Oceanic Whitecaps [1]

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ABSTRACT

The variation of oceanic whitecap coverage with wind speed was determined from the analysis of groups of five or more photographs taken, along with measurements of wind speed and air and water temperatures, during each of 71 observation periods at locations on the Atlantic Ocean and adjacent salt water bodies. The fraction of the sea surface covered by whitecaps is always $<0.1\%$ for wind speeds $V<4$ m sec^{-1}. For winds from 4 to 10 m sec^{-1} the maximum percentage of the sea surface covered by whitecaps is given by $W=0.00135\ V^{3.4}$.

1. Introduction

This article is the second of two by the author devoted to quantitative descriptions of whitecapping. The first (Monahan, 1969) dealt with fresh water whitecaps as they were observed primarily on Lakes Superior, Huron and Erie. The photographic observations of whitecaps that will be described in the present article were made entirely on the Atlantic Ocean and adjacent salt water bodies.

The study reported herein was undertaken for two reasons. Laboratory comparisons (Monahan and Zeitlow, 1969) indicate that salt water whitecaps persist longer than fresh water whitecaps because the salt water bubble spectrum contains relatively more small, slowly rising bubbles than does the fresh water bubble spectrum. This observation led to the hypothesis that for the same wind speed, duration, fetch, and atmospheric thermal stability, a larger fraction of oceans than lakes would be covered by whitecaps. One purpose of the current study was to test this hypothesis.

The second motive for this study was to obtain observations suitable for direct comparison with the several contradictory descriptions of the wind dependence of salt water whitecaps currently in print. Blanchard (1963) concluded that there are no oceanic whitecaps for wind speeds <3 m sec^{-1}, and that the percentage of the sea surface covered by whitecaps increases as the square of the wind speed for speeds >5 m sec^{-1}. He based these conclusions from an analysis of the photographs that appear in a Naval Weather Squadron operational manual (Anonymous, 1952). On the other hand, Munk's (1947) observations of the numerical concentration of sea surface foam patches indicated a very abrupt onset of whitecapping when the wind speed slightly exceeds 6 m sec^{-1}.

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2. Observations

All photographs were taken with Beattie Varitron automatic sequence cameras loaded with Ektachrome type 5256 film. For the purposes of this study photographs were taken from vessels, overwater platforms, and windward shores. The cameras were tilted so that their vertical field of view extended from slightly above the horizon downward through an arc of 44°. Photographs were not taken to leeward of any vessel or platform, thus avoiding sheltering effects.

Each observation listed in column 1 of Table 1 took typically from 30 min to 1 hr to complete, and included the taking of some 10–20 photographs at each of four or five lens aperture settings and the measurement of relative wind speed and direction, wet- and dry-bulb air temperature, and sea-surface temperature. In the case of shipboard observations, the ship's course, speed and position were copied from the ship's log.

3. Data analysis

A contiguous group of five or more photographs (column 4 of Table 1) was selected for analysis solely on the basis of optimum exposure from the up to 100 photographs taken during each observational period. The fraction of the sea surface appearing in each photograph that was covered by whitecaps was then determined by projecting each photographic transparency onto a sheet of paper, tracing the whitecap images onto the paper, cutting the images out of the paper, and then weighing the paper "cut-outs." The details of this technique are described in Monahan (1969).

A measure of the subjective influence of the analyst was obtained by having six persons associated with this study (but not all regular analysts) determine the mean whitecap coverage on the same set of five typical

TABLE 1. Log of whitecap observations and results.

