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Sea Spray Dispersion Over the Ocean Surface: A Numerical Simulation

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A trajectory simulation approach has been used to calculate sea spray dispersion above the ocean surface as a function of droplet size, emission rate, and meteorological conditions. By numerically simulating the stochastic turbulent trajectories of a large number of ejected sea spray droplets of various sizes and ejection speeds, the vertical profile of sea spray concentration was deduced from the average residence time of the droplets in each of a set of horizontal layers within the first 10 m above the ocean surface.

INTRODUCTION

A knowledge of the vertical profile of sea spray concentration in the air above the ocean surface has great value in describing the transport into the atmosphere of water mass, heat, and many biological and chemical species that occur near the air-sea interface [*Blanchard and Syzdek*, 1972, 1982; *Fairall et al.*, 1983; *Cipriano et al.*, 1983]. While there have been many experimental studies of sea spray [*Preobrazhenskii*, 1973; *Wu*, 1973, 1979, 1990; *Monahan et al.*, 1986; *De Leeuw*, 1986], there have been fewer theoretical approaches to this subject [*Burk*, 1984; *Stramska*, 1987; *Edson*, 1987; *Voronov and Gavrilov*, 1989; *Andreas*, 1990, 1992]. Most theoretical studies have used the Eulerian approach, i.e., sea spray dispersion is described by a set of conservation equations in which the turbulent transfer coefficients have to be assumed empirically. Since many of the air-sea transport processes associated with sea spray are droplet size dependent, for example, the enrichment factor of bacteria is greater for large droplets [*Blanchard and Syzdek*, 1982], a Lagrangian modeling approach that predicts the trajectories and size evolution of individual sea spray droplets would be an appropriate vehicle to incorporate the physical and chemical processes involved in air-sea transfer processes. This paper describes our first attempt at producing such a model.

The trajectory simulation approach which we use to indirectly deduce the average profile of sea spray concentration is based on the following ideas: If $T(i, j)$ denotes the average residence time of the ith particles (radius between r_i and $r_i + \Delta r_i$) in the jth layer of the atmosphere (thickness $\Delta H = 0.5$ m and unit horizontal area) and if F_i denotes the average number of ith droplets produced per unit surface area per second at the ocean surface, then $F_i T(i, j)/\Delta H$ is the average number concentration of the ith particles in the jth layer under steady state conditions (Figure 1).

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The residence time $T(i, j)$ is a function of atmospheric turbulence and the physical properties of the spray. Temperature and humidity also play important roles in determining the size evolution of sea spray [*Andreas*, 1990]. A heavy particle dispersion model based on the work by *Zhuang et al.* [1989], which accounts for these factors and for the surface flux of the sea spray, is used to numerically simulate trajectories of sea spray over the ocean surface under different atmospheric stability conditions. In the following sections the particle dispersion model will be described, the surface flux of sea spray will be defined, and the simulated sea spray profile and distribution will be presented and compared with available experimental data.

MECHANISM FOR THE VERTICAL REDISTRIBUTION OF SEA SPRAY

Wind gives rise to sea spray through various mechanisms, but bubble bursting is the primary one [*Wu*, 1979]. Increasing wind speed causes a corresponding increase in the production of whitecaps at the ocean surface. These whitecaps form bubbles in the ocean which, when breaking at the surface, produce sea spray. *Preobrazhenskii* [1973] showed that sea spray can be observed at heights of more than 10 m above the ocean surface in the atmospheric surface layer. However, both calculations [*Wu*, 1979] and experimental data [*Blanchard*, 1963] have demonstrated that sea spray droplets cannot reach a height of more than 20 cm in still air owing to the drag and gravitational forces acting on them. Therefore, wave motion and turbulent mixing must act as lifting forces on the sea spray. Once the sea spray droplets are ejected into turbulent air, the turbulent drag tends to redistribute them in all directions relative to the mean air flow. At the same time, evaporation reduces the mass of the droplets. Large droplets are not suspended long enough to evaporate significantly and tend to fall back into the ocean. Smaller droplets, however, are easily transported upward by atmospheric turbulence. Moreover, the droplets do not as a rule evaporate completely. Because of the difference in the

