The geophysical importance of bubbles in the sea

Ramon J. Cipriano

Atmospheric Sciences Research Center, State University of New York at Albany
1400 Washington Avenue, Albany, New York 12222

Abstract

Sea salt is by far the major constituent cycled through the earth's atmosphere each year. Bursting bubbles in the oceans appear to be primarily responsible. These salt particles play a role in the formation of maritime clouds, which in turn affect the earth's radiation budget. Along with the salt are carried various chemical pollutants and potentially pathogenic microorganisms, often in highly enriched form. Both jet and film drops are produced by bursting bubbles. This paper summarizes our present knowledge of the droplet production and enrichment mechanisms, with particular emphasis on the unsolved problems.

Introduction

Each year the oceans of the world inject 10^9-10^{10} tons of salt into the atmosphere.[1] This is 1 or 2 orders of magnitude greater than inputs from all other sources. Bursting bubbles from whitecaps appear to be primarily responsible. There is good evidence suggesting that most of the condensation nuclei involved in maritime cumulus and stratocumulus cloud formation consist of or are derived from sea salt.[2,3,4,5] These cloud types are ubiquitous and affect the global radiation budget. Their microphysical structure is fundamentally different from continental clouds, allowing them to produce rain much more efficiently,[6] which in turn affects the residence time of smaller particles in the marine atmosphere.[7] The marine aerosol exhibits a geochemical fractionation or enrichment which generally increases with decreasing particle size.[8,9,10,11] Various pollutants such as PCBs, DDT, heavy metals, and radionuclides are transferred from sea to air, often in highly concentrated form.[12] Microorganisms such as bacteria and viruses are found concentrated in aerosols from bursting bubbles,[13,14,15,16] with consequent health implications if pathogens are involved.[17]

Droplet production mechanisms

Film drops

Two types of droplets are produced when bubbles burst. Film drops form from the disintegration of the protruding bubble film. The details of this process are unknown, largely because the film rupture has never actually been observed. Two difficulties present themselves. First, the rupture is quite rapid: for a 250 μm diameter bubble, the film collapses in about 3×10^{-7} sec.[18] But this is now well within the reach of current time-lapse capabilities. A more serious problem is the size of the film drops, for recent evidence suggests most are of submicron dimensions. Thus any photographic scheme which allows observation of the entire film collapse will lack sufficient resolution to reveal many of the individual droplets formed by the collapse.

Most important of the variables controlling film drop production is bubble size: bubbles smaller than about 300 μm diameter produce few or none; 1 mm bubbles produce up to 20 or 30, and this increases to a maximum of about 1000 for 6 mm bubbles; most of the film droplets are ejected in a cloud several centimeters above the water surface.[18,19] However, for a given bubble diameter, the film drop production can be a fraction of the maximum numbers just quoted. Two variables influencing this (there are undoubtedly others) are the "cleanliness" of the bubble (i.e., the amount of surfactant adsorbed to the bubble as it rises), and the bubble surface lifetime (delay between the arrival of the bubble at the water surface and the film collapse). Film drop production generally decreases with increasing bubble dirtiness and surface lifetime (for reasons still hypothetical), although there are exceptions to this. Bubble surface lifetime is itself related to bubble cleanliness, for reasons also poorly understood.

