A New Sea Spray Generation Function for Wind Speeds up to 32 m s^{-1}

EDGAR L ANDREAS

U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire

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ABSTRACT

The sea spray generation function quantifies the rate at which spray droplets of a given size are produced at the sea surface. As such, it is important in studies of the marine aerosol and its optical properties and in understanding the role that sea spray plays in transferring heat and moisture across the air–sea interface. The emphasis here is on this latter topic, where uncertainty over the spray generation function, especially in high winds, is a major obstacle. This paper surveys the spray generation functions available in the literature and, on theoretical grounds, focuses on one by M. H. Smith et al. that has some desirable properties but does not cover a wide enough droplet size range to be immediately useful for quantifying spray heat transfer. With reasonable modifications and extrapolations, however, the paper casts the Smith function into a new form that can be used to predict the production of sea spray droplets with radii from 2 to 500 μm for 10-m winds from 0 to 32.5 m s^{-1}. The paper closes with sample calculations of the sensible and latent heat fluxes carried by spray that are based on this new spray generation function.

1. Introduction

Sea spray droplets come, basically, in three varieties: film droplets, jet droplets, and spume droplets. Film and jet droplets derive from one process—air bubbles bursting at the sea surface. When a bubble rises to the surface, its film-thin top eventually ruptures and ejects tens to hundreds of ''film'' droplets with radii ranging roughly from 0.5 to 5 μm. After the bubble bursts, it collapses and in so doing shoots up a jet of water from its bottom. Because of velocity differences along this jet, it soon breaks up into a few ''jet'' droplets with radii typically from 3 to 50 μm, depending on the size of the bubble.

''Spume'' droplets derive from another process—the wind tears them right off the wave crests. Consequently, they are the largest spray droplets; minimum radii are generally about 20 μm and there is no definite maximum radius. Clearly, spume generation does not begin until the 10-m wind reaches some threshold speed in the range of 7–11 m s^{-1}. Afeti and Resch (1990), Andreas (1992), Andreas et al. (1995), Blanchard (1963, 1989), Kientzler et al. (1954), Koga (1981), Monahan (1986), Monahan et al. (1986), Spiel (1994, 1995), Woolf et al. (1987), and Wu (1993, 1994), among many others, describe and try to quantify both the bubble and spume production mechanisms.

Corresponding author address: Dr. Edgar L Andreas, U.S. Army Cold Regions Research and Engineering Laboratory, 72 Lyme Road, Hanover, NH 03755-1290.
E-mail: eandreas@crrel.usace.army.mil

Knowing the rate at which spray droplets of any given size are produced at the sea surface—the sea spray generation function—is essential for many calculations. Spray droplets are the source of the local marine aerosol. Any modeling of that aerosol therefore requires a sea spray generation function (e.g., Fairall et al. 1983; Fairall and Larsen 1984; Burk 1984; Stramska 1987). In turn, because the aerosol dictates the optical properties of the marine boundary layer, the spray generation function is also crucial to studies of marine scattering and extinction (e.g., Fairall et al. 1982; Gathman 1983; de Leeuw 1989; Hoppel et al. 1989; Gathman and Davidson 1993).

Speculation over whether sea spray also affects the air–sea fluxes of heat and moisture began over 50 years ago (Montgomery 1940). Studies of this question, too, require a sea spray generation function (e.g., Bortkovskii 1973, 1987; Borisenkov 1974; Ling et al. 1980; Mestayer et al. 1989; Fairall et al. 1990; Rouault et al. 1991; Andreas 1992; Ling 1993; Edson et al. 1996).

Spray droplets that eventually become the main constituents of the marine aerosol are typically smaller than those that most influence air–sea heat and moisture transfer. Since my abiding interest is in these air–sea heat and moisture fluxes, I concentrate in the rest of this paper on the spray droplet size range that is relevant to this problem—droplets with radii at formation between 2 and 500 μm (Andreas 1990).

Figure 1 shows, for a 10-m wind speed (U_{10}) of 15 m s^{-1}, original or descendant versions of most of the spray generation functions that have been reported in

