Bubbles Produced by Breaking Waves in Fresh and Salt Waters

JIN WU

Institute of Hydraulic and Ocean Engineering, National Cheng Kung University, Tainan, Taiwan

ABSTRACT

A greater volume of air is entrained by breaking waves to produce many more bubbles in salt, than in fresh, water. There are, however, little differences in their sizes. These results are consistent with reported observations of whitecaps over freshwater lakes and the ocean.

1. Introduction

Differences between phenomena associated with the wave breaking in fresh and salt waters were discovered long ago; for the same wind velocity, whitecaps over the sea surface were found to last longer than those over the surface of freshwater lakes (Monahan 1969), while the size of air bubbles was suggested to be larger in fresh, than in salt, water (Monahan and Zietlow 1969; Cartmill and Su 1993; Haines and Johnson 1995). Their experimental results are taken together with the observation of Loewen et al. (1996) to evaluate the entrainment of air during the breaking of waves, and the composition and behavior of subsequently produced bubbles. Earlier results concentrated on the behavior of bubbles, including coalescence (Scott 1975; Cartmill and Su 1993) and shattering (Slauenwhite and Johnson 1999). We show, on the other hand, that a greater volume of air is entrained in salt than in freshwater to generate many more bubbles in salt water; but contrary to earlier reports, bubbles in both cases are found to have about same sizes. These results are consistent with life spans and total coverages of whitecaps over surfaces of oceans and freshwater lakes.

2. Previous observations

a. Whitecaps

Photographic observations of whitecaps were made by Monahan (1969) in freshwater Lakes Superior, Huron, and Erie. As reported by him, pictures were taken with ample fetches and various conditions of atmo-spheric thermal stabilities. Monahan also noted that the whitecap coverage increased abruptly as the wind velocity increased from 7 to 8 m s^{-1}, and the coverage was generally much less than that over the sea surface. In the laboratory experiment of Monahan and Zietlow (1969), a volume of water was dropped into a receiving tank with the same water sample to simulate the production of bubbles by a breaking wave. The experiment was conducted with fresh and salt waters; the whitecap and the bubble plume were simultaneously photographed. Whitecaps were found to decay faster in freshwater with an exponential decay time of about 2.54 s; the decay time in salt water was about 3.85 s.

b. Bubbles

Measurements were made by Cartmill and Su (1993) of bubbles produced by breaking waves in a laboratory tank filled alternatively with fresh and salt waters. Bubbles in the size range of 34–1200 μm in radius were measured with an acoustic resonator at two depths below the undulating water surface. The number of bubbles in salt water was found to be one order of magnitude greater than that in fresh water for bubbles having their radii greater than 100 μm; the difference is less for smaller bubbles. These differences were attributed to the coalescence of small bubbles in fresh water and the inhibited coalescence in salt water. The total air entrainment was suggested to be much less affected than the bubble size. Bubble number densities at two depths in fresh and salt waters were presented by Cartmill and Su; their original results are shown in Fig. 1, where $n(r)$ is the measured bubble number density, and r is the bubble radius.

Subsequently, Haines and Johnson (1995) observed the production of bubbles by a simulated breaking wave with an intermittent water fall. Bubbles larger

Corresponding author address: Dr. Jin Wu, Institute of Hydraulic and Ocean Engineering, National Cheng Kung University, Tainan, Taiwan.
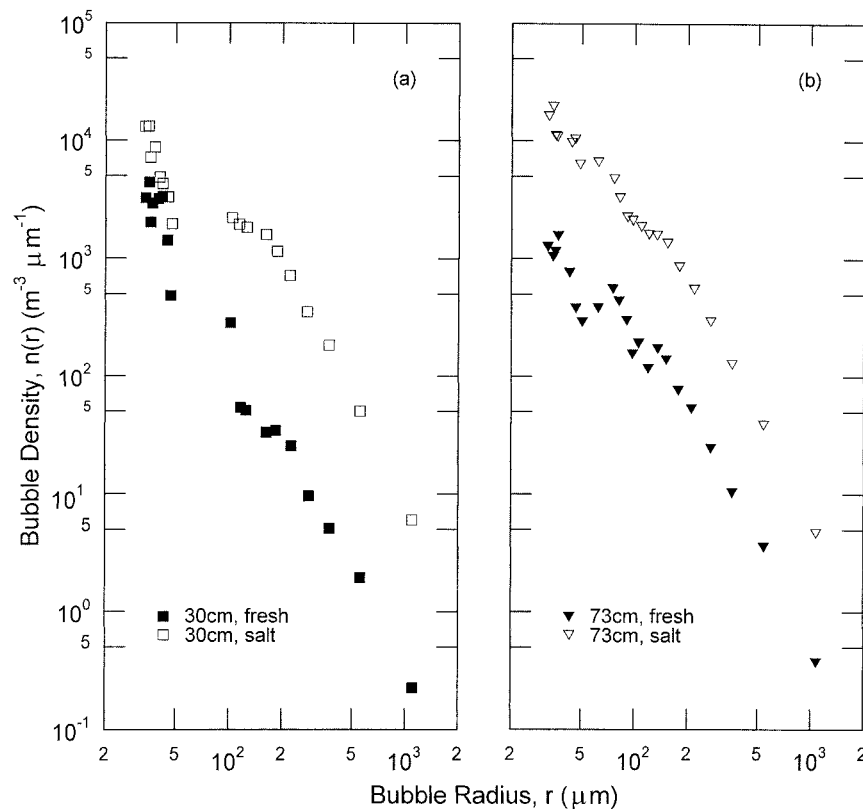E-mail: jinwu@mail.ncku.edu.tw

