Fresh Water Whitecaps

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ABSTRACT

Photographic observations of the whitecap coverage of large fresh water lakes were made in conjunction with measurements of wind velocity, and air and surface water temperatures. The fraction of the water surface covered by whitecaps shows an abrupt increase as the wind velocity increases from ~7 to ~8 m sec^{-1}. This abrupt change is qualitatively in accord with the published observations of "critical" wind velocities associated with numerous other water-surface and surface-related phenomena. The whitecap coverage of fresh water bodies, particularly at the higher wind velocities, is much less than the published values of whitecap coverage of oceans under the same wind conditions.

1. Introduction

The few published observations of the dependence of whitecap coverage on wind speed are not in agreement. Munk's (1947) observations, expressed in terms of the number of foam patches per unit area of sea surface, indicate a very abrupt onset of whitecapping when the wind speed exceeds slightly more than 6 m sec^{-1}. Blanchard (1963), analyzing photographs that appear in a Naval Weather Squadron operational manual (Anonymous, 1952), concluded that there were no whitecaps for wind speeds <3 m sec^{-1}, and that the percentage of the sea surface covered by whitecaps increased as the square of the wind speed for speeds >5 m sec^{-1}.

This paper will describe the results of a photographic study of fresh water whitecapping, performed mainly on Lakes Superior, Huron and Erie, which was undertaken to determine the variation of whitecap coverage with variation of wind speed and atmospheric thermal stability. While the observations herein reported were taken under conditions of ample fetch, and with a desirably wide range in atmospheric thermal stabilities, the fresh water nature of these lakes precludes the use of these observations in any direct verification of the previously published oceanic observations.

2. Observations

All photographs were taken with Beattie Varitron automatic sequence cameras loaded with 100-ft reels of Ektachrome type 5256 film. Each camera was equipped with a Data Recording Back which introduced into one edge of each 25 mm by 37 mm frame the images of a clock and a frame-counter for positive data indexing.

Each sequence of photographs used in this study was taken with a Varitron camera so mounted that it photographed the lake surface on the windward side of the vessel, taking in a vertical field of view extending from slightly above the horizon downward through an arc of 44°. Most of the data were gathered aboard Great Lakes bulk freight vessels, in which case the camera was mounted at the windward rail of one of the upper decks of the forward house.

During each one-half to one hour observation interval 10–20 photographs were typically taken at each of four or five lens aperture settings.

The photography was in each instance accompanied by meteorological observations. The wind speed relative to the moving vessel was measured with a sensitive Casella anemometer hand held in a position appropriate to the relative wind direction, which was also recorded. A sling psychrometer was used to determine wet- and dry-bulb air temperatures while an "A.B.C." sea-surface temperature bucket (Crawford, 1966) was used to determine the temperature of the lake surface. A copy of the relevant portions of the ship's log was made so that the ship's course, speed and position at the time of the whitecap observations could later be determined.

The observations used in this study are listed in Table 1.

3. Data analysis

Of the 50–100 photographs taken during one observation interval there was chosen, solely on the basis of optimum exposure, a group ≥ 10 for individual analysis (column 4 of Table 1).

Each of the chosen photographic transparencies was projected with approximately 25-fold magnification onto a sheet of paper. The border of the projected

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TABLE 1. Log of whitecap observations.

Observation no.	Lake	Date	Number of photos analyzed	Fetch (km)	Surface water temperature (°C)	ΔT* (°C)	Thermal stability
34	Superior	10 June 1967	16	9	unknown	—	—
38	Superior	10 June 1967	10	54	(3.5)**	−1.9	stable
69	Huron	12 June 1967	15	35	13.1	−4.7	stable
75	Erie	12 June 1967	19	45	20.6	−2.6	stable
76	Erie	13 June 1967	19	22	18.6	−1.2	stable
81	Superior	30 June 1967	10	61	3.7	−9.2	stable
108	Superior	1 July 1967	10	32	3.6	−9.2	stable
134	Huron	4 July 1967	10	67	11.6	−2.8	stable
178	Huron	4 July 1967	26	104	11.2	−1.6	stable
206	Superior	3 August 1967	57	28	14.0	−1.1	stable
242	Superior	16 May 1968	10	36	1.9	−2.5	stable
246	Superior	16 May 1968	10	114	1.6	−2.6	stable
252	Huron	17 May 1968	10	93	2.8	−2.8	stable
253	Huron	17 May 1968	10	23	3.3	−3.3	stable
254	Huron	17 May 1968	10	16	3.7	−3.5	stable
255	Huron	17 May 1968	10	12	4.6	−3.2	stable
275	Seneca	25 October 1968	10	2	13.9	5.8	unstable
276	Erie	20 November 1968	10	25	7.4	7.0	unstable
277	Erie	20 November 1968	10	39	8.7	7.0	unstable
278	Erie	20 November 1968	10	17	9.6	7.8	unstable

* Surface water temperature minus deck height air temperature.
** Not measured simultaneously with other observations.

photograph and the horizon were traced onto the sheet of paper, as was the outline of each whitecap. An inverted triangle was then constructed on the paper, as shown in Fig. 1, with only the water surface appearing within the triangle being analyzed further. This procedure was adopted to eliminate the slight possibility that the bow wave of the vessel would otherwise intrude upon the water surface analyzed.

