NOTES AND CORRESPONDENCE

Variations of Whitecap Coverage with Wind Stress and Water Temperature

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ABSTRACT

Results of whitecap coverages from five previously reported oceanic experiments by Monahan and coinvestigators have been analyzed; the fractional coverage of the sea surface (W) was shown to follow a power law, $W = 2U_{10}^{3.75}$, where U_{10} is the wind velocity at 10 m above the mean sea surface. Attempts were then made to associate the coverage with the wind-friction velocity (u_*) deduced from the wind velocity and air-sea temperature difference as $W = 0.2u_*^3$. Finally, we discuss effects of the water temperature on the coverage.

1. Introduction

Under a continuous influence of the wind, waves grow and eventually become unstable locally; the waves then break to dissipate excess energy provided by the wind. The breaking is marked by whitecaps. Earlier observations on whitecap coverage of the sea surface made by Monahan (1971) in the Atlantic Ocean and by Toba and Chaen (1973) in the Pacific Ocean were analyzed by Wu (1979) to show that the variation of coverage with wind velocity can be related to the energy flux from wind to waves. In addition to Monahan (1971) compiled during the Barbados Oceanographic and Meteorological Experiment (BOMEX), data were collected subsequently by Monahan et al. (1981) during the Joint Air-Sea Interaction (JASIN), by Doyle (1984) during the Storm Transfer Response Experiment (STREX), and by Monahan et al. (1985) during the Marginal Ice Zone Experiment (MIZEX). All these sets of data carefully collected by Monahan and his coinvestigators also contain simultaneously measured air and sea temperatures.

The rate of energy supplied by the wind is closely related to the wind stress, of which the coefficient depends strongly on atmospheric stability conditions (Dyer 1974; Wu 1986). In spite of this, the whitecap coverage has always been related principally to the wind velocity without consideration of stability effects rather than to the wind stress incorporating these effects. In this study, all reported data were reanalyzed to associate the whitecap coverage to the wind-friction velocity, being proportional to the square root of the wind stress. Subsequently, effects of the water temperature, suggested by Wu (1979) and discussed by Monahan and O'Muircheartaigh (1986) were evaluated.

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2. Previous results on whitecap coverage and wind-stress coefficient

a. Whitecap coverage

1) ANALYTICAL CONSIDERATIONS

Waves break when there is excessive energy supplied by the wind, while the viscous dissipation is generally insignificant. In an equilibrium state, the energy lost through wave breaking must be balanced by the energy gained from the wind. Consequently, the percentage of sea surface covered by breaking waves under the equilibrium state can be related to the energy flux from the wind (Wu 1979),

$$W \sim \dot{E} \tag{1}$$

where W is the fraction of the sea surface covered by whitecaps, and $\dot{E}$ the rate of energy supplied by the wind per unit area of the sea surface. The rate of energy flux can be expressed as the product of wind stress (τ) and surface drift current (V), and the latter was found (Wu 1975) to be proportional to the wind-friction velocity (u_*); consequently, Eq. (1) is written as

$$W \sim \dot{E} \sim \tau V \sim (\rho u_*^2)u_* \sim u_*^3 \tag{2}$$

where ρ is the density of air. Adopting that the wind-stress coefficient varies with the square root of wind velocity (Wu 1969; Garratt 1977), Wu (1979) found earlier

$$W \sim u_*^3 \sim (C_{10}^{1/2} U_{10})^3 \sim U_{10}^{3.75} \tag{3}$$

where U_{10} is the wind velocity measured at 10 m above the mean sea surface, and C_{10} is the wind-stress coefficient, $C_{10} \sim U_{10}^{1/2}$.

2) OCEANIC RESULTS

Photographic observations of whitecaps made by Monahan (1971) during BOMEX in the Atlantic Ocean and by Toba and Chaen (1973) in the East China Sea were processed to determine the fractional area of sea surface covered by whitecaps. Both sets of results were replotted by Wu (1979) in a form illustrating best the power-law variation as suggested in Eq. (3); see the reproduction in Fig. 1a, in which a remarkable agreement is displayed between the two sets of data.