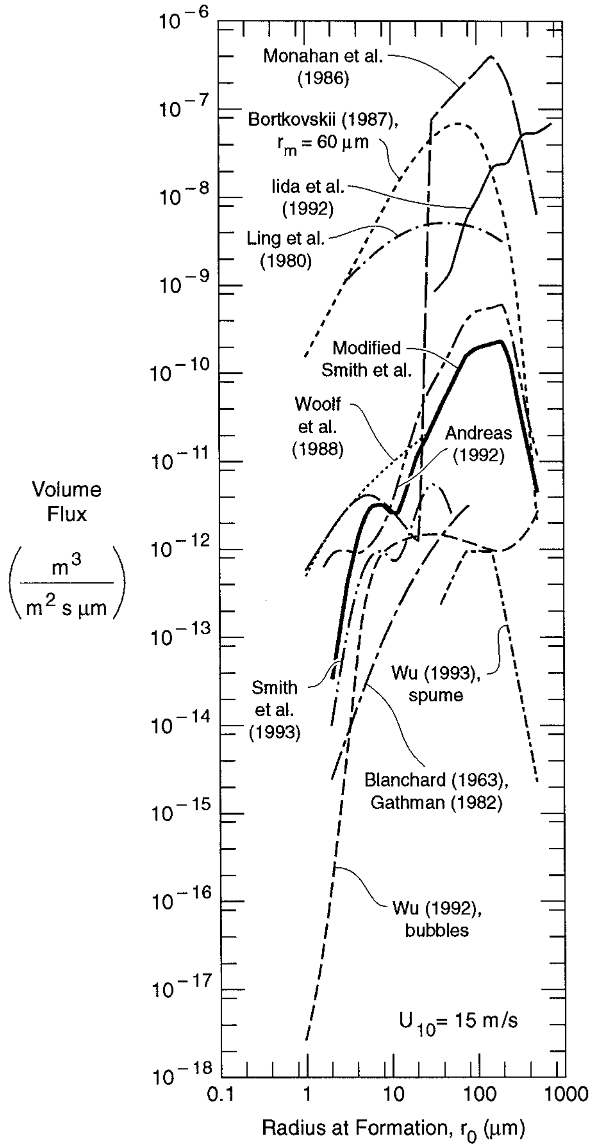

FIG. 1. Various estimates of the sea spray generation function in terms of the volume flux, $(4\pi r_0^3/3)dF/dr_0$, for a 10-m wind speed (U_{10}) of 15 m s^{-1}. In Bortkovskii's (1987) function, r_m, the mode radius, is a free parameter. The "Modified Smith et al." function is the subject of this paper.

the literature. The sea spray generation function, commonly denoted as dF/dr_0 (e.g., Monahan et al. 1986), where r_0 is the radius of a droplet at its formation, has units of number of droplets produced per square meter of surface per second per micrometer increment in droplet radius. The generation function as a volume flux—that is, $(4\pi r_0^3/3)dF/dr_0$—is more relevant to spray heat and moisture transfer, however. This is what is plotted in Fig. 1. Andreas (1992, 1994) and Andreas et al. (1995) discuss most of these functions further and give the relevant equations for computing many of them.

Figure 1 clearly shows that there is no consensus in the magnitude of the spray generation function: At any given radius, the predictions range over six orders of magnitude. There is some consistency, though, in the predicted shape of the spray generation function. Generally, the volume flux is relatively small for droplets with radii less than 2 μm or greater than 500 μm and has a 2 to 3 order-of-magnitude peak between, roughly, 10 and 200 μm. Because this peak is in the spume region, getting the spume production right is essential for evaluating the effects of spray on air–sea heat and moisture transfer (Andreas 1992).

We can discount some of the functions in Fig. 1. Several studies report that the spume peak in the function of Monahan et al. (1986) predicts far too many droplets (Burk 1984; Stramska 1987; Andreas 1992; M. H. Smith et al. 1993). Fairall and Edson (1989) likewise suggest that the function of Ling et al. (1980) predicts too many droplets. By association, the functions from Bortkovskii (1987) and Iida et al. (1992) are also too large. The Blanchard (1963) and Gathman (1982) function is based on Woodcock's (1953) observations at 600 m above the ocean near Hawaii and must surely underestimate the surface spray production. M. H. Smith et al. (1993) made the measurements on which they based their spray generation function 14 m above mean sea level near the high-water mark on a sloping beach. Consequently, they too probably underestimate the spray production, especially for the larger droplets (Mestayer et al. 1996). The Smith et al. function, however, covers the largest wind speed range of any of the functions, U_{10} up to 32 m s^{-1}, and will be the focus of later discussion. Since Wu's bubbles-only (Wu 1992) and spume-only (Wu 1993) generation functions are similar to or lower than the Blanchard-Gathman and Smith et al. functions, at least for U_{10} = 15 m s^{-1}, I assume that they underestimate spray production too.

The production of bubble-derived droplets in the function from Monahan et al. (1986) (i.e., the extreme left side of their function) has led to reasonable modeling results (e.g., Burk 1984; Stramska 1987). Woolf et al. (1988) continued the wave-tank work on which Monahan et al. based their generation function and, thus, corroborate its general magnitude. My opinion is that the bubbles-only part of the Monahan et al. spray generation function is, thus, the best one available for predicting spray production by whitecap bubbles.

Andreas (1990, 1992) demonstrates, however, that spume droplets are probably more important than bubble-derived droplets in transferring heat and moisture across the air–sea interface because of the number and volume produced and the rapidity with which spume droplets exchange heat and moisture with the air. Andreas (1992, hereafter A92) thus extends a spray generation function developed by Miller (1987) and Miller and Fairall (1988) into the spume region. Although this function agrees well with the Woolf et al. (1988) function and the small-radius end of the Monahan et al. (1986) function, there is nothing to corroborate its predictions in the spume region. Katsaros and de Leeuw (1994) and S. D. Smith et al. (1996) consequently suggest it over predicts spume production.

The need for additional work on spray generation is therefore critical. For example, Fairall et al. (1994) extend A92's spray generation function to $U_{10} = 24$ m s^{-1} (though its stated upper limit is 20 m s^{-1}) and use it in their tropical cyclone model to demonstrate that only when they include heat and moisture transfer from spray or rain in their model does the atmospheric boundary layer evolve realistically. Although this is an important conclusion, it would have more impact if we had more confidence in the spray generation function.

Without a costly and hazardous field experiment to measure spray generation in winds above 20 m s^{-1}, where modeling suggests spray effects become significant, we can still deduce some new features of spray generation from existing theory, data, and models. Presenting those results is my purpose here. Using theoretical predictions given in Andreas et al. (1995), I review the wind speed dependence of the spray generation functions depicted in Fig. 1. The function by M. H. Smith et al. (1993, hereafter SEA93), which coincidentally covers the largest wind speed range, satisfies theoretical predictions best. I thus correct its underprediction, extrapolate into the spume region, and thereby develop a new sea spray generation function appropriate for 10-m wind speeds up to 32.5 m s^{-1}.