Observation no.	Body of water	Date	Number of photos analyzed	Wind speed (m sec^{-1})	Wind speed at 10 m height (m sec^{-1})	Fetch (km)	Surface water temperature (°C)	ΔT[a] (°C)	Thermal stability	Whitecap coverage W(%)	Standard deviation (%)
256	Buzzards Bay, Mass.	10 July 1968	10	4.6– 5.5	5.0– 5.9	11	23.85	0.55	Neutral[h]	0.00	0.00
257	Buzzards Bay, Mass.	12 July 1968	12	0.4– 1.6	0.6– 1.8	24	20.9	2.0	Unstable	0.00	0.00
9272	Buzzards Bay, Mass.	13 August 1968	10	4.6– 5.1	5.1– 5.6	89	21.6	0.5	Neutral	0.00	0.00
9273	Buzzards Bay, Mass.	16 August 1968	10	3.8– 3.9	3.9– 4.0	19	19.1	2.1	Unstable	0.05	0.03
9274	Buzzards Bay, Mass.	16 August 1968	20	1.9– 3.5	2.0– 3.6	21	20.6	1.0	Unstable	0.00	0.00
9275	Buzzards Bay, Mass.	16 August 1968	20	0.7– 1.7	0.7– 1.7	15	21.2	1.8	Unstable	0.00	0.00
9276	Buzzards Bay, Mass.	16 August 1968	20	0.5– 0.7	0.5– 0.7	15	21.9	2.6	Unstable	0.00	0.00
279	Atlantic Ocean[b]	2 May 1969	5	6.3– 6.3	6.8– 6.8	>1000	28.4	−0.2	Neutral	0.41	0.12
280	Atlantic Ocean[b]	2 May 1969	5	5.8– 6.0	6.2– 6.5	>1000	28.3	0.0	Neutral	0.52	0.14
281	Atlantic Ocean[b]	3 May 1969	5	6.2– 6.2	6.6– 6.7	>1000	28.0	0.2	Neutral	0.34	0.09
282	Atlantic Ocean[b]	3 May 1969	5	4.9– 5.4	5.2– 5.8	>1000	28.4	−0.8	Stable	0.19	0.11
283	Atlantic Ocean[b]	4 May 1969	5	5.8– 6.4	6.2– 6.9	>1000	28.6	−0.6	Stable	0.79	0.13
284	Atlantic Ocean[b]	4 May 1969	5	5.7– 5.7	6.1– 6.2	>1000	28.6	0.0	Neutral	0.34	0.15
285	Atlantic Ocean[b]	5 May 1969	5	6.7– 6.8	7.2– 7.3	>1000	28.3	−0.05	Neutral	0.50	0.22
286	Atlantic Ocean[b]	5 May 1969	5	6.2– 6.4	6.7– 6.9	>1000	28.6	−0.85	Stable	0.40	0.11
287	Atlantic Ocean[b]	6 May 1969	5	6.0– 6.3	6.5– 6.8	>1000	28.3	−0.85	Stable	0.47	0.07
288	Atlantic Ocean[b]	7 May 1969	5	5.7– 6.1	6.1– 6.6	>1000	28.3	−0.05	Neutral	0.12	0.03
289	Atlantic Ocean[b]	9 May 1969	5	8.0– 8.8	8.3– 8.8	>1000	28.65	0.6	Unstable	0.93	0.47
291	Atlantic Ocean[b]	9 May 1969	5	7.3– 7.4	7.5– 7.5	>1000	28.5	0.15	Neutral	0.44	0.12
292	Atlantic Ocean[b]	9 May 1969	5	6.1– 6.3	6.3– 6.5	>1000	28.5	1.35	Unstable	0.36	0.21
293	Atlantic Ocean[b]	10 May 1969	5	5.8– 6.0	6.0– 6.1	>1000	28.45	0.4	Neutral	0.11	0.03
294	Atlantic Ocean[b]	10 May 1969	5	6.3– 6.5	6.5– 6.7	>1000	28.6	0.0	Neutral	0.42	0.15
295	Atlantic Ocean[b]	11 May 1969	5	5.9– 6.3	6.1– 6.5	>1000	28.8	−1.2	Stable	0.20	0.09
296	Atlantic Ocean[b]	11 May 1969	5	5.5– 5.7	5.7– 5.9	>1000	28.4	0.05	Neutral	0.07	0.03
297	Atlantic Ocean[b]	12 May 1969	5	4.3– 4.8	4.6– 5.2	>1000	28.4	−0.95	Stable	0.31	0.05
298	Atlantic Ocean[b]	12 May 1969	5	2.6– 6.4	2.9– 6.9	>1000	28.6	0.0	Neutral	0.15	0.10
299	Atlantic Ocean[b]	13 May 1969	5	6.5– 6.5	6.9– 7.0	>1000	28.1	−0.8	Stable	0.75	0.47
304	Atlantic Ocean[b]	16 May 1969	5	7.7– 7.7	7.3– 7.3	>1000	28.5	−0.1	Neutral	0.36	0.11
305	Atlantic Ocean[b]	16 May 1969	5	4.1– 4.6	3.9– 4.3	>1000	28.5	0.45	Neutral	0.12	0.01
