Circulation-Wave Coupling With a Wave Parameterization For the Idealized California Coastal Region

Le Ly and Curt Collins
Dept. of Oceanography
Naval Postgraduate School
Monterey, CA 93043

1. Introduction

Momentum and energy transfers across the air-sea interface under realistic ocean conditions are important not only in theoretical studies, but also in many applications including marine atmospheric and oceanic forecasts and climate modeling on all scales. Surface breaking waves are believed to be an important supplier of turbulent energy besides shear production of the classical turbulence theory. Waves contain a considerable amount of momentum and energy, and they redistribute these quantities over great distances. Wind waves supply energy for turbulence due to breaking. Ocean waves strongly effect the air-sea system on all scale. A part of the energy and momentum is transferred directly from the atmosphere to ocean currents while another part is transferred to surface waves. The influence of surface waves on the air-sea system has been studied experimentally and numerically by many investigators.

Despite the importance of surface wave effects on the air-sea system, air-wave-sea coupling in general, and circulation-wave coupling in particular, has received little attention. There are some air-wave-sea systems developed by various investigators including Doyle, 1995; Lionello et al., 1996, 1999; Welsh et al., 1999; Wilczak et al., 1999. The investigators limited their studies on the surface roughness effects on the air-sea system using Charnock's (1955) and Janssen's (1989) formulas.

The same approach has been used by Welsh et al. (1999), Wilczak et al. (1999), and Lionello et al. (1999) in their coupled hydrodynamic and WAM wave models for Lake Michigan (Welsh et al., 1999), regional coupled MM5 (mesoscale-atmospheric model), POM (Princeton Ocean Model; Blumberg and Mellor, 1987), and WAM wave model (Wilczak et al., 1999), and an atmosphere-POM-WAM for the Mediterranean region (Lionello et al., 1999).

Based on a new concept of oceanic turbulence and a wave breaking condition of the linear wave theory, a surface wave parameterization is developed and presented. This wave parameterization with wave-dependent roughness is tested against available data on wave-dependent turbulence dissipation, roughness length, drag coefficient, and momentum fluxes using a coupled air-wave-sea model. We also present a circulation-wave coupling study using a wave dependent roughness (Ly and Garwood, 2000) and taking the wind-wave-turbulence-current relationship into account. The NAval postgraduate school ocean Model (NAM, POM-based model) includes a new turbulence closure with the wave parameterization is presented. The wave parameterization in the model is able to relate model variables to wave parameters such as wave height, age, phase speed, period, and length. The NAM box model (idealized California coastal regions) is used in a circulation-wave coupling study with idealized wave height and wave age fields. This study is focused on the sensitivity of the current field to the surface waves. This study also demonstrates the capability of the NAM model in reproducing an observed upwelling feature for the idealized California coastal region.

2. Circulation-Wave Coupling With a Surface Wave Parameterization

a. The Model with Coupling Physics

In addition to traditional shear production in the air-sea system, a new turbulence concept considers surface waves to be an important supplement of turbulent energy. A turbulence closure with a surface-wave parameterization is developed and tested again all available wave-dependent observed data of ocean turbulent dissipation (ε) distribution, wave-dependent roughness length (z_{0a}), drag coefficient (C_d) and momentum fluxes. Simulations show that waves have an important role in causing ε to differ from the classical wall-layer theory and z_{0a} , with a value of 0.30 for the empirical constant. The model-predicted ε, and wave-dependent z_{0a} , C_d and C_{gd} agree well with data. Fig. 1 shows the model ε-distribution in the ocean is in comparison with observed data of all sources and the classical theory prediction.

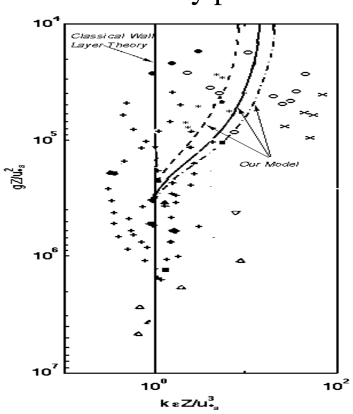

Figure 1. Nondimensional ε as function of depth z. The vertical line show the classical wall-layer turbulence prediction. The three curves show the model prediction with a new wave parameterization for various wave breaking status. Data points of various sources are adapted from Agrawal et al. (1992). (Adapted from Ly and Garwood, 2001).

The NAval postgraduate school ocean Model (NAM) is a POM-based model, which uses a new turbulence closure with the wave parameterization and wave-dependent roughness length, which takes the wind-wave-turbulence-current relationship into account. The model can relate the model variables to typical wave parameters, such as wave age (C_w), length (λ), height (h), period (T), and phase speed at the spectral peak (C_p). The NAM box model with a wave parameterization has been used in a circulation-wave coupling with idealized wave height and wave age fields. The NAM ocean model is used in a case-study which shows the model capability in reproducing observed upwelling off the California Coast .