Data on film drop size distributions are scant. Blanchard and Syzdek[20] used glass slides coated with MgO to determine the film drop size distribution of drops resolvable with the light microscope for 740 μm diameter bubbles. The distribution peaked at about 4-6 μm, as shown in Figure 1.
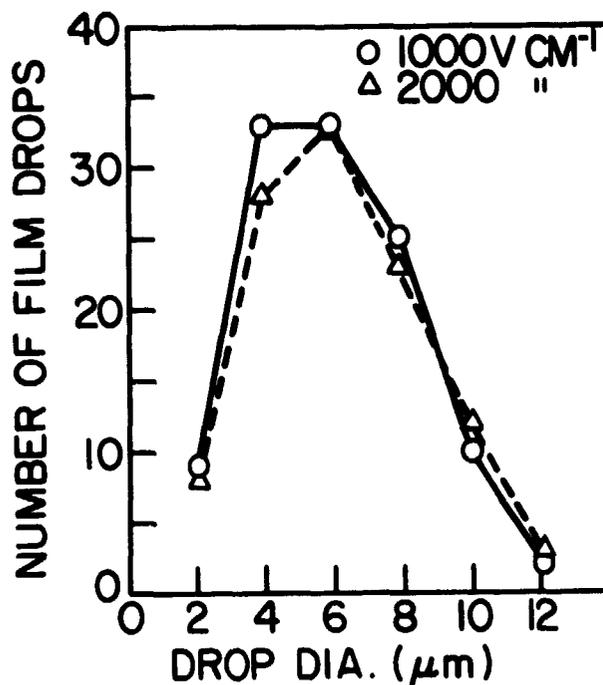
Figure 1. Film drop size distribution (2 μm bandwidth) obtained from 30 bubbles of 740 μm diameter bursting in a 3.3 x 10³ ppm nutrient broth solution. Film drops were collected electrostatically, at the indicated field strength, on glass slides coated with MgO. Data from Blanchard and Syzdek (1975).

The maximum film drop production mentioned above was determined with a thermal gradient diffusion cloud chamber, which is capable of growing drops of <0.01 μm diameter to 5-10 μm. The cloud of droplets so produced tends toward monodispersity regardless of the initial size distribution. However, data obtained by the author suggests that for larger bubbles (>1 μm dia.), most film drops are submicroscopic. For example, when the aerosol produced by bursting of 1.8 mm dia. bubbles in seawater was examined simultaneously with a TSI[R] 3020 condensation nuclei counter (capable of counting hygroscopic particles <0.01 μm dia.) and a Royco optical particle counter (dia. >0.3 μm), the Royco count was only 10-30% of the 3020 count.

