Global Drag-Coefficient Estimates From Scatterometer Wind and Wave Steepness

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***Abstract*—A neural-network model was developed to retrieve the wave steepness (δ), which was used to represent the sea state (particularly wave state), from the European Remote Sensing (ERS) scatterometer onboard ERS-1/2. Using the retrieved δ and scatterometer wind speed, we calculated and examined the drag coefficient (C_D) over the global ocean. The results show that C_D changes significantly when wave steepness is included in the calculation. Combining wave steepness and wind speed increases C_D by nearly 14% on average. That change is spatially variable, ranging from -18.76% for the tropical Eastern Pacific Ocean to 104% for the Southern Ocean.**

***Index Terms*—Air–sea interaction, neural networks (NNs), remote sensing.**

I. Introduction

THE EXCHANGE of momentum and energy between the atmosphere and ocean through wind stress is very important for ocean modeling, climate prediction, and air–sea interaction studies. Typically, wind stress at the ocean surface is calculated using a bulk parameterization equation $\tau = \rho_a C_D U_{10N}^2$ [1] that does not take into account the influence of wave state. Here ρ_a is the density of air, U_{10N} is the wind speed at 10 m above the sea surface under neutral atmospheric stability, and C_D is a dimensionless drag coefficient describing the surface roughness. Drag coefficient is a key factor in estimating momentum transfer at the interface, and the sea state plays an important role in determining C_D [2]. Recently, a linear parameterization of C_D as a function of wind speed and wave steepness has been proposed and verified by open-ocean deep-water measurements in the Indian Ocean [3]. In this study, we examined the dependence of C_D on wave steepness over the global ocean using wave-steepness data retrieved from scatterometer data by a neural-network (NN) algorithm.

Wind stress is important in understanding and modeling of the air–sea interaction processes. Correspondingly, many studies have been conducted on C_D, and various relations have been proposed between C_D and wind speed [4]–[6]. In previous studies, empirical coefficients were used to describe the sea state; wind speed was the only variable employed to describe the air–sea momentum exchange with some purely empirical coefficients. However, it is apparent that the drag coefficient depends not only on wind force but also on the sea state [7]–[9]. For example, the Charnock coefficient (α) was suggested to be a proper description of aerodynamic roughness over the ocean [10]. More recently, wave steepness has been proposed to be an important variable in determining C_D [7].

Experiments have shown that drag C_D can vary by up to 50% in different wave states [11]. Guan and Xie [12] developed a function that uses wave steepness and 10-m wind speed as key parameters to calculate C_D. However, they overestimated C_D for mature waves [3]. As wave steepness is difficult to estimate over an open ocean, it is not routinely taken into account in calculating C_D. Recently, Deng *et al.* [13] has calculated C_D using the wave steepness from Wavewatch III ocean-surface wave-model outputs for the tropical and northern Pacific. In this study, we applied an NN model to estimate wave steepness over the global oceans and obtained the resulting spatial distribution of C_D. The time period of our study is from August 27 to 29, 1998.

Scatterometer wind-speed data [European Remote Sensing (ERS)-2] were used to calculate C_D. Since the radar scatterometer measures the backscatter from centimeter-scale processes caused by wind blowing over the ocean, the wind derived from the scatterometer backscatter represents the relative motion between wind vector $\vec{U}$, 10 m above the sea surface and the ocean-surface-current vector ($\vec{U}_S$). Thus, the scatterometer wind potentially includes the effect of ocean-surface currents $\vec{U}_{10} = \vec{U} - \vec{U}_S$, where $\vec{U}_{10}$ is the wind vector above the sea surface. This approach has an advantage over the anemometer wind and atmosphere-model wind products in calculating C_D [14].