306	Atlantic Ocean[b]	17 May 1969	5	7.0– 7.3	7.7– 8.0	>1000	28.5	−2.35	Stable	1.00	0.08
307	Atlantic Ocean[b]	17 May 1969	5	8.0– 9.0	8.0– 9.0	>1000	28.5	0.15	Neutral	0.29	0.02
308	Atlantic Ocean[b]	18 May 1969	5	9.0– 9.0	9.0– 9.0	>1000	28.5	−1.1	Stable	2.25	0.17
309	Atlantic Ocean[b]	18 May 1969	5	8.0– 9.0	8.0– 9.0	>1000	28.5	−0.65	Stable	1.65	0.32
311	Atlantic Ocean[b]	18 May 1969	5	8.0– 8.0	8.0– 8.0	>1000	28.5	0.45	Neutral	0.92	0.31
312	Atlantic Ocean[b]	19 May 1969	5	7.5– 8.0	7.5– 8.0	>1000	28.0	−0.5	Stable	1.47	0.33
315	Atlantic Ocean[b]	19 May 1969	5	8.3– 8.5	8.3– 8.5	>1000	28.0	−0.35	Neutral	0.59	0.27
316	Atlantic Ocean[b]	23 May 1969	5	8.0–11.9	8.1–12.0	>1000	28.0	1.0	Unstable	0.59	0.08
317	Atlantic Ocean[b]	23 May 1969	5	6.9– 7.6	7.1– 7.7	>1000	28.0	1.0	Unstable	0.41	0.08
319	Atlantic Ocean[b]	24 May 1969	5	5.0– 5.7	5.1– 5.8	>1000	28.2	0.3	Neutral	0.00	0.00
321	Atlantic Ocean[b]	25 May 1969	5	4.6– 5.2	4.6– 5.3	>1000	28.0	1.7	Unstable	0.05	0.03
322	Atlantic Ocean[b]	25 May 1969	5	4.6– 4.6	4.7– 4.7	>1000	28.0	0.95	Unstable	0.00	0.00
323	Atlantic Ocean[b]	26 May 1969	5	5.2– 5.6	5.3– 5.8	>1000	28.1	−0.8	Stable	0.45	0.41
324	Atlantic Ocean[b]	26 May 1969	5	5.4– 8.2	5.4– 8.5	>1000	28.3	−0.45	Stable	0.06	0.05
325	Atlantic Ocean[b]	26 May 1969	5	8.1– 8.7	8.4– 8.9	>1000	28.3	−0.45	Stable	0.13	0.08
326	Atlantic Ocean[b]	26 May 1969	5	7.1– 7.9	7.2– 8.1	>1000	28.2	0.75	Unstable	0.18	0.14
327	Atlantic Ocean[b]	27 May 1969	5	9.7–10.0	9.9–10.2	>1000	28.0	−1.65	Stable	2.51	1.91
335	Atlantic Ocean[b]	28 May 1969	5	7.2– 8.1	7.3– 8.2	>1000	28.1	−0.65	Stable	1.40	0.47
345	Buzzards Bay, Mass.	16 July 1969	5	13.0–14.0	12.3–13.3	673	18.8	−2.4	Stable	0.15	0.04
9349	Atlantic Ocean[c]	23 July 1969	5	13.2–13.8	12.7–13.2	445	24.2	1.8	Unstable	2.11	0.19
363	Buzzards Bay, Mass.	24 July 1969	5	12.6–13.0	12.6–13.0	43	17.5	−0.3	Neutral	1.27	0.46
364	Buzzards Bay, Mass.	24 July 1969	5	12.6–14.3	12.6–14.3	26	17.5	−0.3	Neutral	2.21	1.08
365	Buzzards Bay, Mass.	24 July 1969	5	10.7–11.3	10.7–11.3	26	17.4	−0.3	Neutral	0.91	0.63
9352	Atlantic Ocean[d]	26 July 1969	5	2.4– 2.6	2.3– 2.4	194	28.9	−1.1	Stable	0.01	0.01
368	Buzzards Bay, Mass.	27 July 1969	5	8.2– 8.5	8.2– 8.5	25	17.4	−0.1	Neutral	0.13	0.01
369	Buzzards Bay, Mass.	27 July 1969	5	7.2– 8.2	7.2– 8.2	25	17.4	−0.1	Neutral	0.12	0.05
370	Buzzards Bay, Mass.	27 July 1969	5	7.2– 8.3	7.2– 8.3	25	17.4	−0.1	Neutral	0.00	0.00
9359	Gulf of Honduras	29 July 1969	5	6.9– 7.4	6.5– 7.0	>1000	28.9	−1.65	Stable	0.37	0.21
9360	Caribbean Sea	31 July 1969	10	4.9– 7.2	4.7– 6.8	362	28.9	1.7	Unstable	0.00	0.00
9361	Gulf of Mexico	1 August 1969	10	3.9– 4.1	3.7– 3.9	396	30.0	1.6	Unstable	0.00	0.00
9362	Gulf of Mexico	1 August 1969	5	1.2– 1.9	1.0– 1.8	37	30.0	0.65	Unstable	0.00	0.00
9363	Straits of Florida	1 August 1969	5	0.1– 3.6	0.1– 3.4	87	30.55	1.45	Unstable	0.02	0.02