Following the discussion under analytical considerations, a line with a 3.75 slope was fitted on the basis of least squares to the data in Fig. 1a. Expressed as

$$W = 1.7U_{10}^{3.75} \tag{4}$$

where W is measured in ppm and U_{10} in m s^{-1}, the line is seen in the figure to represent the data well, verifying the energy consideration. Subsequently, Monahan and O'Muircheartaigh (1980) used two different statistical methodologies to fit the data, and suggested lines having slopes of 3.41 and 3.52, with that of 3.41 shown in Fig. 1a; both lines, however, deviate from the main body of the data outlined with fine dashed lines (Wu 1982). We note further that the 3.75 power was deduced on the basis of physical reasoning not just curve fitting, and that the type of formula shown in Eq. (4) should be upgraded to associate the whitecap coverage with wind-friction velocity.

b. Wind-stress coefficient

1) STABILITY PARAMETER

Relative importance of buoyancy effects associated with density stratifications with respect to forced effects driven by the shear stress on turbulent transfers is generally represented by the Monin–Obukhov length, L, defined as (Dyer 1974),

$$L = -\frac{u_*^3}{g\kappa\overline{\rho' w'}/\bar{\rho}} \tag{5}$$

where g is the gravitational acceleration, κ the von Kármán universal constant, ρ' and w' are fluctuations of the air density and the vertical component of wind velocity, respectively; and the over bar indicates the temporal average. The Monin–Obukhov length is, however, inconvenient to use, as variables u_* and $\overline{\rho' w'}$ are exactly the ones to be determined. Reflecting stability effects and being readily definable, an approximate parameter was proposed from available measurements $\Delta T/U_{10}$ where ΔT is the air–sea temperature difference (Wu 1986), established on the basis of available data (Smith 1980),

$$\text{Unstable cases:} \quad \Delta T/U_{10} = -1.30(-Z/L)^{0.6}$$

$$\text{Stable cases:} \quad \Delta T/U_{10} = 1.35(Z/L)^{0.6} \tag{6}$$

where $Z = 10$ m is the standard anemometer height.

2) WIND-STRESS COEFFICIENT

Following a review of various models correcting stability effects on the wind-stress coefficient, Wu (1986) proposed

$$\text{Unstable cases:} \quad C_s/C_{10} = \exp(-0.95Z/L)$$

$$\text{Stable cases:} \quad C_s/C_{10} = \exp(-0.70Z/L) \tag{7}$$

where C_s and C_{10} are the wind-stress coefficients under unstable (or stable) and neutral conditions. The neutral coefficient was suggested by Wu (1980) as

$$C_{10} = (0.8 + 0.065U_{10}) \times 10^{-3} \tag{8}$$

in which U_{10} is also expressed in m s^{-1}.

Combining Eqs. (6) and (7), Wu (1986) proposed the following correction of the wind-stress coefficient for stability effects

Unstable cases:

$$C_s/C_{10} = \exp[0.614(-\Delta T/U_{10})^{5/3}]$$

Stable cases:

$$C_s/C_{10} = \exp[-0.424(\Delta T/U_{10})^{5/3}]. \tag{9}$$

3. Analyses of data compiled during BOMEX, JASIN, STREX, and MIZEX

a. Compilation and preparation of data

1) COMPILATION

In addition to the results shown in Fig. 1a, photographic whitecap observations during JASIN were reported by Monahan et al. (1981) and during STREX by Doyle (1984); both videographic and photographic observations during MIZEX-84 were reported by Monahan et al. (1985). In all these studies, the wind velocity, as well as air and sea temperatures, were also measured. The results of JASIN and STREX are reproduced respectively in Fig. 1b, c, those of MIZEX from films in Fig. 1d, and from video recordings in Fig. 1e. The dashed line drawn in each figure was suggested by the original authors to represent the data. These lines fitted entirely on the basis of the least-squares method to the data are seen to deviate greatly from their true trends.

2) PRESENTATION

The type of presentation in logarithmic scales shown in Fig. 1, now a standard presentation of whitecap data, was used by Wu (1979) to illustrate the power-law

