P1D.6 *IMPACTS OF THE OCEAN SURFACE VELOCITY ON WIND STRESS COEFFICIENT AND WIND STRESS OVER GLOBAL OCEAN DURING 1958-2001*

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Abstract:

By accounting for the effects of ocean surface velocity (wave-induced surface drift velocity and current velocity) on the drag coefficient, the spatial distribution of drag coefficient and wind stress are computed over the global ocean during 1958-2001, using an empirical drag coefficient parameterization formula based on wave steepness and wind speed. The global ocean current field is generated from the Hybrid Coordinate Ocean Model (HYCOM) and the waves from Wavewatch III (WW3). The spatial variability of the drag coefficient and wind stress is analyzed. Preliminary results indicate that, the ocean surface drift velocity exerts an important influence on the wind stress. The results also show that accounting for the effect of the ocean surface velocity on the wind stress can lead to significant improvement in the modeling of ocean circulation and air-sea interaction processes.

Key words**:** wind stress, drag coefficient, ocean surface velocity, HYCOM, WW3, air-sea interaction

1. Introduction

The air-sea momentum exchange is of great importance on many oceanic and atmospheric studies, such as air-sea interaction, climate researches, and ocean modeling. Wind stress drag coefficient C_D, a dimensionless coefficient describes the surface roughness, is a key important variable that reflects the main characters of processes at the air-sea interface, such as momentum exchanges at the sea surface through wind stress.

In this paper, a relation given by Guan at el. (2004) is introduced to describe the sea surface drag coefficient. The theory of Guan at el. (2004) serves as a unified approach to reconcile the various forms of linear parameterization by introducing the wave steepness δ as another parameter besides 10-m wind velocity. Since sea surface roughness is due mainly to surface waves, take the wave state into account in C_D parameterization is necessary, and employ the wave steepness δ serves as the representation of the surface wave state is reasonably. Non-dimensional dominant wave steepness δ, a pure wave parameter measuring the wave status, is defined as, $\delta = H\omega_p^2 / g$, here, H is the significant wave height, ω_p is the angular frequency at the windsea spectral peak, and g is gravitational acceleration. Both the wind and wave information are contained in the parameterization of C_d according to the theory of Guan at el.(2004).

Traditionally, C_D is demonstrated to have a clear, mostly linear trend of increase with wind speed and is often expressed as a function of wind speed for easy operation, while larger scatter in the data suggested the other simultaneous influences, such as ocean surface velocity (wave –induced drift velocity and current velocity). Ocean surface velocity influences

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remain an important contemporary issue in air–sea interaction research. Kara et al. (2007) revealed that the ocean surface velocity effects on wind stress drag coefficient is to reduce C_d by about 2% globally. It is no deniable that C_d is a multi-factor-dependent coefficient, therefore, to improve the parameterization of C_d , two factors should be included as well as wind speed. One is wave status, which proposed above, the other is ocean surface velocity. In the region of sea surface velocity exists, it may not be simply only the wind velocity that is important for determining C_d , but the difference between near-surface wind velocity and ocean surface velocity. $\vec{U}_{10}$ is the 10-m wind velocity relative to the sea surface. Since the real ocean surface is not quiescence, taking the wind speed as the relative velocity is unreasonable. The wave-induced motion (especially the swell-induced motion) is a kind of drift, and one may wonder the impact of this drift on the air-sea interaction variables. The dependence of C_d on ocean surface drift velocity over the global Ocean will be examined herein.

The wind stress plays a weightily role in modeling various wind-driven air–sea interaction processes including sea state prediction, large-scale ocean circulation, and climate evolution. Accurate parameterization of the wind stress is needed to optimize the reliability of these model predictions. Many researches often approximate the surface wind stress τ exerted by the atmosphere on the ocean as a function of the 10-m wind velocity: $\tau = \rho_a C_d |\vec{U}_{10}| \vec{U}_{10}$, here $\vec{U}_{10}$ is 10-m wind velocity. This relationship neglects the ocean surface wave velocity $\vec{U}_w$ and current velocity $\vec{U}_c$ dependence in τ . Kelly et al. (2001) showed that scatterometer-derived wind stress over the tropical Pacific to be a function of air-sea velocity difference. It is reasonably to use following relation: $\tau_1 = \rho_a C_d |\vec{U}_{10} - \vec{U}_c - \vec{U}_w| (\vec{U}_{10} - \vec{U}_c - \vec{U}_w)$ which includes the effects of the ocean surface velocity. Use the improved wind stress τ_1 has been proven to lead to significant improvements in modeling of the tropical Atlantic Ocean by Pacanowski (1987), and the similar results in simulations of the tropical Pacific Ocean, by Luo et al. (2005).

