JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 95, NO. C6, PAGES 9779–9782, JUNE 15, 1990

Comment on "Vertical Distributions of Spray Droplets Near the Sea Surface: Influences of Jet Drop Ejection and Surface Tearing" by J. Wu

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1. Introduction

In his comments on vertical profiles of sea spray droplets near the sea surface, measured by *De Leeuw* [1986], *Wu* [this issue] rejects the explanation for the observed features as proposed by *De Leeuw* [1986, 1987]. The features addressed by Wu are a minimum in the concentration profiles at a level around 0.2–0.5 m above the instantaneous sea surface (the profiles were measured with Rotorod impaction samplers mounted on the mast of a wave-following buoy), and a maximum at 1–2 m that was observed in wind speeds greater than 7 m/s. The level where this maximum occurs (1–2 m), as well as its relative intensity, depends on wind speed.

Wu [this issue] ascribes the observed minimum in the profiles to physical effects which are basically the same as those proposed by *De Leeuw* [1986, 1987] to explain the maximum. The maximum, in turn, is explained by Wu from the production of spume droplets from the wave crests, which was briefly discussed by *De Leeuw* [1986]. In this comment we show that Wu's conclusions are not supported by the experimental evidence presented by *De Leeuw* [1986, 1987] and in other relevant publications.

2. Comments on Wu's Interpretation

2.1. *Minimum in the Concentration Profile in Low Wind*

The minimum in the concentration profile was observed in all wind speeds, except 13 m/s [*De Leeuw*, 1986]. It is explained by *Wu* [this issue] in terms of production of jet droplets that are carried aloft by wave-induced airflow. Thus the effective ejection height would be extended to 0.5 to 1 m, i.e., the level where the minimum is observed. The negative concentration gradient in this zone reflects the variation in the droplet rise speeds.

Over the ocean the wave-induced air flow is caused, according to Wu, by flow separation on the short waves that are superimposed on the dominant waves. When the waves break, the vertical accelerations of fluid particles exceed the gravitational acceleration. This is based on laboratory observations of flow separation on dominant waves. Because of the short fetch, the dominant laboratory waves have a phase velocity less than the wind speed, which gives rise to high wind shear. The dominant waves in laboratory conditions have their oceanic counterpart in the short waves which are superimposed on the dominant waves.

The condition for flow separation is the occurrence of a stagnation point, corresponding to the onset of wave breaking for air flow over water waves [*Banner and Melville*, 1976]. Wu illustrates his arguments with a profile measured by *De Leeuw* [1986] in a wind speed of 5.5 m/s. In this wind speed, however, the fraction of the sea surface covered with whitecaps is about 0.0015 [*Monahan and O'Muircheartaigh*, 1986]. In view of this low fraction, the influence of breaking waves on the profiles can only be marginal, and it is certainly insufficient to support Wu's explanation of the observed minimum.

De Leeuw [1986] ascribed the minimum to the limited ejection height of the jet droplets. The freshly produced droplets are carried away from the ejection zone by the air flow in the wave troughs. The ejection zone is the layer between the surface and the maximum level (18 cm) to which the largest jet droplets may rise in still air [e.g., *Blanchard*, 1983]. The ejection heights vary with droplet size and ejection sequence; i.e., the top drop produced by each bubble is ejected higher than the second one, etc. Thus the droplet ejection heights are distributed over a range of levels. The droplets are transported to higher levels by turbulence caused by shear stress. This gives rise to the exponential decrease of concentrations away from the surface source that is commonly observed in diffusion-dominated processes.

2.2. *Maximum in the Concentration Profiles in Wind Speeds Higher Than 7 m/s*

According to *Wu* [this issue], the maximum is primarily caused by spume droplets produced by direct surface tearing from the wave crests. On this basis Wu estimates that at the highest wind speed of 13 m/s for which profiles were reported by *De Leeuw* [1986], the contribution of spume droplets to the total sea salt aerosol generation is 30%.

This estimate is not supported by data on the wind speed dependence of the droplet concentrations. De Leeuw [1986] indicates that spume droplets contribute to the maximum in the concentration profiles, but he suggests that the main cause is momentarily trapping of aerosol in an elevated layer. These issues are further addressed below.

