy exchange between wind, waves and ocean is given, and the theoretical background and basic definition of parameters for the numerical experiments are discussed. The case study, the modeling system and observational data are described in Section 3. Modeling results of turbulence quantities and comparison with observational data are shown in Section 4. A more comprehensive discussion about the role of different parameters is presented in Section 5. Finally, the summary and conclusion of this research are described in Section 6.

2. Theory

Understanding and correctly parameterizing the exchange of momentum and energy between wind, waves and ocean are key to reasonably simulating the near surface region. Here, our focus is on the effect of surface wave breaking on turbulence quantities in the water column. We simulate the wave field using a common nearshore wave propagation model. Here, we assume wind as the main source of ocean surface momentum. A fraction of the wind momentum is consumed to generate local surface waves.

2.1. Wave modeling

The surface wave field evolution is described assuming that the waves can be described by irrotational inviscid linear wave theory. Clearly, breaking waves in the nearshore zone are not linear, the motions in the active breaking region are not irrotational, and waves can be dissipated by inviscid effects. However, the above assumptions are frequently employed with surprisingly successful results for wave prediction in the nearshore and surf-zones (e.g. Ruessink et al., 2001; Newberger and Allen, 2007) and the use of a simplified theory allows for progress over the complex domain of a tidal inlet. Further, we will show that the prediction of local wave quantities is skilled compared to observations. Nonetheless, as a result of the irrotational and inviscid assumptions, the detailed dynamics of air-sea energy exchange are not accounted for herein, instead we focus on the fate of the TKE provided to the water column by breaking wave events.

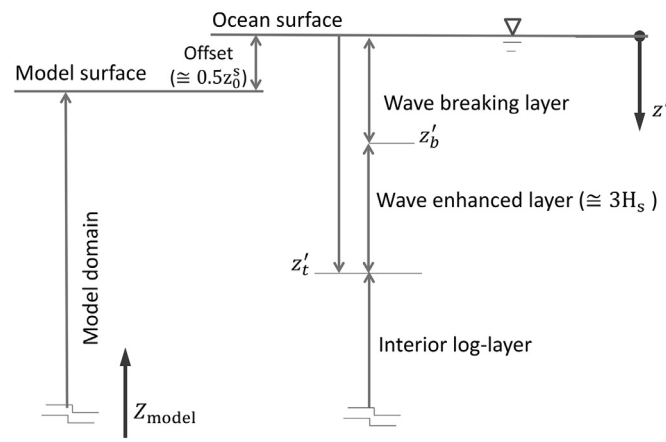

Fig. 1. Simplified schematic description of water column surface layers affected by breaking waves. Here H_s and z_0^s are the significant wave height and the surface roughness (see Section 2.2.1).

The governing equation for wave action balance (Komen et al., 1994), $\mathcal{N} = E(\omega_{\text{wave}}, \theta)/\omega_{\text{wave}}$, then reads:

$$\frac{\partial \mathcal{N}}{\partial t} + \nabla_{\boldsymbol{X}} \cdot [(\boldsymbol{c}_g + \boldsymbol{U})\mathcal{N}] + \frac{\partial (c_{\omega_{\text{wave}}}\mathcal{N})}{\partial \omega_{\text{wave}}} + \frac{\partial (c_\theta \mathcal{N})}{\partial \theta} = \frac{S^{\text{tot}}}{\omega_{\text{wave}}} \tag{1}$$

where E is the wave energy at relative angular frequency ω_{wave} traveling at an angle of θ, $\boldsymbol{c}_g$ is the intrinsic wave group velocity vector, $\boldsymbol{U}$ is ambient current velocity vector and $\boldsymbol{X}$ is the horizontal geographic coordinate system. The propagation velocities in spectral space $(\omega_{\text{wave}}, \theta)$ are given by $c_{\omega_{\text{wave}}}$ and c_θ. The terms on the left hand side of the equation are responsible for local changes and propagation of the wave energy. The right hand side of the equation represents source and sink terms associated with wave generation, dissipation and nonlinear wave-wave interactions, where:

$$S^{\text{tot}} = S^{\text{in}} + S^{\text{nl}} + S^{\text{ds,w}} + S^{\text{ds,br}} + S^{\text{ds,b}}. \tag{2}$$

S^{in} is the energy input from wind to the wave field, S^{nl} is the nonlinear wave-wave interaction, $S^{\text{ds, b}}$ is the dissipation due to bottom friction, $S^{\text{ds, br}}$ is the dissipation due to depth-induced surface wave breaking, and $S^{\text{ds, w}}$ is the dissipation due to white-capping.

2.2. Wave-enhanced turbulence

Surface breaking waves enhance the turbulence in the ocean surface layer by acting as a source of turbulence kinetic energy (TKE) (Kitaigorodskii et al., 1983; Thorpe, 1984). A one-dimensional vertical Mellor and Yamada (1982) turbulence closure model was adapted by Craig and Banner (1994) to account for wave-affected near surface turbulence. They suggested that the surface boundary condition for turbulent kinetic energy, k, could be approximated by a flux boundary condition:

$$F_k^s = -\frac{\nu_{\text{turb}}}{\sigma_k}\frac{\partial k}{\partial z}, \tag{3}$$

in which F_k^s is the flux of energy injected to the surface of the ocean due to surface wave dissipation (Section 2.2.1). Here ν_{turb} is the vertical eddy viscosity and σ_k is the turbulence Schmidt number (Mellor and Yamada, 1982). z is the positive upward vertical coordinate with $z = h$ at the surface and $z = 0$ at the bottom.

As shown in Fig. 1, the breaking layer is the closest layer to the mean sea surface where the direct injection of the turbulence and bubbles from surface breaking waves is taking place (from surface to depth of z'_b). Here z' is depth below mean sea surface. In the wave-enhanced layer, the effects of the turbulence injected by waves on the mixing properties of water column should be detected. Inside this layer, a balance between downward diffusion of the dissipated