Comments on "Variations of Whitecap Coverage with Wind Stress and Water Temperature"

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In a recent paper Wu (1988) has chosen, not for the first time, (e.g., Wu 1979) to reanalyse and interpret whitecap data collected primarily, or as in present instance entirely, by Monahan, his co-workers, and students. It is unfortunate that in assembling the whitecap data sets upon which Wu (1988) was based, two sets were extracted from a recent unpublished technical report (Monahan et al. 1985) without seeking clarification as to their significance from the authors. The indiscriminate use of the second of these sets, the MIZEX 84 video set, by Wu, has given rise to confusion, which it is appropriate to dispel forthwith.

The 1984 Marginal Ice Zone Experiment (MIZEX 84) represented the second occasion on which both film and video records of the sea surface were collected to permit their subsequent analysis for fractional whitecap coverage (Monahan et al. 1985; Monahan and Woolf 1986). The same recording protocols were in effect during the 1983 Marginal Ice Zone Experiment (MIZEX 83, Monahan et al. 1985). The specific reason for obtaining both sorts of records during these field experiments was to make it possible to intercompare the results obtained from the analyses of the film and video records, and to learn from these intercomparisons.

Recently, with the availability of two additional video-based data sets, those from the preliminary Humidity Exchange Over the Sea (HEXPILOT) experiment of 1984 (Monahan et al. 1985) and from the main HEXOS (HEXMAX) experiment carried out in 1986 (Monahan et al. 1988), it has been possible to give a simple physical interpretation to the quantity derived from the analysis, using a Hamamatsu Area Analyser, of the video tapes, and a quite distinct physical interpretation to the quantity obtained from the analysis of the photographs in accord with the technique of Monahan (1969). As will be seen, these interpretations are consistent with the recently published model of the evolution of bubble plumes and their associated whitecaps (Monahan 1988a), and complement the too long overlooked findings of Bondur and Sharkov (1982).

Stage A and Stage B in the evolution of an individual whitecap bubble cloud, the only two stages relevant to the present discussion, are illustrated in Fig. 1. The young Stage A whitecaps, which are the surface manifestations of plunging aerated plumes, can be identified with the "crests" of "dynamic foam" described by Bondur and Sharkov (1982). These features, which according to these authors have individually a typical area of about 0.4 m^2 for winds near 10 m s^{-1}, are effectively the only whitecaps that contribute to W_A, the fractional whitecap coverage determined by analyzing videotapes with the Hamamatsu Area Analyser, since the brightness discrimination level setting on this instrument required to avoid spurious contributions from bright wave facets is such that only young whitecaps with albedos of 0.5 or higher are detected. The mature Stage B whitecaps are, on the other hand, the prime contributors to W_B, the fractional whitecap coverage deduced from the analysis, in the manner described by Monahan (1969), of photographs of the sea surface. These relatively low albedo whitecaps correspond to the "striplike" or "patchy" structures of "static foam" in the nomenclature of Bondur and Sharkov, and were found by these investigators to each have a typical area of about 12 m^2 when observed under 10 m s^{-1} wind conditions. Since each whitecap spends significantly less of its lifetime in Stage A than in Stage B, at any instant there are considerably fewer of the smaller Stage A whitecaps than there are of the larger Stage B ones on the same unit area of the ocean surface.

The ratio of the areas of individual Stage A to Stage B whitecaps, A_A/A_B, implicit in the foregoing, is consistent with the A_A/A_B ratios to be inferred from the projected Stage A and Stage B bubble spectra (Monahan 1988a) and void fractions (Monahan et al. 1987).

The initial analysis of the W_A-values obtained by the processing of the four whitecap video data sets listed above has yielded Eq. (1) (Monahan et al. 1988),

$$W_A = 2.92 \times 10^{-7} U^{3.204} e^{0.198 \Delta T} \quad (1)$$

where U is the deck-height wind speed given in m s^{-1},

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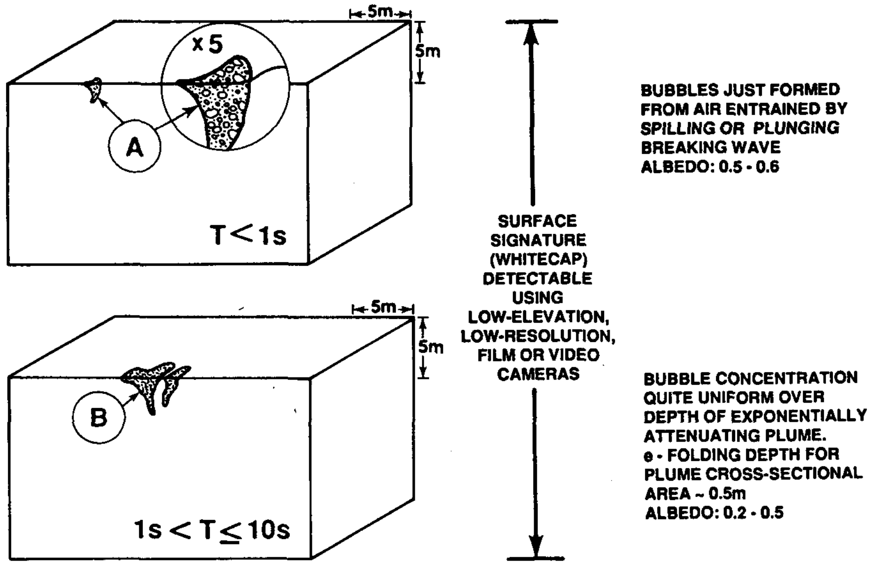