[a] Surface water temperature minus deck height air temperature.
[b] To windward of Barbados, BOMEX Experiment No. 65.
[c] Off New Jersey Coast.
[d] To windward of Bahamas.
[e] Off Georgia Coast.
[f] Off Cape Hatteras.
[g] Along line from Cape Cod to Bermuda.
[h] Near neutral, $-0.4C < \Delta T < +0.6C$.

TABLE 1.—(*continued*)

Observa-no.	Body of water	Date	Number of photos analyzed	Wind speed (m sec^{-1})	Wind speed at 10 m height (m sec^{-1})	Fetch (km)	Surface water tempera-ture (°C)	ΔT (°C)	Thermal stability	Whitecap coverage W (%)	Standard deviation (%)
9364	Straits of Florida	1 August 1969	10	5.7– 8.4	5.4– 8.0	213	30.55	3.15	Unstable	0.00	0.00
9365	Atlantic Ocean[e]	2 August 1969	5	3.8– 3.8	3.6– 3.6	268	30.55	1.50	Unstable	0.00	0.00
9366	Atlantic Ocean[f]	3 August 1969	5	6.0– 7.2	5.7– 6.8	903	29.45	2.7	Unstable	0.03	0.01
371	Atlantic Ocean[g]	10 August 1969	5	17.3–17.9	17.1–17.7	>1000	25.6	−0.8	Stable	7.61	1.10
372	Atlantic Ocean[g]	11 August 1969	5	7.5	7.4	>1000	25.4	0.7	Unstable	0.00	0.00
373	Atlantic Ocean[g]	14 August 1969	5	8.4	8.3	>1000	28.4	0.05	Neutral	0.00	0.00
374	Atlantic Ocean[g]	17 August 1969	5	10.9	10.8	>1000	27.4	1.6	Unstable	0.30	0.21
375	Atlantic Ocean[g]	17 August 1969	5	8.8– 9.8	8.7– 9.7	>1000	28.0	−0.35	Neutral	0.39	0.06
376	Atlantic Ocean[g]	17 August 1969	5	8.8–10.5	8.7–10.4	>1000	27.8	1.1	Unstable	0.50	0.10

(average coverage 0.641%) oceanic whitecap photographs. The standard deviation among the six estimates for the mean percentage whitecap coverage on the five photographs was 0.256%. When only the results of the four regular analysts (who are responsible for over 98% of the oceanic analyses) were considered, the standard deviation among their values for the mean percentage whitecap coverage was 0.087%.

Where the observations had been made from vessels under way, the absolute wind speed (column 5 of Table 1) and direction (not shown) at anemometer height was determined for each observation period by means of vector addition from the measurements of relative wind speed and direction and the log of the ship's course and speed.

The wind speed at an elevation of 10 m (column 6 of Table 1) was obtained by taking the absolute speeds at the various known anemometer heights and adjusting them in accord with the assumption of the presence of logarithmic wind profiles (essentially those presented by Roll, 1965, Fig. 37, p. 136).

