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Ocean current and wave effects on wind stress drag coefficient over the global ocean

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[1] The effects of ocean surface currents and dominant waves on the wind stress drag coefficient (C_D) are examined over the global ocean. Major findings are as follows: (1) the combination of both ocean wave and current speeds can result in reductions in daily C_D (>10%), but the notable impact of the latter is only evident in the tropical Pacific Ocean; (2) the presence of waves generally makes winds weaker and C_D lower almost everywhere over the global ocean; (3) strong ocean currents near the western boundaries (Kuroshio and Gulf Stream) do not substantially influence C_D since the winds and currents are not always aligned; and (4) the change in speed used in bulk flux parameterization also causes large changes in fluxes. Globally, the combined outcome of ocean currents and waves is to reduce C_D by about (2%), but spatial variations (0% to 14%) do exist. **Citation:** Kara, A. B., E. J. Metzger, and M. A. Bourassa (2007), Ocean current and wave effects on wind stress drag coefficient over the global ocean, *Geophys. Res. Lett.*, *34*, L01604, doi:10.1029/2006GL027849.

1. Introduction

[2] The momentum exchange through wind stress at the atmosphere and ocean interface is of importance for many purposes, including air–sea interaction studies, climate studies, ocean modeling, and ocean prediction on various time scales. The total wind stress magnitude (τ) at the ocean surface is typically calculated from the square of the wind speed at 10 m above the sea surface (V), the density of air (ρ_a), and a dimensionless drag coefficient (C_D) using $\tau = \rho_a C_D \mathrm{V}^2$ [*Fairall et al.*, 2003]. Turbulent energy fluxes are proportional to V. The change in fluxes due to the change in V is easily estimated. The dependence of C_D on sea surface currents and ocean waves will be examined herein.

[3] Possible impacts of ocean currents and wind waves on V and C_D were discussed in both theoretical studies [e.g., *Hwang*, 2005], and various regions of the global ocean [e.g., *Wuest and Lorke*, 2003]. In regions of strong currents (e.g., Kuroshio and Gulf Stream), it may not be simply the wind speed that is important for determining C_D, but the difference in near–surface winds and surface ocean currents. On the other hand, based on the authors' knowledge there is no quantitative study examining spatial and temporal variability of wind and wave effects on C_D over the entire global ocean. Such an investigation is essential because climate studies are often concerned about large–scale processes. Given the strong sensitivity of C_D to water vapor effects at very low wind conditions [e.g., *Kara et al.*, 2005], one would also need to determine the role of ocean currents and waves at these very low wind conditions.

[4] It may be important to take ocean current and wave effects into account in determining C_D over the global ocean. However, experimental measurements for ocean currents and waves are rarely available and those that are available do not have sufficient temporal and spatial resolution to determine their global distribution. Local process studies over many parts of the global ocean often exclude such current and wave effects on wind stress through C_D. In some regions, such effects might be so small (i.e., weak ocean currents and negligible wave heights) that they can be considered insignificant. If so, there is no need to include the impact of such factors, eliminating the need to obtain local current speed and wave height information at a specific time and place.

[5] Examining the spatial and temporal distribution of the influence of ocean currents and waves on C_D requires reliable global data sets. The quality of readily available archived numerical weather prediction (NWP) products, such as European Centre for Medium–Range Weather Forecasts (ECMWF) and the Navy Operational Global Atmospheric Prediction System (NOGAPS) has greatly improved since 1990s. They even provide high temporal resolution (e.g., 3–6 hourly) output over the global ocean. Thus, using the near surface meteorological variables from the existing NWP centers, C_D including air–sea stability can be determined. As to waves (i.e., significant wave height, dominant period, etc.), and ocean currents (speed and direction), their global coverages can also be obtained from wave models and ocean general circulation models (OGCMs) at high temporal resolution (see section 2).

[6] Given the need for a quantitative analysis of the impact of ocean currents and waves on C_D over the global ocean, the main focus of this paper is two–fold: (1) to present spatial variations of daily and monthly mean changes in the wind speed at 10 m above the sea surface and corresponding C_D when including vector averages of ocean currents and waves, and (2) to determine regions in the global ocean where surface currents and waves can have significant influence on C_D.