2. The wind speed dependence of spray generation

The production rate of bubble-derived sea spray droplets, dF_b/dr_0, has long been speculated to go as, roughly, the third power of the wind speed or the third power of the friction velocity u_* (Wu 1979, 1988; Monahan et al. 1982, 1986). That is,

$$\frac{dF_b}{dr_0} \propto u_*^3 \propto U_{10}^3. \tag{2.1}$$

In turn, on thermodynamic grounds, Andreas et al. (1995) argue that the rate of production of total spume-droplet surface area, $\dot{\Omega}_T$, should be approximately proportional to u_*^3;

$$\dot{\Omega}_T \propto u_*^3. \tag{2.2}$$

Here

$$\dot{\Omega}_T = 4\pi \int_0^\infty r_0^2 \frac{dF}{dr_0}\, dr_0, \tag{2.3}$$

where dF/dr_0 is again the spray generation function for droplets of initial radius r_0.

It is easy to check whether any of the spray generation functions collected in Fig. 1 adhere to (2.2). First, though, I need to explain how I computed u_* from U_{10} since (2.2) requires u_*, while U_{10} is the wind speed parameter in all of the spray generation functions in Fig. 1. The neutral-stability drag coefficient for a reference height of 10 m is defined as

$$C_{DN10} = \left(\frac{u_*}{U_{N10}}\right)^2, \tag{2.4}$$

where U_{N10} is the wind speed that would be observed at 10 m for the given u_* if atmospheric stratification were neutral. Since here I am primarily interested in high winds, where the stratification is rarely far from neutral, I assume that $U_{N10} \approx U_{10}$ and use Large and Pond's (1981) formulation for C_{DN10}:

$$10^3\, C_{DN10} = \begin{cases} 1.20 & \text{for } 4 \le U_{10} \le 11 \text{ m s}^{-1} \quad (2.5\text{a}) \\ 0.49 + 0.065U_{10} & \text{for } 11 \text{ m s}^{-1} \le U_{10}. \quad (2.5\text{b}) \end{cases}$$

SEA93 also use this formulation, and S. D. Smith (1988) points out that the Large and Pond result is not statistically different from the formulation he deduced (S. D. Smith 1980) from another dataset. Geernaert (1990, his Fig. 8) makes this point graphically.

Figure 2 shows my inventory of spray generation functions plotted as (2.2) suggests. Crudely, the production mechanism distinguishes between left and right panels. The functions in the left panel—by virtue of the stated size range covered, the sampling location, or the stated production mechanism—depict bubble-derived droplets. Again, by virtue of the size range or the implicit production mechanism, the functions in the right panel have a significant spume component. Where possible, and as indicated in Fig. 2, (2.3) is integrated over similar radius ranges to produce results that are comparable.

Somewhat surprisingly, all the functions plotted in the left panel are very nearly proportional to u_*^3, although this panel admittedly collects the generation functions for predominantly bubble-derived droplets. In other words, (2.2) does not necessarily apply to these functions. But look at (2.3). If dF/dr_0 can be written as the product of two functions—one that contains the wind speed dependence $g(U_{10})$ and another that contains radius information $h(r_0)$—any integration of dF/dr_0 over r_0 will have the same wind speed dependence. In other words, if the shape of dF/dr_0 does not depend on wind speed, any function of radius formed from dF/dr_0 will have the same wind speed dependence, $g(U_{10})$. This is exactly the situation for the Woolf et al. (1988) and Wu (1992) functions in the left panel of Fig. 2. Woolf et al. and Wu were aware of (2.1) and, thus, made it a cornerstone of their generation functions by using size distributions that did not depend on wind speed. Thus, for these two functions at least, Fig. 2 merely shows that you get out what you put in.

The function from SEA93 is the surprising one in the left panel of Fig. 2. Although their generation function surely underpredicts spume generation and its shape depends on wind speed (i.e., the u_*^3 dependence was not put in a priori), it is roughly proportional to u_*^3 for U_{10} up to 32 m s^{-1}. Because we have no trustworthy spray