Further evidence suggesting submicron film drop production was obtained from a laboratory model of a breaking wave, shown in Figure 2. Seawater, circulated by a centrifugal pump, falls from a height of 33 cm into a circular tank 0.5 m in diameter. The aerosol produced by the upwelling plume of bubbles was passed through a Sinclair diffusion battery, the penetration through which is determined by particle size.[21] Figure 3 shows the penetration curves of the model wave aerosol at 90% and 75% relative humidity, compared with the penetration curves of monodisperse aerosols of 0.05 μm, 0.02 μm, and 0.01 μm radii. Although drops other than film drops are produced by the experimental configuration shown in Figure 2, there are good reasons to believe the submicron drops revealed in Figure 3 are indeed film drops.[22]
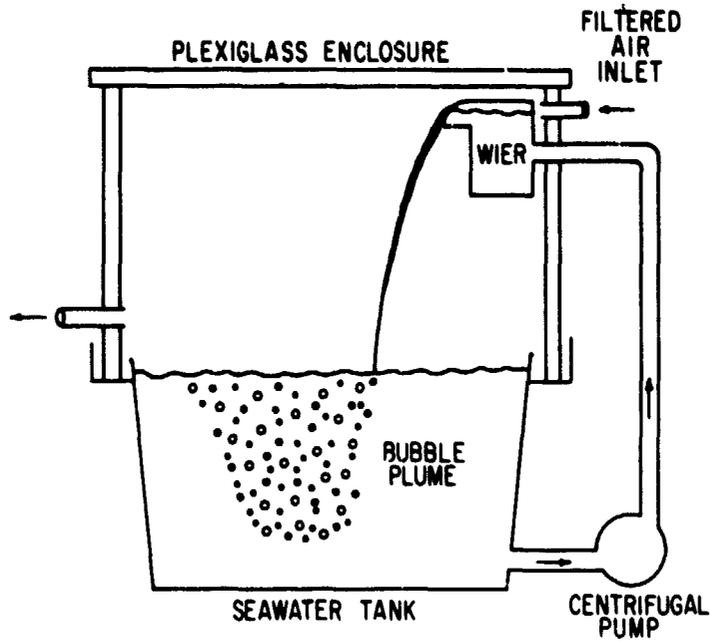
Figure 2. Scale drawing of a laboratory simulation of a breaking wave or whitecap. Tank diameter is 0.5 m, waterfall height 33 cm.
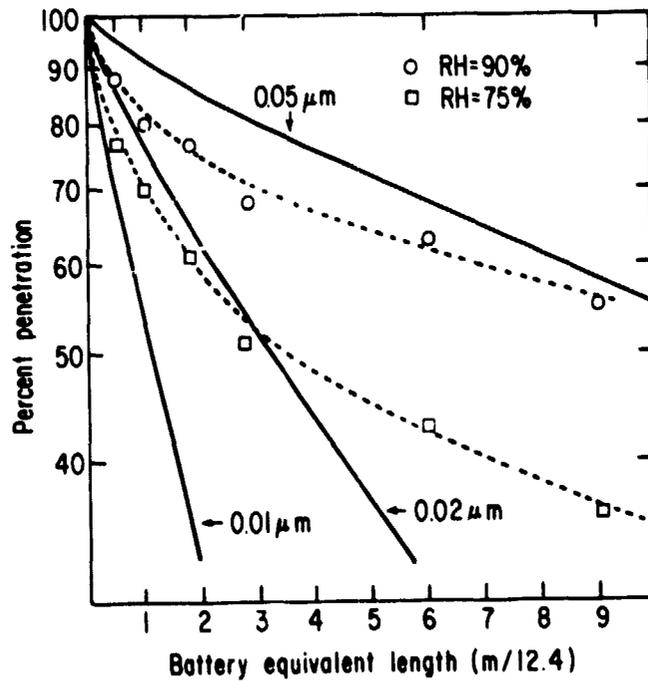
Figure 3. Diffusion loss of the model wave aerosol at 90% relative humidity, together with calculated diffusion loss for monodisperse aerosols of 0.05 μm, 0.02 μm, and 0.01 μm radii.

Jet Drops

Jet drops are also produced by bursting bubbles. These are formed by the collapse of the cavity remaining after the film rupture. A jet of water is propelled upwards from the center of this cavity, becomes unstable, and breaks into discrete droplets. Surface tension is the major energy source.[18] Jet drops are about one-tenth the bubble diameter.[23] The number of jet drops per bubble decreases from as many as five or six for a 300 μm diameter bubble to only one for bubbles larger than about 3 mm.

The breakup of the jet into individual droplets has been observed for a large ... (1.7 mm dia.) by time-lapse photography with 3×10^{-4} sec resolution.[24] Detai of jet breakup for smaller bubbles are as yet unobserved, although certainly well wit.. current capabilities. The calculated top jet drop ejection speed increases with decreasing drop size, reaching 8×10^3 cm sec^{-1} at 70 μm bubble diameter.[18] (Film drop ejection speeds are unknown.) Top jet drop ejection height reaches a maximum of nearly 20 cm for 200 μm drops. The upper bound jet drop diameter relevant to atmospheric processes is, of course, determined by sedimentation, 20 μm being a reasonable value. The lower bound jet drop diameter is unknown; direct observations extend only to ~7 μm. The existence of submicron jet drops is at this point hypothetical; it is, however, doubtful that such drops are produced in large numbers in nature, since bubbles smaller than 10 μm diameter are rapidly forced into solution due to surface tension.[23,25]