II. Method and Data

Calculating C_D requires reliable wind-speed data. The ERS mission provides high-quality archived wind products. The microwave scatterometer was launched onboard the ERS-1 spacecraft in July 1991 and operated continuously until April 1995, when ERS-2 was launched, taking over its mission and

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continuing to provide observations until March 2000, transmitting and receiving vertically polarized signals at 5.3 GHz with a spacing of 25 km in 19 cells over the swath with a high temporal repetition rate (three days). In order to obtain C_D, a reliable 10-m neutral wind is required. Portabella and Stoffellen [15] derive a statistical conversion method by adding 0.7 m/s to ERS-1/2 winds to obtain the scatterometer 10-m neutral winds (U_{10}). Although the near-surface static stability has a considerable effect on the wind speed and direction above the ocean surface, the scatterometer winds are in fact statistically close to real winds [16].

The NN method is an empirical retrieval algorithm based on a highly connected array of elementary processors called neurons, and this method is widely used in satellite remote sensing [17]–[19]. Here, the NN model is constructed based on the structure of the NN algorithm established by Guo *et al.* [20], [21]. The training and validation data of the NN are derived from matchups of ERS-1/2 observations and buoy measurements. The buoy data are taken from the National Data Buoy Center (NDBC). The input data include incidence angle (θ), $\cos(\Phi - \varphi)$, where Φ is the azimuth angle and φ is the wind direction, normalized radar cross section (NRCS), and wind speed (U_{10}), all of which come from the ERS-1/2 level 1B available products. The output data are wave steepness (δ), which is computed as follows [3]:

$$\delta = H\omega_P^{5/2} U_{10B}^{1/2} / g^{3/2} \tag{1}$$

and, for deep water [22]

$$T = 0.91 \times 2\pi/\omega_P \tag{2}$$

therefore

$$\delta = 4.469 \times H\pi^{5/2} U_{10B}^{1/2} / T^{5/2} g^{3/2}. \tag{3}$$

Here, ω_p is the frequency of the wave spectral peak, T is the significant wave period, H is the significant wave height, and U_{10B} is the wind speed above the sea surface as measured by buoys. NDBC buoys collect wave data hourly. We pick the buoys far from the coast (> 50 km) in order to avoid the effect of the coast. We require that the buoy wave data and satellite scatterometer data be close in space and time, specifically, that their maximum spatial differences in latitude or longitude be less than $0.15°$, and that their maximum difference in time be less than 0.5 h. A total of 10 485 of ERS-1/2 scatterometer observations and corresponding NDBC buoy data were used. The buoy locations are shown in Fig. 1(a). These buoys have deep-water locations with average depth of 2212 m and with a minimum depth of 88.4 m. Of the total data, two-thirds were used to train the NN, and the remainder was used to verify the results. The δ correlation coefficient with the buoy measurements is 0.89, the root mean square is 0.0012, and the average absolute error is 0.0264 [Fig. 1(b)]. Here, the ERS-2 level 1B products are used to retrieve wave steepness using the NN model for the period from August 27 to 29, 1998 when the scatterometer had just covered the entire world ocean once. The distribution of the retrieved wave steepness δ is shown in Fig. 2(a). We choose typical values of -1.0 for B and 0.48 for