In this paper, two fine resolution models, HYCOM and Wavewatch III, have been used to obtain the necessary wave and current variables.

2. Calculate the drag coefficient

Guan at el.(2004) developed a algorithm as follow,

$$C_d = [0.78 + 0.475\ f(\delta) |\vec{U}_{10}|] \times 10^{-3} \quad (1)$$

$$f(\delta) = 0.85^{B} A^{1/2} \delta^{-B} \quad (2)$$

where $|\vec{U}_{10}|$ is 10-m wind speed, $\delta = H\omega_p^2 / g$ is dominant wave steepness, *H* is significant wave height, ω_p is the angular frequency at the windsea spectral peak. Both *A* and *B* are from function $gz_0 / u_*^2 = A\beta_*^B$, where z_0 is the ocean surface roughness, u_* is the friction velocity of air, and β_* is the wave age. *A* and *B* are coefficients determined by observations. Different values of *A* and *B* have been proposed by various researchers. Since controversy remains over the nature of the dependence of roughness on wave age, here we set *A* = 0.02, *B* = 0.7 according to Sugimori et al. (2000). The positive value of *B* implies that mature waves are rougher than younger waves, and the negative corresponds to the contrary. Many researches indicated that, δ is completely comprised of wave parameters and it is more suitable than wave age for describing the wave dependence of drag coefficient.

Here, wind speed in (3) is replaced by a complex wind velocity consisted of wind velocity, current velocity and wave velocity.

$$C_d = [0.78 + 0.475 f(\delta) | \vec{U}_{tot} |] \times 10^{-3} \quad (3)$$

$$\vec{U}_{tot} = \vec{U}_{10} - \vec{U}_w \quad (4a)$$

$$\vec{U}_{tot} = \vec{U}_{10} - \vec{U}_c \quad (4b)$$

$$\vec{U}_{tot} = \vec{U}_{10} - \vec{U}_w - \vec{U}_c \quad (4c)$$

where $\vec{U}_{tot}$ is relative wind velocity, $\vec{U}_{10}$ is wind velocity, $\vec{U}_c$ is current speed vector(generated form HYCOM) and $\vec{U}_w$ is wave velocity. (4a) represents the relative velocity includes the wave velocity effects, (4b) includes the effects of current velocity, and (4c) includes both the effects.

According to the theory of Bourassa(2006),

$$\vec{U}_w = 0.8\vec{V}_{orb} \quad (5)$$

$$\vec{V}_{orb} = (3.14H/T) \cdot \vec{D} \quad (6)$$

where $\vec{V}_{orb}$ is the orbital velocity of the sea surface waves, *H* is significant wave height, *T* is dominant wave period and $\vec{D}$ is unit mean wave direction vector. All wave data used here are simulated by WW3, and the current data are output from HYCOM.

3. Results and analysis

Fig.7 shows the C_d values varie from 0.7×10^{-3} to 0.9×10^{-3} with some extreme values great than 1.5×10^{-3}. The region with large C_d value does not always correspond to the region that with high wind speeds. For example, in the westerly region, high winds prevails, but C_d is about 0.8×10^{-3}. Due to the significant, if not dominant, role of wave status form drag in the wind stress, the degree of development of the sea state provides one reason for this phenomenon. Large wave steepness values exist in this area, so, the waves can not be fully developed. It is also should be noticed that, the decrease of C_d with wave steepness is equivalent to the increase of C_d with wave age. Yet the dependence of C_d has not been easily resolved in drag coefficient measurements. While a few observational studies have reported evidence of wave steepness dependence in the drag coefficient primarily for short fetch and coastal sites, this behavior has been masked in the few open-ocean studies that reported data for a wide range of wave age. At higher winds where the sea state becomes dominated by the windsea, C_d values over the open Ocean are more nearly conform to the relationship for a fully developed sea. This implies a less rapid increase of C_d with increasing winds. It also indicates that wave δ - based formula will more accurately estimate the C_d in high wind conditions.

