Oceanic Whitecaps and Sea State

JIN WU

College of Marine Studies, University of Delaware, Newark, DE 19711

5 December 1978 and 19 February 1979

ABSTRACT

Results of whitecap coverages of the ocean surface obtained by previous investigators in both the Atlantic Ocean and the Pacific Ocean are reanalyzed. The variation of coverage with wind velocity appears to be related to the rate of energy supplied by the wind. The coverage is also found to vary with stability conditions of the atmospheric surface layer. Empirical formulas are deduced for various sea states and stability conditions, and application of these formulas to remote sensing of marine wind velocity is discussed.

1. Introduction

Under continuous influence of the wind, waves grow and eventually the water surface becomes unstable locally; the waves then break to dissipate excess energy provided by the wind. The breaking is marked by whitecaps—patches of bubbles and foam, first appearing near the wave crests. Field experiments have been conducted by Monahan (1971) in the Atlantic Ocean and by Toba and Chaen (1973) in the Pacific Ocean to relate white-cap coverage of sea surface to wind velocity. Their results are further analyzed to study on the basis of energy considerations the occurrence of whitecaps, and to examine effects of stability of the atmospheric surface layer on the persistence of whitecaps. The feasibility of applying these results for the remote sensing of marine wind velocity is also discussed.

2. Analytical consideration

Wave breaking is a result of continuous, excessive energy supplied by the wind. In the equilibrium state, we can consider that energy lost by wave breaking is balanced by energy gained from the wind, and that the pattern of wave breaking is similar at all wind velocities. The percentage of the sea surface covered by breaking waves under this state can then be related to energy flux from the wind. We can write simply

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

where W is the fraction of sea surface with white-cap coverage and $\dot{E}$ the rate of energy supplied by the wind per unit area of the sea surface.

The rate of work done by the wind on a unit area of the sea surface can be expressed as the product of wind stress (τ) and surface drift current (V). Since the wind-stress coefficient varies with the square root of the wind velocity (Wu, 1969) and the wind-induced surface drift current is proportional to the wind-friction velocity (Wu, 1975), we have

$$W \sim \dot{E} = \tau V \sim \tau u_* \sim (C_{10}U_{10}^2)(C_{10}^{1/2}U_{10}) \sim U_{10}^{3.75}, \tag{2}$$

where u_* is the wind-friction velocity, U_{10} the wind velocity measured at the standard anemometer height (10 m above the mean sea level) and C_{10} is the wind-stress coefficient, $C_{10} \sim U_{10}^{1/2}$.

3. Measurements of oceanic whitecaps

a. Monahan's results

Photographic observations of whitecaps were made by Monahan (1971) on the Atlantic Ocean and adjacent saltwater bodies. Taken from vessels, platforms and the windward shore, the pictures covered a vertical field of view extending from slightly above the horizon downward through an arc of 44°. At the same time, the wind velocity, the wet- and dry-bulb air temperatures and the sea surface temperature were recorded. The area of sea surface covered by whitecaps was later determined from photographs. Monahan's results are plotted separately according to stability conditions in Fig. 1a. The following criteria were used by Monahan to describe the stability conditions: stable ($\Delta T < -0.4$°C), neutral (-0.4°C $< \Delta T < 0.6$°C) and unstable ($\Delta T > 0.6$°C), where ΔT is the difference between the sea surface temperature and the air temperature. Monahan's photographic technique is believed unlikely to provide a resolution of the coverage of less than 0.01%. Consequently, some data points with nearly zero whitecap coverage at rather high wind velocities