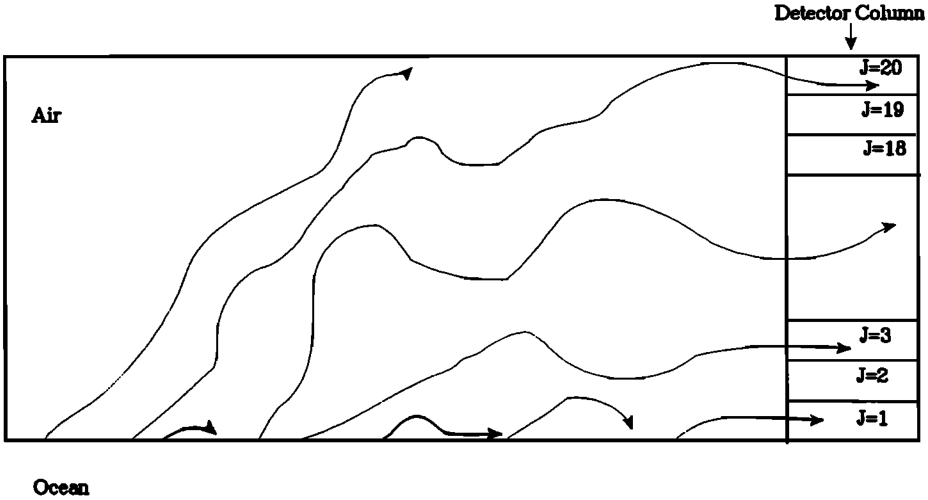

Fig. 1. Schematic representation of the simulation of sea spray droplet trajectories over the ocean.

motions of small and large droplets, the particle size distribution changes with height, with relatively more small droplets in the upper layers and more large droplets in the lower layers [*Preobrazhenskii*, 1973]. The steady state distribution of sea spray droplets over the ocean surface will largely depend on (1) the generation of sea spray at the ocean surface, (2) atmospheric turbulence, and (3) the rate of evaporation of the droplets [*Wu*, 1979; *Stramska*, 1987].

Oceanic Production Rates of Sea Spray

The production rate of sea spray depends on the factors which determine the spectrum of bubbles breaking at the ocean surface, such as the wind dependence of whitecap formation, the relationship between whitecaps and bubbles, the relationship between the bubbles and the ejected sprays, and the ejection heights of the spray droplets. Both theoretical and empirical formulae for sea spray production rates have been proposed [*Cipriano and Blanchard*, 1981; *Monahan et al.*, 1986; *Wu et al.*, 1984; *Zhuang*, 1987]. The bubble concentration near the ocean surface has been relatively well established through both experimental and theoretical studies. It has been suggested that the size distribution of bubbles follows a power law behavior with radius after normalization with respect to water depth and wind speed. The total number concentration of bubbles near the ocean surface has been proposed to be a function of the friction velocity [*Kerman*, 1986]. This is consistent with the fact that the friction velocity ultimately determines the effect of wind on bubble production. *Zhuang* [1987] obtained the spray production rate by combining a theoretical bubble production rate (simply the product of bubble concentration [*Kerman*, 1986] and bubble rise speed under steady state conditions [*Cipriano and Blanchard*, 1981]) with an observed relationship between bubble diameter and jet drop diameter [*Blanchard*, 1963]. When compared with available experimental data, *Zhuang* [1987] found that the theoretical production rate produces too few small ($r < 30$ μm) and large ($r > 140$ μm) droplets and that it depends crucially on the selection of a characteristic size of the bubbles. Consequently, in this study we adopt the spray production rate given by *Cipriano and Blanchard* [1981], which is based on physical reasoning similar to that used by *Zhuang* [1987] but uses their experimental data on bubble concentration. Because both film and jet droplets are generated by bubble bursting, we modified *Cipriano and Blanchard*'s [1981] jet drop production rate by including film drop production based on their simple estimate of the relative jet and film drop contributions. Figure 2 shows the resulting surface flux of sea spray as a function of droplet size. Since this surface flux is produced by a laboratory model of a breaking wave, no information on friction velocity is available. However, based on *Kerman*'s [1986] study, we assume that the friction velocity affects the magnitude and not the shape of the surface flux.

