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Kinetic energy flux budget across air-sea interface

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ABSTRACT

The kinetic energy (KE) fluxes into subsurface currents (EF_c) is an important boundary condition for ocean circulation models. Traditionally, numerical models assume the KE flux from wind (EF_{air}) is identical to EF_c, that is, no net KE is gained (or lost) by surface waves. This assumption, however, is invalid when the surface wave field is not fully developed, and acquires KE when it grows in space or time. In this study, numerical experiments are performed to investigate the KE flux budget across the air-sea interface under both uniform and idealized tropical cyclone (TC) winds. The wave fields are simulated using the WAVEWATCH III model under different wind forcing. The difference between EF_{air} and EF_c is estimated using an air-sea KE budget model. To address the uncertainty of these estimates resides in the variation of source functions, two source function packages are used for this study: the ST4 source package (Ardhuin et al, 2010), and the ST6 source package (Babanin, 2011). The modeled EF_c is significantly reduced relative to EF_{air} under growing seas for both the uniform and TC experiments. The reduction can be as large as 20%, and the variation of this ratio is highly dependent on the choice of source function for the wave model. Normalized EF_c are found to be consistent with analytical expressions by Hwang and Sletten (2008) and Hwang and Walsh (2016) and field observations by Terray et al. (1996) and Drennan et al. (1996), while the scatters are more widely in the TC cases due to the complexity of the associated wave field. The waves may even give up KE to subsurface currents in the left rear quadrant of fast moving storms. Our results also suggest that the normalized KE fluxes may depend on both wave age and friction velocity (u_*).

1. Introduction

The kinetic energy (KE) flux from surface waves to ocean currents (EF_c) is responsible for the enhancement of the near surface turbulent kinetic energy (TKE) dissipation rate (e.g., Terray et al., 1996). Prediction of EF_c is not only essential for estimating bubble and sea spray generation, air-sea gas exchange, and other air-sea interaction processes, but also of great importance in determining both transfer rates across the air-sea interface to the mixed layer below and the evolution of the mixed layer itself.

EF_c is an important boundary condition for the turbulent closure models used to represent the small-scale turbulence in the oceanic boundary layer that cannot be resolved by the ocean models, such as the popularly used Mellor-Yamada level 2.5 closure (Mellor and Yamada, 1982). Turbulent closure models usually solve the TKE equation to obtain eddy viscosity (K) and eddy diffusivity for buoyancy (K_B) and energy (K_E):

$$\frac{\partial TKE}{\partial t} = \frac{\partial}{\partial z}\left(K_E\frac{\partial TKE}{\partial z}\right) + K\frac{\partial U}{\partial z}\frac{\partial U}{\partial z} + K_B\frac{\partial B}{\partial z} - \varepsilon \tag{1}$$

where the net flux of TKE at the ocean surface (z = 0) is given as $K_E\frac{\partial TKE}{\partial z} = EF_c$. Eq. (1) is only presented here to illustrate the importance of EF_c in turbulent closure models. The details of this equation including all terms, boundary conditions, and choice of parameters can be found in Noh and Kim (1999).

As important as EF_c is, it is often forgotten because, traditionally, numerical models assume the KE flux from wind (EF_{air}) is identical to EF_c and parameterize it using the friction velocity u_* as mu_*^3, where m is an empirical constant (Noh and Kim, 1999). Fully coupled models such as the Unified Wave Interface-Coupled Model (UWIN-CM) developed by University of Miami (Chen and Curcic, 2016; Curcic et al., 2016) that utilized UMWM (an efficient wave model to provide fully atmosphere-wave-ocean coupling in hurricane forecast systems, Donelan et al., 2012) and the Navy's Coupled Ocean Atmosphere Mesoscale Prediction System – Tropical Cyclone (COAMPS-TC, Smith et al., 2013) have explicitly taken into account of the wind-wave and wave-current momentum fluxes, but no special attentions have been given on the energy flux.

The assumption of EF_c equals to EF_{air} is invalid when the surface wave field is not fully developed. When surface waves propagate, they

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transport energy in the wave propagation direction. When waves grow (decay) in time, they extract more (less) KE from air than they give up to the subsurface currents. If the surface wave field is not homogeneous, the divergence of these fluxes will also contribute to the difference between EF_{air} and EF_c. Therefore, both spatial and temporal evolutions of the wave field need to be taken into account for accurate estimation of EF_c. This is especially true under tropical cyclone (TC) conditions where the surface wave field is complex and fast varying in space and time and may significantly affect the energy flux from wind into ocean.

Additionally, transfer of momentum and energy can occur both up and down in that swells can interact with the airflow and create wave-driven winds (Harris, 1966). Donelan et al. (1997) measured the air-sea momentum flux via eddy correlation off the coast of Virginia and found that swell aligned with the wind can deliver momentum to the atmosphere. When this happens, the momentum and KE flux to the ocean will be reduced consequently. In this study, we found that this negative flux is very small compare to the air input (less than 1%) in all our experiments and it can be neglected in the budget calculation.

Ocean wave modeling is a very useful and convenient way to obtain the spatial and temporal distribution of directional wave spectra without the limitations associated with measurements, although the model output may differ from observations because of uncertainties in wind input, model physics, and numeric. During the past 4 decades, considerable improvements have been made in predicting ocean wave directional spectra. Third generation wave models (e.g., WAVEWATCH III (Tolman, 1998), the Wave Model (WAM; Hasselmann et al., 1988), and Simulating Waves Nearshore (SWAN; Booij et al., 1999)) have been used to study surface wave responses during hurricanes, and the modeled wave parameters (significant wave height, mean/dominant wave length, mean/dominant wave direction) are shown to compare well with observations (Phadke et al., 2003; Moon et al., 2003; Xu et al., 2007; Fan et al., 2009b; Allard et al., 2014; Fan and Rogers, 2016). Fully coupled atmosphere-wave-ocean model is suggested for accurate hurricane predictions as well as the corresponding ocean responses (Chen et al., 2007, 2013; Fan et al., 2009a; Liu et al., 2011). Thus, it is essential to understand the behavior of the wave model generated KE flux, which is an important forcing for ocean circulation models, under different wind conditions.