3. Physical Processes Affecting the Aerosol Profile

Wu's explanation is not complete. It is based on only a subset of the features observed by *De Leeuw* [1986], and further evidence seen in data presented by *De Leeuw* [1987] is not considered at all. Although the processes discussed by Wu certainly influence the aerosol profile near the air-sea interface, other mechanisms should be considered as well. The rejection of one mechanism in favor of another can be based only on experimental and/or theoretical evidence.

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Paper number 90JC00288.
0148-0227/90/90JC-00288$02.00

This requires a comprehensive treatment of the physics involved. In the following discussion we address various mechanisms that may contribute to the shape of the aerosol profile. These include both the production and subsequent dispersal of sea salt aerosol, as well as removal by deposition at the sea surface.

3.1. *Production of Spume Droplets*

The apparently unphysical result of a maximum concentration away from the surface can be explained in two ways: (1) by an elevated source and (2) by a local transport process that causes momentary trapping.

The simplest explanation is the existence of a source at some level above the surface. An elevated source for sea spray aerosol is the direct production of spume droplets by surface tearing from the wave crests. The occurrence of this supplementary droplet production mechanism has been suggested by *Monahan et al.* [1983*a*] to explain the pronounced enhancement of the large-droplet end of aerosol spectra, which these authors measured at a height of 14 m above the sea surface in winds exceeding 9–11 m/s. This wind speed is higher than the lowest wind speed in which the maximum in the aerosol profile has been observed by *De Leeuw* [1986], i.e., 7 m/s.

Wu [this issue] ascribes the observed [*De Leeuw*, 1986, 1987] maximum in the droplet concentration profile at high winds exclusively to the supplementary production of spume droplets, based on laboratory observations by *Koga* [1981]. *Koga* [1981] and *Koga and Toba* [1981], observed trajectories of spume droplets larger than 450 μm in diameter, produced by surface tearing from the crests of dominant waves. Owing to the short fetch, the phase velocity c of these waves is much less than the wind friction velocity u_*, resulting in high wind shear.

As Wu argues (see also the discussion in section 3.2.1), the dominant laboratory waves have their open-ocean counterpart in the short waves superimposed on the dominant waves. Consequently, in oceanic conditions, spume droplet production should occur at the crests of these shorter waves, i.e., distributed along the contours of the dominant waves. This would mean that most of the spume droplet production would take place at heights of some tenths of meters. This is too low to contribute to the maximum in the droplet concentration profile.

Of course spume droplets are also produced at the crests of larger breaking waves. Spume droplets produced at the crests of the dominant waves may contribute to the maximum in the droplet concentration profile, which is observed at levels similar to the wave heights. On the other hand, the fraction of dominant waves that break is too small to yield a significant contribution to the droplet concentrations unless the spume droplet production per breaking wave is extremely high. At a wind speed of 10 m/s, for example, the fraction of the sea surface covered by whitecaps is 0.007 [*Monahan and O'Muircheartaigh*, 1986]. This includes whitecaps from all waves, with a lifetime of several seconds. The contribution of the breaking dominant waves is only a fraction of this number.

There is no question that the production of spume droplets influences the profile and the concentration, but to what extent has to be determined. This question is addressed below on the basis of experimental data on wind speed dependence of sea spray aerosol concentrations, its variation with height, and the wind history.

3.1.1. *Wind speed dependence.* The effect of spume droplets on the total sea spray production becomes more important as wind speed increases. Hence different aerosol concentration versus wind speed relationships are expected corresponding to wind speed regimes lower than or exceeding 9 m/s (see the model presented by *Monahan et al.* [1983*b*]). Monahan et al. indicate that their model is not adequate as a description of the spume production term and they do not recommend its use until further data necessary to refine the model have been collected. *Stramska* [1987] concludes that the *Monahan et al.* [1983*b*] spume droplet production term yields unrealistically high values for particles larger than 20 μm in diameter.

The occurrence of two different regimes in the wind speed dependence of the aerosol concentration is not obvious from the data presented by *De Leeuw* [1986, Figure 5]. These data are taken at a height of 11 m above the sea surface, and the analysis of data for lower levels leads to the same conclusion [*De Leeuw*, 1985]. Inspection of other data on the wind speed dependence of sea spray concentrations [e.g., *Lovett*, 1978; *Exton et al.*, 1983; *Monahan et al.*, 1983*a*] leads to the same conclusion. Therefore the effect of spume droplets cannot be as high as is indicated in the analysis by *Wu* [this issue].