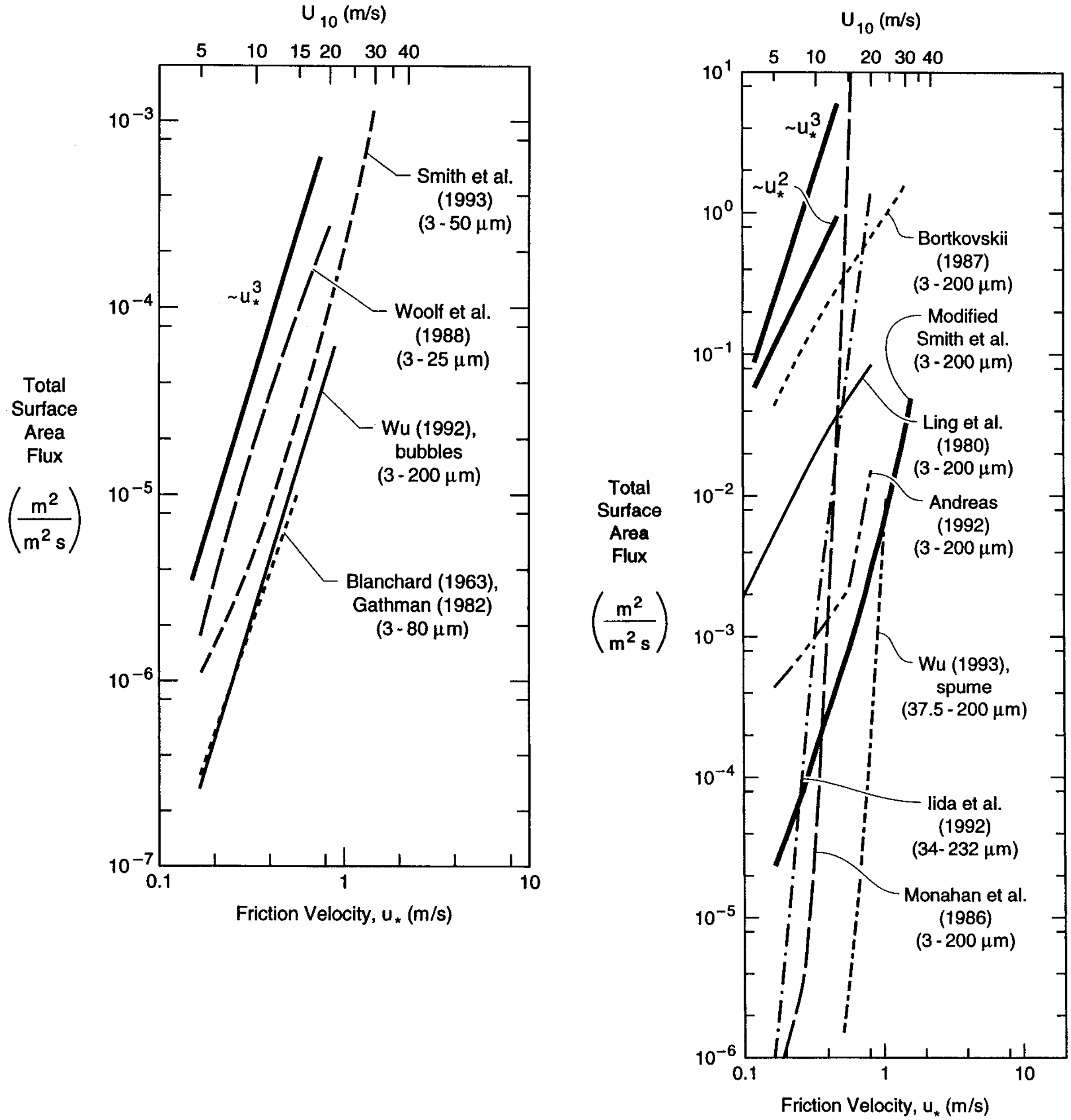

FIG. 2. The total production rate of droplet surface area, $\dot{\Omega}_T$ [see (2.3)], vs u_* for all the spray generation functions under consideration. The size range in parentheses tells the radius range over which (2.3) is integrated for the given generation function. The left panel depicts results for (predominantly) bubble-derived spray droplets; the right-panel functions presumably have a significant spume component. The heavy, straight, solid lines show slopes for $\dot{\Omega}_T$ proportional to u_*^2 or to u_*^3.

generation function for winds above 20 m s^{-1}, I will return to this function shortly.

The Blanchard–Gathman function in Fig. 2 also is closely proportional to u_*^3, though its predictions are almost an order of magnitude below the function from Woolf et al. (1988). Although Blanchard (1963) deduced this function [Gathman (1982) later coded it] long before anyone had advocated (2.1) or (2.2), I take the goodness of its u_*^3 fit as more evidence of Blanchard's skill and physical intuition.

In contrast to the left panel, the spume-dominated functions in the right panel of Fig. 2 show a host of u_* dependencies. The functions from Bortkovskii (1987) and Ling et al. (1980) suggest that $\dot{\Omega}_T$ goes roughly as u_*^2. Wu's (1993) spume-only function and the spume component of the Monahan et al. (1986) function are roughly exponential in u_*. According to Iida et al. (1992), $\dot{\Omega}_T$ goes approximately as u_*^6. A92's generation function predicts that $\dot{\Omega}_T$ increases more slowly than u_*^2 for winds below 15 m s^{-1} but faster than u_*^3 for higher winds.

In summary, Fig. 2 implies that we still have not found a totally reliable sea spray generation function that covers the relevant size range, droplet radii from 2 to 500 μm. Also, functions discounted in the introduction, largely intuitively—namely, those of Bortkovskii (1987), Ling et al. (1980), and Iida et al. (1992), Wu's (1993) spume-only function, and the spume formulation in the Monahan et al. (1986) function—are now also discounted on theoretical grounds. A92's function, though in the right ballpark, has a $\dot{\Omega}_T$ dependence higher than u_*^3 for winds above 15 m s^{-1}, which makes extrapolating it to even higher winds risky.

The remaining function plotted in Figs. 1 and 2, ''Modified Smith et al.,'' is the ultimate product of this paper.

3. Modifying the Smith et al. (1993) spray generation function

Because Fig. 2 shows that the SEA93 $\dot{\Omega}_T$ values are nearly proportional to u_*^3 and because of the large wind speed range that the SEA93 function covers, it merits further attention. My first concern, however, is that it underpredicts total droplet production because of the measurement site where the data were collected.

As explained, because the bubble-derived term in the generation function of Monahan et al. (1986) leads to reasonable modeling results, I assume that it provides the most accurate estimates of film and jet-droplet production for wind speeds up to 20 m s^{-1}. This function does not come without uncertainties, however. Woolf et al. (1988) paint an interesting picture of the difficulties in sampling spray droplets in the wave tanks that they and Monahan et al. used to develop their spray generation functions. But because Woolf et al. list reasons for both underestimating and overestimating wave tank droplet concentrations, I take the Monahan et al. generation function at face value.

