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Contributions of film and jet drops to marine aerosols produced at the sea surface

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ABSTRACT

Bubble populations at the sea surface were deduced from oceanic measurements; drop productions through the bursting of artificially generated bubbles were also observed. Taking these results together, contributions of film and jet drops to marine aerosols under various wind velocities are estimated; they appear to consist of mainly jet drops.

1. Introduction

Air is entrained into the near-surface ocean by breaking waves. Subsequently, air bubbles because of their buoyancy are returned to the sea surface and burst; those produced through fragmentation of the film cap are film drops, and those, through the break-up of a water jet formed by the collapse of the bubble cavity, are jet drops (Kientzler et al., 1954; Blanchard, 1963; Day, 1964). These drops are associated meteorologically with the formation of clouds (Woodcock, 1952), oceanographically with evaporation from the sea (Wu, 1974), environmentally with the enrichment of heavy metals and bacteria (Duce and Hoffman, 1976; Blanchard, 1978) and practically with damage to ship turbines and light interference of guidance systems (Ruskin et al., 1981; Schacher et al., 1981).

Because a vast number of them can be generated by artificially produced bubbles, film drops were conjectured to be the major contributor to marine aerosols (Cipriano and Blanchard, 1981). As pointed out by Blanchard (1983), however, this clearly depends on the size distribution of oceanic bubbles. Combining recent comprehensive studies on aerosols produced by air bubbles bursting at the still water surface (Resch et al., 1986) and on size and concentration of bubbles in the near-surface ocean (Wu, 1988), we have estimated relative contributions of film and jet drops to the production of marine aerosols under various wind velocities.

2. Summary and analysis of previous results

2.1. *Size and concentration of bubbles at the sea surface*

Combining reported complementary measurements of bubbles in the near-surface ocean (Kolovayev, 1976; Johnson and Cooke 1979), a general description on concentrations and sizes of bubbles at various depths under a wide range of wind velocities was proposed (Wu, 1988). From the latter, the following is abstracted.

2.1.1. Size distribution. Size spectra of bubbles measured by Kolovayev (1976) and Johnson and Cooke (1979) were shown to follow a power-law distribution

$$f(D) \sim D^{-4}, \tag{1}$$

where $f(D)$ is the frequency of occurrence of bubbles having diameter D. The above is applicable to bubbles as small as 100 μm in diameter, where the size distribution is peaked.

2.1.2. Vertical distribution. The vertical distribution of bubble populations was first suggested (Wu, 1981) to follow an exponential expression

$$N(z)/N_0 = \exp(z/z_b), \tag{2}$$

where $N(z)$ is the bubble population at depth z, N_o the population at the sea surface, and z_b a length characterizing the vertical entrainment of bubbles. The characteristic length z_b was suggested to follow

$$z_b = 0.4, \qquad U_{10} < 7 \text{ m s}^{-1},$$
$$z_b = 0.4 + 0.12(U_{10} - 7), \qquad U_{10} > 7 \text{ m s}^{-1}, \tag{3}$$

in which z_b is expressed in *m*, and U_{10} in m s^{-1} is the wind velocity at 10 m above the mean sea surface.

2.1.3. Wind dependency. Bubble populations at the sea surface were deduced (Wu, 1981) from the data of Kolovayev (1976) and Johnson and Cooke (1979) over a narrow range of wind velocities; a power-law type variation was proposed by Wu (1981) to represent their data. Subsequently, vertical distributions of the acoustic scattering cross section of bubbles measured by Thorpe (1982) over a wide range of wind velocities were used to determine the surface value (Wu, 1986). Considering that the bubble concentration and the acoustic cross section have a similar variation with wind velocity, the following was suggested,

$$N_o = 57\ U_{10}^{3.5}, \tag{4}$$

where N_o has the dimension of m^{-3} and U_{10} of again m s^{-1}.

2.1.4. A general description. Functional variations discussed above were then combined to obtain a general description of bubble populations as

$$N(z, D) = 57\ U_{10}^{3.5} \exp(z/z_b) f(D), \quad f(D) \sim D^{-4}, \tag{5}$$

in which z_b can be obtained from Eq. (3).

2.2. Drop productions through bubble bursting

2.2.1. Film drops. Using a holographic technique, Resch et al. (1986) observed the bursting process of an artificially produced single bubble at the still water surface. They obtained from both fresh water and seawater the distribution in space of film drops immediately after the rupture of the interfacial film cap. Histograms of the number of film drops in terms of the drop diameter were reported for bubbles of four diameters, $D = 4$, 6, 8 and 10 mm.