Fig. 1. Bubble number densities measured by Cartmill and Su (1993). The depth of measurements and the type of water are indicated in the figure.

than 50 μm in radius were measured with a photographic method. Haines and Johnson reported that bubbles were more numerous and smaller and persisted longer in salt, than in fresh, water. Their data, however, were not as finely quantified as those reported by Cartmill and Su (1993). Roughly, the number of bubbles per unit volume in saltwater is consistently greater than that in freshwater, with a larger difference over smaller sizes.

More recently, Loewen et al. (1996) using a photographic technique to measure large bubbles ($r > 800$ μm) entrained by breaking waves in fresh and salt waters. Images of the cloud of bubbles, immediately beneath and behind the breaking wave crest, were analyzed. No significant differences were observed between vertical distributions of bubbles in fresh and salt waters. Note that experiments of Loewen et al. were conducted with gentle spilling breakers in a small wave tank, while those of Cartmill and Su (1993) were with more violent plunging breakers in a much larger facility. Loewen et al. found that differences between bubble number densities in both waters were accordingly small, especially for two smaller amplitude wave packets. For the largest packets, the number density in salt water is also consistently greater than that in fresh water; results for this case are reproduced in Fig. 2.

3. Further analyses

a. Whitecaps

Coverages of sea-surface whitecaps were parameterized by Wu (1979) on the basis of energy consideration of breaking waves; the coverage increased rapidly with the wind velocity, following a power law. The coefficient of power law was obtained from the data reported by Monahan (1971), Monahan et al. (1981), and Doyle (1984). The results were represented by

$$W = 2U_{10}^{3.75}, \tag{1}$$

in which W is the whitecap coverage in ppm (parts per million), and U_{10} expressed in meters per second is the wind velocity at 10 m above the mean sea surface. The above expression is diagramed in Fig. 3; for clarity, the original oceanic data are not shown in the figure.

Coverages of whitecaps over the surface of freshwater lakes reported by Monahan (1969) are reproduced in Fig. 3. The wind velocity was measured at the deck height and was multiplied by 1.05 to obtain the wind velocity U_{10} at the standard anemometer height. As reported by Monahan, there is no distinct dependence of the coverage on atmospheric stability conditions, and the coverages are generally smaller than those over the sea surface. The data appear to follow nearly the same
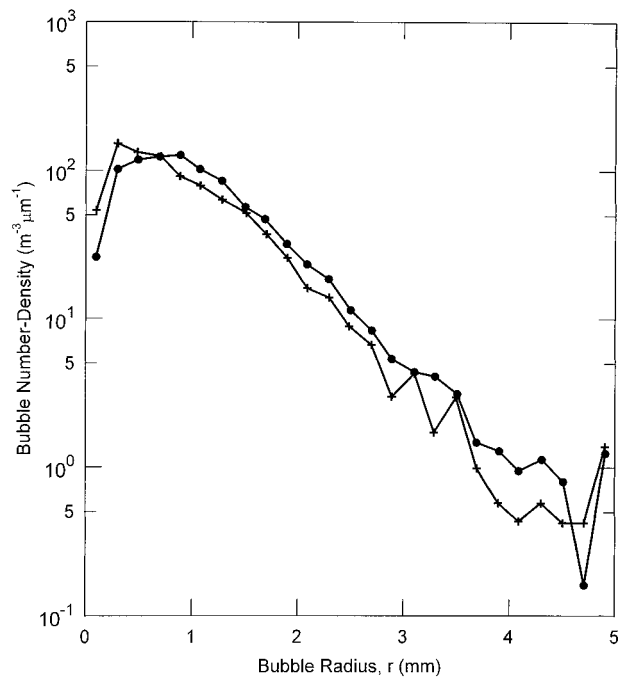
FIG. 2. Numbers of bubbles produced in fresh (+) and salt (●) waters. The results are reproduced from Loewen et al. (1996).