2. Methods and Data

[7] The correct parameterization of C_D is still somewhat controversial [*Taylor and Yelland*, 2001]. Testing the dif-

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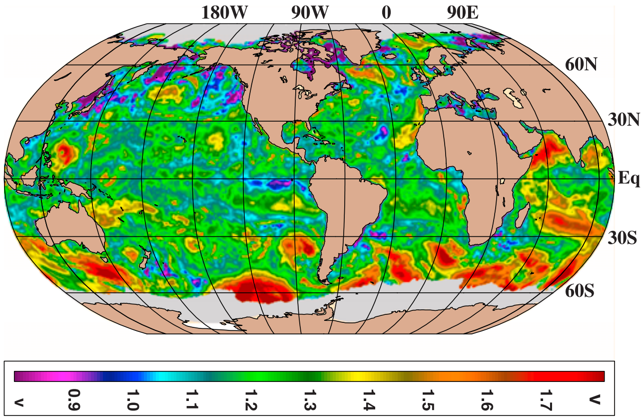


Figure 1. Spatial variations of wind drag coefficient over the global ocean on 1 Aug 2005 (00Z). Note values in the color bar must be multiplied by 10^{-3}. Effects of ocean currents and waves are excluded in calculating these drag coefficients. The regions where ice exists are masked out (shown in gray).

ferent formulations, *Bonekamp et al.* [2002] found that either a wave–age or wave–steepness dependent Charnock parameter was marginally superior to a linear dependence on wind speed. However, both sea state parameterizations perform better than linear bulk formula for most wind sea–dominant data sets. In fact, the mean is fairly well represented by the bulk formula, while the variability may not.

[8] In this paper, a bulk parameterization that takes full account of stability in calculating C_D is used. Such a parameterization is presented by *Kara et al.* [2005]. It is based on the state–of–the–art Coupled Ocean–Atmosphere Response Experiment (COARE) bulk algorithm (version 3.0), employing a turbulence theory based on the iterative estimations of the scaling variables to determine stability–dependent C_D [*Fairall et al.*, 2003]. C_D is expressed as polynomial functions of air–sea temperature difference, using air temperature at 10 m, V_a at 10 m and relative humidity at the air–sea interface to include air–sea stability. Due to deficiencies in the COARE algorithm itself at high winds, a constant C_D is used in the parameterization for winds >20 m s^{-1}.

[9] It is normally assumed that the stress direction is equal to the wind direction; however, both currents and waves can modify the stress direction [*Grachev et al.*, 2003; *Drennan and Shay*, 2006; *Bourassa*, 2006]. We account for this directional change in calculation of the magnitude of the stress.

[10] Global data sets used for calculating C_D are as follows: (1) Near–surface atmospheric variables including 10 m wind speed from 1° × 1° NOGAPS; (2) wave information from 1° × 1° Wave Watch 3 (WW3), a third generation wave model; and (3) ocean currents from an eddy–resolving 1/12° × 1/12° cos (latitude) OGCM, the HYbrid Coordinate Ocean Model (HYCOM). Details of all data are publicly available online, https://www.fnmoc.navy.mil/PUBLIC/ for data sets 1 and 2, and http://hycom.rsmas.miami.edu/for data set 3. Simulated ocean currents were binned to 1° squares, so that C_D could be calculated on

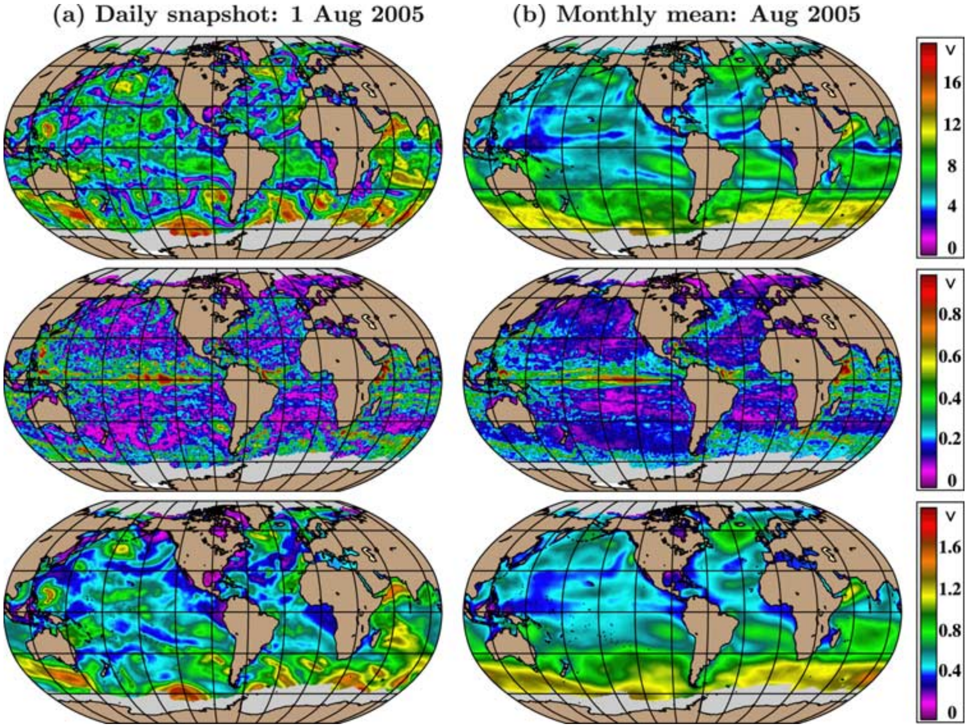


Figure 2. Daily snapshot and monthly mean of (from top to bottom) wind speed at 10 m above the sea surface, ocean current speed and dominant wave speed based on the orbital velocity (see text for calculations) at (a) 1 Aug 2005 (00Z), and (b) Aug 2005. The ice mask (gray) at high latitudes (which is not the focus of this study) is based on the NOAA ice climatology in August.