The equations for momentum, temperature and salinity contain the vertical turbulent exchange coefficients that are determined by a turbulence closure scheme (Ly, 1991, 1995; Ly and Garwood, 2000) with a surface wave parameterization (Ly and Garwood, 2001). This scheme consists of equations for the turbulent kinetic energy (TKE), E, for the turbulent dissipation, ε, and for turbulent exchange coefficient, K_m, and wind-wave-turbulence-current relationship equations. The equation for TKE can be written as follows

$$\partial E/\partial t + \vec{U} .\nabla E + W \partial E/\partial z = \alpha_1 K_m [(\partial U/\partial z)^2 + (\partial V/\partial z)^2 - \alpha_3 g/\alpha_1 \rho_0 \partial\rho/\partial z] + \alpha_4 \partial/\partial z (K_m \partial E/\partial z) - \alpha_2 E^2/K_m + F_e , \qquad (1)$$

The equation for ε has the form

$$\partial\varepsilon/\partial t + \vec{U} .\nabla \varepsilon + W \partial \varepsilon/\partial z = \beta_1 K_m [(\partial U/\partial z)^2 + (\partial V/\partial z)^2 - \beta_3 g/\beta_1 \rho_0 \partial\rho/\partial z] + \beta_4 \partial/\partial z (K_m \partial \varepsilon/\partial z) - \beta_2 \varepsilon^2/E + F_\varepsilon , \qquad (2)$$

F_e in equation (1) and F_ε in equation (2) are the horizontal mixing terms, which are similar to F_θ in equations for temperature and salinity. The first two terms on the right-hand side (RHS) in (1) and (2) represent shear production. The next terms are the buoyancy and vertical diffusion terms. The next terms on the RHS represent dissipation. The turbulent exchange coefficient for momentum is expressed in terms of TKE and energy-dissipation using the Kolmogorov equation

$$K_m = \alpha_{e\varepsilon} E^2/\varepsilon , \qquad (3)$$

where $\alpha_{e\varepsilon} = \alpha_2 = 0.046$ is a universal coefficient. In ocean and atmosphere modeling practices, $\alpha_{e\varepsilon}$ and α_2 may be varied to provide a realistic relationship between turbulent and thermo-dynamical structures. The set of constants α and β

link the exchange coefficients for buoyancy and transport with K_m as follows

$$K_h = \alpha_3 K_m \ ; \ K_{\varepsilon h} = \beta_3 K_m , K_e = \alpha_4 K_m \ ; \ K_\varepsilon = \beta_4 K_m \qquad (4)$$

The constants α and β have the following values (Ly, 1991): $\alpha_1 = 1.0$; $\alpha_2 = 0.046$; $\alpha_3 = 1.0$; $\alpha_4 = 0.73$ and $\beta_1 = 1.43$; $\beta_2 = 1.97$; $\beta_3 = 1.45$; $\beta_4 = 0.73$

b. Wind-Wave-Turbulence-Current Relationship

The wind stress, heat, and salinity fluxes are prescribed at the free surface. Heat and salinity fluxes are assumed zero at the bottom. All fluxes are assumed zero at the lateral boundaries (Blumberg and Mellor, 1987). In the ocean mixed layer, surface wave breaking is an important source of turbulent energy, supplementing shear production. Wave breaking plays an important role in enhancing TKE and dissipation in the upper ocean layer. The 1-D air-wave-sea coupled model results have been compared against all available observed data and used in the circulation-wave coupling study. The new version of the parameterization is based on results of both experimental and numerical studies, which show that breaking waves strongly enhance not only TKE dissipation, but also TKE. The new version of the parameterization is also modified to incorporate a boundary condition for velocity across the interface (Ly and Benilov, 2001).

Hereafter, subscript "*a*" is used for marine atmosphere characteristics, and subscript "*s*" for the oceanic ones. Based on conservation of energy and similarity theory (Ly, 1986), breaking wave effects can be incorporated in an equation for the TKE flux. Using a wave breaking condition from the linear wave theory, the oceanic TKE at the interface can be written in terms of wind stress and wave parameters (Ly, 1995; Ly and Garwood, 2000; Ly and Benilov, 2001). A similar equation can be written for the TKE dissipation. The current-wave relationship can be obtained from the equation for the energy fluxes. In the above equations, if $h = 0$ (no waves), we have traditional conditions for TKE, ε, and velocity at the interface (the wave layer becomes an interface surface in this case) (Ly, 1986; Ly and Garwood, 2000; Ly and Benilov, 2001).

The following wave-dependent roughness length (Ly and Garwood, 2000)

$$z_{0a} = 0.30\, u^2_{*a} / g c_w \qquad (5)$$

This roughness length has been used in the 1-D air-wave-sea coupled model and tested against available data. The comparison shows an agreement with observed data of all sources (Ly and Garwood, 2000). For the developed waves with wave age $c_w = 20\text{-}30$ the roughness length reduces to Charnock's (1955) formulation with the Charnock's constant of between 0.01-0.015.