form of power law shown in Eq. (1), on the basis of which the data from freshwater lakes can be represented by the dashed line, expressed as

$$W = 0.3U_{10}^{3.75}. \qquad (2)$$

In summary, whitecaps over the ocean and freshwater lakes appear to follow the same functional variation with the wind velocity. The whitecap coverage over the sea surface is much greater, by nearly seven times, than that over the freshwater lake.

b. Bubbles

As reported by Loewen et al. (1996), the plume of bubbles produced by breaking waves behaved quite similarly in fresh and salt waters. This is actually expected, as noted earlier there are very little differences in fluid properties in these two kinds of waters to cause varying mechanical actions of wave breaking. With plumes of similar overall structures being generated in two waters, measurements of Cartmill and Su (1993) although only at two depths can be analyzed to discuss productions of bubbles in two waters.

As discussed earlier, Cartmill and Su (1993) considered that differences between bubbles in fresh and salt waters are primarily in the distribution of their sizes and discussed the following two effects: coalescence and surface tension. Large differences are seen in Fig. 1 at each depth between the number densities observed in fresh and salt waters. From their results, we obtained the total number of bubbles (N) per unit volume of water
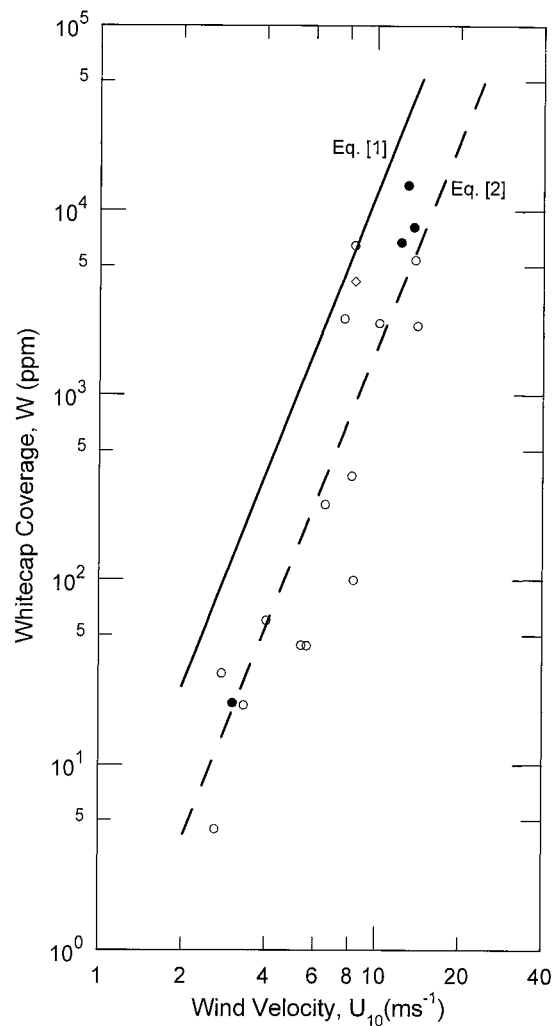

FIG. 3. Variation of whitecap coverage with wind velocity. The data are from Monahan (1969) in freshwater lakes under stable (○), and unstable (●), and unknown (◇) atmospheric conditions; Eq. (1) is for oceanic whitecaps and Eq. (2) for freshwater lakes.

in the size range of their measurements (34–1200 μm in radius) and the average radius ($\bar{r}$) (see Table 1). The total air volume (c) was also determined of bubbles in all cases. Again, all the results were obtained over the size range of measurements of 34–1200 μm.

The total entrainment expressed in the concentration of air in water is often called the void ratio. Large differences are seen between the total air contents in fresh and salt waters; contrary to the suggestion of Cartmill and Su (1993), differences are actually quite significant at both depths. The total entrainments in salt water are much larger at both depths than those in freshwater, by about 2.7 times at the 30-cm depth and by about 12 times at the 73-cm depth.