the same grid. The binning was necessary to have a consistency in grid resolutions of each data set.

3. Impact of Currents and Waves on the Drag Coefficient

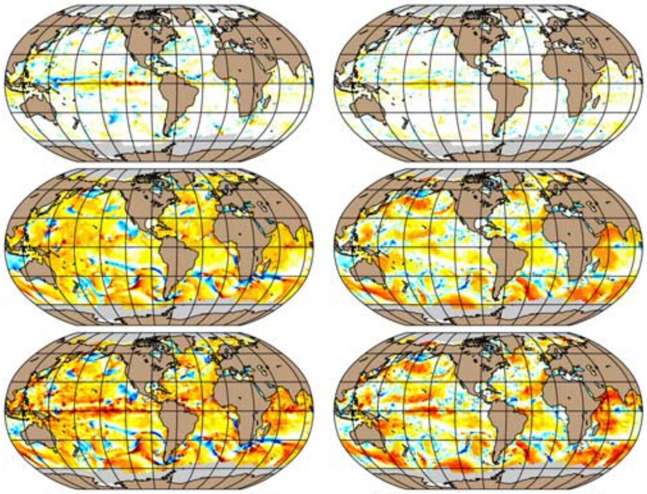
[11] In order to explore possible influences of ocean currents and waves on C_D, in the COARE–based C_D parameterization (see section 2), V is simply replaced by vector averages of V–VC (V–VW), providing an insight of the effects of current speed (wave speed). Here, V is the wind speed relative to the sea surface, VC is the ocean current speed at the sea surface, and VW is the wave speed. For simplicity, we drop vector notation from each term. Note that the vector averages are formed after V, VC and VW are decomposed to their components in directions. V is also replaced by V–VC–VW to determine the impact of both currents and waves on C_D at the same time.

[12] Using the data sets (section 2), V and VC values are used directly from NOGAPS and HYCOM, respectively. VW is calculated using data from the WW3 model. Following *Bourassa* [2006], VW is expressed as 0.8 V_{orb}. The orbital velocity ($V_{\mathrm{orb}} = 3.14\ H/T$) is based on significant wave height (H) and dominant wave period (T). We obtain V, VC and VW at each 1° × 1° grid point over the global ocean.

[13] C_D is first calculated based solely only on V (i.e., without including effects of VC and VW). Calculations are performed at each 3 hourly time interval at each grid for a given. As an example, Figure 1 shows how variable C_D can be over the global ocean for a given day, at 00Z on 1 Aug 2005. C_D has generally a value of $<1.0 \times 10^{-3}$ in the eastern tropical Pacific, and $>1.6 \times 10^{-3}$ at high southern latitudes and in the Indian Ocean at this particular time. Magnitude of V values used for calculating C_D are provided in Figure 2, along with means in Aug 2005. Large C_D values (Figure 1) generally correspond to regions having high V over the global ocean.

[14] VC and VW are generally very small (<1 m s^{-1}) in comparison to V, and this is evident from both the daily snapshot and monthly mean values (Figures 2a and 2b). VC variability may seem to be noisy, but note that they are from a fine resolution eddy–resolving OGCM (section 2). Relatively large VC (>1 m s^{-1}) are seen in the central tropical Pacific. Currents are also strong in the Kuroshio and Gulf Stream, having speeds of (>1 m s^{-1}). The binning of current speed (from 1/12° resolution to 1°) also resulted in losing the actual strength of some OGCM–based currents at these two regions. As to VW shown in (Figures 2a bottom and 2b bottom), they are generally weak in regions of the western boundary currents. This is because of relatively small wave heights (not shown).