In Fig. 1, we see that the SEA93 spray generation function underpredicts film and jet-droplet production in comparison to the Monahan et al. (1986) function. But that figure also shows that the Monahan et al. function and the SEA93 function have roughly the same shape for droplet radii between 4 and 15 μm. (See also Figs. 6 and 7 in SEA93.)

SEA93 collected their data on a 10-m tower with instruments, nominally 14 m above mean sea level. Because this tower was near the high-water mark on a sloping beach, sometimes the waterline was right at the foot of the tower, but at other times, it was 300 m away. Although measurements at the tower at 2 m showed a tidal signal, the 14-m measurements showed no obvious tidal effects. Consequently, SEA93 assumed that the source of the droplets reaching their 14-m instruments was beyond the immediate surf zone. Because of the transit time required for droplets to travel from this source region to the tower, I see potential for two possible mechanisms to bias the SEA93 function: evaporation and gravitational settling.

For droplets with radii less than 4 μm, the SEA93 volume flux function in Fig. 1 falls precipitously in comparison to the Monahan et al. function. Figures 6 and 7 in SEA93 also highlight this large difference between the two functions at small radii, but SEA93 offer no explanation. I suggest that it results because smaller droplets evaporate more rapidly than larger droplets. At the SEA93 site, the spray droplets had a finite transit time, which could have been several seconds, between their source region and the instrument tower. Droplets with initial radius 5 μm, however, are only about 3.4 μm after only 1 s in air with a relative humidity of 80% (Andreas 1990; Andreas et al. 1995). Smaller droplets decrease their radius more rapidly, while larger droplets decrease more slowly. Thus, droplets from one size bin move to smaller size bins faster than droplets from larger size bins replenish the original bin. The small size bins are consequently underrepresented if the relative humidity is less than saturation.

Figure 1 also shows that the SEA93 volume flux begins decreasing at $r_0 = 30$ μm, while most of the other functions depicted are still increasing. I presume that this premature decline in the volume flux results from another sampling bias in the SEA93 data. Larger droplets simply settle under gravity faster than smaller droplets (Andreas 1989, 1990). Settling during transit between the source region and the SEA93 sampling site, therefore, preferentially depleted the number of larger droplets that SEA93 sampled.

To minimize the effects of these sampling biases, I focus on droplets with initial radii from 4 to 15 μm when comparing the Monahan et al. and SEA93 functions. Again, Fig. 1 shows that the two functions have approximately the same shape in this interval.

Figure 3 reiterates that the Monahan et al. and SEA93 spray generation functions differ in magnitude. This figure shows the total volume flux,

$$\dot{V}_{\mathrm{T}} = \frac{4\pi}{3}\int_4^{15} r_0^3 \frac{dF}{dr_0}\, dr_0, \tag{3.1}$$

for the radius range 4 to 15 μm and for 10-m wind speeds from 5 to 20 m s^{-1}, ranges shared by both the Monahan et al. and SEA93 functions. The line in the figure is

$$\dot{V}_{\mathrm{TM}} = 3.5\dot{V}_{\mathrm{TS}}, \tag{3.2}$$

where $\dot{V}_{\mathrm{TM}}$ and $\dot{V}_{\mathrm{TS}}$ are computed from (3.1) for the Monahan et al. and SEA93 functions, respectively.

To derive (3.2), I did a least squares fitting of the points in Fig. 3 with the intercept forced to zero. If I had not forced the intercept to zero, that version of (3.2) would have introduced an additional wind speed de-

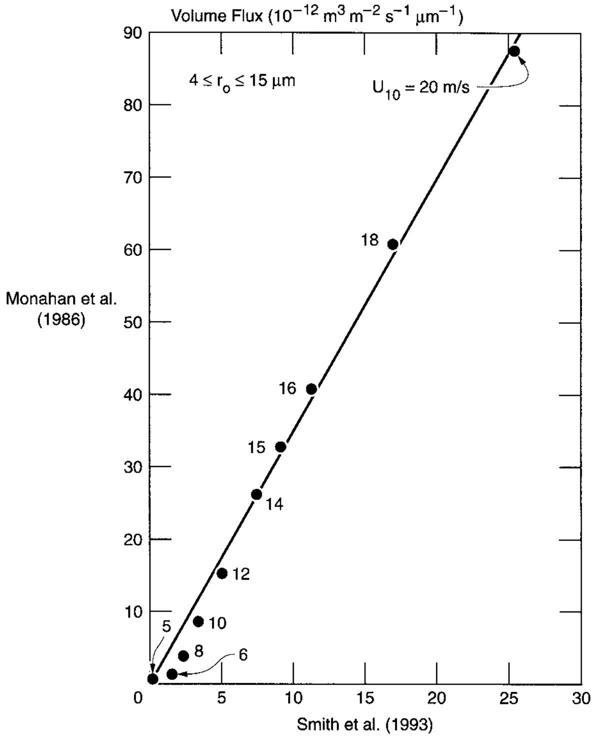

FIG. 3. The total volume flux of droplets with initial radii between 4 and 15 μm predicted by the Monahan et al. (1986) and Smith et al. (1993) spray generation functions. The numbers near the data markers give the 10-m wind speed. The line is (3.2).

pendence into the modified SEA93 spray generation function. But remember, the u_*^3 dependence is one of the attractions of SEA93 and should not be altered.