The number of film drops obtained by Resch et al. from sea water is replotted on logarithmic scales, instead of log-linear scales as in the original, in Fig. 1a versus the diameter of their parent bubbles. A systematic variation now appears to emerge in this type of presentation; the line fitted to the data can be approximated by a power law

$$n_{fa} = 0.65\ D^{2.15}, \tag{6}$$

where n_{fa} is the number of film drops produced by a bubble having the diameter D (mm); the subscript $_a$ is attached to indicate that these are the results obtained with artificial bubbles. From histograms reported by Resch et al., we also obtained the average drop diameter (d_f) for each size of bubble, see Fig. 1b. The film drops are seen to have an overall average diameter of 95 μm, but increase with the diameter of their parent bubble. The ratio between the film-drop and bubble diameter was also calculated and is presented in Fig. 1b; it falls in the range of $1 - 1.8\%$ and decreases as the size of bubble increases.

2.2.2. Jet drops. Much of our knowledge of jet drops was provided by Kientzler et al. (1954), while all the results were nicely reviewed and summarized by Blanchard (1963, 1983). The diameter of jet drops d_j was found to range between $0.1 - 0.15$ times that of their parent bubble, and the number produced by a single bubble never exceeded 10, and decreased as the bubble diameter increased, as:

$$n_{ja} = 7 \exp(-D/3), \tag{7}$$

where n_{ja} is the number of jet drops produced by a bubble having the diameter D (mm); eq. (7) is also illustrated in Fig. 1a.

3. Relative compositions of film and jet drops

The bubble population at the sea surface can be obtained from eq. (5) for $z = 0$ as:

$$N_o(D) = 57\ U_{10}^{3.5} D^{-4}, \tag{8}$$

where again $N_o(D)$ is expressed in m^{-3}, U_{10} in m s^{-1}, and D in mm. The number of film and jet drops produced can then be found from $n_{fa}N_o(D)$ and $n_{ja}N_o(D)$, respectively.

As for the relative compositions of film and jet drops, we can estimate them by simply combining eqs. (1), (6) and (7) to obtain

$$n_{fo} \sim 0.65\ D^{-1.85}$$
$$n_{jo} \sim 7 \exp(-D/3)\ D^{-4}, \tag{9}$$

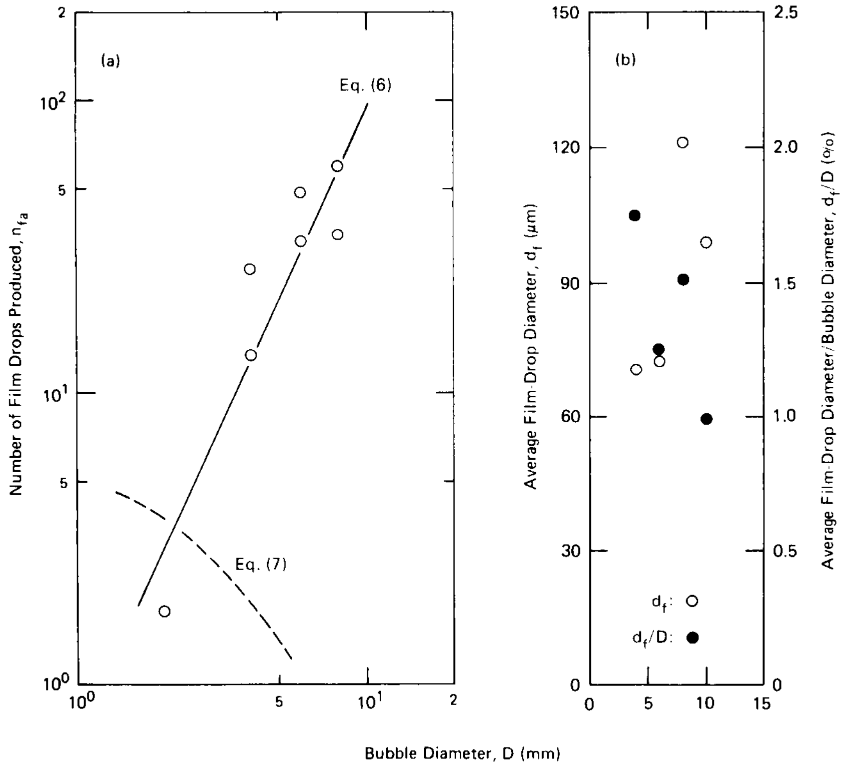

Fig. 1. Numbers and diameters of film drops produced by bubbles of various sizes. The results were deduced from that data obtained by Resch et al. (1986).

where the subscript $_0$ is attached to indicate that the size distribution of oceanic bubbles has been incorporated. The results are illustrated in Fig. 2, which are applicable to all wind velocities by multiplying the number in the diagram with 57 $U_{10}^{3.5}$ as shown in eq. (8), to obtain the bubble population.

