ON THE CONTRIBUTION OF SPRAY DROPLETS TO EVAPORATION

(Research Note)

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Abstract. The effect of spray droplets in the marine surface layer on evaporation is considered. Independent evidence from energy constraints, from visibility and from sea salt content of air is used. The estimation shows that, except perhaps for hurricane wind strength, the increase of total evaporation from evaporating droplets is negligible. This is in agreement with recent experimental evidence.

1. Introduction

For an understanding of the consequences of the anthropogenic greenhouse effect on life on earth, a solid knowledge of the hydrological cycle is essential. The overwhelming part of evaporation happens over the oceans. For light winds to strong breezes, reasonable parameterisations of evaporation are available (Kruspe, 1977; Isemer and Hasse, 1987; Smith, 1989). Unfortunately, for higher wind speeds, undisturbed measurements at sea are rather difficult. On the other hand, whitecap generation and spray production from bursting bubbles start with strong breezes and increase approximately with the third power of wind speed. Hence, there is the question of whether spray droplets would significantly increase evaporation. This question was one of the reasons for the Humidity Exchange over Sea – Experiment (HEXOS, Katsaros *et al.*, 1987). Ling *et al.* (1978) apparently were the first to model numerically the fate of spray droplets in the marine surface layer, including change of droplet sizes by evaporation. Their publication, based on laboratory data, was one incentive for the HEXOS programme. Bortkovskii (1987) has treated the question of evaporation augmentation for the open sea on the basis of whitecap and foam coverage, bubble spectra and spray generation. He came to the conclusion that a net effect is noticeable. Unfortunately, most of the necessary data show large scatter, so that the magnitude of the effect is rather uncertain. For example, bursting bubbles eject droplets into the air, that reach typical heights of 10 to 20 cm, a rather ridiculous height for measurements over the open ocean in strong winds and heavy seas. Results from experimental and modelling work by different groups were presented in a workshop on the fate and influence of marine spray (Mestayer *et al.*, 1990). Edson (1989) and Rouault *et al.* (1991) modelled dispersion of evaporating spray droplets in the marine surface

layer. The latter model, as the authors explained, is evaluated for conditions that are quite artificial compared to those encountered over the sea and can not yet give a prediction of the contributions of droplets to evaporation. In the present research note, we follow an independent approach by considering energy and mass balance constraints.

2. The Energy Constraint

Consider the following argument: Evaporation needs heat. Assume that the heat is taken from the droplet itself and that the droplet is fully evaporated. With L heat of vaporisation, m droplet mass, c specific heat of water, and ΔT temperature change, we have

$$L \cdot m = c \cdot m \, m = c \cdot m\Delta T$$

$$\Delta T = L/c \sim 600 \text{ K} .$$

This is clearly unrealistic. The lowest temperature that a droplet could attain is the dewpoint temperature of the surrounding air, where evaporation would stop. Thus only order 10 °C cooling is possible. It is evident that the cooling of droplets themselves would be far from sufficient. In most situations, less than 1% of the water content of droplets could evaporate. Therefore, heat for evaporation of droplets has to come from the surrounding air. Because of the low density of air, the heat content of the surface air layer is too small to sustain evaporation for any length of time exceeding a few minutes. Hence, in a steady state, the heat necessary for evaporation of droplets needs to be taken from the sensible heat flux. As a consequence, the increase of latent heat flux due to evaporation of droplets is limited by provision of sensible heat.

The sensible heat flux is driven by the temperature difference between air and sea and by turbulent mixing. It is usually smaller than the latent heat flux. For a rough estimation of magnitude, we may assume that half of the sensible heat flux is used for evaporation from spray, while the other half passes on through the surface layer. Thus, the latent heat flux may be enhanced by half the Bowen ratio (i.e., the ratio of sensible and latent heat flux). With Bowen ratios of typically 0.3 in midlatitudes and 0.1 in the subtropics and tropics, we may expect an increase of latent heat flux and an equivalent increase of evaporation of perhaps 10%.

To put it into other words: From a situation without droplet production to a situation where there are enough droplets to use the sensible heat effectively for evaporation, the bulk transfer coefficient for water vapour may increase by perhaps 10%. Within the experimental scatter, and the expected increase of c_E with increasing turbulence (i.e., with the square root of the drag coefficient), this might not even be noticed.

3. The Added Surface Area Argument

The rough estimate given above is for illustration only. It probably overestimates the effects of droplet evaporation. It is based on the argument that droplets are produced by whitecaps, and whitecaps cover only a fraction of the sea surface. Heuristically, we may assume that there are patches in the air where the heat flux is affected, while the remaining area is not affected. Even in the affected patches, the droplets occupy only a small fraction of each volume of air.