Equation (3.2) also implies

$$\frac{dF_M}{dr_0} = 3.5\frac{dF_S}{dr_0}, \tag{3.3}$$

where dF_M/dr_0 and dF_S/dr_0 denote the Monahan et al. (1986) and SEA93 spray generation functions. That is, if we multiply the original SEA93 function by 3.5, the result will be a generation function that, in the film and jet-droplet range, is comparable to the one from Monahan et al. Coincidentally, M. H. Smith (1998, personal communication) accepts that the SEA93 function may be low by a factor of 2 or 3.

The benefit of using the SEA93 function is that it is based on observations in a natural environment and models droplet radii up to 50 μm. The large-droplet end of that function thus likely reflects some spume production. The function from Monahan et al. (1986), on the other hand, derives from observations in a windless wave tank and, so, says nothing about spume generation. We need, however, to extend the SEA93 function to include spume droplets with radii up to 500 μm.

A92 similarly extrapolates Miller's (1987) generation function by following the suggestion in Monahan et al. (1986) that the spray generation function depends on radius in the same way that the near-surface spray concentration does. Katsaros and de Leeuw (1994) take exception with this practice, arguing correctly that the spray generation function is related to droplet concentration only through a radius-dependent fall speed. Andreas (1994), however, explains that, in light of the uncertainty in existing measurements, such fine tuning is unwarranted and further cites Bortkovskii (1987), Wu (1993), and Monahan et al. as setting precedent for such extrapolations. Hence, I again extrapolate into the spume region on the basis of near-surface droplet concentration measurements.

First, however, it must be explained that there is a dichotomy in ways of presenting sea spray data and functions. I prefer to express quantities in terms of the spray droplet radius at its formation, r_0. Some others prefer using the radius of spray droplets in equilibrium at a relative humidity of 80%, r_{80}. Here r_0 and r_{80} are related by (Andreas 1989, A92) as

$$r_{80} = 0.518 r_0^{0.976}, \tag{3.4}$$

where both r_0 and r_{80} are in micrometers. As a rule of thumb, r_0 is approximately twice r_{80}. I bring this up because SEA93 present their spray generation function in terms of r_{80}; henceforth I denote it as dF_S/dr_{80}. Andreas et al. (1995) explain how to convert this to dF_S/dr_0, but it turns out to be easier extrapolating dF_S/dr_{80} into the spume region than dF_S/dr_0.

Following A92 (see also Andreas 1994), in which the spume extrapolation is based on droplet concentration data obtained within 20 cm of the surface and reported in Wu et al. (1984), I assume

$$\frac{dF_S}{dr_{80}} = \begin{cases} C_1(U_{10})r_{80}^{-1}, & 10 \le r_{80} \le 37.5\ \mu\text{m} \quad (3.5\text{a}) \\ C_2(U_{10})r_{80}^{-2.8}, & 37.5 \le r_{80} \le 100\ \mu\text{m} \quad (3.5\text{b}) \\ C_3(U_{10})r_{80}^{-8}, & 100 \le r_{80} \le 250\ \mu\text{m}. \quad (3.5\text{c}) \end{cases}$$

Wu (1993) likewise infers that the near-surface Wu et al. droplet concentration data represent spume production.

In (3.5), C_1, C_2, and C_3 are wind-speed-dependent coefficients that are easy to evaluate. Simply compute dF_S/dr_{80} at $r_{80} = 10$ μm using the original SEA93 function (given in the appendix) and then solve (3.5a) for C_1. With C_1, use (3.5a) to compute dF_S/dr_{80} at 37.5 μm and use (3.5b) to evaluate C_2. Derive C_3 similarly. For example, for $U_{10} = 15$ m s^{-1} and with r_{80} in μm and dF_S/dr_{80} in m^{-2} s^{-1} μm^{-1}, $C_1 = 1.955 \times 10^3$, $C_2 = 1.331 \times 10^6$, and $C_3 = 3.344 \times 10^{16}$.

In summary, because of my concern that the original SEA93 function underestimates production of spume droplets, especially, I use it only for radii up to $r_{80} = 10$ μm (roughly, $r_0 = 20$ μm). For larger radii, I use (3.5).

Converting from dF/dr_{80} to dF/dr_0 requires (3.4). This not only converts between droplets expressed as r_{80} and as r_0, but also

$$\frac{dF}{dr_0} = \frac{dF}{dr_{80}}\frac{dr_{80}}{dr_0}, \tag{3.6}$$

where

$$\frac{dr_{80}}{dr_0} = 0.506 r_0^{-0.024}. \tag{3.7}$$

Consequently, my modified version of the SEA93 spray generation function (hereafter called the MS function), good for $2 \le r_0 \le 500$ μm and $0 < U_{10} \le 32.5$ m s^{-1}, is

$$\frac{dF_{MS}}{dr_0} = 3.5\frac{dF_S}{dr_{80}}\frac{dr_{80}}{dr_0}, \tag{3.8}$$

where the 3.5 comes from (3.3). Remember, in (3.8) I use the original SEA93 expression for dF_S/dr_{80} for $1 \le r_{80} \le 10$ μm and (3.5) for larger radii. Figure 1 compares dF_{MS}/dr_0 with other reported spray generation functions at $U_{10} = 15$ m s^{-1}. Figure 4 shows a plot of dF_{MS}/dr_0 as a volume flux. In this figure, the smooth transition at $r_0 = 20$ μm between the original SEA93 function and the spume extrapolation using (3.5) supports my contention that the large-droplet end of the SEA93 function reflects spume production.

4. Discussion

Figures 1 and 4 show that the MS function has the distinctive volume-flux peak near $r_0 = 200$ μm that is a consequence of the extrapolation into the spume region using (3.5). A92's (his Fig. 3; also see Andreas 1994) spray generation function, which derives from the same spume extrapolation, has this same peak. Because of (3.3), the MS function agrees well with the Monahan et al. (1986) function in the film and jet region (see Fig. 1).