0022-3670/79/051064-05$05.25

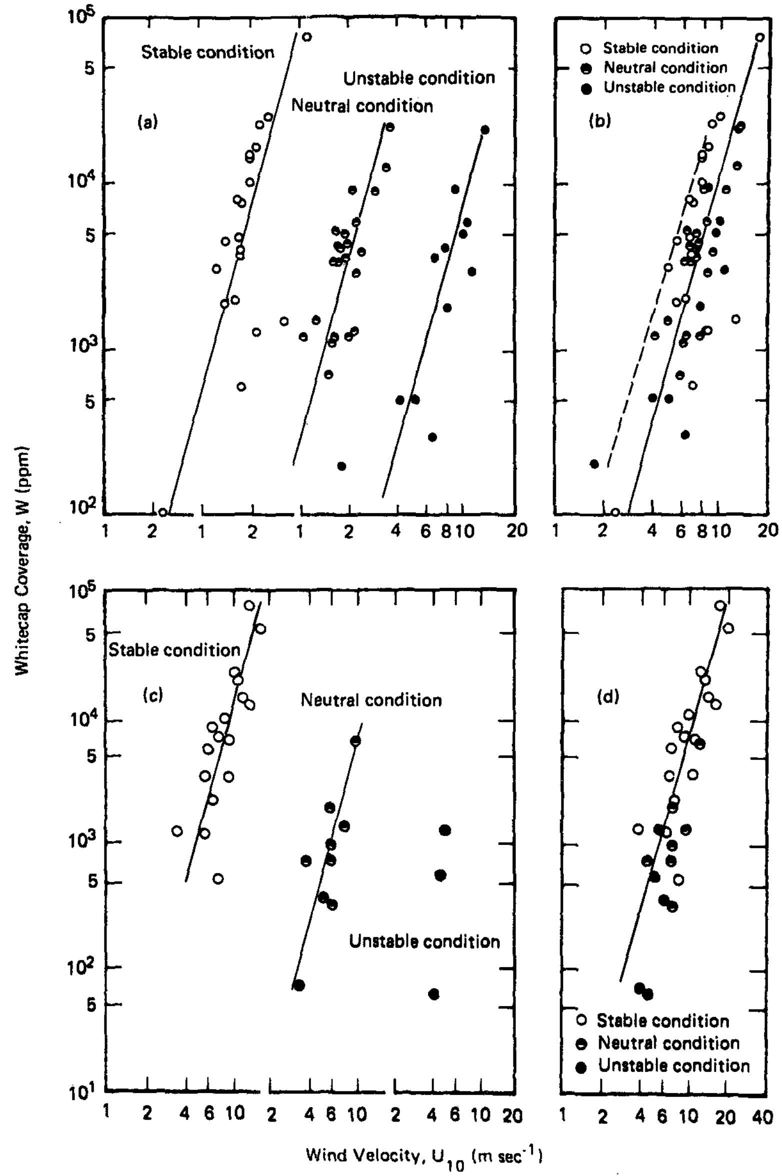

FIG. 1. Measurements of oceanic whitecaps. Monahan's (1971) results are shown in (a) and (b). Toba and Chaen's (1973) results in (c) and (d). The solid lines are faired according to $W \sim U_{10}^{3.75}$, while the dashed line in (b) represents the envelope reported by Monahan (1971).

(more under unstable conditions, few under neutral conditions and none under stable conditions) are omitted from Fig. 1a. Besides photographic resolution, sampling of a rather small area of the sea surface and probable shadowing by large waves may contribute to such results. Moreover, a fairly well-displayed trend of the data shown within the frame of Fig. 1a further substantiates our omission of those data outside the frame ($W < 100$ ppm).

A straight line with a slope of 3.75:1, as suggested by (2), is seen in Fig. 1a to fit reasonably well to each set of data, or

$$W = \alpha U_{10}^{3.75}, \quad (3)$$

where W is expressed in ppm (parts per million), U_{10} is expressed in m s^{-1}, and the values of the coefficient α obtained at different stability conditions are shown in Table 1. At this stage, the scatter of the results shown in Fig. 1a does not warrant choosing any finer curve fitting such as adopting an exponent other than 3.75 or using different exponents for various stability conditions. Table 1 shows some difference in whitecap coverages between neutral and unstable conditions, but a much greater whitecap coverage

TABLE 1. Values of α in $W = \alpha U_{10}^{3.75}$ for various stability conditions.