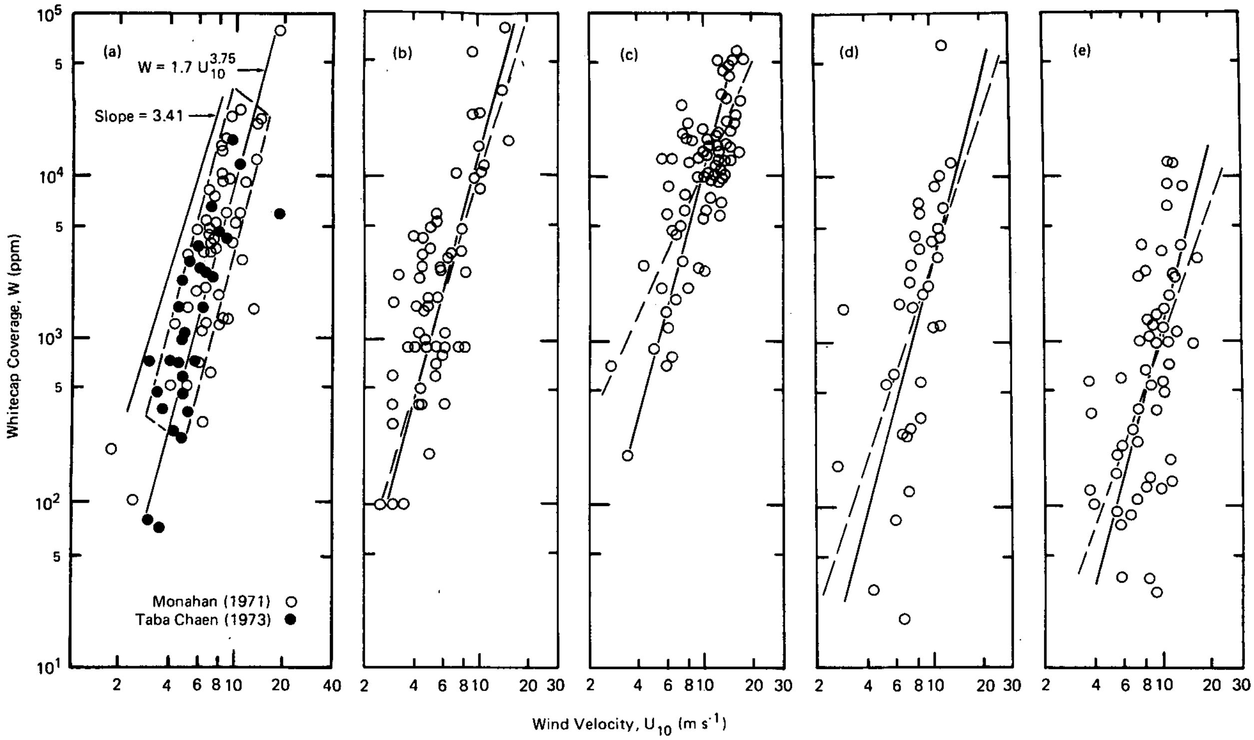

FIG. 1. Variation of whitecap coverage with wind velocity. (a) is reproduced from Wu (1979); the data in the other figures are from the following experiments: (b) JASIN (Monahan et al. 1981), (c) STREX (Doyle 1984), (d) and (e) MIZEX—film and video (Monahan et al. 1985).

variation of whitecap coverage with wind velocity. It has served well, but is due for a refinement. The coverage should be associated with the wind-friction velocity; as discussed earlier, the latter not the wind velocity is the governing parameter.

b. *Dependency on wind conditions*

1) ON WIND VELOCITY

A solid line with a slope of 3.75 corresponding to the power-law variation shown in Eq. (3) was fitted again on the basis of least squares to each set of the data shown in Fig. 1. The line is seen once again to represent the data more closely than the dashed line; the latter underrepresented the rate of whitecap-coverage increase with wind velocity, with more data points at low winds below the line and at high winds above the line. Even the solid line appears to underrepresent the rate of increase for two MIZEX datasets. Similar deviations are seen from data presented in linear scales, not shown here. It should be noted that our intention is to show that the data follow the 3.75 law reasonably well; as it happened, the line provided even a better representation of the data than that fitted by the original authors with a free exponent. Coefficients and exponents corresponding to the solid lines fitted here and the dashed lines proposed by the original authors are compiled in Table 1.

In Monahan (1971), no expression was proposed to represent the data. For the two sets of data obtained during MIZEX over the same site but with different techniques, Monahan et al. (1985) stated that the results obtained from video recordings (Fig. 1d) were quite consistent with those from films (Fig. 1e). These

TABLE 1. Coefficients and exponents of the proposed formulas, $W - \alpha U_{10}^{n}$.