FIG. 1. The first two stages of whitecap decay and bubble cloud evolution as identified in optical/physical model (Monahan 1988a).

and ΔT is the sea-surface temperature minus the air temperature, in °C.

It is illuminating to compare the W_A-values calculated using Eq. (1), with the W_B-values for the same wind speeds obtained from Eq. (2) (Monahan and O'Muircheartaigh 1986),

$$W_B = 1.95 \times 10^{-5} U^{2.55} e^{0.0861 \Delta T} \qquad (2)$$

which in turn was based on the analysis of five whitecap film data sets. This latter expression was referred to in Wu (1988). These W_A- and W_B-values, and the W_A/W_B ratios, for a range of wind speeds are listed in the upper portion of Table 1. The W_A- and W_B values determined by Bondur and Sharkov (1982) from low-elevation (100 m) aerial photographs taken at three wind speeds, and the associated W_A/W_B ratios, are presented in the lower half of Table 1. While it is clear from the earlier discussion that W_A and W_B are physically related quantities, it should be apparent from Table 1 that they are by no means equivalent, with W_A for any given sea state being typically less than 11% of W_B. Thus in no circumstances should measurements of W_A be averaged in with those of W_B.

The W_A- and W_B-values from Bondur and Sharkov (1982) are, in light of the confidence limits included on their Fig. 2, quite compatible with those derived from Eqs. (1) and (2). This gives support to the general model of whitecap bubble cloud evolution depicted in part on the accompanying Fig. 1.

The statement in Wu (1988) that W_A "was shown to follow a power law, $W = 2U_{10}^{3.75} \cdots$" is not confirmed by any objective statistical evidence. The only meaningful way to demonstrate the validity of a hypothetical value of the exponent of U in a $W_B(U)$ power-law expression, i.e., of λ in the notation of Monahan and O'Muircheartaigh (1980, 1982, 1986) or n in the usage of Wu, is to show that the mean squared error obtained when a power law with the candidate λ exponent is fitted to a large body of W_B, U data is not significantly larger than the minimum mean squared error associated with the optimal λ obtained by the application of a formal statistical methodology. The presentation of such objective measures of goodness of fit is to be recommended over the appeal to the reader to use his or her "eyeball" to see how well a particular line fits data displayed in log–log space. The

TABLE 1. W_A- and W_B-values.

Deck-height wind speed (m s^{-1})	5	5.7	9.5	10	10.5	15	20
W_A [Eq. (1), $\Delta T = 0$]	5.07×10^{-5}	7.71×10^{-5}	3.96×10^{-4}	4.67×10^{-4}	5.46×10^{-4}	1.71×10^{-3}	4.30×10^{-3}
W_B [Eq. (2), $\Delta T = 0$]	1.18×10^{-3}	1.65×10^{-3}	6.07×10^{-3}	6.92×10^{-3}	7.84×10^{-3}	1.95×10^{-2}	4.05×10^{-2}
W_A/W_B	0.043	0.047	0.065	0.068	0.070	0.088	0.106
Results from Bondur and Sharkov (1982), Fig. 2							
W_A	—	1.3×10^{-4}	4×10^{-4}	—	7×10^{-4}	—	—
W_B	—	7×10^{-3}	1.2×10^{-2}	—	1.65×10^{-2}	—	—
W_A/W_B	—	0.019	0.033	—	0.042	—	—

issue of how best to determine λ has already been discussed at some length in the pages of this journal (Monahan and O'Muircheartaigh 1980; Wu 1982; Monahan and O'Muircheartaigh 1982).