The surface boundary conditions of the NAM ocean model include wind stress, heat and salinity fluxes. The bottom boundary conditions for TKE and ε, heat and salinity fluxes all approach zero. There are also conditions for bottom stress, which is determined by matching velocities with the log law of the wall (Blumberg and Mellor, 1987).

c. Circulation-Waves Coupling

The NAM box model (idealized California coastal regions) is used in a circulation-wave coupling study with idealized wave height and wave age fields. The study is focused on the sensitivity of the current field to the surface waves and on demonstration the capability of the NAM model in reproducing an observed upwelling feature for the idealized California coastal region. A stratified ocean with a specified initial temperature distribution is used in the experiment. This distribution is similar to observations off California. The initial salinity is assumed constant at 35.0 *psu*. Both initial temperature and salinity fields are horizontally homogeneous. The basin is 100 km wide and 500 km long. The depth approximates the bottom topography of the California Pacific coast. The basin covers a region with an ocean depth of 2000*m*, a continental shelf-slope and a narrow shelf of depth less than 100*m*. A horizontally homogeneous upwelling-favorable (northernly) wind stress of 2 $dyne\ cm^{-2}$ was imposed in a band 300-*km* long and 60-*km* wide in the south-eastern part of the basin. No wind stress curl and no surface heat flux are imposed. The temperature field of the 10-day simulation shows evidence of coastal upwelling along the shore, which is typical for the California coastal region in summer. Coastal upwelling is an observed and important physical phenomenon, which this numerical model can reproduce.

3. Conclusions

A new turbulence closure with the wave parameterization and wave-dependent roughness length is used for coupled model developing and testing against available data. The wave parameterization in the model is able to relate model parameters to wave parameters, which are standard outputs of wave prediction models. The NAM includes a new turbulence closure with the wave parameterization. The NAM box model (idealized California coastal regions) is used in a circulation-wave coupling study with idealized wave height and wave age fields. The study shows a strong sensitivity of the current field to the surface waves. The simulations show the capability of the NAM model in reproducing an observed upwelling feature for the idealized California coastal region.

REFERENCES

Agrawal, Y.C., E. A. Terray, M. A. Donelan, P. A. Hwang, A. J. Williams, W. Drennan, K. K. Kahma, and S. A. Kitaigorodskii, 1992. Enhanced dissipation of kinetic energy beneath breaking waves. *Nature*, 359, 219-220.

Blumberg, A. F. and Mellor, G. L. 1987. A description of a three-dimensional coastal ocean circulation model. *Three-Dimensional Coastal Ocean Models*, N. S. Heaps (Ed.), 1-16.

Charnock, H. 1955. Wind stress on a water surface. *Quart. J. Roy. Meteorol. Soc.* 81, 639-640.

Doyle, J. D., 1995. Coupled ocean wave/atmosphere mesoscale model simulations of cyclogenesis. *Tellus,* 47!, 766-778.

Janssen, P. A. E. M. 1989. Wave-induced stress and the drag of air flow over sea waves. *J. Phys. Oceanogr.* 19, 745-754.

Lionello, P., P. Malguzzi, and A. Buzzi, 1998. Coupling between the atmospheric circulation and the ocean wave field: an idealized case. *J. Phys. Oceanogr.*, 28, 161-177.

Lionello, P., P. Malguzzi, E. Elvini, A. Sanna, M. G. Villani, 1999. Progress in coupled meteo-oceanic predictions in the Mediterranean region. *Third Conf. on Coast. Atmosph. & Oceanic Pred. & Proc.* New Orleans, LA, 3-5 Nov. 247-252.

Ly, L. N. 1986. Modeling the interaction between atmospheric and oceanic boundary layers, including a surface wave layer. *J. Phys. Oceanogr.*, 16, 1430-1443.

Ly, L. N. 1991. An application of the *E-ε* varepsilon turbulence model to studying coupled air-sea boundary layer structure. *Boundary-Layer Meteorol.*, 54, 327-346.

Ly, L. N. 1995. A numerical coupled model for studying air-sea-wave interaction. *Phys. Fluids,* 7(10), 2396-406.

Ly, L. N. and R. W. Garwood, Jr. 2000. Numerical modeling of wave-enhanced turbule nce in the oceanic upper layer. *J. Oceanogr.*, 56, 373-383.

Ly, L. N. and A. Yu. Benilov (2001). Air-Sea Interaction: Surface Waves. *Encyclopedia of Atmospheric Sciences*. Ed. by J. Holton, J. Pyle and J. Curry. Academic Press. (Submitted).

Ly, L. N. and R. W. Garwood, Jr. 2001. An ocean circulation model with surface wave parameterization. *Applied Num. Math.* (To be appeared).

Welsh, D. J. S., R. Wang, P. Sadayappan, and K. W. Bedfort, 1999. Parallel coupling of hydrodynamic and wind-wave models. *Third Conf. on Coast. Atmosph. & Oceanic Pred. & Proc.* New Orleans, LA, 3-5 Nov., 111-112.

Wilczak, J., J. W. Bao, L. Kantha, and J. K. Choi, 1999. A regional. coupled atmosphere-ocean-wave modeling system. *Third Conf. on Coast. Atmosph. & Oceanic Pred. & Proc.* New Orlearns, LA, 3-5 Nov., 124-129.

Wittmann, P., M. Clancy and T.Mettlach,1995. Operational wave forecasting at FNMOC. *Fourth Inter. Workshop on Wave Hindcasting,* Downsview, On., Canada, 335-342