Droplet enrichment mechanisms

Material can adsorb to the surface of a bubble both as it rises (bubble scavenging), and also as it penetrates the bulk water surface, if a monolayer of material is floating there. Film drops are formed from the bubble surface itself. Material which comprises the jet drops, particularly the top drop, is skimmed from the surface of the bubble cavity by a capillary wave which in effect acts as a microtome.[26] Thus it might be expected that the composition of both jet and film drops can be vastly different from that of the bulk water in which the bubbles burst. The enrichment of bacteria in jet drops has already been demonstrated,[15] and evidence strongly suggestive of film drop bacterial enrichment now exists.[22] In nature, both bubble scavenging and bulk surface microlayer transfer surely operate. Which of the two mechanisms predominates is unknown. Strong arguments favor scavenging,[27] particularly in cases where the flux of upwelling bubbles is great, for this causes divergence of the water surface adequate to push aside floating monolayers.

Relevance to geophysics

The relative contribution of jet and film drops to the marine aerosol and its enrichment is a complex problem. In view of the relationships between jet and film drop size distributions versus bubble size, the shape of the bubble spectrum in whitecaps is of critical importance. The size distribution of sea salt particles is such that most of the salt mass is contributed by drops larger than 1 μm, whereas these comprise a small fraction of the total number. Most cloud condensation nuclei (CCN) are smaller than 1 μm.[4,6] Comparison of the bubble and aerosol spectra produced by the model whitecap shown in Figure 1 suggests that the global salt mass flux is controlled by jet drops, from bubbles smaller than 1 mm, and that the CCN flux is controlled by film drops, from bubbles larger than 1 mm.[3,22] It is important to determine the validity of this laboratory simulation: there is evidence that a feedback mechanism exists whereby the addition of surface active material to the oceans, by man or otherwise, can lead to a significant modification of film and jet drop production.[28]

The processes of drop formation and enrichment mentioned here must apply to some extent to bubbles in all types of liquids. It is anticipated that new parallels will be found in many other disciplines.

References

1. Blanchard, D. C., and A. H. Woodcock, "The Production, Concentration, and Vertical Distribution of the Sea-Salt Aerosol," Annals N. Y. Acad. Sci., Vol. 338, pp. 330-347. 1980.
2. Blanchard, D. C., "The Oceanic Production Rate of Cloud Nuclei," J. Rech. Atmos., Vol. 4, pp. 1-6. 1969.
3. Cipriano, R. J., and D. C. Blanchard, "Bubble and Aerosol Spectra Produced by a Laboratory Breaking Wave," J. Geophys. Res., in press.
4. Dinger, J. E., H. B. Howell, and T. A. Wojciechowski, "On the Source and Composition of Cloud Nuclei in a Subsident Air Mass over the North Atlantic," J. Atmos. Sci. Vol. 27, pp. 791-797. 1970.
5. Woodcock, A. H., "Smaller Salt Particles in Oceanic Air and Bubble Behaviour in the Sea," J. Geophys. Res., Vol. 77, pp. 5316-6321. 1972.
6. Mason, B. J., The Physics of Clouds, Clarendon Press, Oxford, pp. 79-80. 1971.

7. Junge, C., "Our Knowledge of the Physico-Chemistry of Aerosols in the Undisturbed Marine Environment," J. Geophys. Res., Vol. 77, pp. 5183-5200. 1972.

8. Barker, D. R., and M. Zeitlin, "Metal Ion Concentrations in Sea-Surface Microlayer and Size-Separated Atmospheric Aerosol Samples in Hawaii," J. Geophys. Res., Vol. 77, pp. 5076-5086. 1972.

9. Chesselet, R., J. Morelli, and P. Buat-Menard, "Variations in Ionic Ratios between Reference Sea Water and Marine Aerosols," J. Geophys. Res., Vol. 77, pp. 5116-5131. 1972.

10. Duce, R. A., A. H. Woodcock, and J. L. Moyers, "Variation of Ion Ratios with Size among Particles in Tropical Oceanic Air," Tellus, Vol. 19, pp. 369-379. 1967.