	Values proposed by original authors		Present fitting	
Data	α	n	α	n
BOMEX—Photo (Monahan 1971)	—	—	1.70	3.75
JASIN—Photo (Monahan et al. 1981)	4.50	3.31	2.31	3.75
STREX—Photo (Doyle 1984)	92.8	2.11	2.06	3.75
MIZEX—Photo (Monahan et al. 1985)	2.13	3.12	0.530	3.75
MIZEX—Video (Monahan et al. 1985)	1.33	2.83	0.215	3.75

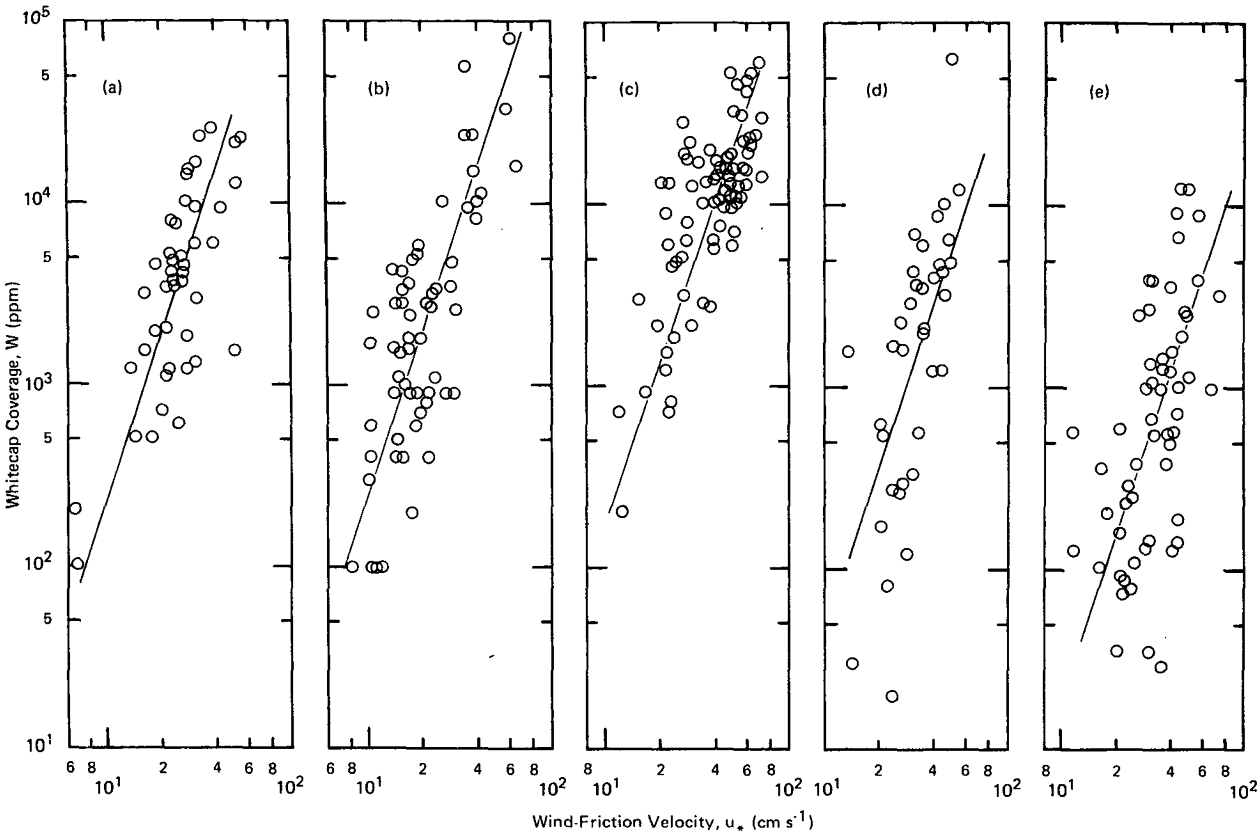

FIG. 2. Variation of whitecap coverage with wind-friction velocity. The datasets are (a) BOMEX, (b) JASIN, (c) STREX, (d) MIZEX—film, and (e) MIZEX—video. The lines are fitted according to $W \sim u_*^3$.

two sets of data in fact are off by the ratio between the two coefficients shown in the table, 0.530/0.215 = 2.5.