Modeling the Turbulent Trajectories of Sea Spray Droplets

The trajectory of a sea spray droplet is complicated by atmospheric turbulence, gravity, and exchanges of heat and mass with its environment. *Andreas* [1990] proposed four time constants to represent these effects on the evolution of a sea spray droplet and found that for droplet radii between

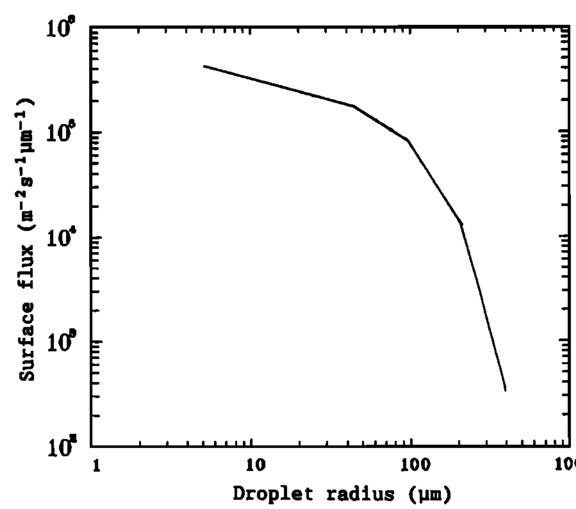

Fig. 2. Production rate of sea spray at the ocean surface [after *Cipriano and Blanchard*, 1981] with a modification to include the film drop contribution in the drop size range 5 μm $< r <$ 15 μm.

40 and 300 μm the effects of both gravity and turbulence are important. He then suggested that a time dependent model is necessary to account for these two effects. In this paper such a time-dependent particle dispersion model is described and is used to study the motion of sea spray droplets.

The motion of heavy particles in a turbulent flow is different from that of light particles or fluid elements. First, because of their inertia, heavy particles cannot follow the high-frequency fluctuations of the turbulent air exactly. The greater the inertia of the particles, the slower will be their response to the driving fluid velocity. Gravity will also pull them downward. Thus there will always be some relative motion between heavy particles and the surrounding fluid. This is called the "inertial effect." Second, owing to the lack of coincidence between the velocity of the heavy particles and the velocity of the surrounding air, a heavy particle interacts consecutively with different air parcels. In other words, a heavy particle tends to quickly fall out of one eddy and enter a new one. Because of this inertial effect, the velocity history of heavy particles will be different from that of marked fluid elements. Thus we may expect that heavy particles will lose their turbulent velocity correlation more quickly than fluid elements, for which the velocity changes only because of "eddy decay." *Yudine* [1959] referred to this second phenomenon as the "crossing trajectory effect." The inertial effect and crossing trajectory effect are considered to be crucial aspects of heavy-particle motion in turbulent flow.

The heavy-particle dispersion model starts with the following governing equation for heavy spherical particle motion

$$d\mathbf{U}_p/dt = F(\mathbf{U}_a - \mathbf{U}_p) - \mathbf{g}, \tag{1a}$$

where $F = 0.75C_d\rho|\mathbf{U}_a - \mathbf{U}_p|/(2r\rho_d)$, $C_d = 24/Re(1 + 3Re/16)$ is the drag coefficient; $Re = 2r|\mathbf{U}_a - \mathbf{U}_p|/\nu$, the Reynolds number; ρ and ρ_d, the air and particle densities, respectively; r, the radius of the particle; $\mathbf{U}_a(= \mathbf{U}(z) + \mathbf{U}'_a)$, the velocity of the driving fluid element; $\mathbf{U}_p$, the velocity of the particle; and $\mathbf{g}$, the gravitational acceleration. Since $\mathbf{U}_a$ and $\mathbf{U}_p$ are stochastic variables, we know of no analytical solutions to $(1a)$, and so we solved it numerically. Note that $\mathbf{U}'_a$ is the velocity fluctuation of the driving fluid encountered by the particle and the driving fluid does not remain the same all the time but changes irregularly. Random walk theory [*Ley and Thomson*, 1983] is used to model the velocity $\mathbf{U}'_a$

$$U'_a(i+1) = U'_a(i)\alpha + \mu(i+1) \tag{1b}$$

$$W'_a(i+1) = W'_a(i)\alpha + \lambda(i+1) \tag{1c}$$

where i denotes the time step; $\alpha = \exp -(\Delta t/T_L + \Delta r/L)$ is the coefficient of the Lagrangian temporal correlation and Eulerian spatial correlation; Δt, the time interval chosen as 0.1 of the Lagrangian time scale T_L; and Δr, the distance between the positions of driving fluid element at times $(T + \Delta t)$ and T, which is much smaller than the Eulerian length scale L. Finally, $\mu(i+1)$ and $\lambda(i+1)$ are random variables whose properties are chosen to ensure that the driving fluid elements move in accordance with the known turbulence statistics