11. Hoffman, G. L., and R. A. Duce, "Consideration of the Chemical Fractionation of Alkali and Alkaline Earth Metals in the Hawaiian Marine Atmosphere," J. Geophys. Res., Vol. 77, pp. 5161-5169. 1972.

12. GESAMP: Joint Group of Experts on the Scientific Aspects of Marine Pollution. Interchange of Pollutants between the Atmosphere and the Oceans, Rep. Stud. GESAMP (13), 55 pp. 1980.

13. Baylor, E. R., M. B. Baylor, D. C. Blanchard, L. D. Syzdek, and C. Appel, "Virus Transfer from Surf to Wind," Science, Vol. 198, pp. 575-580. 1977.

14. Bezdek, H. F., and A. F. Carlucci, "Surface Concentration of Marine Bacteria," Limnol. Oceanogr., Vol. 17, pp. 566-569. 1972.

15. Blanchard, D. C., and L. D. Syzdek, "Concentration of Bacteria in Jet Drops from Bursting Bubbles," J. Geophys. Res., Vol. 77, pp. 5087-5099. 1972.

16. Hejkal, T. W., P. A. LaRock, and J. W. Winchester, "Water-to-Air Fractionation of Bacteria," Appl. Environ. Microbiol., Vol. 39, pp. 335-338. 1980.

17. Wendt, S. L., K. L. George, B. C. Parker, H. Gruft, and J. O. Falkinham, III, "Epidemiology of Infection by Nontuberculous Mycobacteria, III: Isolation of Potentially Pathogenic Mycobacteria from Aerosols," Am. Rev. Respir. Dis., Vol. 122, pp. 259-263. 1980.

18. Blanchard, D. C., "The Electrification of the Atmosphere by Particles from Bubbles in the Sea," Prog. Oceanogr., Vol. 1, pp. 71-202. 1963.

19. Day, J. A., "Production of Droplets and Salt Nuclei by the Bursting of Air-Bubble Films," Quart. J. R. Met. Soc., Vol. 90, pp. 72-78. 1963.

20. Blanchard, D. C., and L. D. Syzdek, "Electrostatic Collection of Jet and Film Drops," Limnol. Oceanogr., Vol. 20, pp. 762-774. 1975.

21. Sinclair, D., and L. Hinchcliffe, "Production and Measurement of Submicron Aerosols, II." In: Assessment of Airborne Particles, Chapter 10 (Ed. by T. T. Mercer, P. E. Morrow and W. Stober), Charles C. Thomas. 1972.

22. Cipriano, R. J., Bubble and Aerosol Spectra Produced by a Laboratory Simulation of a Breaking Wave, Ph.D. dissertation, State University of New York at Albany. 1979.

23. Blanchard, D. C., and A. H. Woodcock, "Bubble Formation and Modification in the Sea and Its Meteorological Significance," Tellus, Vol. 9, pp. 145-158. 1957.

24. Kientyler, C. F., A. B. Arons, D. C. Blanchard and A. H. Woodcock, "Photographic Investigation of the Projection of Droplets by Bubbles Bursting at a Water Surface," Vol. 6, pp. 1-7. 1954.

25. Johnson, B. D., and R. C. Cooke, "Organic Particle and Aggregate Formation Resulting from the Dissolution of Bubbles in Seawater," Limnol. Oceanogr., Vol. 25, pp. 653-661. 1980.

26. MacIntyre, F., "Geochemical Fractionation during Mass Transfer from Sea to Air by Breaking Bubbles," Tellus, Vol. 22, 451-461. 1970.

27. Blanchard, D. C., "Bubble Scavenging and the Water-to-Air Transfer of Organic Material in the Sea," Advances in Chemistry, No. 145. Applied Chemistry at Protein Interfaces, American Chemical Society. 1975.

28. Blanchard, D. C., and E. J. Hoffman, "Control of Jet Drop Dynamics by Organic Material in Seawater," J. Geophys. Res., Vol. 83, pp. 6187-6191. 1978.