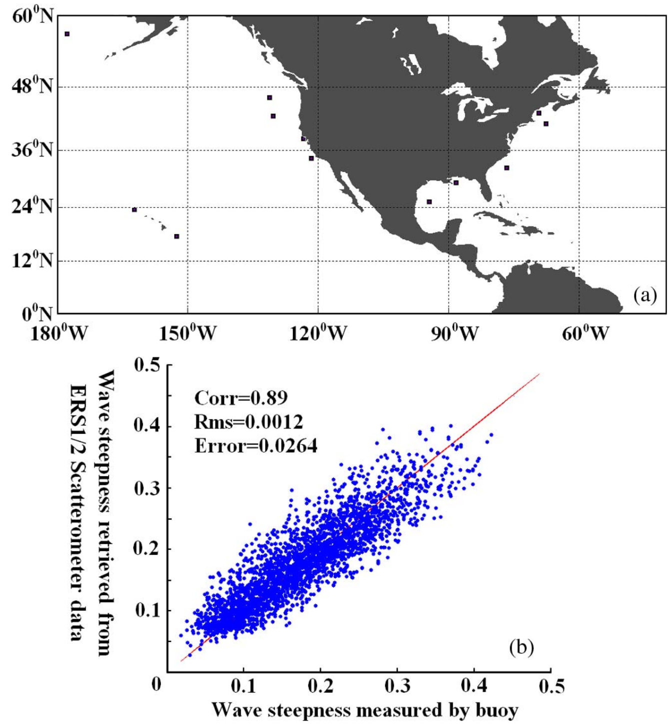

Fig. 1. (a) Distributions of buoys in the (diamonds) North Pacific and North Atlantic Ocean and (b) comparison of δ between the buoy records and those retrieved from ERS-1/2 data.

A to calculate the equivalent Charnock parameter $f(\delta)^2$ using (6) [Fig. 2(b)].

The Charnock formulation for calculating C_D is

$$C_{DC} = [0.78 + 0.47\alpha^{1/2} U_{10N}] \times 10^{-3}. \tag{4}$$

Kumar *et al.* [3] proposed a functional dependence that uses wave steepness and 10-m neutral wind speed as the key parameters in calculating C_D

$$C_{DN} = [0.78 + 0.47 f(\delta) U_{10N}] \times 10^{-3} \tag{5}$$

where

$$f(\delta) = 0.85^B A^{1/2} \delta^{-B}. \tag{6}$$

Both A and B are obtained from the function via observations

$$gz_0/u_*^2 = A\beta_*^{-B}. \tag{7}$$

Here, z_0 is the ocean-surface roughness, u_* is the friction velocity, and β_* is the wave age. However, different A and B values were used by various researchers [9]; positive B implies that mature waves are rougher than younger waves, while negative B implies the opposite. Thus, the nature of dependence of sea-surface roughness on wind waves still has not reached a consensus. The formulation proposed by Smith *et al.* [23] has been widely used by researchers, and further tested by Kumar *et al.* [3]. The drag coefficient C_{DN} considering the effect of wave steepness is calculated using (5). The result is shown in Fig. 3(a).