Figure 2 (right panel) shows that my manipulations have not altered the desirable wind speed dependence seen in the original SEA93 function. In this figure, $\dot{\Omega}_T$ computed from the MS function increases nearly as u_*^3 throughout its entire wind speed range. Its level is also comparable to $\dot{\Omega}_T$ computed from the A92 function, which we have had more experience using and, thus, feel is fairly accurate (A92; Andreas 1994; Andreas et al. 1995; Fairall et al. 1994).

Figure 5 shows a utilitarian comparison of the A92 and MS spray generation functions. In this figure, I repeat calculations shown in Andreas (1994) for the turbulent or interfacial sensible and latent heat fluxes and the associated fluxes fostered by spray droplets. Those original calculations used the spray model and the sea spray generation function developed in A92 for typical HEXMAX [Humidity Exchange Over the Sea (HEXOS) Main Experiment] conditions (DeCosmo 1991). Figure 5 shows similar calculations but also includes spray heat flux estimates based on the MS spray generation function. The calculations in Fig. 5 also differ (only slightly) from those in Andreas (1994) because here I use the

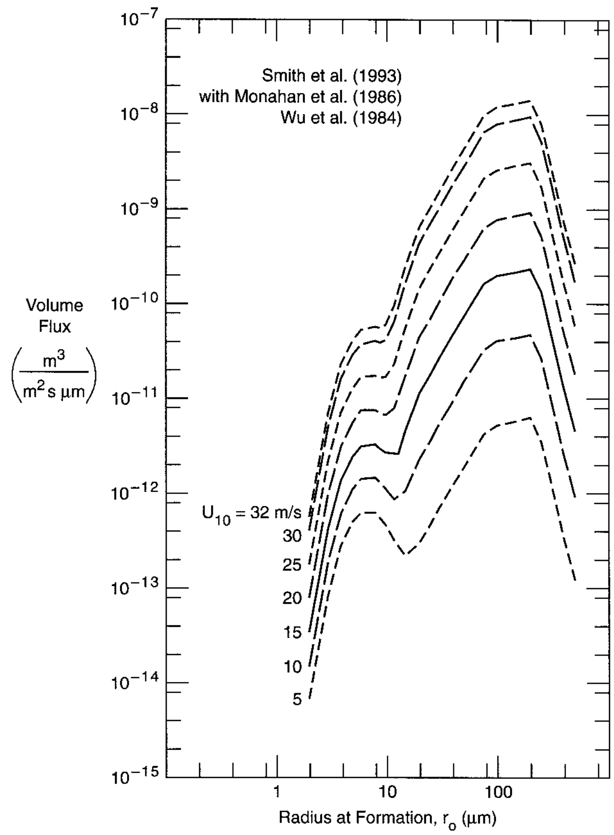

FIG. 4. The modified Smith et al. (1993) sea spray generation function [Eq. (3.8)] as a volume flux, that is, as $(4\pi r_0^3/3)dF_{MS}/dr_0$. That function resulted from amplifying its bubble-droplet predictions using Monahan et al. (1986) and extrapolating it into the spume region using Wu et al. (1984). The parameter is the 10-m wind speed.

Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) version (Fairall et al. 1996) of the Liu et al. (1979) model for the scalar roughness lengths necessary for computing the turbulent heat fluxes. For my original calculations, I had used constant neutral-stability bulk-transfer coefficients for sensible and latent heat.

Realize in Fig. 5 that the quantities labeled ''Spray Heat Flux'' are baseline values. Because of possible feedback between the enhanced surface fluxes and the near-surface temperature and humidity fields, these baseline values will probably need to be multiplied by constants of order one to estimate the resulting sensible and latent heat fluxes above the droplet evaporation layer. Katsaros and de Leeuw (1994) and DeCosmo et al. (1996) point out how negative feedback may moderate the magnitudes of these baseline spray fluxes. Fairall et al. (1994) and Edson and Andreas (1997) attempt to quantify this feedback.

We see in Fig. 5 that the MS spray generation function yields baseline spray fluxes comparable to A92's function. In low wind speeds—where spray effects are negligible anyway—it makes predictions that are an order

