P4.17 DROP EQUILIBRIUM IN THE PRESENCE OF SOLAR ABSORPTION

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1. INTRODUCTION

It is well-known that near cloud boundaries, cloud drops experience significant radiative heating/cooling rates which affects vapor growth rates (Roach, 1976). These radiative heating and cooling rates can be large, reaching values of nearly -15 K hr^{-1} for longwave (LW) cooling and 2 K hr^{-1} for solar, or shortwave (SW), heating. Furthermore, in the case of stratiform clouds, this heating and can extend over a large fraction of the depth of the cloud (e.g. Harrington et al., 2000) altering drop growth, and the drop size spectrum, throughout the entire depth of the cloud (see Hartman et al., 2002).

Previous studies of the influence of radiative effects on drop growth have focused primarily on whether or not cloud top LW cooling can increase drop growth rates sufficiently so that collision-coalescence is enhanced (e.g. Austin et al., 1995; Ackerman et al., 1995; Harrington et al., 2000). Most of these studies show not only enhanced collection rates, but also changes in the structural evolution of the cloud layer. Some studies have illustrated strong influences of layer cloud evolution on radiatively influenced growth (e.g. Bott et al., 1990) whereas other studies have shown small effects (e.g. Harrington et al., 2000). Not all previous studies have had collision-coalescence as their main goal. A few studies (Davies, 1985; Austin et al., 1995; Harrington et al., 2000) have examined radiative influences on the equilibrium supersaturation of stratiform clouds and how this might alter the drop size distribution.

Guzzi and Rizzi (1980) were perhaps the first to show that larger drop growth tends to be enhanced whereas small drop growth tends to be suppressed under LW cooling. This is due to the fact that the LW effect increases rapidly with size, so drops smaller than about 10 µm are only slightly influenced. The strong influence of LW cooling allows the larger drops to persist in a subsaturated environment (Roach, 1976) and this tends to drive the supersaturation down. Hence, small drop growth is either suppressed or are negative (evaporation). Harrington et al. (2000) showed that this effect, at the top of stratiform clouds, can produce a small drop mode.

Reflecting on these previous studies, an immediate question tends to come to mind: *When radiative influences are important, under what conditions are water drops of various sizes in equilibrium with the surrounding vapor field?* This is the same as asking what sort of influence radiative heating/cooling has on the Köhler curves. Though the radiative term has been examined for a number of years, the influences of radiation on drop equilibrium has been relatively ignored.

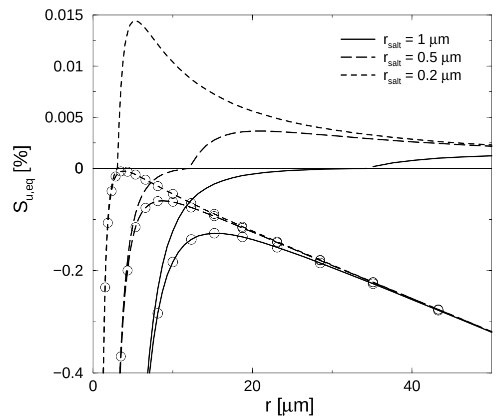

Figure 1. Köhler curves without (standard lines) and with (lines with circles) LW cooling (E_d = -20 W m^{-2} cooling, see below) as a function of salt particle radius.

Roach's (1976) study was perhaps the only one to examine this issue. His idealized studies showed that: (1) the maximum in the Köhler curve is shifted to lower supersaturations ($S_{u,eq}$), even to subsaturations, (2) as drop size increases, $S_{u,eq}$ continues to drop, and (3) under moderate LW heating, $S_{u,eq}$ increases with drop size. Examples of these effects are shown in Fig. 1 for various sizes of NaCl.

In this paper, we examine drop equilibrium for cases of cloud top LW cooling, SW heating, and cloud-base LW heating.

2. METHOD

In this study we wish to examine the vapor conditions under which a drop will remain in equilibrium with its environment if radiative heating/cooling is considered. As in the case of Roach (1976), we begin with the drop growth equation:

$$\frac{dm}{dt} = 4\pi r G(T, P)\left[S_u - \frac{A}{r} + \frac{B(m_s)}{r^3} - C(r)Q_R\right] \qquad (1)$$

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where S_u is the supersaturation, A/r is the curvature term, B/r^3 is the solution term which is a function of the salt mass, and $C(r)Q_R$ is the radiative term. The term Q_R can be shown to be directly proportional to the fluxes incident on the drop. For the case of a two-stream model, we can write (see Harrington et al., 2000):

$$Q_R = 4\pi r^2 \sum_{i=1}^{n} Q_{a,i}(r) E_{d,i} \qquad (2)$$

where the sum is over the SW and LW spectral intervals used, $Q_{a,i}$ is the absorption coefficient for spectral interval i, and $E_{d,i}$ is the net radiative effect for spectral interval i (negative for cooling, positive for warming). Drops are in equilibrium when dm/dt = 0, or when the bracketed term in Eq. 1 is zero. Hence,

$$S_u = \frac{A}{r} - \frac{B}{r^3} + C(r)Q_R \equiv S_{u,eq} \qquad (3)$$

must be the case at equilibrium. This relation is exactly the same as that used by Roach (1976).