$$\mu(i+1) = (1 - \alpha^2)^{1/2}\sigma_u\gamma(i+1) \tag{1d}$$

$$\lambda(i+1) = (1 - \alpha^2)^{1/2}\sigma_w\eta(i+1) \tag{1e}$$

where $\gamma(i+1)$ and $\eta(i+1)$ are the independent standard normal random variables and σ_u and σ_w are the standard deviations of turbulent velocity in horizontal and vertical directions, respectively. Given an initial velocity and the drag coefficient, (1) can then be integrated forward in time to simulate heavy-particle trajectories. The model includes the inertial effect naturally and also takes into account both Eulerian spatial decorrelation and Lagrangian temporal decorrelation which are responsible for the crossing trajectory effect. *Zhuang et al.* [1989] have shown that this model yields good agreement with experimentally observed rates of heavy particle dispersion. For a more complete description of the heavy particle dispersion model, readers are referred to *Zhuang* [1987].

A unique feature of this model is that mass transfer effect on the droplets can be readily included in the simulation. The simplified size evolution equation for sea spray is [*Andreas*, 1990]

$$\frac{dr}{dt} = [(f-1) - y]r^{-1}\left[\frac{\rho_s RT}{D'_w M_w e_{\mathrm{sat}}(T_a)} + \frac{L_v\rho_s}{T_a k'_a}\left(\frac{L_v M_w}{RT_a} - 1\right)\right]^{-1} \tag{2}$$

$$y = \frac{2M_w\sigma_s}{RT_a\rho_w r} - \frac{\nu\Phi_s m_s(M_w/M_s)}{(4\pi r^3\rho_s/3) - m_s}. \tag{3}$$

In this equation, r is the instantaneous radius of the droplet; ρ_s, the density of the droplet; f, the fractional humidity; T_a, the ambient air temperature; $e_{\mathrm{sat}}(T_a)$, the saturation vapour pressure over a pure flat water surface with temperature T_a; R, the universal gas constant; D'_w, the modified molecular diffusivity of water vapour in air; k'_a, the thermal conductivity of air; L_v, the specific latent heat of vaporization of water; ρ_w, the density of pure water; σ_s, the surface tension of a flat surface with the same salinity and temperature as the spray droplet; Φ_s, the practical osmotic coefficient of the droplet; ν, the total number of ions into which a salt molecule in the droplet dissociates; m_s, the mass of salt in the droplet; and M_w and M_s, the molecular weights of water and salt, respectively. A detailed derivation of this equation and values for the parameters are given by *Pruppacher and Klett* [1978] and *Andreas* [1989, 1990].

The atmospheric surface layer turbulence must also be specified along with the surface flux of the sea spray in order to carry out the simulation. Despite differences between the physical properties of the ocean surface and land [*Takeda*, 1981], measurements [*Schmitt*, 1979] have demonstrated the validity of the Monin-Obukhov similarity theory [*Monin and Obukhov*, 1954] over the ocean. According to the Monin-Obukhov similarity theory, the wind profile is given by

$$\frac{dU}{dz} = \frac{u_*}{\kappa z}\Phi\left(\frac{z}{L}\right), \tag{4}$$

where $L(m)$ is the Monin-Obukhov length which characterizes the atmospheric stability conditions; κ, Von Karman's constant; and Φ, a universal function given by

$$\Phi = 1 + 5z/L \qquad L > 0 \text{ stable} \tag{5a}$$

$$\Phi = 1 \qquad L = \infty \text{ neutral} \tag{5b}$$

$$\Phi = (1 - 16z/L)^{-1/4} \qquad L < 0 \text{ unstable} \tag{5c}$$

For neutral atmosphere we obtain from (4) and (5) the mean wind profile

$$U = u_*/\kappa z \log (z/z_0), \tag{6}$$

where the surface roughness length over the ocean is taken to be $z_0 = 0.0156u_*^2/g$ [*Wu*, 1979].

The expressions for standard deviations of turbulent velocity are

$$\sigma_u = 1.3u_*(1 - z/L) \qquad L > 0 \tag{7a}$$

$$\sigma_u = 1.3u_* \qquad L = \infty \tag{7b}$$

$$\sigma_u = 1.3u_*(1 + 3|z/L|)^{1/3} \qquad L < 0 \tag{7c}$$

$$\sigma_w = 2.3u_*(1 - z/H) \qquad L > 0 \tag{7d}$$

$$\sigma_w = 2.3u_* \qquad L = \infty \tag{7e}$$

$$\sigma_w = u_*(12 + .5|H/L|)^{1/3} \qquad L < 0, \tag{7f}$$

where H is boundary layer height.