The fetch (column 7 of Table 1) associated with each observation was determined from the knowledge of the ship's or platform's position and the previously obtained true wind direction.

4. Results

The results of this study are presented in Table 1. The wind speed dependence of oceanic whitecapping is depicted in Fig. 1 where the vertical bars attached to each data point represent the standard deviation from the mean whitecap coverage for the sequence of photographs used in obtaining that point. The accuracy of the mean whitecap coverage value for a given sequence of photographs can be estimated by reducing the length of those vertical bars by a factor equal to the square root of one less than the number of photographs used to determine that data point (column 4 of Table 1). This factor would thus be 2 for the vast majority of data points presented in Fig. 1. The range of wind speeds (10 m elevation) encountered during a given observation period is represented by the span of the horizontal bars attached to each data point in this figure.

For wind speeds $V<4$ m sec^{-1}, whitecap coverage W is invariably $<0.1\%$. Over the range of wind speeds from 4 to 10 m sec^{-1} a curve given by

$$W=0.00135V^{3.4} \tag{1}$$

coincides with the highest whitecap coverage observations at the various wind speeds, thus forming an envelope over all the data points in this range. No clear separation of data points on the basis of atmospheric thermal stability is indicated from this figure.

The observations whose results are marked by filled-in symbols were obtained to windward of Barbados during the Barbados Oceanographic and Meteorological Experiment (BOMEX), under conditions of ample fetch and often long duration. The open symbols mark the results obtained from the analysis of observations taken elsewhere, often under conditions of limited fetch and/or duration. The BOMEX results indicate significant whitecapping at lower wind speeds, and greater whitecap coverage at all wind speeds, than the results obtained from observations taken at more northerly locations in the Atlantic Ocean and in bays, straits and gulfs.

5. Discussion

a. Comparison with previous oceanic whitecap results

Fig. 2 summarizes the oceanic whitecap results of Blanchard (1963) and Munk (1947), as well as those of the present study (filled circles). While the shape of Blanchard's curve is in rough accord with the curve that could be drawn to envelope the data points of the present study [Eq. (1)], Blanchard's results indicate significantly higher whitecap coverage for all winds speeds >3 m sec^{-1}. This discrepancy between Blanchard's results and those reported in the present paper may reflect on the nature of the wind measurements which are associated with the sea surface photographs in the Naval Weather Squadron operational manual (Anonymous, 1952) used by Blanchard. In that