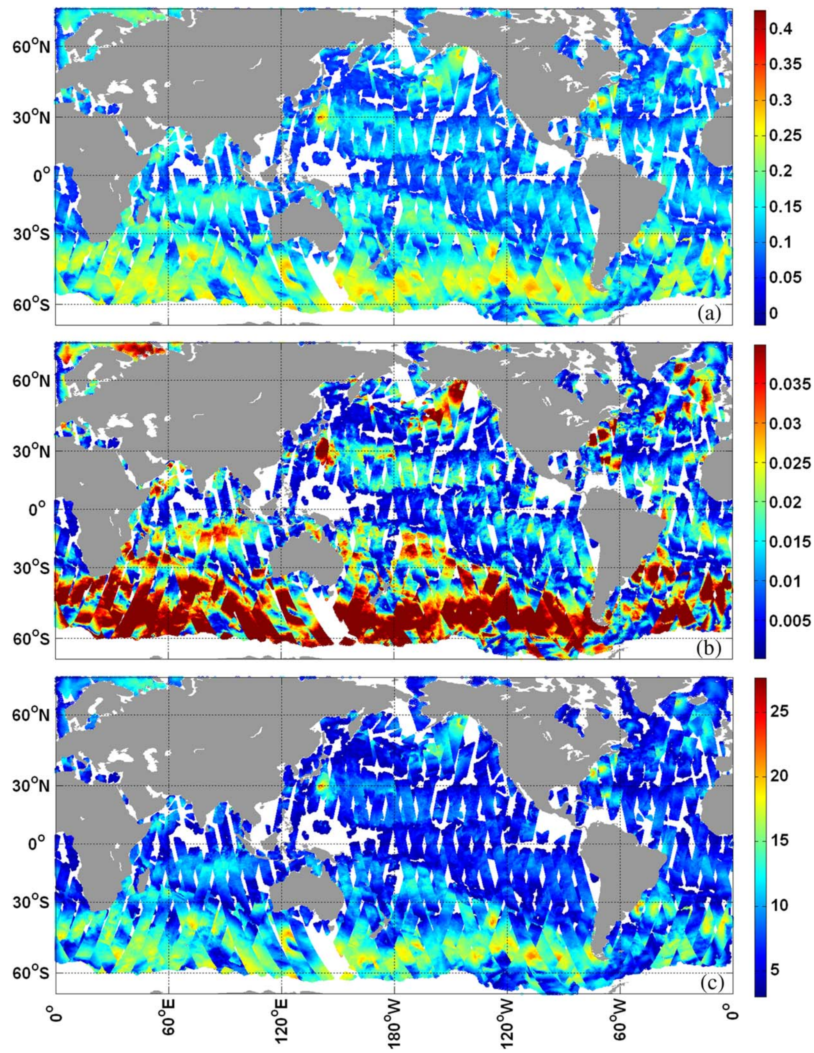

Fig. 2. (a) Distributions of wave steepness (δ) derived from ERS-2 data, (b) distribution of equivalent Charnock parameter $f(\delta)^2$ using (6), and (c) distributions of wind speed (in meters per second) over the global oceans from August 27 to 29, 1998.

III. Impacts of Wave Steepness on Drag Coefficient

Our results show that the values of C_{DC} (that depend on the wind speed only) vary from 0.92 to 2.2×10^{-3} and are generally smaller than 1.1×10^{-3} in most areas of the northern and tropical Pacific Ocean and the northern and tropical Atlantic Ocean; values greater than 1.6×10^{-4} are found at high southern latitudes and most of the Indian Ocean [Fig. 3(b)].

The retrieved global wave steepness [Fig. 2(a)] ranges from 0.02 to 0.43 and averages at 0.185 in the world oceans. There is a spatial distribution similar to that of wind speed [Fig. 2(c)]. The wave steepness is generally small in the Northern and middle Pacific and Atlantic Ocean but greater than 0.2 in the southern westerly zone and most regions of the Indian Ocean. The C_{DN} [that depends on δ and U_{10N} dependent, Fig. 3(a)] ranges from 8.0×10^{-4} to 3.5×10^{-3} and is often smaller than 1×10^{-3} in the tropical and Northern Pacific Ocean and some selected Atlantic Ocean regions where both wave steepness and wind speed are small. By comparison, C_{DN} is typically greater than 2.0×10^{-3} in middle southern latitudes and most of the Indian Ocean because of the influence of wave steepness in these regions.

Fig. 3(c) shows the percentage $(C_{DN} - C_{DC})/C_{DC} \times 100\%$, thus revealing the effect of wave steepness on C_D. The magnitude of $\Delta C_D(C_{DN} - C_{DC})$ is generally between -1.2×10^{-4} and 0.8×10^{-3}, with a maximum of 1.8×10^{-3}. Overall, the inclusion of wave steepness increases C_D by about 13.9%. However, spatial variations (from -18.76% to 104%) do exist (e.g., in the Southern Hemisphere's westerlies). By examining the effects of wave steepness, we found that in the tropical and Eastern Pacific and some Atlantic Ocean regions, ΔC_D is negative due to the combined effect of low wind speed and small wave steepness, while in the Southern Hemisphere's westerlies and most of the Indian Ocean, where high wind dominates the sea state, ΔC_D is generally greater than 0.6×10^{-3}. The results reveal a notable influence of wave steepness on the drag coefficient and indicate that areas of high wind speeds generally have higher values for δ and C_D, while in regions of weak winds and small δ values, the values are smaller than those of C_{DC}.