The Lagrangian time scale and Eulerian length scale are given by

$$T_L = 0.4zu_*/((1 + 5z/L)\sigma_w^2) \qquad L > 0 \tag{8a}$$

$$T_L = 0.26z/u_* \qquad L = \infty \tag{8b}$$

$$T_L = 0.4zu_*(1 + 16|z/L|)^{1/2}/\sigma_w^2 \qquad L < 0 \tag{8c}$$

$$L = T_L\sigma_w \tag{8d}$$

For simplicity we neglect the waviness of the surface. The shortcomings of this assumption have been discussed by *De Leeuw* [1986, 1989, 1990], but to include moving waves would make the model intolerably complex. Finally, we assume an air temperature of 20°C, seawater of 30‰ salinity, and a relative humidity of 80%.

SIMULATION RESULTS

All spray droplets are released initially at the ejection heights measured by *Blanchard* [1963], with a zero droplet velocity ($U_p(0) = 0$) and a random air velocity ($U'_a(0) = \mu(0)$, $W'_a(0) = \lambda(0)$). The spray trajectories were computed from (1) with the surface flux (Figure 2) and wind conditions (equations (4)–(8)) specified above. Eighty drop size categories ($r = 5, 10, 15, \cdots, 400$ μm) were considered, and 1000 trajectories were calculated for each size category to get a statistically stable simulation.

The size evolution of the droplets was calculated using (2) and (3), according to which, at a humidity of 80% and an initial salinity of 30‰, a droplet will reach an equilibrium size at about one half of its original size. Most large droplets ($r > 75$ μm) were found to fall back into the ocean before they attained their equilibrium size.

In principle, all of the surface area upstream of the detector column (Figure 1) contributes to the sea spray concentration. For tracer particles a ratio of at least 100:1 between upstream uniform fetch distance and measurement height is required for a valid dispersion calculation [*Schuepp et al.*, 1990]. This so-called "footprint" effect can be seen in Figure 3 where the mass flux profiles of spray simulated with two different fetch distances (200 m and 2000 m) are plotted.

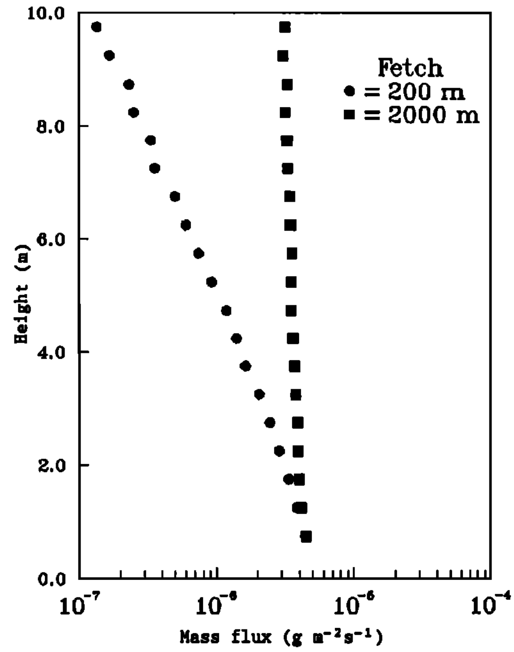

Fig. 3. Calculated profiles of vertical spray flux for two different upstream fetch distances under neutral conditions. The 10-m wind speed, U_{10}, is 12 m s^{-1}.

With a 200-m fetch the mass flux decreases almost linearly with height. This means that the sea spray concentration profile will change with horizontal distance. With a 2000-m fetch the mass flux is nearly constant with height, indicating that a steady state sea spray concentration has been achieved. The small nonzero mass flux in Figure 3 in the steady state case is the result of droplets escaping into the higher atmosphere and droplets evaporating in the unsaturated airflow. Our simulation shows that droplet evaporation has a minor effect on the sea spray mass flux profile. It may be noted that the two mass flux profiles in Figure 3 depart substantially only above the first meter. This occurs because the liquid water content below the first meter is dominated by large droplets which arise locally, while at higher levels the liquid water content is composed primarily of smaller droplets which have arisen from the entire surface area upstream. All subsequent simulations have used a 2000-m fetch, which should allow near steady state results.