Fig.1 shows the details of effects of ocean surface wave induced velocity on C_d. ΔC_d varies from -0.01×10^{-3} to 0.01×10^{-3} approximately, the changes are less than 1% in most parts. In tropical Atlantic area, the change can reaches 1%. Fig.2 presents the influences of ocean surface current velocity on C_d. ΔC_d is generally between -0.007×10^{-3} and 0.003×10^{-3}, the maximum change reaches 1% at the equatorial Pacific. Fig.3 presents the influences of both wave induced velocity and current velocity on C_d. ΔC_d are generally from -0.01 × 10^{-3} to 0.01 × 10^{-3}. In most area, the change is about 1%.

Most of the researches in small-scale air-sea interaction are focused on the air-sided processes, including the transfer of momentum and sensible and latent heat. Also, the transportation of macro magnitude processes such as energy input from the wind to sea was assumed only depends on wind speed at a certain height above the ocean surface in many conceptual models. Very few attempts have been made to augment or replace wind speed with wave or current parameters in air-sea modeling. However, reality is usually far more complex. It is note that ocean waves can break without wind forcing by inherent hydrodynamic processes in water, such as wave-current interactions and shoaling.

As mentioned above, to obtain a reliable estimation of any reference variable defined in air-sea interaction field, the events on the water side including the waves and ocean surface velocity are indispensable. Following we discuss the wind stress by taking the wave information and ocean surface velocity effects into consideration.

Fig.4 shows the effects of wave induced velocity on wind stress, the $\Delta\tau$ generally vary from -0.012 Nm^{-2} to 0.012 Nm^{-2}, most of values are in the range of -0.009 Nm^{-2} to 0.009 Nm^{-2}, the maximum change can be 20%. In westerly and tropical areas, the change of wind stress is larger than other places. Fig.5 presents the value change of wind stress caused by surface current velocity. It is from -0.012 Nm^{-2} to 0.005 Nm^{-2}. There is obviously a maximum value region located at the central tropical Pacific, the percentage of change is close to 20%. The details of the influences of both wave induced velocity and current velocity on wind stress can be found in Fig.6. The maximum values of changes are occurred in the westerly and tropical regions.

4. Conclusions

The drag coefficient C_d and wind stress τ are believed to play a key role in many air-sea boundary studies. In order to understand the theory and evolution of these processes, it must be described quantitatively.

The question of a possible sea state dependence on the drag coefficient has received a lot of attention recently. The dependence of C_d on wave age for pure windseas has now been established, but in the open ocean where the variation in wave age is small, this is of secondary importance. The open ocean is dominated by swells, and how these impact the drag coefficient has not yet been established. Evidence to date has been contradictory.

Employing the wave steepness δ which characterizes the wave development for the case where effectively in local equilibrium with the relative wind, to model the C_d, we add surface wave and current velocity besides the wind velocity. All the analysis supports a sound conclusion that currents and waves can cause substantial changes in the C_d. This may explain some of the observed scatter in the measured C_d reported in the literature.

Over global Ocean, where we placed our focus on, the impacts of ocean surface velocity on C_d are to change it by generally vary form -0.01 × 10^{-3} to 0.01 × 10^{-3}. The effects of ocean surface velocity on wind stress are to change it by generally vary from -0.012 Nm^{-2} to 0.012 Nm^{-2} with the maximum change of 20%. The C_d includes the effects of wave and current velocity should be introduced to the ocean modeling, and further research is necessary to identify how this new C_d can improves the model performance.