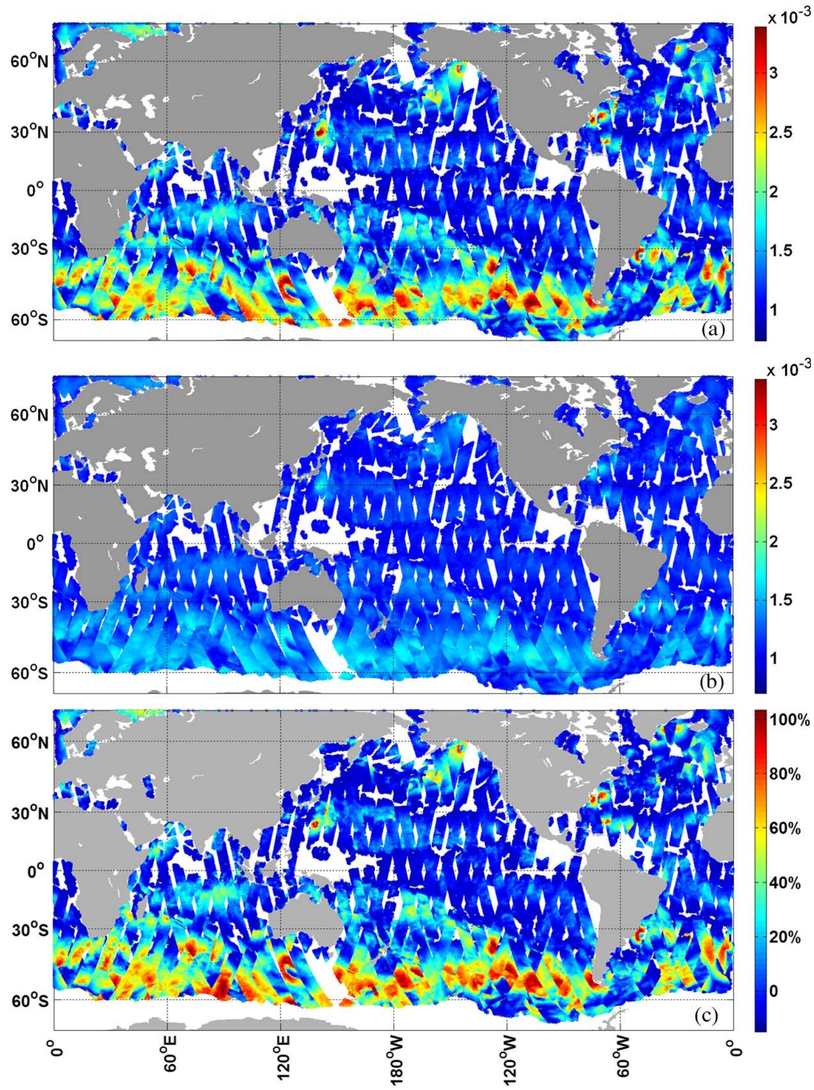

Fig. 3. (a) Distribution of C_{DN} based on wind speed and wave steepness, (b) distribution of C_{DC} calculated from wind speed and a constant $\alpha = 0.011$ proposed by Smith *et al.* [24], and (c) distribution of the percentage $(C_{DN} - C_{DC})/C_{DC} \times 100\%$.

IV. Conclusion

In this paper, we have employed an NN method to retrieve the wave steepness, which was used to calculate a corresponding drag coefficient. The input data for the NN were θ, $\cos(\Phi - \varphi)$, NRCS, and U_{10}, obtained via the ERS-2 scatterometer. Thus, this study provides, for the first time, information on the influence of wave steepness on satellite-data-based drag-coefficient calculations for the global oceans. This study shows that C_D changes significantly when wave steepness is employed in its calculation. Overall, computing C_D with wave steepness increases the global average value by about 13.9%. In terms of regional variability, C_D increases in the Southern Hemisphere oceans and most of the Indian Ocean and decreases in the tropical and Eastern Pacific Ocean and some Atlantic Ocean regions. These effects can greatly influence the performance of ocean models or air–sea interaction climate models. Therefore, when calculating C_D, it is recommended that the effect of wave steepness be taken into consideration.

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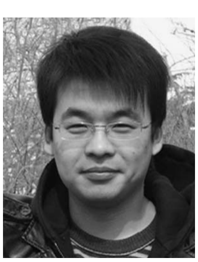

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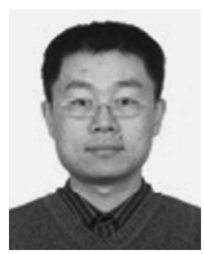

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