As shown in Figs. 1a, 2, a dividing diameter of bubbles is established at 2.15 mm; below this diameter, more jet drops are actually produced by bubbles, while more film drops are produced above this diameter. Note that this dividing diameter is not affected by the size distribution of oceanic bubbles; the latter can only change the slope of curves shown in Fig. 2.

As for the total relative numbers of film and jet drops produced, we can integrate eq. (9) and compare two integrals; such integrations were performed from lower limits of various bubble diameters (D_l) to an upper limit of 10 mm. Relative contributions of film and jet drops to the production of marine aerosols obtained with different lower integration limits are presented in Table 1.

It is clearly illustrated in Table 1 that marine aerosols produced at the sea surface consist mainly of jet drops. Although more film drops are produced by large bubbles, $D > 2.15$ mm, there are just too many small bubbles which produce many more jet drops. As discussed earlier, the size distribution, on which the present estimate is based, extends only to bubbles as small as 100 μm in diameter, corresponding to the smallest D_l in Table 1. Only the values associated with $D_l = 100$ μm shown in Table 1 should be counted, with the others being listed as references. The lack of an established size distribution for small bubbles ($D < 100$ μm) does not affect the conclusion of the present results; as discussed earlier, the production of jet drops outnumbered that of film drops from small bubbles with $D < 2.15$ mm. Note that due to optical limitations, droplets

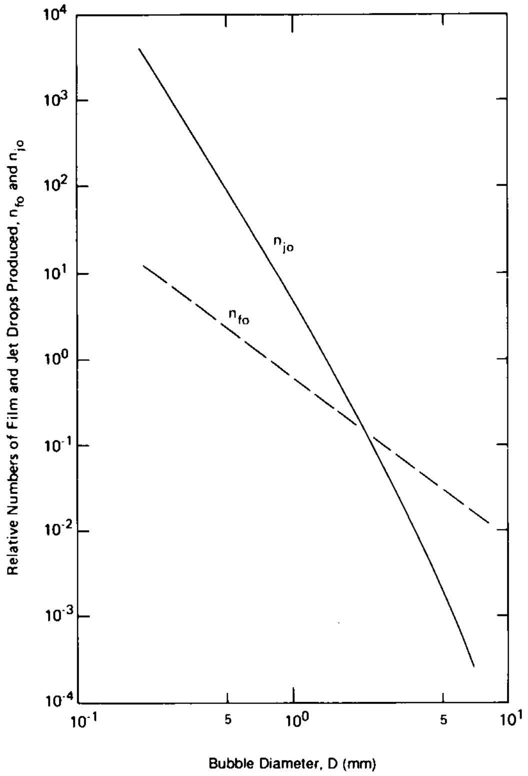

Fig. 2 Numbers of film and jet drops produced by oceanic bubbles. The numbers, corresponding to those shown in eq. (9), are arbitrary.

smaller than 8 μm in diameter were not measured by Resch et al. (1986); the dividing diameter may therefore shift somewhat to a lower value with more refined measurements.

4. Concluding remarks

Because of their larger sizes, it was suggested by Blanchard and Woodcock (1957) that jet drops

Table 1. *Relative compositions of film and jet drops obtained from the integration of eq. (9) from D_l to $D = 10$ mm*

Lower integration limit, D_l (mm)	Relative compositions of drops (%) film drops	jet drops
0.1	0.2	99.8
0.2	0.8	99.2
0.3	2.2	97.8
0.4	4.3	95.7
0.5	7.2	92.8

play the most important role in air-sea exchanges. This view was subsequently challenged by Cipriano and Blanchard (1981) on the basis of their measured bubble spectra produced by a water jet, and an assumed relationship between film drops and parent bubbles. Such an estimate is greatly upgraded here by using the size distribution of oceanic bubbles and the experimentally determined number of film drops produced by bubbles. Although much still needs to be learned about other relevant factors used in this kind of estimate, such as the bubble surface lifetime and the bubble flux spectrum, the conclusion that initially produced marine aerosols consist mainly of jet drops is likely to be true, as the dominance of jet drops is just too overwhelming.

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