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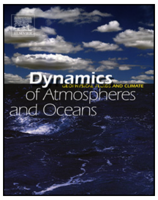

Foam input into the drag coefficient in hurricane conditions

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ABSTRACT

A semi-empirical model is proposed for the estimation of the foam impact on the variation of the effective drag coefficient, C_d, with the reference wind speed U_{10} in stormy and hurricane conditions. The proposed model treats the efficient air–sea aerodynamic roughness length as a sum of two weighted aerodynamic roughness lengths for the foam-free and foam-covered conditions. On the basis of available optical and radiometric measurements of the fractional foam coverage and partitioning of the ocean surface into foam-covered and foam-free areas, the present model yields the resulting dependence of C_d vs. U_{10} within the range from low to hurricane wind speeds. This dependence is in fair agreement with those obtained from both open-ocean and laboratory measurements of the vertical variation of the mean wind speed. The velocity value, at which the fractional foam coverage is saturated, is found to be responsible for the difference of C_d behavior in the laboratory and open-ocean conditions.

1. Introduction

Saturation/reduction of the effective drag coefficient, C_d, for the air–sea interface with wind speed rising up to hurricane (typhoon) conditions has been a focus of intensive experimental investigation over the last decade. Many field experiments (Powell et al., 2003; Black et al., 2007; Edson et al., 2007; Jarosz et al., 2007; Holthuijsen et al., 2012), laboratory (Donelan et al., 2004; Reul et al., 2008; Troitskaya et al., 2012), and theoretical studies (Bye and Jenkins, 2006; Kudryavtsev and Makin, 2007; Bye and Wolff, 2008; Mueller and Veron, 2009; Soloviev and Lukas, 2010; Suzuki et al., 2013; Soloviev et al., 2014, etc.) have been conducted to study variations of the ocean-surface momentum transfer and effective drag coefficient with wind speed in hurricane conditions. A reduction of the ocean-surface drag coefficient in hurricane conditions instead of its monotonic growth with wind speed (predicted by the Charnock relation that is commonly employed in moderate wind conditions Charnock, 1955) has been found by Powell et al. (2003). As conjectured by Powell et al. (2003) and Holthuijsen et al. (2012), the foam cover increases due to wave breaking and forms a slip surface on the atmosphere–ocean interface that leads to a saturation/reduction of the effective drag coefficient in hurricane conditions. Saturation in the drag coefficient growth has been observed in laboratory experiments by Donelan et al. (2004) who note that “one may expect a qualitatively different behavior in its properties than that suggested by observations in moderate wind conditions”.

The principal role of the air–sea foam layer has been first suggested by Newell and Zakharov (1992). According to empirical data, foam formation is highly correlated with wind speed and sea gravity waves breaking (Stogryn, 1972; Monahan and O’Muircheartaigh, 1980; Monahan and Woolf, 1989; Reul and Chapron, 2003; Callaghan et al., 2007, etc.). The foam fractional

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coverage (foam fraction) monotonically increases with wind speed up to its saturation level (Holthuijsen et al., 2012). Properties of the near-surface water and the foam fractional coverage are changed when the wind speed increases (Camps et al., 2005; Boutin et al., 2012): foam salinity is dropping, while the main share of the foam coverage is formed by wind-aligned streaks, i.e. the "old" foam characterized by foam bubbles of larger sizes than those of whitecaps. In detail, wave breaking produces whitecaps together with wind-aligned streaks (Monahan and O'Muircheartaigh, 1980; Monahan and Woolf, 1989; Reul and Chapron, 2003; Callaghan et al., 2007; Holthuijsen et al., 2012). Whitecaps production rises with wind speed and reaches its maximum when U_{10} exceeds the storm strength $U_{10} \approx 25\,\mathrm{m\,s^{-1}}$ (see e.g., Powell et al., 2003; Anguelova and Webster, 2006; Anguelova and Peter, 2012; Holthuijsen et al., 2012). The coefficient of the foam fractional coverage, α_f, up to whitecaps saturation stage is sufficiently small, $\alpha_f \sim 0.01$–0.15. In turn, wind-aligned streaks continue to grow with wind speed. As the wind reaches the hurricane strength ($U_{10} \approx 30$–$35\,\mathrm{m\,s^{-1}}$), wind-aligned streaks of foam bubbles combined with whitecaps cover the ocean surface, and when U_{10} reaches $\approx 40\,\mathrm{m\,s^{-1}}$, a foam layer covers the ocean surface almost completely when the foam fraction approaches the saturation value (Reul and Chapron, 2003; Powell et al., 2003; El-Nimri et al., 2010; Holthuijsen et al., 2012).