From the total bubble number, we also obtained the relative bubble number densities (see Figs. 4a–d). The data are grouped in two different fashions in the figure to evaluate effects of the depth and of water properties.

TABLE 1. Total bubble number and air entrainment at two depths in fresh and salt waters.

	30-cm depth			73-cm depth		
	Bubble No. N	Bubble radius $\bar{r}$ (μm)	Air content c (m^3/m^3)	Bubble No. N	Bubble radius $\bar{r}$ (μm)	Air content c (m^3/m^3)
Freshwater	22 437	193.9	6.85×10^{-7}	9411	173.6	2.06×10^{-7}
Salt water	68 362	187.1	1.86×10^{-6}	114 326	173.3	2.49×10^{-6}

Overall, there are, as suggested earlier, many more bubbles produced in salt, than in fresh, water. Such a difference is greater at the shallow depth where bubbles are produced; it becomes insignificant at the deep depth. However, the relative density of bubbles at the shallow depth, again where they were generated, is greater in freshwater over small sizes, and is greater in salt water over large sizes. In freshwater, more large bubbles are seen at a greater depth, but the trend is reversed in salt water. This very distinction demonstrated an enhanced tendency of coalescence in freshwater and an inhibited tendency in salt water.

The results shown in Table 1 are, of course, for bubbles in the size range of 34–1200 μm in radius. The upper bound of measured sizes embraced well large bubbles, while the measurement of Cartmill and Su (1993) definitely missed the important portion of small bubbles. Many studies have confirmed that the size spectrum of bubbles follows the variation of $n(r) \sim r^{-s}$, first proposed by Wu (1981), and that values of the exponent
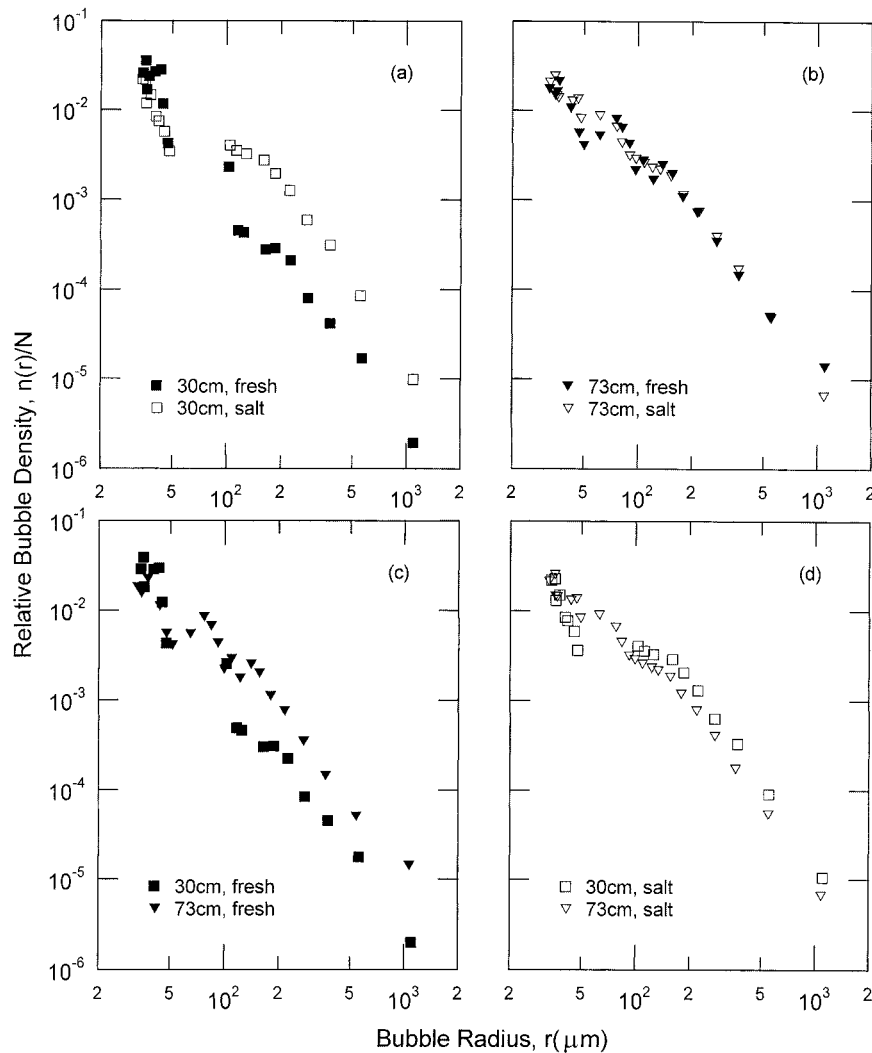