The main objective of this paper is to investigate the effect of surface gravity waves on the KE transfer budget across the air-sea interface under moderate to high wind conditions. In particular, we focus on the difference between the KE fluxes from wind and those into currents by explicitly calculating the KE gained (or lost) due to the spatial and time variation in the surface waves. WAVEWATCH III (WWIII) is used to generate the wave fields for all the calculations.

An uncertainty in these estimates resides in the variation of source functions. Field measurements by Powell et al. (2003) and laboratory work by Donelan et al. (2004) and Takagaki (2012) have suggested that the drag coefficient flattens or even decreases with wind speed at high winds. Takagaki et al. (2016a, b) found in their tank experiments that the distinctive breaking of wind waves is the causes of the saturation of drag coefficients at strong wind speeds. Hence, several modifications to the source functions are implemented in WWIII to reflect such behavior. Liu et al. (2017) compared the performance of four different source function packages within the WWIII framework through intensive comparisons with radar altimeter measurements, scanning radar altimeter measurements, and buoy observations during hurricane Ivan in 2004. Source package ST3 (Janssen, 1991, 2004; Bidlot et al., 2007), ST4 (Ardhuin et al., 2010) and ST6 (Babanin, 2011; Rogers et al., 2012; Zieger et al., 2015) are found to give the most accurate results within the four. ST4 is adapted from Janssen (1991) and Bidlot et al. (2005, 2007) with a reduction of u_* (hence drag coefficient) implemented through reducing the wind input for high frequencies and high winds and allow a balance with a saturation-based dissipation. ST6 is developed based on Donelan et al. (2006) with constraints on the wind input from air-flow separation, wave steepness, and wave breaking. In this study, both source packages are used to calculate the KE gained or lost due to the spatial and time variation in the surface waves and to illustrate the uncertainty brought about by the variation of source functions.

The outline of this paper is as follows. The relation between the fluxes from wind, EF_{air}, and fluxes to currents, EF_c, are formulated in Section 2; a brief outline of the experimental design is introduced in Section 3; the air-sea budget calculation results using the ST4 source function are analyzed in Section 4; Section 5 discusses the uncertainty of the budget calculation due to different source functions using ST6 for illustration; A summary of the major results of this study and concluding remarks are presented in Section 6.

2. Wave spectrum and KE flux budget

Consider a two-dimensional system of orthogonal Cartesian coordinates with x increasing eastward, and y increasing northward. We are concerned with the air-sea KE fluxes influenced by surface gravity waves that are characterized by a wave spectrum $\psi(\omega, \theta)$, where ω is the wave angular frequency and θ is the wave direction. The ocean is assumed to be very deep ($k|D| >> 1$, where k is the wave number, and D is the water depth), therefore surface waves are not influenced by the ocean bottom. This assumption implies the deep water dispersion relation, $\omega^2 = gk$. We will focus our analysis on ocean areas away from the boundaries without concerns of any boundary effects.

WWIII version 4.18 (Tolman et al., 2014) is used to simulate the evolution of wave spectra for all experiments. The model explicitly accounts for wind input, wave-wave interaction, and dissipation due to whitecapping and wave-bottom interaction, and solves the spectral action density balance equation for directional wavenumber spectra. In this study, the wave spectrum in WWIII is calculated in 24 directions. In each direction, the spectrum is discretized using 40 frequencies extending from $f = 0.0285$ to 1.1726 Hz (wave length of 1.1–1920 m) with a logarithmic increment of $f_{n+1} = 1.1f_n$, where f_n is the nth frequency. The diagnostic tail, proportional to f^{-5}, is imposed at a cutoff frequency that is equal to 10 times of the mean frequency. Since the kinetic energy in the wave field is dominated by large waves near the peak, the effect of different spectra tail parameterization on KE is negligible and not investigated in this study.

The differences between the KE fluxes from wind and those into subsurface currents are estimated by explicitly calculating the KE gained or lost due to the spatial and time variation in the surface waves.

The total energy (E) contained in the wave field is obtained from the complete wave spectrum $\psi(\omega, \theta)$ as

$$E = \iint \rho_w g \psi(\omega, \theta)\cdot d\theta \cdot d\omega, \tag{2}$$

where ρ_w is the density of water. The horizontal fluxes of E are obtained as

$$EF_x = \iint \rho_w g C_g(\omega, \theta)\psi(\omega, \theta)\cos\theta \cdot d\theta \cdot d\omega, \tag{3}$$

$$EF_y = \iint \rho_w g C_g(\omega, \theta)\psi(\omega, \theta)\sin\theta \cdot d\theta \cdot d\omega, \tag{4}$$

where EF_x and EF_y are the total wave energy flux in the x and y directions, respectively, and C_g is the group velocity of the waves. Then, KE flux budget can be given as:

$$EF_{air} = EF_c + \left(\frac{\partial EF_x}{\partial x} + \frac{\partial EF_y}{\partial y}\right) + \frac{\partial E}{\partial t}, \tag{5}$$

On the right-hand side in Eq. (5), the term in the parentheses is the horizontal divergence of KE flux in the wave field, and the last term is the local time derivative of KE in waves, that is, KE gained (lost) by growing (decaying) waves.