The total area of the paper covered by whitecaps was determined by one of two methods. In the early analyses the area of each whitecap image was measured directly with a polar planimeter and the individual areas were then summed. The more recent analyses were carried out by first excising all the whitecap images found in the triangular region of a tracing and then weighing all the "cut-outs" together on a precision balance. Dividing the mass of all the paper "cut-outs" by the areal density of the paper yielded the total whitecap area.

To obtain an estimate of the subjective influence of the particular analyst on the results obtained for a given sequence of photographs, a limited sequence of five photographs portraying typical low whitecap coverage conditions (average coverage of 0.234%) was chosen for independent reduction by all three analysts. The standare deviation between the three analysts' values for the mean percentage whitecap coverage on the five photographs was 0.026%.

An attempt was also made to determine if the use of oblique rather than normal photographs in any way effected the results of this study. On each of the tracings from 55 photographs from observation 206 a horizontal line was drawn half-way between the horizon and the apex of the inverted triangle, thus dividing the triangle into near-field (less oblique) and far-field (more oblique) regions (see Fig. 1). The actual lake surface area included in the near-field region was typically 120 m², while the far-field region, extending as it did to the horizon, encompassed a lake surface area >1 km². The two regions on each tracing were then analyzed separately. While the largest individual whitecap coverage fractions occured in the near-field region, in the mean for this large group of photographs, a greater fraction of the far field appeared to be covered by whitecaps than the near field; thus, some positive bias was resulting from the use of oblique photography. The analyses of the far-fields alone for observation 206 yield a mean whitecap coverage of 0.698% while the analyses of the entire triangles yield 0.565%.

By means of vector addition the absolute wind speed and direction were determined for each observation interval from the measured relative wind speed and direction and the record of the vessel's course and speed. Knowing the true wind direction, and the vessel's

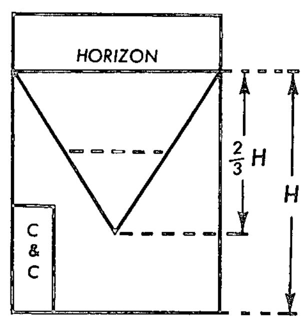

FIG. 1. Diagram of projected photographic image. Inverted triangle delineates region used in analysis. Rectangle labeled C & C represents the image of the clock and counter.

position at the time of an observation, made it possible to determine the fetch (column 5 of Table 1).

4. Results

Fig. 2, together with Table 1, presents the results of this study. The vertical bars attached to a data point in Fig. 2 represent the standard deviation from the mean whitecap coverage for the sequence of photographs analyzed. The accuracy of the mean whitecap coverage value for a given sequence of photographs can be assessed by visualizing these vertical bars reduced in length by a factor equal to the square root of the number one less than the number of photographs in the particular sequence (column 4 of Table 1). The horizontal bars attached to a data point in Fig. 2 span the range of wind speeds measured during a given observation interval.

The fraction of the water surface covered by whitecaps shows an abrupt increase as the wind speed increases from ~7 to ~8 m sec^{-1}. For wind speeds <7 m sec^{-1} the whitecap coverage is invariably $<0.1\%$. For winds speeds >8 m sec^{-1} the whitecap coverage is greater when the atmosphere is thermally unstable than when it is stable.

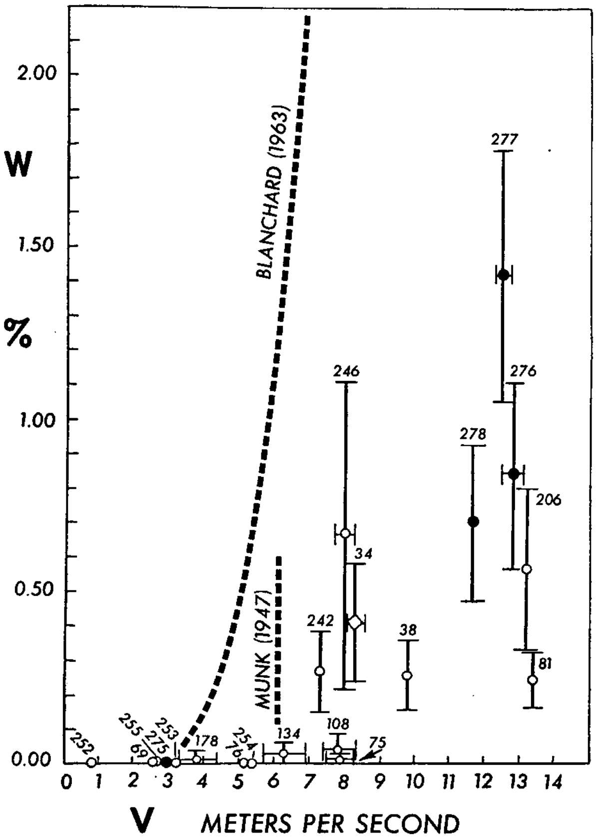

FIG. 2. Percentage of whitecap coverage W vs deck height wind speed V. Open circles, observations when atmosphere thermally stable; filled circles, observations when atmosphere thermally unstable; open diamond, observation when atmospheric stability unknown. Number accompanying each point is observation number (see Table 1). Vertical bars present standard deviations from mean values. Horizontal bars span range of wind speeds measured during observation intervals. Dashed vertical line indicates wind speed at which Munk (1947) found an abrupt increase in numerical concentration of salt water foam patches.