3.1.2. *Variation of wind speed dependence with height.* Away from the source, the aerosol concentrations are expected to have the same wind speed dependence at all levels in the constant flux layer. However, the wind speed dependence of the particle concentrations [*De Leeuw*, 1986, Figure 7] has a minimum near 1 m. This cannot be explained by an extra source at an elevated level such as the production of spume droplets. This minimum in the wind speed dependence can be understood, however, by assuming that the particles are trapped in an elevated layer and that the depth of this layer increases with wind speed. This will be discussed further in section 3.2.1. The increasing depth of the trapping layer balances in part the increase in the concentrations due to the increase in wind speed, leading to a wind speed dependence weaker than at other levels.

3.1.3. *Wind history.* To determine the contribution of spume droplet production to the total production rate, the wind history must be considered also. As was indicated by *De Leeuw* [1986], the profile presented for 13-m/s wind speed was measured in decreasing winds after a storm. In decreasing winds, the surface stress decreases to lower than the value derived from the wind speed dependence of the surface stress [*Mundy*, 1987]. Hence also the production rates of both bubble-mediated droplets and spume droplets decrease. The shape of the measured profile was ascribed in part to the gradual fallout of aged particles that had previously been mixed throughout the boundary layer. In the subsiding winds, the turbulence becomes too weak to keep the large particles in suspension. In the wave troughs these particles are removed by deposition on the water surface. When this is not balanced by production of fresh particles, a strong gradient may result as was observed by *De Leeuw* [1986].

3.2. *Ejection of Jet Droplets From the Sea Surface*

Having concluded that the shape of the profile cannot be explained by spume droplet production alone, we must consider additional effects. *Edson* [1987] (see also *Mestayer et al.* [1989]), in his Lagrangian model describing the dispersal of aerosol in a wind wave tunnel, assumes an elevated source function at the maximum ejection height of the jet droplets. This is based on the short time the particles need to reach the tops of their trajectories in still air [cf. *Wu*, 1979]. *Edson* [1987] assumes that the particles are further transported by turbulence and gravitation, which are enforced at the maximum ejection height. Droplet concentration spectra calculated this way are similar to particle size distributions measured in the laboratory and in the field, lending credibility to the method. *Rouault et al.* [1988], in a time-dependent Eulerian treatment of this problem, use the same elevated source function. Integration in time of the calculated concentrations yields mean profiles showing a maximum near the top of the particle ejection trajectory. This is because the particles spend more time at the top of the trajectory than at intermediate levels, thus increasing the probability of their being sampled.

3.3. *Wave-Induced Effects on Droplet Transport*

The translation of these laboratory models to oceanic conditions is not straightforward. In particular, the presence of waves was not considered by *Edson* [1987] and *Rouault et al.* [1988]. The effects described by *De Leeuw* [1986, 1987] are observed mainly in intermediate to high winds in the region of the direct influence of the oceanic waves. The observation of the maximum in the aerosol profile led to the consideration that some mechanism might exist that gives the particles some extra lift, leading to an appreciable increase of the maximum ejection height.

Turbulence, which is generally considered the main source for transport of particles throughout the atmospheric boundary layer, leads to logarithmic concentration profiles in the marine surface layer. Close to the waves, the concentration profiles are not logarithmic, and a maximum can be observed in wind speeds exceeding 7 m/s, as was discussed above. Apparently, a local mechanism exists which effectively transports the particles away from the surface source to a level where they are momentarily trapped. *De Leeuw* [1986] proposed the following mechanism, which was later referred to as the "water-rotor" model. When wind speeds are larger than the wave phase velocity, for instance, young waves which do not yet propagate in phase with the wind, an upward flow is induced in the lee of the crest. This causes a local drop in the pressure, which gives rise to an inverse surface flow, thus creating an eddy in the lee of the crest [e.g., *Hsu et al.*, 1981]. Experimental evidence for the occurrence of such eddies has been observed in laboratory experiments [e.g., *Banner and Melville*, 1976; *Konishi*, 1981; *Hsu et al.*, 1981] and in one field experiment [*Anisimova et al.*, 1976].