FIG. 4. Relative bubble number densities.

s were found to approach 2 near breaking waves and 4 farther away (Wu 1994). Recently, Haines and Johnson (1995) reported that values of 2.7 and 2.6 for simulated breaking waves in respectively fresh and salt waters. Accepting these values, those small bubbles missed in the measurements should not influence the interpretation of the air entertainment in both waters. We also like to clarify a general misconception that bubbles produced in salt water are smaller. They are seen in Table 1 to be as large as those in freshwater. Most distinctly, size distributions of bubbles are shown to be quite different at two depths. Results at the shallow depth are, of course, associated more closely with the production of air bubbles, while those results at the deep depth are more likely influenced by coalescence or even shattering effects.

Loewen et al. (1996) indicated that their measurement technique was only consistent down to bubble sizes of about 0.8 mm in radius, while a couple of data points at very large sizes are seen in Fig. 2 to be rather erratic. Excluding the data near both ends ($r < 0.8$ mm, $r > 4.5$ mm), we obtained from the figure the ratio between average numbers of bubbles produced in fresh and salt waters; the latter is nearly twice that in the former.

4. Discussion

The results discussed herewithin indicate very clearly that the freshwater/salt-water effect is manifested during the breaking process. First, the observation of a faster decay of whitecaps in freshwater than in salt water (Monahan and Zietlow 1969) is consistent with that under the same wind velocity the whitecap coverage over the sea surface is greater than that over freshwater lakes (Monahan 1971). This latter observation is compatible with that both the volume of air entrainment and the number of bubbles are greater in salt water. It appears from the analyses of Cartmill and Su's (1993) results that bubbles are not smaller in salt water as suggested by Haines and Johnson (1995); there are simply more bubbles produced in salt water. The latter is also consistent with measurements of Loewen et al. (1996).

Taken together all available results, the breaking process appears to be more important than the bubble coalescence (Scott 1975) or shattering (Slauenwhite and Johnson 1999) in determining bubble structures in fresh and salt waters. A larger volume of air is entrained in salt, than in fresh, water. Further studies are needed to understand the cause of this difference; we speculate that it is associated with the influence of both surface tension and viscosity, especially the former, on the breaking process at finer scales of the air–sea and the bubble–water interfaces.

REFERENCES

Blanchard, D. C., 1993: The electrification of the atmosphere by particles from bubbles in the sea. *Progress in Oceanography,* Vol. 1, Pergamon, 72–202.

Cartmill, J. W., and M. Y. Su, 1993: Bubble size distribution under saltwater and freshwater breaking waves. *Dyn. Atmos. Oceans,* **20,** 25–31.

Doyle, D. M., 1984: Marine aerosol research in the Gulf of Alaska and on the Irish West Coast. Whitecaps and the Marine Atmosphere Rep. 6, University College, Galway, Ireland.

Haines, M. A., and B. D. Johnson, 1995: Injected bubble populations in seawater and fresh water measured by a photographic method. *J. Geophys. Res.,* **100,** 7057–7068.

Loewen, M. R., M. A. O'Dor, and M. G. Skafel, 1996: Bubbles entrained by mechanically generated breaking waves. *J. Geophys. Res.,* **101,** 20 759–20 769.

Monahan, E. C., 1969: Freshwater 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.

——, I. G. O'Muircheartaigh, and M. P. Fitzgerald, 1981: Determination of surface wind speed from remotely measured whitecap coverage, a feasibility assessment. European Space Agency SP-167, 103–109.

Scott, J. C., 1975: The role of salt in whitecap persistence. *Deep-Sea Res.,* **22,** 653–657.

Slauenwhite, D. E., and B. D. Johnson, 1999: Bubble shattering: Differences in bubble fromation in fresh water and seawater. *J. Geophys. Res.,* **104,** 3265–3275.

Wu, J., 1979: Oceanic whitecaps and sea state. *J. Phys. Oceanogr.,* **9,** 1064–1068.

——, 1981: Bubble populations and spectra in near-surface ocean: Summary and review of field measurements. *J. Geophys. Res.,* **86,** 457–463.

——, 1994: Bubbles in near-surface ocean: Their various structures. *J. Phys. Oceanogr.,* **24,** 1955–1965.