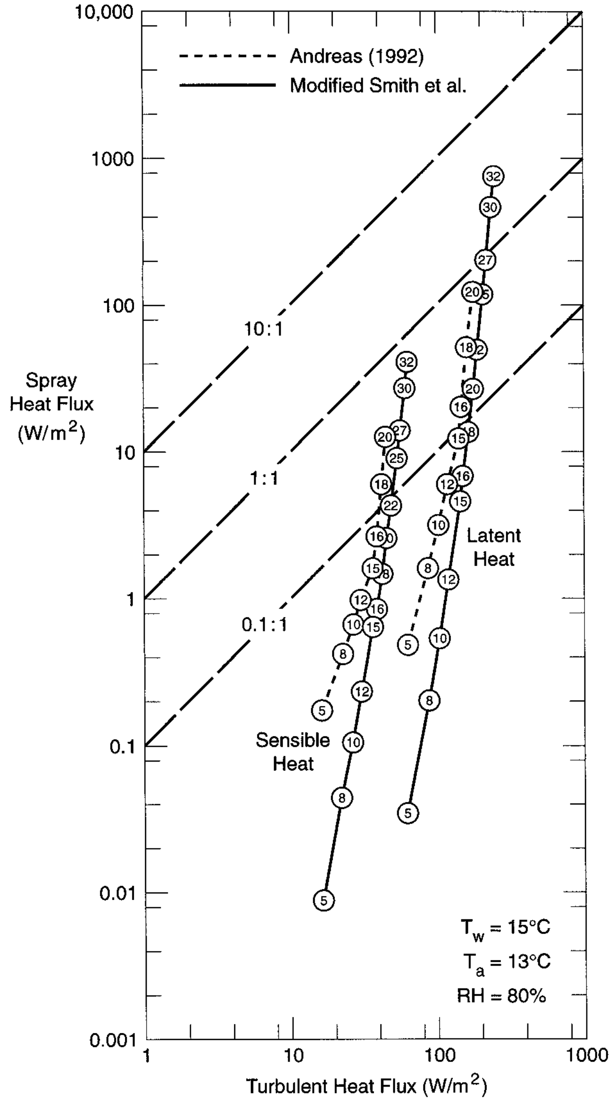

FIG. 5. Estimates of the magnitudes of the sensible and latent spray heat fluxes based on the Andreas (1992) spray model and two formulations for the spray generation function—the one developed in Andreas (1992) and the modified Smith et al. function described here. The turbulent heat fluxes come from bulk aerodynamic estimates. The surface water temperature (the initial temperature of the spray droplets) is T_w, the air temperature is T_a, and the relative humidity is RH. The number in each circle is the 10-m wind speed in meters per second. The diagonal lines show where the spray and turbulent fluxes are equal (1:1), where the spray flux is 10% of the turbulent flux (0.1:1), and where the spray flux is 10 times the turbulent flux (10:1).

of magnitude lower than the A92 function. But because of its higher wind speed dependence for winds less than about 16 m s^{-1}, the MS function produces spray flux estimates only a factor of 3 lower than the A92 function for 10-m winds of 15–16 m s^{-1}. At higher wind speeds, the MS function produces spray flux estimates that are about 4 times less than the A92 function because the MS function has a lower wind speed dependence than the A92 function in this range.

In summary, the A92 and MS spray generation functions produce similar predictions for spray heat fluxes when used in A92's spray heat flux model. The benefit of the MS function, however, is that it is applicable for 10-m winds up to 32 m s^{-1}. Figure 5 suggests the possibility of extremely large spray heat and moisture transfer in such winds.

5. Conclusions

The theoretical prediction that the production rate of total spume-droplet surface area should go as u_*^3 focused our attention on the spray generation function of M. H. Smith et al. (1993). The extensive wind speed range that this function covers also calls us to it. Its weakness, however, is that, because of the sampling on which it was based, it likely underestimates the production rate of all droplets, especially spume droplets.

Using the function of Monahan et al. (1986), which in my opinion is the best one for predicting the production rate of film and jet droplets, I amplify the SEA93 function to correct its under prediction of bubble-derived droplets. I also extrapolate it further into the spume domain using knowledge of the near-surface spray concentration, a technique used in several earlier studies.

The result is a spray generation function good for 10-m wind speeds up to 32.5 m s^{-1} and for droplets presumed to be the most important in carrying heat and moisture across the air–sea interface—that is, ones for which the radius at formation is between 2 and 500 μm. The so-called modified Smith et al. function still has the desirable wind speed dependence of the original function and, because of its wide wind-speed range, thus, has theoretical and practical advantages over any other reported spray generation functions.

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APPENDIX

The Original Smith et al. (1993) Spray Generation Function

M. H. Smith et al. (1993) give their sea spray generation function in terms of the droplet radius reduced to a relative humidity of 80%, r_{80}. For $1 \leq r_{80} \leq 25$ μm, their function is

$$\frac{dF_S}{dr_{80}} = \sum_{i=1}^{2} A_i \exp\{-f_i[\ln(r_{80}/r_i)]^2\}, \qquad \text{(A1)}$$

which gives the number of droplets with radius r_{80} produced per square meter of surface per second per micrometer increment in r_{80}. In (A1), $f_1 = 3.1$, $f_2 = 3.3$; $r_1 = 2.1\ \mu$m, $r_2 = 9.2\ \mu$m; and A_i is a function of the wind speed 14 m above the surface, U_{14}. For $0 < U_{14} \le 34$ m s^{-1}, SEA93 give

$$\log(A_1) = 0.0676U_{14} + 2.43, \tag{A2a}$$

$$\log(A_2) = 0.959U_{14}^{1/2} - 1.476. \tag{A2b}$$

Since we usually have the wind speed at 10 m rather than U_{14}, it is necessary to estimate U_{14}. I do this using (2.5), the same drag formulation that SEA93 used in reducing their data. First, given U_{10}, estimate C_{DN10} from (2.5). Next, realize that in neutral stability

$$U(z) = \frac{u_*}{k}\ln(z/z_0), \tag{A3}$$

where $U(z)$ is the wind speed at height z, k (=0.4) is the von Kármán constant, and z_0 is the roughness length for wind speed. Ignoring stability effects in the high winds that foster extreme spray production, we can show that (A3) gives

$$U_{14} = U_{10} + \frac{u_*}{k}\ln\left(\frac{14}{10}\right). \tag{A4}$$

But, from (2.4), $u_* = C_{DN10}^{1/2}U_{10}$, so

$$U_{14} = U_{10}\left[1 + \frac{C_{DN10}^{1/2}}{k}\ln\left(\frac{14}{10}\right)\right]. \tag{A5}$$

We also see here that a 14-m wind of 34 m s^{-1}, the stated upper limit for (A1), corresponds to a U_{10} value of 32.5 m s^{-1}.

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