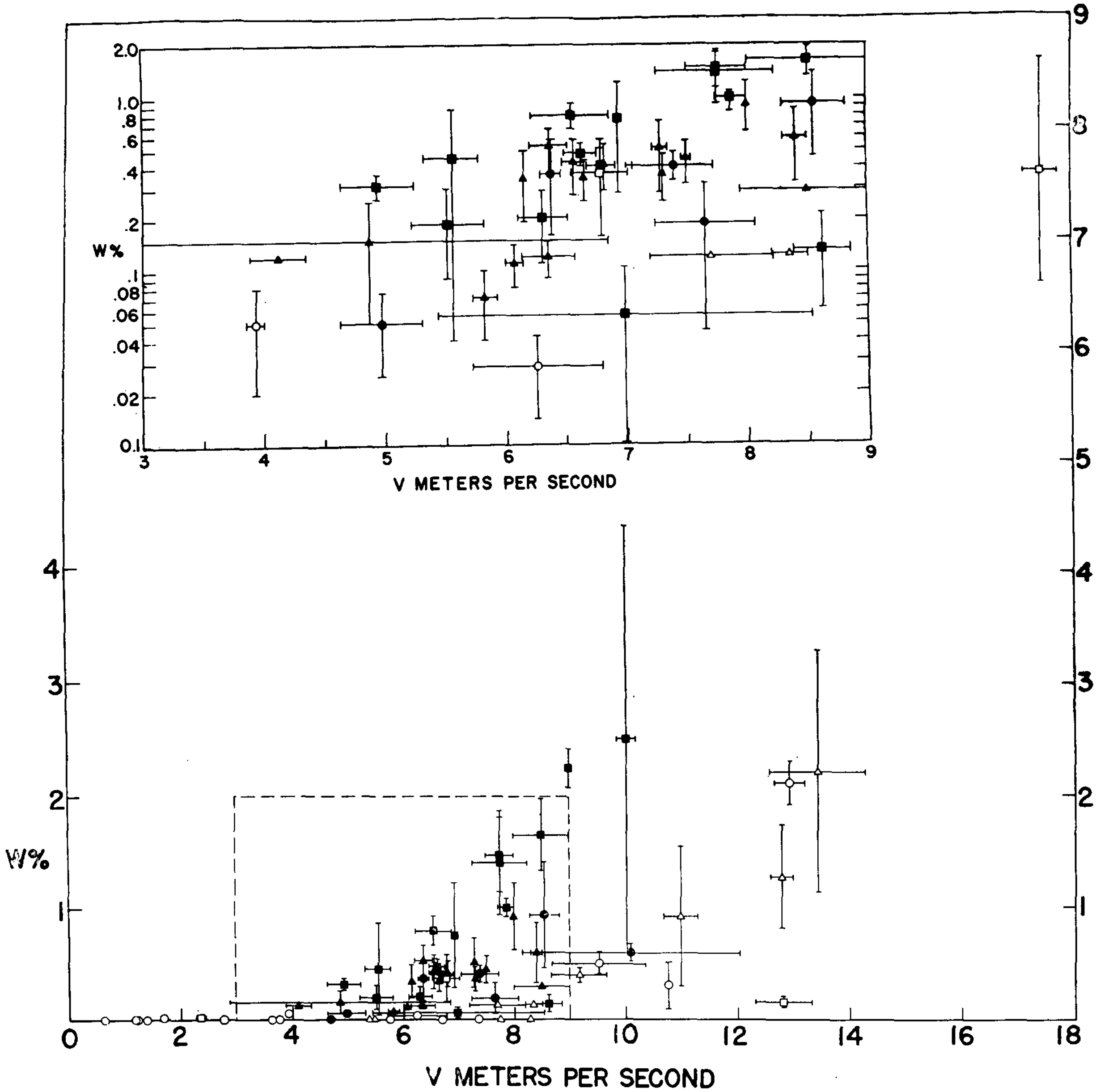

FIG. 1. Percent oceanic whitecap coverage (W) vs 10 m elevation wind speed (V): squares, observations when atmosphere was thermally stable; triangles, stability near neutral ($-0.4C<\Delta T<0.6C$); circles, thermally unstable. Filled symbols represent BOMEX results, open symbols all other results (see Table 1). Vertical bars indicate standard deviations from mean values. Horizontal bars span range of wind speeds measured during observation periods. Insert shows semi-log representation of data from within box formed by dashed line.

manual no indication is given of how the reported wind speeds were obtained.

While Munk's (1947) results, expressed in terms of the number of foam patches per unit area of sea surface, are not directly convertible into values of the fractional oceanic whitecap coverage without a knowledge of the average area of an individual whitecap, it is clear that the current study does not support Munk's contention that there is an abrupt onset of whitecapping as the wind speed exceeds 6 m sec^{-1}.

The results of the current study support the suggestion of Gathman and Trent (1968), based on the analysis of 44 photographs, that whitecaps are totally absent for wind speeds $\leqslant 6$ kt (3.1 m sec^{-1}).

An explanation for the absence in the oceanic results of an indication of the effect of atmospheric thermal stability on whitecap coverage, an effect that was pronounced in the results of the fresh water whitecap study (Monahan, 1969), is evident from a recognition that the extreme air-surface water temperature differences typically encountered during the Great Lakes observations were almost totally absent during the oceanic observations (column 9 of Table 1).

The broad range in whitecap coverage encountered among observations taken at approximately the same wind speed and atmospheric thermal stability is due not only to variations in fetch and wind duration but also to variations in whitecap bubble stability due to variations in sea water surface tension caused by the occasional presence of organic films (Abe *et al.*, 1963; Garrett, 1967).

b. Comparison of oceanic with fresh water observations

It can be assumed for identical meteorological conditions (i.e., same wind speed, atmospheric thermal stability, fetch and duration) that the rate R of whitecap production per unit area of water surface and the initial area A_0 of individual whitecaps are the same on the oceans as on the lakes. The whitecap area formed per second per unit area of ocean or lake is thus A_0R.