The occurrence of such an eddy, or wave rotor, in the open ocean has not been confirmed, probably because the field experiments are extremely difficult. Therefore scales could not be given, and Wu's comments on *De Leeuw*'s [1986, 1987] consideration of flow separation on dominant waves are not relevant. Laboratory results indicate that the flow separation required to induce the eddies occurs only on waves for which $c < u_*$, i.e., for wavelengths of the order of 0.26 m at $u = 15$ m/s over the ocean, as indicated by *Wu* [this issue]. Following Wu, these short waves are important because the wave-augmented air flow at the lee of the crest may cause the updraft required to carry the droplets away from the ejection zone. Quantitative information on this phenomenon is as yet available only from the observations by *Bortkovskii* [1987]. In the open ocean, Bortkovskii observed droplets ejected to heights of approximately 1 m.

The variability of the wind speed and the intrinsic noisy character of u_*, as well as the generation of young waves that are not yet in phase with the wind, give rise to a variety of wavelengths on which flow may separate. Time-dependent measurements in the North Sea indicate that the aerosol is influenced by waves with frequencies considerably higher than those of the dominant waves [*De Leeuw*, 1989].

De Leeuw [1986, 1987] argues that the updraft caused by wind-wave coupling in the lee of the waves gives the particles the extra lift required to carry them aloft from the ejection zone. This preferential upward transport mechanism adds to the shear-induced turbulence as described above. Its effect is the removal of droplets from the ejection zone to higher levels. Owing to the local character of these updrafts, the particles are "trapped" at these higher levels until they are removed by turbulence and gravitation. Thus momentarily an elevated source may exist locally that gives rise to the enhanced mean concentrations observed at elevated levels.

This also explains the observed variation with height of the observed particle concentration versus wind speed relationships. Since the wave-induced air flow increases with wind speed, the elevated source function is "smeared" over a larger depth while simultaneously the particles are more efficiently removed from the trapping zone by shear-induced turbulence which also increases with wind speed.

4. Conclusion

We believe to have shown, based on experimental facts, that the explanations by *Wu* [this issue] for the observed shape of the droplet concentration profiles near the sea surface are not justified. Arguments have been presented in support of *De Leeuw*'s [1986] original explanation. These are not in contradiction with the effects described by Wu and from both Wu's contribution and the present discussion we can estimate the order of magnitude of the scales involved in the wave-induced effects. Much research has to be done, however, before a quantitative description of the observed features can be given. This includes both experimental work and theoretical investigations. Extension of *Edson*'s [1987] model to field conditions, including the wave-induced effects on air flow and the surface displacements, seems most promising [*De Leeuw*, 1989].

Acknowledgments. Useful discussions with Janice DeCosmo (Univ. of Washington) are acknowledged. This comment was written while the author held a National Research Council Associateship at the Naval Postgraduate School.

References

Anisimova, Ye., P., A. A. Speranskaya, and O. N. Likhacheva, Deformation of the wind velocity profile over developing wind waves, *Izv. Atmos. Oceanic Phys.*, *12*, 748–754, 1976.

Banner, M. L., and W. K. Melville, On the separation of air flow over water waves, *J. Fluid Mech.*, *77*, 825–842, 1976.

Blanchard, D. C., The production, distribution, and bacterial enrichment of the sea-salt aerosol, in *Air-Sea Exchange of Gases* *and Particles*, edited by P. S. Liss and W. G. N. Slinn, pp. 407–454, D. Reidel, Hingham, Mass., 1983.

Bortkovskii, R. S., *Air-Sea Exchange of Heat and Moisture During Storms*, Revised English edition, edited by E. C. Monahan, 194 pp., D. Reidel, Hingham, Mass., 1987.

De Leeuw, G., Vertical distribution of sea-spray particles at low heights and calculated extinction coefficients, *Rep. FEL 1985-33*, 62 pp., Phys. and Electron. Lab., TNO, The Hague, The Netherlands, 1985.

De Leeuw, G., Vertical profiles of giant particles close above the sea surface, *Tellus Ser. B*, *38*, 51–61, 1986.