Figure 4 illustrates the effect of atmospheric stability on the sea spray concentration profile, where the same sea spray production rate (Figure 2) is assumed for all atmospheric stability conditions. As expected, in the lowest layer ($z \leq 2$ m) the liquid water content changes little with atmospheric stability. This occurs because the surface ejection conditions of the sea spray (assumed invariant) dominate the concentration and turbulence changes little with atmospheric stability near the surface. The high liquid water content in the lowest layer results from droplets having zero vertical velocities (corresponding to their ejection heights) and thus having large residence times within the layer, as well as large droplets falling back into the ocean. However, the effect of turbulence becomes increasingly important with height. A very small amount of water was found above 7 m under stable conditions, whereas stronger turbulent mixing resulted in more water in the higher layers under both

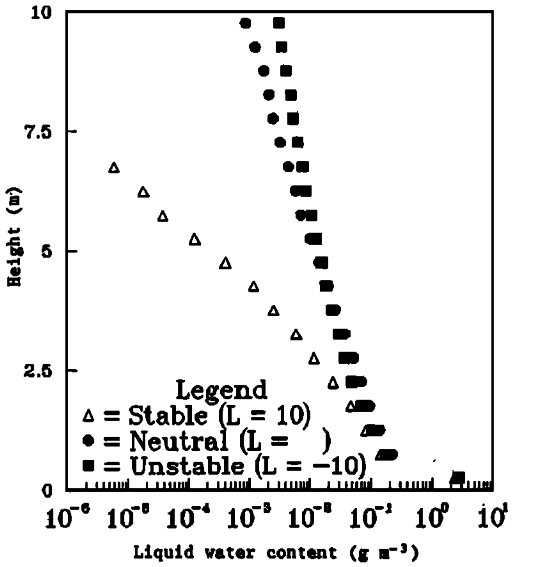

Fig. 4. Simulated variation of liquid water content with height above the ocean surface for three values of atmospheric stability designated by the Monin-Obukhov length L. The simulations were performed with the same sea spray production rate as in Figure 2 and a constant wind speed (U_{10} = 12 m s^{-1}). This corresponds to a friction velocity $u_* = 0.32$ m s^{-1} for stable, 0.5 m s^{-1} for neutral, and 0.55 m s^{-1} for unstable stratification.

neutral and unstable conditions. It should be noted that we have used the same mean wind speed at 10 m for all the stability conditions. This means that the friction velocity u_* (equation 4) is smaller under stable conditions than under unstable conditions. Since in nature the spray production will be roughly proportional to u_*^3 [*Kerman*, 1986] and since under stable conditions the actual wind speed is rather lower than our assumed value of 12 m s^{-1}, the actual differences between the liquid water contents under stable, unstable, and neutral conditions should be even more pronounced than those shown in Figure 4.

In what follows, the features of the sea spray distribution will be discussed based on simulations under neutral conditions.

To illustrate the mass distributions of the sea spray, simulated volume density functions of sea spray at three heights are plotted in Figure 5. As expected, the peak radius moves toward smaller values above the first meter, but it varies little with height at higher levels. Above 5 m the sea spray consists entirely of droplets with radius $r < 70$ μm. Figure 6 shows the simulated size distribution of the sea spray at three heights above the ocean surface. The power laws $N(r) \sim r^{-3.0}$ (10 μm $< r <$ 40 μm) and $N(r) \sim r^{-8.0}$ (40 μm $< r <$ 100 μm) are good fits to the simulated distribution function at 1 m above the ocean. The curves at 5 m and 8 m seem to follow a similar trend but are shifted toward smaller values of radius. *Wu* [1990] plotted *De Leeuw*'s [1986] data and showed a slope of -5.5 for droplet radii larger than 15 μm.

There are a number of difficulties in directly comparing our numerical simulation with field observations. First, in most field experiments, wind speed has been measured as the primary environmental parameter and sometimes as the only parameter. A particular wind speed could correspond to many different friction velocities, depending on the atmospheric stability conditions. Since the sea spray concentration is determined by both the atmospheric stability (Figure 4) and the ejection flux of sea spray from the ocean surface, which is in turn controlled by the friction velocity, a simulation cannot provide a unique sea spray concentration profile given only the wind speed. Second, as shown in Figure 3, the upstream uniform fetch (or source) has a large influence on the distribution of sea spray in the air. Because of the unsteadiness of the atmospheric wind and patch occurrence of whitecaps, a uniform upstream fetch is not always guaranteed under field conditions. In fact, *Wu et al.* [1984] observed that the sea spray mass flux varies even