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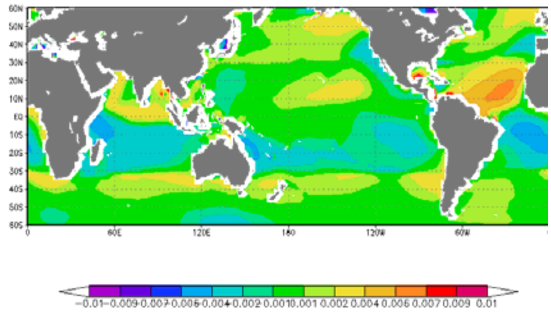

Fig.1 Changes of C_d value by the influences of wave induced velocity. (unit: 10^{-3})

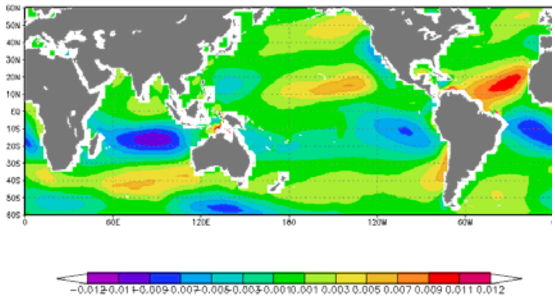

Fig.4 Changes of wind stress by the influences of wave induced velocity. (unit: N/m^2)

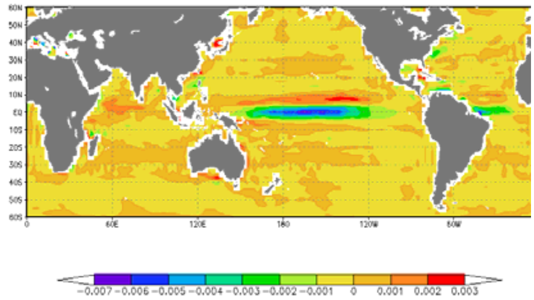

Fig.2 Changes of C_d value by the influences of current velocity. (unit: 10^{-3})

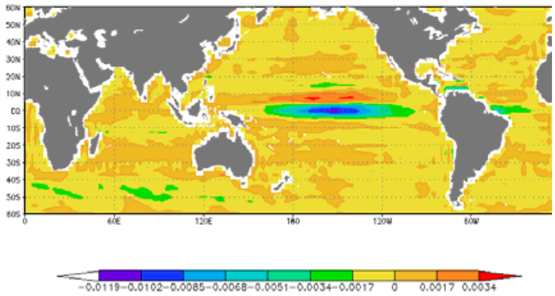

Fig.5 Changes of wind stress by the influences of current velocity. (unit: N/m^2)

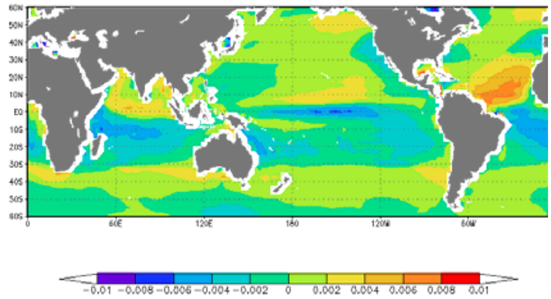

Fig.3 Changes of C_d value by the influences of current velocity and wave induced velocity. (unit: 10^{-3})

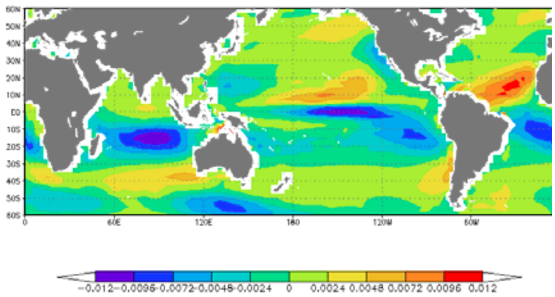

Fig.6 The changes of wind stress by the influences of wave induced velocity and current velocity. (unit: N/m^2)

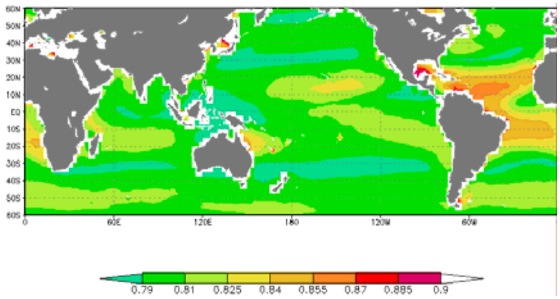

Fig.7 1959-2001 44-year mean C_d without the influences of Ocean surface velocity. (unit: 10^{-3})