Foam input into air–sea interaction in hurricane conditions was studied by Shtemler et al. (2010). The air–sea system has been modeled by distributing foam spots homogeneously over the sea surface as a three-fluid system of the foam layer sandwiched between the atmosphere and the sea. They argued on physical grounds that the average roughness length for the foam–atmosphere interface should correlate with the characteristic size of the sea foam bubbles at hurricane wind speeds. Indeed, the characteristic size of the sea foam bubbles of the order of 0.1–2 mm (see, for example, Soloviev and Lukas (2006) and references therein) well agrees with the experimental correlation for average aerodynamic roughness length ~ 0.1–2 mm (Powell et al., 2003). Such a correlation between the aerodynamic and geometric roughness lengths at strong winds over the foamed sea surface distinguishes mobile systems from fixed beds. Namely, the aerodynamic roughness length of fixed beds significantly differs from the geometrical sizes of solid particles that constitute the beds (see a review by Dong et al., 2001 and references therein): for wind-blown sand surfaces Bagnold (1941) proposed a 1/30 law for the proportionality coefficient between the aerodynamic and geometric roughness. This law has been supported by Nikuradse's tests (Nikuradse, 1950) in pipes with inner walls artificially roughened by ideal sand grains of uniform radius. For non-ideal fixed beds, this coefficient depends on the wind speed and may vary significantly in a wide range of values. Fortunately, aerodynamic "roughness length has proven to be much more sensitive to the properties of ground surface" than other parameters, such as the surface drag coefficient and the effective surface momentum flux. For instance, for some fixed beds, the drag coefficient increases only $\sim 10^2$ times, while the aerodynamic roughness length increases $\sim 10^4$ times (Dong et al., 2001). They believe this is a reason why the aerodynamic roughness length has been widely used to characterize the aerodynamic properties of various fixed-bed surfaces. The difference between the aerodynamic roughness of fixed and mobile beds has been discussed in that work also. They noted that mobile surfaces should adapt to the wind by changing roughness. For relatively weak winds blown over a mobile bed, such as water, the roughness length is well approximated by the well-known Charnock's equation (1955). However, Charnock's equation predicts unrealistically high values of the effective drag coefficient for strong winds and should be substituted by a proper relation for the roughness of the sea surface foamed in hurricane conditions. In the absence of such relation, the sea surface roughness may be evaluated through indirect estimates of C_d (e.g., Powell et al., 2003) based on measurements of the vertical variation of the mean wind speed up to storm and hurricane conditions at some distance above the sea surface and then extrapolated using the log-law model of the wind profile to the fictitious zero wind speed. In addition to the effective roughness length, Z_0, this procedure completely determines the effective values of the drag coefficient, C_d, and the surface friction velocity, U_*, vs. the wind speed at 10 m reference height, U_{10}. This provides parameters of the logarithmic profile of the wind speed for further theoretical modeling of the atmosphere-sea interaction in hurricane conditions. For instance, Chernyavski et al. (2011) model the sea surface stability based on the effective aerodynamic roughness in the logarithmic wind profile instead of the effective aerodynamic roughness based on Charnock's formula. They also demonstrate that the wind stability model for hurricane conditions based on Charnock's formula underestimates by an order the growth rate of perturbations (the coefficient of the exponential growth of small perturbations of the air–sea interface induced by a logarithmic wind with time).

Such estimations of C_d, U_*, and Z_0 are based on the logarithmic law for wind profiles. At least, approximate validity of these assumptions in storm and hurricane conditions is the key point for such models (Tennekes, 1973). The applicability of Tennekes' (1973) theory to hurricane conditions is discussed by Smith and Montgomery (2014) (see also references therein). Remind that for the applicability of Tennekes' theory, the radial wind component should be negligibly small as compared with the tangential one, and they illustrate that this condition is approximately satisfied for storm and hurricane (typhoon) conditions with a relatively low error (lines 1 and 2 in Fig. 4 in Smith and Montgomery, 2014). This is also supported by nearly vertical trajectories of the dropsondes observed during storm and typhoon stages of supertyphoon Jangmi (Sanger et al., 2014). Hence, for storm and hurricane conditions, relatively small radial wind components, as well as deviations of the tangential wind components from the log-law may be expected. In particular, turning of the wind vector that occurs near the ocean surface (which violates the constant flux layer and the applicability of the logarithmic layer) should be neglected. However, these conditions cannot be satisfied for supertyphoon stage (Sanger et al., 2014, see also lines 3 in Fig. 4, Smith and Montgomery, 2014). Smith and Montgomery (2014) also demonstrate strong deviations from the log-law of the mean wind speed which results from averaging over several typhoons including a few supertyphoons (see Fig. 7 in Smith and Montgomery, 2014). Powell et al. (2003) and Holthuijsen et al. (2012) argue that they obtain representative resulting mean wind profiles by averaging wind data sets obtained by grouping dropsondes with similar mean boundary layer wind speeds.