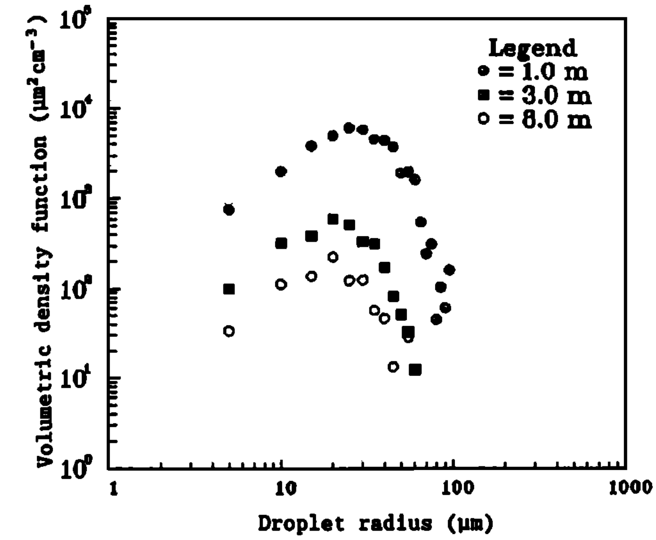

Fig. 5. Simulated volumetric density function of sea spray at three heights above the ocean surface. The wind speed, U_{10}, is 12 m s^{-1}.

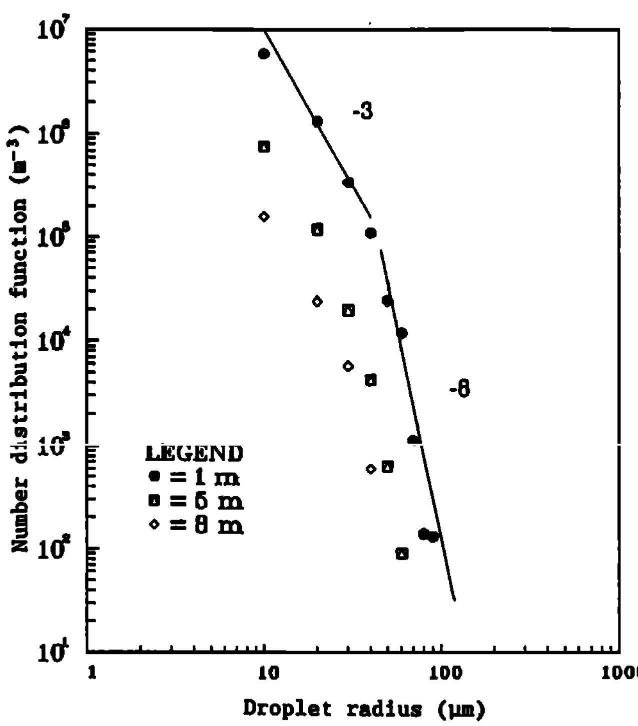

Fig. 6. Simulated size distribution of sea spray at three heights above the ocean surface. The wind speed, U_{10}, is 12 m s^{-1}.

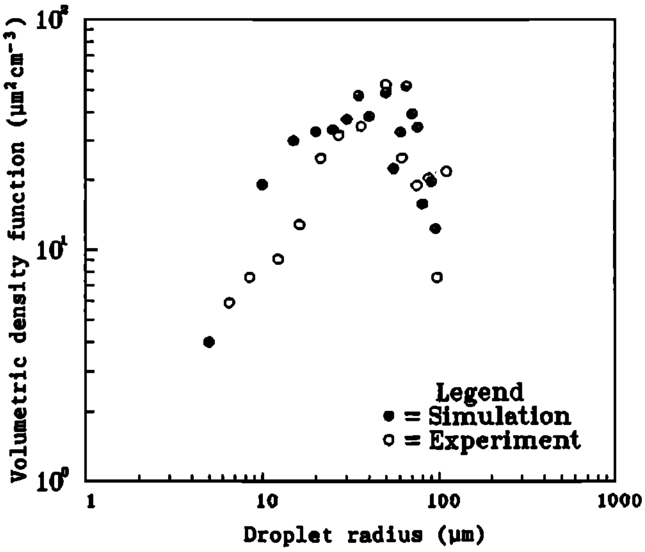

Fig. 7. Comparison of the volumetric density function obtained from experimental data [*De Leeuw*, 1990] and our simulation at a height of 11 m. The simulation was performed at a wind speed, U_{10}, of 25 m s^{-1} and a humidity of 80%, as in the experiment.