Now the area of a particular whitecap, $A(t)$, t seconds after it was formed, is given by

$$A(t)=A_0e^{-t/\tau} \tag{2}$$

(Monahan and Zietlow, 1969), where τ is the appropriate exponential time constant. Hence the rate at which an individual whitecap's area changes can be expressed as

$$\frac{dA(t)}{dt}=-\frac{A(t)}{\tau}, \tag{3}$$

and the whitecap area decay per second per unit area of water surface is just W/τ, where W is the total area of whitecaps per unit area of water surface.

If a steady state is assumed, the rate of whitecap area formation is then just equal to the rate of whitecap area decay, and we have

$$A_0R=W/\tau, \tag{4}$$

$$W=A_0R\tau. \tag{5}$$

It was found in laboratory tank experiments (Monahan and Zietlow, 1969) that τ is 2.54 sec for fresh water whitecaps and 3.85 sec for salt water whitecaps. It is concluded, therefore, for the same meteorological conditions, that the fraction of a sea surface covered by whitecaps is 1.51 times the fraction of a lake surface covered by whitecaps.

A direct comparison between the results of the fresh water whitecap study (Monahan, 1969; open circles in Fig. 2) and the present oceanic whitecap study is not possible because the meteorological conditions and fetches associated with the fresh water observations do not coincide with the conditions under which the oceanic observations were made.

However, in a recent study dealing with wave forecasting, Cardone (1969), assuming that the percentage

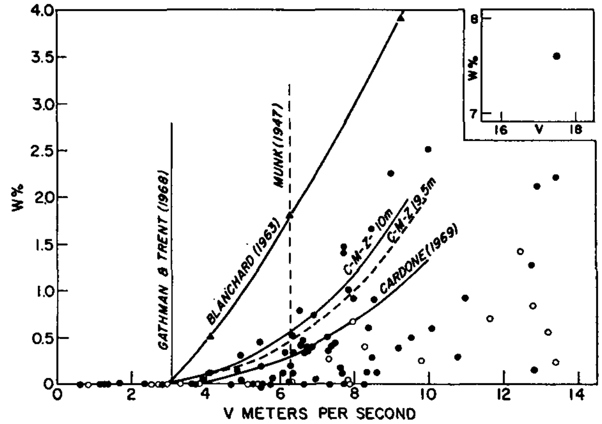

Fig. 2. Summary of all available data on whitecap coverage (W) vs wind speed (V). Labeled curves are described in text. Dashed vertical line indicates wind speed at which Munk (1947) found an abrupt increase in numerical concentration of oceanic foam patches. Solid vertical line indicates speed below which Gathman and Trent (1968) found no whitecaps. Open circles are fresh water whitecap results (Monahan, 1969) plotted vs deck height wind speeds; filled circles, all salt water whitecap results of present study, plotted vs 10 m elevation wind speeds. Note insert.

of the water "surface covered by whitecaps . . . is directly related to the rate of energy transfer from the air flow to the fully developed spectral components (of the waves) through a combined Miles-Phillips type instability mechanism," and utilizing the published observations of fresh water whitecaps (Monahan, 1969), was able to calculate the relationship of whitecap coverage to wind speed that should apply to a fully developed (not fetch or duration limited) sea in a fresh water "ocean" under conditions of neutral atmospheric thermal stability. Cardone's calculated curve (in terms of 19.5 m elevation winds) is included in Fig. 2.

When the ordinate values of the points forming Cardone's curve are each multiplied by the salt water to fresh water whitecap ratio of 1.51 derived in the present paper, a curve predicting the oceanic whitecap coverage to be encountered when the atmosphere is neutrally stable and the sea is fully developed is obtained. This curve, labeled C-M-Z-19.5m, is also shown on Fig. 2. Finally, by adjusting the abscissa values of the points forming this curve in accord with the assumed family of logarithmic wind profiles (Roll, 1965), a curve representing the expected oceanic whitecap coverage (fully developed sea, neutral atmospheric stability) as a function of wind speeds measured at 10 m is generated (curve labeled C-M-Z-10m on Fig. 2). This final curve, which can be represented over the range of wind speeds from 4–10 m sec^{-1} by

$$W=0.0012V^{3.3}, \tag{6}$$

compares well with the equation previously presented [Eq. (1)]; it defines a curve through the highest oceanic whitecap coverage values encountered at the various 10 m elevation wind speeds in this range.

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