We consider the effects of droplets in more detail. The enhancement of water vapour flux by droplet evaporation hypothetically stems from two processes: (i) Evaporation at the sea surface is rate limited by the slow molecular transport of water molecules through the viscous sublayer at the sea surface. (Evaporation from droplets could occur above the viscous sublayer, thus bypassing the rate limiting layer.) (ii) The total amount of surface available for evaporation could be increased by the surface of droplets in the air. We discuss these two ideas in turn.

The first idea, to bypass the molecular sublayer, is not fully applicable. Except for the first moment of ejection, the droplet would not have much velocity relative to the surrounding air. Note that spray droplets are of the size of cloud droplets. This size is small compared to the size of turbulence elements. The exchange of heat and water vapour with the surrounding air is through molecular action. Thus, the viscous sublayer at the sea surface is replaced by the spherical sublayer of molecular transport around the droplet. There is some difference, but droplet evaporation does not constitute a full bypass.

The second argument is that the presence of droplets increases considerably the surface area for evaporation. We first note that the ratio of surface area A to volume V depends on drop radius r:

$$A/V = 3/r.$$

Film drops are of order $10\,\mu m$, jet drops of order $100\,\mu m$. For a rough estimate, we assume that the droplets are represented by a droplet of uniform size $r = 10\,\mu m$. In order to calculate the surface area, we need an estimate of droplet water content in the air. For most wind conditions, visibility is not affected. Note that only at Beaufort force 12, "visibility is very seriously affected", but even then not blurred. Hence, the typical cloud liquid water content of $0.1\,g\,m^{-3}$ may be taken as an upper limit ($0.1\,g\,m^{-3}$ liquid water content corresponds to a meteorological range of visibility of $250\,m$, e.g., Twomey (1977, p. 236)). The specific weight of water is roughly $1\,g\,cm^{-3}$. Hence we have $v = 0.1\,cm^3$ volume of water in $1\,m^3$ of air. For the $10\,\mu m$ droplet, this corresponds to an area of

$$A = 3v/r = 300\,cm^2\,.$$

This is for a volume of $1\,m^3$, with a typical cloud water content. For a column of cross-section of $1\,m^2$, the area increase would be a meagre 3% per m height.

Summing up: It appears unlikely that evaporation of droplets contributes strongly to an enhancement of the latent heat flux in the surface layer, except perhaps for hurricane strength winds. At the same time, the total (latent plus sensible) heat flux from sea to air remains essentially unchanged by droplet evaporation.

4. Evidence from Sea Salt Content

The above estimate is for steady state conditions in the surface layer. There may, however, be an export of droplets from the sea surface to the Planetary Boundary Layer. In the boundary layer, heat for evaporation could be provided from other sources. Since the droplets originating from bursting bubbles are of the size of cloud droplets, turbulent transport of these droplets throughout the PBL is certainly possible.

In order to see if the evaporation of droplets in the PBL could significantly contribute to the total sea-air transfer of water vapour, we perform a rough estimation. This is based on measurements of sea salt content of marine air as a function of wind speed as compiled by Junge (1963). The average sea salt content, averaged over all wind conditions over the North Sea, was $11.6\,\mu g\,m^{-3}$ NaCl (Chamberlain, 1983). Evaporation of $1000\,\mu g$ seawater requires $30\,\mu g$ NaCl sea salt. Unfortunately, Junge's measurements give a salt content rather than a salt flux. We may argue that salt is felt in the air some 10 km inland from the shore, and that it was possible for Junge and others to measure salt content as a function of wind speed. This implies that production and removal must take place within the typical time scale of change of wind speed. Hence, for an estimate, we take the half life of sea salt in the PBL to be of order 3 hr or 10^4 sec. We may assume the PBL to have a height of 500 m. We obtain the total evaporation rate E from droplets

$$E = 11.6\,\mu g\,m^{-3} \cdot 500\,m/0.03/10^4\,s = 0.02\,g\,m^{-2}s^{-1}$$

or the corresponding heat flux from droplet evaporation

$$L \cdot E = 0.05\,Wm^{-2}\,.$$

This is a negligible contribution. Even if we would assume a time scale of 10^3 s rather than 10^4 s, and assume the flux to be higher by another factor of 10 in gale force winds (Beaufort 9), the resulting evaporation from droplets would still be very small. Together, we conclude that for all larger scale air-sea interaction work where parameterisations like those in the aerodynamic bulk transfer methods are used, we need not consider spray droplets as source of evaporation.

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