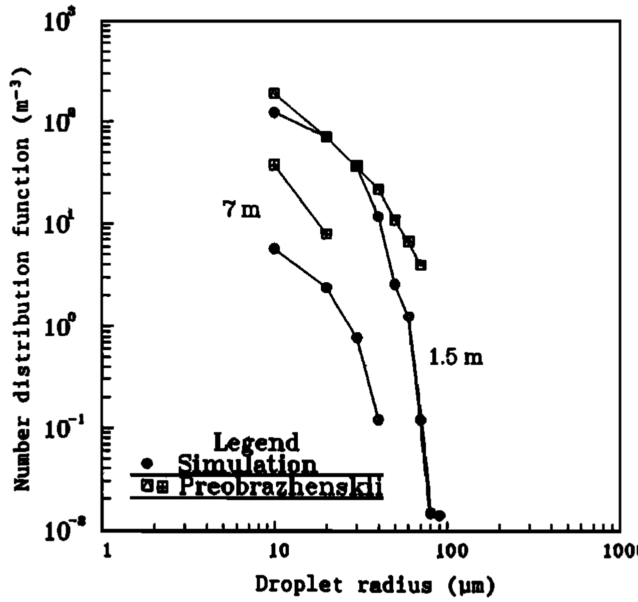

Fig. 8. Comparison of the number distribution functions between experimental data [*Preobrazhenskii*, 1973] and our numerical simulation. The simulated data are normalized at r = 20 μm and at a height of 1.5 m. The experimental wind speed at 7 m was between 6 and 10 m s^{-1}. The simulation was performed at a 10-m wind speed, U_{10}, of 12 m s^{-1} and a humidity of 80%.

within the first meter of the atmosphere in a field experiment. Thus the fetch effect imposes an uncertainty when comparing a simulation having a large uniform upstream source with a field experiment. Third, the spray production rate in Figure 2 was produced in a laboratory using a weir waterfall to simulate a breaking wave and may be different from the case of a transient breaking wave in nature. Another difficulty when comparing a simulation with field experiments is that our simulations assume a flat ocean surface. In reality, waves may be expected to induce additional turbulence, which we do not take into account, because no quantitative information is available [*De Leeuw*, 1990]. In addition, waves also complicate the definition of the droplet ejection height.

Nevertheless, in Figure 7 the simulated spray volume density function is compared with recent experimental data [*De Leeuw*, 1990]. Overall, the agreement between the simulation and the experimental data is quite good. Since De Leeuw's experiment was performed under very strong wind conditions (U = 25 m s^{-1}), the agreement in Figure 7 may imply that our (constant) surface flux of sea spray (Figure 2) corresponds to a large friction velocity. Some scattering of the simulated data is caused by the limited number of trajectories calculated. In Figure 8 the widely used experimental data of *Preobrazhenskii* [1973] are simulated. Because of the large surface flux, the simulation has resulted in too many droplets in the air. In order to allow a meaningful comparison the simulated data are normalized by a factor of 1000 such that the simulated data and the experimental data coincide at r = 20 μm and at a height of 1.5 m. Figure 8 shows that the simulated sea spray concentrations at both heights above the ocean drop off faster than the experimental data. The slow drop-off of Preobrazhenskii's data has been noted in previous experimental intercomparisons [*Wang and Street*, 1978; *Wu*, 1982; *Stramska*, 1987]. *Wu* [1982] attributed this discrepancy to the difference between laboratory and field conditions. In field conditions the wave motions give some of the spray an extra lift in addition to its initial ejection velocity [*De Leeuw*, 1990]. In addition, the fetch effect mentioned earlier may also contribute to this discrepancy. It should be noted that we chose to compare our simulation only with *Preobrazhenskii*'s [1973] data obtained under moderate winds, since very strong wind conditions would further violate the model assumptions about the sea spray production rate and the shape of the interface.

CONCLUSIONS

A simple trajectory simulation approach to study sea spray profiles has been presented. The simulation has demonstrated the effects of upstream fetch and atmospheric stability on sea spray concentration. The simulated sea spray volume and size distributions agree reasonably well with available experimental data. This study has shown that it is possible to estimate sea spray profiles using a turbulent trajectory simulation approach, provided the surface flux and boundary conditions are well defined. The main advantage of this approach is that it is in principle equally applicable to both complex and simple situations. For many practical purposes, the present study can provide a quick and economical result where an experimental study would be difficult and costly. This numerical model can also be used to simulate a variety of air-sea exchange processes, such as the transfer of contaminants from surface water into the atmosphere.

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