Investigator(s)	Stability conditions: Stable	Neutral	Unstable	Overall
Monahan (1971)	2.90	1.75	1.45	2.00
Toba and Chaen (1973)	2.90	1.30		1.55

under stable conditions. Data from all three stability conditions plotted together in Fig. 1b illustrate again these trends. Monahan (1971), on the other hand, reported that no clear separation of results on the basis of stability was indicated by the data he plotted on linear scales.

The overall whitecap coverages regardless of stability conditions are plotted in Fig. 1b, in which a line with a slope of 3.75 is forcefully fitted to the data. Due to combining data from different stability conditions, the coverage appears to vary more rapidly with the wind velocity. A different empirical formula, $W = 13.5U_{10}^{3.4}$ was presented by Monahan (1971) to indicate the envelope of all the data; a dashed line corresponding this expression is also shown in Fig. 1b.

b. Toba and Chaen's results

The sea surface in the East China Sea and in the southern region off Japan was photographed by Toba and Chaen (1973) under various wind speeds. The pictures were taken at 14 m above the sea surface from a ship; the top of each picture was aligned with the horizon. The wind speed and the air and the sea-surface temperatures were also recorded. Toba and Chaen found no systematic variation of the whitecap coverage with the direction of photography (upwind, downwind and crosswind). The results were then obtained by averaging the coverages photographed from all four directions as shown in Fig. 1c, in which the same stability criteria adopted by Monahan (1971) are used and the coverages much less than 10 ppm are omitted.

Following the discussion in the last section, straight lines with 3.75:1 slope were fitted in Fig. 1c to the data obtained under stable and neutral conditions; too few data points were obtained under unstable conditions to warrant the curve fitting. Once again, the proposed power law represents well the results obtained by Toba and Chaen; the coefficients obtained from the fitted lines are presented in Table 1. The whitecap coverages obtained by Toba and Chaen under stable conditions compare very favorably with those obtained by Monahan, and the coverage under the stable condition is again larger than under the neutral condition. The data obtained by Toba and Chaen under all three stability conditions are shown in Fig. 1d, and as discussed previously, they vary more rapidly with the wind velocity. As in most of Monahan's (1971) presentation, Toba and Chaen also plotted their data (W versus U_{10}) on linear scales; in such a plot the functional variation of whitecap coverage with wind velocity can hardly be traced. (Fortunately, the data were tabulated in both reports.)

c. Summary

Both sets of results—Monahan and Toba and Chaen—regardless of their stability conditions are plotted in Fig. 2. As seen in Table 1, these two sets