2) ON WIND-FRICTION VELOCITY

Using Eqs. (8) and (9) and the temperature data reported by the original authors, the results shown in Fig. 1 were converted to the form of W versus u_*; see Fig. 2. A line according to the power law shown in Eq. (2) and expressed in the following was fitted to each set of data,

$$W = \beta u_*^3. \quad [10]$$

The first three sets of data are seen to follow well the proposed trend, but the two MIZEX sets are again with the rate of increase of whitecap coverage with wind velocity underrepresented by the foregoing law. It is very interesting to note that populations of bubbles produced by breaking waves in the near-surface ocean, a phenomenon most closely associated with that of whitecaps, follows a similar dependency on the wind-friction velocity (Farmer and Lemon 1984; Wu 1988).

The coefficient β obtained from each plot with u_* expressed in cm s^{-1} is presented in Table 2. It is interesting to see that the variation derived earlier (Wu 1979) can be applied to datasets of BOMEX, JASIN, and STREX, with the coverage following rather closely the power law of u_*^3; even in absolute magnitudes the agreement is fair, with values of β deviating at most by about 20% from their average. As for the two MIZEX datasets, both the discrepancy between them and the difference between them and the first three sets of data are by about the same factor as shown in Table 1. The discrepancy in data collected over the same site suggests an examination of the techniques of the data acquisition, especially the video technique which was not used in other investigations.

3) SUMMARY

In view of close agreements among datasets from BOMEX, JASIN, and STREX and of interdiscrepancy

TABLE 2. Values of β from various experiments.

Data source	β
BOMEX/Photo	0.184
JASIN/Photo	0.243
STREX/Photo	0.169
MIZEX/Video	0.041
MIZEX/Photo	0.020

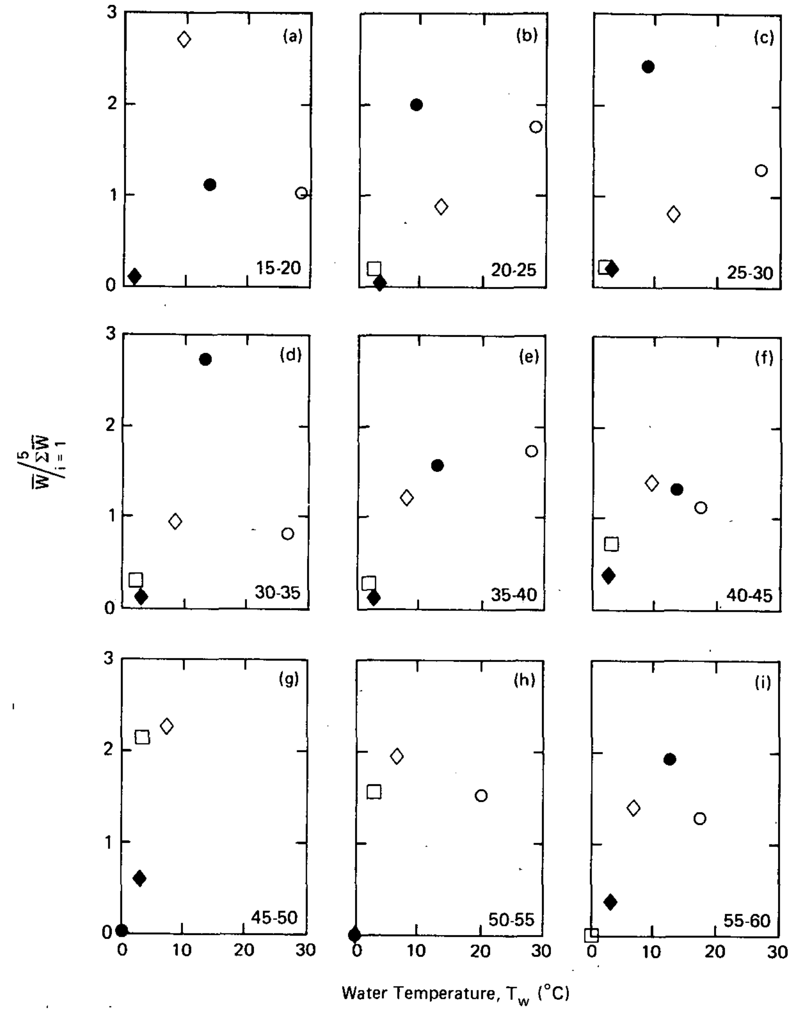

FIG. 3. Variations of whitecap coverage with water temperature. The symbols are BOMEX (○), JASIN (●), STREX (◇), MIZEX (Photo, ♦), and MIZEX (Video, □); the numbers in each plot indicate the range of wind-friction velocities in cm s^{-1}.

between the two MIZEX sets, we are proposing an empirical law by averaging the first three sets of data. The variations can be written very simply as

$$W = 2U_{10}^{3.75} \quad \text{or} \quad W = 0.2u_*^3 \qquad (11)$$

in which again W is expressed in ppm, U_{10} in m s^{-1} and u_* in cm s^{-1}.