5. Discussion

A comparison of the present results with the work of Blanchard (1963) mentioned previously shows that the whitecap coverage of fresh water bodies, particularly at higher wind speeds, is much less than the published values of whitecap coverage of oceans under the same wind conditions. A portion of Blanchard's data curve is shown in Fig. 2. The more abrupt onset of salt water whitecapping as the wind speed increases to >6 m sec^{-1} reported by Munk (1947) is in qualitative agreement with the present fresh water results. Unfortunately, Munk's observations, expressed in terms of the number of foam patches per unit area of sea surface, are not convertable into values for the fractional coverage of the sea by whitecaps. Similarly, the data on the presence or total absence of salt water whitecaps presented by Gathman and Trent (1968) do not lend themselves to direct comparison with the results of the present study.

The present observations, which indicate the existence of a threshold wind velocity for fresh-water whitecap production of from 7–8 m sec^{-1}, are in accord with published reports of critical wind velocities associated with other sea-surface related phenomena such as sea spray production (Monahan, 1968), generation of wind-driven currents (Mandelbaum, 1956), and gull soaring in patterns indicative of convective regimes (Woodcock, 1940; Munk, 1947). Physical theories for the existence of just such critical wind velocities have often been postulated (Munk, 1947; Roll, 1965; Wu, 1969).

The laboratory wind flume studies of Toba (1961) demonstrated that bubbles began to form by air entrainment in fresh water once the wind speed was increased above 7.5 m sec^{-1}, and that the rate of bubble formation increased rapidly with further increase in wind speed. Considering the extremely limited fetch in the flume Toba's results are in remarkably good agreement with the present fresh water whitecap field observations. Glotov *et al.* (1961), working with a salt water wind flume, found what they described as an "exponential" increase in bubble concentration with increase in wind speed once the wind speed rose beyond 10 m sec^{-1}.

For approximately the same value of deck height wind speed greater whitecap coverage is observed when the atmosphere is thermally unstable than when it is stable, in agreement with many observations made at sea (Roll, 1965). This is an illustration of the shortcoming inherent in any attempt to correlate an air-water interface phenomenon with wind speed alone. The broad spread in whitecap coverage values which remains when only observations taken at approximately the same wind speed and atmospheric stability are considered is due in part to unknown variations in wind duration (and hence "sea state"), and in part to unknown variations in surface tension (and hence white cap bubble stability) caused by organic films (Abe, 1962).

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REFERENCES

Abe, T., 1962: On the stable foam formation of sea water in seas (preliminary report). *J. Oceanogr. Soc. Japan, 20th Anniv. Vol.*, 242–250.

Anonymous, 1952: Wind estimations from aerial observations of sea conditions. Unpubl. rept., Jacksonville, Fla., Weather Squadron Two (VJ-2), 1–28.

Blanchard, D. C., 1963: The electrification of the atmosphere by particles from bubbles in the sea. *Progress in Oceanography*, Vol. 1, New York, Pergamon Press, 71–202.

Crawford, A. B., 1966: A replacement at last for "The Old Oaken Bucket." *Geo. Marine. Tech.*, **2**, 25–27.

Gathman, S., and E. M. Trent, 1968: Space charge over the open ocean. *J. Atmos. Sci.*, **25**, 1075–1079.

Glotov, V. P., P. A. Kolobaev and G. G. Neuimin, 1961: Investigation of the scattering of sound by bubbles generated by an artificial wind in sea water and the statistical distribution of bubble sizes. *Soviet Phys.—Acoust.*, **7**, 341–345.

Mandelbaum, H., 1956: Evidence for a critical wind velocity for air-sea boundary processes. *Trans. Amer. Geophys. Union*, **37**, 685–690.

Monahan, E. C., 1968: Sea spray as a function of low elevation wind speed. *J. Geophys. Res.*, **73**, 1127–1137.

Munk, W. H., 1947: A critical wind speed for air-sea boundary processes. *J. Marine Res.*, **6**, 203–218.

Roll, H. V., 1965: *Physics of the Marine Atmosphere*. New York, Academic Press, 152–167.

Toba, Y., 1961: Drop production by bursting air bubbles on the sea surface (III): Study by use of a wind flume. *Mem. Coll. Sci., Univ. Kyoto, Ser. A.*, **29**, 313–344.

Woodcock, A. H., 1940: Convection and soaring over the open sea. *J. Marine Res.*, **3**, 248–253.

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