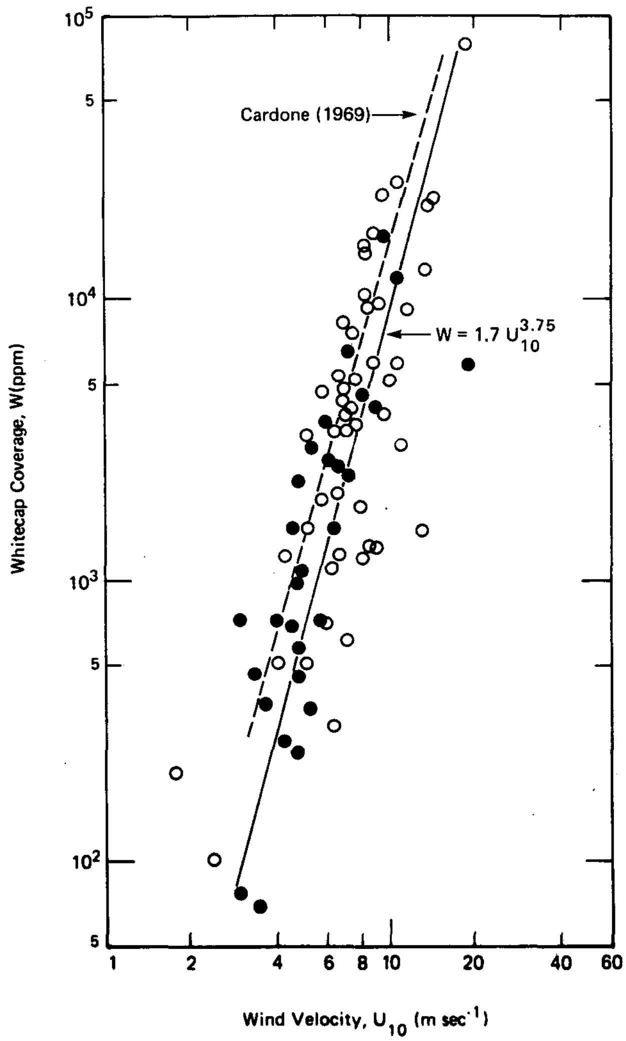

FIG. 2. Whitecap coverages under various sea states. Monahan's (1971) results are indicated by ○, Toba and Chaen's (1973) results by ●.

of data show remarkable agreement, and can be fitted by a line represented by

$$W = 1.7U_{10}^{3.75}. \quad (4)$$

The data obtained under different stability conditions from two studies are seen in Fig. 1 and Table 1 to be different in values but follow nearly the same trend of variation with the wind speed indicated in Eq. (2). In other words, the differences are not in the exponent but in the coefficient of the power law. The same variation of the whitecap coverage with the wind speed substantiates the energy consideration. The difference in the coefficient of the power law under different stability conditions will be discussed further in the next section.

Monahan (1971) reported standard deviations of whitecap-coverage data and errors in wind-velocity measurements, and comparable standard deviations of whitecap data were also reported by Toba and Chaen (1973). The errors in coverage and velocity measurements of both investigations are large, indicating their results should be treated with caution. Nonetheless, the consistent trend regarding stability effects indicated by these two independent investigations can hardly be neglected.

4. Discussion

a. Comparison with other whitecapping models

The present analytical consideration is based on dimensional grounds and the quantitative results are derived directly from the whitecap-coverage data. A much more complicated model was proposed earlier by Cardone (1969). He calculated the rate of wave growth by the wind from Miles-Phillips' instability mechanism, adopted Pierson-Moskowitz fully developed wave spectrum, and finally related the whitecap coverage to the rate of energy transferred to the fully developed portion of the spectrum. Cardone also used the fresh-water whitecapping data obtained by Monahan (1969) and assumed that the whitecap coverage in salt water is 50% greater than in freshwater under the same wind velocity; his results are shown as a dashed line in Fig. 2.

Cardone's line follows closely the present line and shows a greater coverage than that indicated by the data. In any event, the present line is preferred, because of still disputed mechanisms of wave generation by the wind, and of uncertainties in quantitative rates of energy transfer from the wind to waves. On the practical side, present results expressed in a much simpler form and based more heavily on the coverage data it is more convenient and more reliable for application. Admittedly, following improvement of our understanding on energy transfer from the wind to waves and on dissipation of wave energy through whitecapping, a refined model along Cardone's approach should be developed.

b. Stability effects on whitecapping persistence

Although still lacking general agreement, most investigators appear to suggest that the wind-stress coefficient is slightly greater when the atmospheric surface layer is unstable (Garratt, 1977). Consequently, under the same wind velocity the wave breaking should be slightly more violent under an unstable condition with a greater wind stress than under a stable condition. The opposite trend indicated by the whitecap coverage led us to look for other explanations.

The energy flux from the wind affects only the *occurrence* of wave breaking, as illustrated by consistent variations of whitecap coverage with wind velocity. The photographs of whitecap coverage, on the other hand, are also influenced to a large extent by the *persistence* of foaming. In other words, the exponent 3.75 in $W = \alpha U_{10}^{3.75}$ is related to the energy flux from the wind, and the coefficient α should also reflect the persistence of foaming. If this argument is valid, the results shown in Table 1 indicate that the bubbling and foaming appear to last longer under more stable conditions.