As discussed previously, it was suggested much earlier that the whitecap coverage (Wu 1979) should be associated with the wind-friction velocity.[1] Following this concept, Monahan and O'Muircheartaigh (1986) proposed the following

$$W = 1.95 \times 10^{-5} U^{2.55} \exp(0.0861\Delta T) \qquad (12)$$

as the best fit to all sets of data discussed here, as well as those of Toba and Chaen (1973). However, the foregoing expression does not represent a correlation between the whitecap coverage and wind-friction velocity. The latter is not only the most appropriate physical parameter describing the whitecap coverage as also stated in Monahan and O'Muircheartaigh, but it has also been used to provide descriptions of accompanying phenomena, such as bubble populations mentioned previously. As for the data processing, we should like again to emphasize the guidance of physical reasonings, such as the advance of energy consideration and the use of wind-friction velocity, in addition to the curve fitting. Second, effects of the water temperature on whitecap coverage were discussed earlier (Wu 1979; Monahan and O'Muircheartaigh 1986); it will be shown here that the whitecap coverage MIZEX datasets obtained near zero water temperatures was generally smaller than those in other sets obtained under much

[1] The author again urged at the 1983 Galway Whitecap Workshop organized by Dr. Edward Monahan that the whitecap coverage should be associated with the wind-friction velocity instead of wind velocity.

higher temperatures. Consequently, it may not be advisable to process the MIZEX data along with the others as in the deduction of Eq. (12) before effects of the water temperature have been understood and corrected.

c. Dependency on water temperature

The rapid increase of the whitecap coverage with either the wind velocity or wind-friction velocity clearly establishes them as the main governing parameter; a quantitative variation of the coverage with wind-friction velocity is shown in Eqs. (10) and (11). Consequently, differences in the overall magnitude among experiments and deviations of data within each set from the fitted power law can be owing to either experimental errors in measurements or other effects influencing whitecap coverage. Among the latter, the water temperature was suggested (Wu 1979; Monahan and O'Muircheartaigh 1986) to have a substantial influence. Wu proposed to associate the coefficient α of the power law with the water temperature; on the other hand, Monahan and O'Muircheartaigh suggested that the variation should be associated with the exponent n. Further studies are needed to resolve this; for now it suffices to reason that the exponent is related to the energy flux from the wind, while the coefficient represents the environmental conditions such as the water temperature on the life of whitecaps.

Monahan and O'Muircheartaigh (1986) attempted to attribute the difference between datasets to the overall average water temperature of the set. The range of temperature variation in each set was rather large; therefore, a more valid assessment of temperature effects is to examine the data within bands of approximately the same wind-friction velocity. Consequently, we divided the wind-friction velocity into 5 cm s^{-1} bands, and found for each band the factor (γ) between the average $\bar{W}$ for each set within the band and the overall average value for the band

$$\gamma = \bar{W}/\sum_{i=1}^{5} \bar{W}. \tag{13}$$

These factors are presented in Fig. 3, where $\bar{T}$ is the average water temperature of data points for each set within the band. No systematic trends are apparent; only the whitecap coverage near zero water temperatures appears to be lower. The latter provides some explanation that the two MIZEX datasets show much smaller whitecap coverages as compared with the others.

4. Concluding remarks

The process of wind–wave interaction is governed largely by the wind stress; the latter is proportional to the product of the wind-stress coefficient and the square of the wind velocity. The wind-stress coefficient has been known to vary in addition to the wind velocity with the atmospheric stability conditions; consequently, the wind velocity cannot be used conveniently as an alternate parameter of the wind stress. The use of the wind-friction velocity, being proportional to the square root of the wind stress, represents an upgrade of analyzing the whitecap data. To illustrate that the coverage is proportional to the third power of the wind-friction velocity, we again verify the energy consideration proposed earlier. Furthermore, the results indicating that there are no systematic variations of the whitecap coverage with water temperature for other than near zero temperatures appear to provide more support to the suggested variations. Finally, wave breaking and accompanying oceanic whitecaps are an important oceanographic phenomenon; appreciation should be expressed to Monahan's group for providing us exclusively with those comprehensive sets of data.

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