[15] Realizing the large spatial variability in wind, ocean current and wave speed, we now focus on daily and monthly mean changes in V and C_D (Figure 3) when including VC and VW in V. The outcome of adding vector averages of VC components themselves to V components is small over the global ocean except the tropical Pacific where VC is relatively large and its components generally have same the direction as V. Overall, including VC generally results in a decrease of ≈20% in the central equatorial Pacific on 1 Aug 2005 (Figure 3a), but changes in daily C_D are relatively small (Figure 3b). In reference to a given daily V value of 8 m s^{-1} (see Figure 1), the 20% reduction translates to a V value of ≈6.5 m s^{-1}, entering C_D calculation in this particular region. The impact of including wave effects on daily V (i.e., V–VW), and hence C_D, is much larger than that of current effects (i.e., V–VC) over many parts of the global ocean. The overall influence of daily VC (VW) is to reduce V by 1.0% (5.4%) globally. The corresponding decrease in daily C_D is small, 0.3% (1.7%).


(a) Daily change: ΔV (b) Daily change: ΔC_D

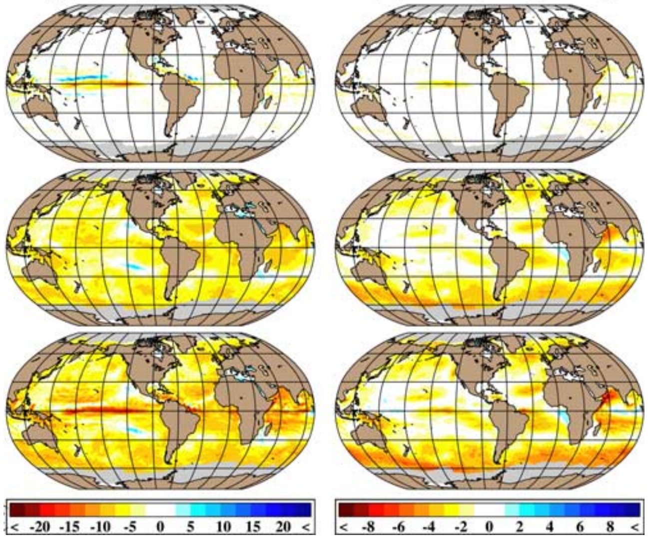

(c) Monthly change: ΔV (d) Monthly change: ΔC_D

Figure 3. Percentage change in (a) wind speed and (b) wind stress drag coefficient when adding (top) effects of surface ocean currents (V–VC), (middle) surface ocean waves (V–VW), and (bottom) both of them (V–VW–VC) on 1 Jan 2005 (00Z). (c, d) Similar percentage changes but values are averaged over a month, during Aug 2005. In all plots, blue (red) color indicates percentage increase (decrease).

[16] The combination result of adding daily VC and VW to V (i.e., V–VC–VW) is further to reduce V (e.g., >20%), but relatively less for C_D over a large extent of the global ocean (Figures 3a, bottom; and 3b, bottom). For example, a C_D value of $\approx 1.2 \times 10^{-3}$ in the central equatorial Pacific

(see Figure 1) reduces by ≈10% (1.1×10^{-3}). Because a vector averaging is performed for V–VC–VW using horizontal and vertical components of the each term, a consistent increase or decrease in the final result that may be evident the individual V–VC and V-VW fields should not be expected. For example, there is almost no change in the daily V–VC case and ≈–5% change for the V–VW case in the northern Indian ocean, but the resulting V–VC–VW can even be ≈<–10%. This is also reflected in C_D when using V–VC and V–VW in the C_D parameterization at the same region.

[17] Insights gained from examining the impact of daily VC and VW on both V and C_D are extended to monthly time scales, and again this is done during northern (southern) hemisphere summer (winter) over the global ocean (Figures 3c and 3d). In comparison to values on 1 Aug 2005, monthly mean change in C_D can usually be ignored at mid–latitudes, while a reduction of ≈5% is noted at other places.

[18] One thing to emphasize is that the data sources used here (NOGAPS, WW3 and HYCOM) have their unique errors as do other similar data sources. Thus, one might argue that there is not nearly enough information to make an estimate as to whether the wind errors from using these data source would not swamp out any signal in C_D changes shown in this paper. On the other hand, they are considered good enough for our purposes. For example, comparisons of 1291 month–long wind speed time series from NOGAPS (used in this paper) and ECMWF with respect to those at mooring buoy locations gives a median wind speed bias of 0.62 m s^{-1} and 0.53 m s^{-1}, respectively (not shown).

4. Conclusion

[19] Currents and waves can cause substantial changes in the drag coefficient on daily time scales. This may explain some of the observed scatter in the measured C_D reported in the literature. For the calculation of surface turbulent fluxes via bulk parameterizations, the change in V is much more important; however, the change in C_D is non negligible when integrated over time. Heat and moisture transfer coefficients have little dependence on V, except through changes in atmospheric stability; therefore changes in these coefficients are expected to be less than changes in C_D. Monthly averaged speed is typically reduced by 5%, resulting in 5% reduction in heat fluxes, and 10% in stress. Such effects can subtly influence the performance of ocean–only, coupled ocean–atmosphere or ocean-wave–atmosphere climate models.

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