The effects of water temperature on foaming were studied by Miyake and Abe (1948), who reported that the temperature had a great influence on the life of foaming but had little effect on the degree of foaming. The life of foaming was found in an enclosed tank to decrease exponentially with increasing water temperature, i.e.,

$$P = \exp(-T_w/25), \quad (5)$$

where P is the persisting period of foaming and T_w the water temperature. There are no indications that the air temperature in the tank was kept the same as the water temperature. While we are not attributing the observed larger differences in the life of foaming to the stability conditions, we wish to note that a lower water temperature in their tank corresponded to a more stable condition. Reasoning along this line, the foaming produced at stable conditions should persist longer than that produced under neutral and unstable conditions, which is not in contradiction with the discussion in the previous paragraph.

An opposite trend was reported by Monahan (1969) for freshwater whitecapping with a greater coverage under unstable conditions. Interesting enough, Monahan and Zietlow (1969) found that the lifetime of bubbles in fresh water is very much different from that in salt water. Inasmuch as the persistence of foaming is cited above as a probable explanation of stability effects, it is really not that

TABLE 2. Values of β in $U_{10} = \beta W^{0.267}$ for various stability conditions.

Investigator(s)	Stability conditions: Stable	Neutral	Unstable	Overall
Monahan (1971)	0.75	0.86	0.91	0.83
Toba and Chaen (1973)	0.75	0.93		0.89

much surprising to have different effects of stability on freshwater and saltwater whitecapping.

c. Whitecap coverage and remote sensing

The possibility of determining marine wind velocity from satellite observations of whitecaps with a microwave radiometer was discussed by Williams (1969). He reported that the microwave radiometer could be used to obtain the percentage of foam and whitecap coverage on the ocean surface. If a functional relationship such as those discussed in the previous section can be established between whitecap coverage and wind velocity, we can therefore determine the wind velocity from a remote sensor.

For remote sensing of marine wind velocity, the stability condition of the atmospheric surface layer is generally unknown. If we use the averaged results shown in Fig. 2 obtained by different investigations under various stability conditions, we have from Eq. (4)

$$U_{10} = 0.87 W^{0.267}. \tag{6}$$

The coefficients of similar relationships for various stability conditions from different investigations are presented in Table 2. Despite the variation with stability conditions, the maximum error between the overall averaged relationship [Eq. (6)] and the individual groups, shown in Table 2, is about ±10% within the wind-velocity range of 5 to 20 m s^{-1}.

Acknowledgment. I am very grateful for the support of this work provided by the Physical Oceanography Program, National Science Foundation, under Grant OCE77-26508.

REFERENCES

Cardone, V. J., 1969: Specification of the wind field distribution in the marine boundary layer for wave forecasting. Rep. TR 69-1, Geophys. Sci. Lab., New York University.

Garratt, J. R., 1977: Review of drag coefficients over oceans and continents. *Mon. Wea. Rev.*, **105**, 915–929.

Miyake, Y., and T. Abe, 1948: A study on the foaming of sea water. Part 1. *J. Mar. Res.*, **7**, 67–73.

Monahan, E. C., 1969: Fresh water whitecaps. *J. Atmos. Sci.*, **26**, 1026–1029.

——, 1971: Oceanic whitecaps. *J. Phys. Oceanogr.*, **1**, 139–144.

——, and C. R. Zietlow, 1969: Laboratory comparisons of freshwater and salt-water whitecaps. *J. Geophys. Res.*, **74**, 6961–6966.

Toba, Y., and M. Chaen, 1973: Quantitative expression of the breaking of wind waves on the sea surface. *Rec. Oceanogr. Works Japan*, **12**, 1–11.

Williams, G. F., Jr., 1969: Microwave radiometry of the ocean and the possibility of marine wind velocity determination from satellite observations. *J. Geophys. Res.*, **74**, 4591–4594.

Wu, Jin, 1969: Wind stress and surface roughness at air-sea interface. *J. Geophys. Res.*, **74**, 444–455.

——, 1975: Wind-induced drift currents. *J. Fluid Mech.*, **68**, 49–70.

CORRIGENDUM

In the article "An inertial model of steady coastal upwelling" by Joseph Pedlosky (*J. Phys. Oceanogr.*, **8**, 171–177), the term $(1 - d)x/L$ in Eq. (4.5) should be $(1 - d)x\theta/L$. Fig. 5 of that paper was prepared from the correct formula and is unchanged.