The statement in Wu (1988) that "Monahan and O'Muircheartaigh (1986) on the other hand suggest the variation [in W_B due to changes in sea surface temperature, T_W] should be associated with the exponent n [λ]," may leave the incorrect impression with the reader. Monahan and O'Muircheartaigh (1986) did note that the λ-values associated with the data sets collected in colder, more northerly, waters were characteristically smaller than the λ-values they determined from the data sets collected in the warmer, often trade wind, regions. They recognized that this was a consequence of the fact that in the mid- and high-latitudes, in contrast to in the trade wind regions, the durations of the high wind episodes associated with whitecap photography were often too short to give rise to a fully developed sea; and that the W_B-values measured on such occasions were as a result depressed. They thus concluded that the apparent dependence of λ upon T_W was in fact a reflection of the influence of wind duration on λ. In the same paper they also proposed two mechanisms, both influenced by the changes in kinematic viscosity that result from changes in T_W, that would cause the power-law coefficient, α, to vary with changes in sea-water temperature.

The inclusion in the aggregate data set used to derive Eq. (2) of several high latitude sets of observations, including the film data recorded in the Arctic during MIZEX 83 (but not including either the MIZEX 84 film or video data, as incorrectly suggested by Wu 1988), explains why the λ of Equation 2 is considerably smaller than the λ's reported in Monahan and O'Muircheartaigh (1980), which were based in large measure on film data collected in the trade-winds in the vicinity of Barbados (Monahan 1971).

The values of λ and of μ, the exponent of U in the $W_A(U)$ power-law expression, obtained from the respective analyses of the MIZEX 84 film and video records were fairly similar. This gave rise to the comment by Doyle and Higgins in Monahan et al. (1985) that "the results obtained from the video records are quite consistent with those of the film records," a remark taken exception to in Wu (1988). Looking now at the λ obtained from the analysis of five film data sets [Eq. (2)], and at the μ that resulted from the preliminary analysis of four video data sets [Eq. (1)], there is a basis for suggesting that μ is in fact larger than λ. Noting that A_A is typically much smaller than A_B (Bondur and Sharkov 1982), and that the spatial resolution of the video-based whitecap analysis technique is somewhat less than the resolution of the film-based procedure, it can be concluded that while each approach may well detect the bulk of the sea surface area brighter than the respective technique's threshold albedo, the fraction of the Stage A whitecaps missed in the video analysis is greater than the fraction of the typically much larger Stage B whitecaps that goes undetected during the film analysis. Both Bondur and Sharkov (1982), and Monahan and Monahan (1986) have reported that the typical dimensions of individual whitecaps increase with freshening winds. In particular, the analysis of some 1500 visual estimates of whitecap breadth, recorded at the behest of the Deutsches Hydrographisches Institut by observers on the Alte Weser Light-station in the North Sea, showed a strikingly strong, positive, dependence of whitecap size on wind speed (Monahan and Monahan 1986). From the foregoing, it is reasonable to infer that the percentage deficiency in Stage A whitecap detection associated with the video technique will diminish more rapidly with increasing wind speed than will the smaller percentage deficiency in Stage B whitecap area detection identified with the film technique, and it is thus plausible to suggest that herein lies the explanation of why λ is found to be smaller than μ.

Monahan and O'Muircheartaigh (1986) have accepted the contention of Wu (1979, 1988) that W_B should be proportional to u_*^3, the cube of the friction velocity, in those instances where the observations were made of a fully developed sea. The fact that λ', the power-law exponent in the $W_B(u_*)$ expression obtained from the MIZEX 84 film data, was found to be 3.47, and that μ', the exponent in the $W_A(u_*)$ expression derived from the MIZEX 84 video data, was determined to be 3.28 (Monahan and Woolf 1986), may reflect in some measure the dependence upon u_* of percentage deficiency in whitecap area detection, but most certainly demonstrates the weakness of attempting to draw firm inferences from single data sets, often characterized by a limited range of U, and u_*, values.

While acknowledging that the observation that the instantaneous fraction of the sea surface covered by whitecaps was simply proportional to the product of the wind stress and the surface drift velocity, a quantity which itself is proportional to the friction velocity of the air, was a contribution made by Wu (1979) to our understanding of the factors controlling whitecapping, it is appropriate to note that Cardone (1969; Ross and Cardone 1974), from his reanalysis of a limited fresh water whitecap film data set (Monahan 1969), had earlier concluded that whitecap coverage was directly proportional to the "rate of energy transfer from the air flow to the fully developed" portion of the wave spectrum. Monahan and O'Muircheartaigh (1980) made the point that it is the rate of whitecap area formation, not the instantaneous fractional whitecap coverage per se, which is proportional to the rate at which energy is being dissipated via wave breaking. The relationship between the rate of whitecap area formation and fractional whitecap coverage was first set out in Monahan (1971), and described in detail in Monahan (1988b).

Recognizing that Wu (1979) did indeed introduce the presentation in log–log space of W_B, U data sets "to illustrate the power-law variation of whitecap coverage with wind speed" (Wu 1988), it should be noted that both Blanchard (1963) and Monahan (1971) had previously adopted explicit power-law formulations for the $W_B(U)$ expression.

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