De Leeuw, G., Near-surface particle size distribution profiles over the North Sea, *J. Geophys. Res.*, *92*, 14,631–14,635, 1987.

De Leeuw, G., Investigations on turbulent fluctuations of particle concentrations and relative humidity in the marine atmospheric surface layer, *J. Geophys. Res. 94*, 3261–3269, 1987.

Edson, J. B., Lagrangian model simulation of the turbulent transport and evaporation of jet droplets in a wind-water tunnel, Masters thesis, 102 pp., Penn. State Univ., University Park, 1987.

Exton, H. J., J. Latham, P. M. Park, and M. H. Smith, The production and dispersal of maritime aerosol, in *Oceanic Whitecaps*, edited by E. C. Monahan and G. Mac Niocaill, pp. 175–193, D. Reidel, Hingham, Mass., 1983.

Hsu, C.-T., E. Y. Hsu, and R. L. Street, On the structure of turbulent flow over a progressive water wave: Theory and experiment in a transformed, wave-following co-ordinate system, *J. Fluid Mech.*, *105*, 87–117, 1981.

Koga, M., Direct production of droplets from breaking wind-waves—Its observation by a multi-colored overlapping exposure photographing technique, *Tellus 33*, 552–563, 1981.

Koga, M., and Y. Toba, Droplet distribution and dispersion processes on breaking wind waves, *Sci. Rep. Tohoku Univ., Ser. 5*, *28*, 1–25, 1981.

Konishi, T., Analysis of wind structure over water waves using a flow visualization method, *Pap. Meteorol. Geophys.*, *32*, 99–108, 1981.

Lovett, R. F., Quantitative measurement of airborne sea-salt in the North Atlantic, *Tellus*, *30*, 358–364, 1978.

Mestayer, P. G., J. B. Edson, C. W. Fairall, S. E. Larsen, and D. E. Spiel, Turbulent transport and evaporation of droplets generated at an air-water interface, in Turbulent Shear Flows, vol. 6, edited by J.-C. Andre, J. Cousteix, F. Durst, B. E. Launder, F. W. Schmidt, and J. H. Whitelaw, pp. 129–147, Springer-Verlag, New York, 1989.

Monahan, E. C., and I. G. O'Muircheartaigh, Whitecaps and the passive remote sensing of the ocean surface, *Int. J. Remote Sens.*, *7*, 627–642, 1986.

Monahan, E. C., C. W. Fairall, K. L. Davidson, and P. Jones-Boyle, Observed inter-relations between 10 m winds, ocean whitecaps and marine aerosols, *Q. J. R. Meteorol. Soc.*, *109*, 379-392, 1983*a*.

Monahan, E. C., D. E. Spiel, and K. L. Davidson, A model of marine aerosol generation via whitecaps and wave disruption, *Oceanic Whitecaps*, edited by E. C. Monahan and G. Mac Niocaill, pp. 167–174, D. Reidel, Hingham, Mass., 1983*b*.

Mundy, J. F., Variation of the wind stress related to frontal passages during FASINEX 1986, M.S. thesis, 76 pp., Nav. Postgrad. Sch., Monterey, Calif., 1987.

Rouault, M., P. G. Mestayer, and R. Schiestel, The CLUSE numerical model of spray droplet surface flux, transport and evaporation in laboratory boundary-layer, Proceedings, NATO Advanced Workshop "Humidity Exchange Over the Sea Main Experiment (HEXMAX) Analysis and Interpretation," edited by W. A. Oost, S. D. Smith, and K. B. Katsaros, technical report, pp. 178–187, Dep. of Atmos. Sci., Univ. of Wash., Seattle, 1988.

Stramska, M., Vertical profiles of sea-salt aerosol: A numerical model, *Acta Geophys. Polonica*, *35*, 87–100, 1987.

Wu, J., Spray in the atmospheric surface layer: Review and analysis of laboratory and oceanic results, *J. Geophys. Res.*, *84*, 1693–1704, 1979.

Wu, J., Vertical distributions of spray droplets near the sea surface: Influence of jet drop ejection and surface tearing, *J. Geophys. Res.*, this issue.

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(Received July 31, 1989;
accepted January 16, 1990.)