In order to compute $S_{u,eq}$ we need cloud fields and the radiative fluxes. In this case, idealized clouds will suffice. We use a standard mid-latitude summer sounding and modify the lowest 1 km to contain a mixed-layer with stratiform clouds of varying depths. Cloud liquid water content (LWC) is computed by assuming a moist adiabatic lapse rate that is modified to mimic LES stratus profiles.Then, by assuming constant

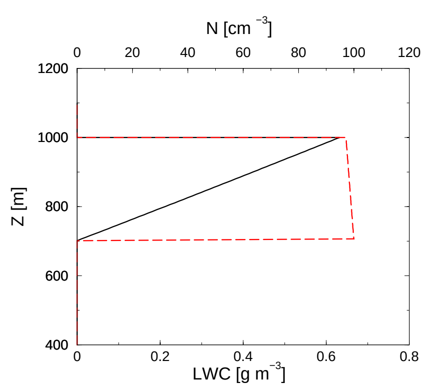

Figure 2. LWC (black, solid) and N (red, dashed) as a function of height for a 300m deep stratus cloud.

drop concentrations (N) with height, and that the water drops are distributed in size by a gamma distribution, we can compute the radiative heating/cooling rates through our model clouds. Figure 2 shows the LWC and N profiles that this model produces. For the cases presented here, we use only the 300 m deep cloud shown.

Longwave and shortwave radiative profiles through these adiabatic clouds are computed using a two-stream model with 6 solar and 12 infrared bands and Δz = 5m.Optical properties are computed using the method of Harrington and Olsson (2001) and are included in Eq. 3 following Harrington et al. (2000). Figure 3 shows LW and SW heating rates for various differences in the temperature of the surface and the overlying air (ΔT_{sfc}). Since T_{sfc} can be 5 to 40 C warmer than the overlying air, significant LW heating of cloud base can occur, as Fig. 2 shows. (40 C is rather extreme, however it does occur in arctic regions.)

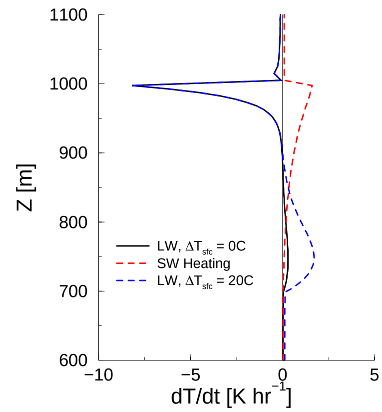

Figure 3. LW and SW heating rates. SW heating rate is for overhead sun ($\theta_0 = 0^0$).

By using the output from the radiative transfer model at each height in the cloud, along with an assumed salt mass, values of $S_{u,eq}$ throughout the depth of the cloud can be derived.

3. RESULTS

3.1 Cloud Top

Since LW cooling and SW heating maximize at cloud top, it behooves us to examine $S_{u,eq}$ in this region. We would expect this region of any stratiform cloud to be particularly sensitive to alterations in the drop growth equation. This is because dynamic motions that force S_u are relatively weak,

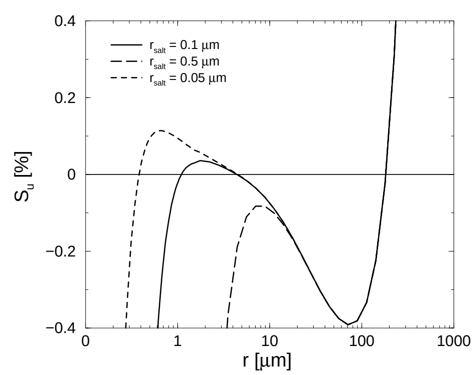

Figure 4. $S_{u,eq}$ for 3 salt sizes with $\theta_0 = 0^0$ and plotted for drops at cloud top.

hence any physical process that affects dm/dt could be important. Further, since cloud top is the region where LWC maximizes, collision-coalescence is strengthened in this region, thus alterations to the growth equation could affect collection (see Hartman et al., 2002).

Figure 4 shows theoretical variations in $S_{u,eq}$ for drops residing at cloud top. In general, all of the curves experience a reduced maximum at small sizes due to the strong LW cooling at cloud top (Fig. 3). For drops with r < 80 µm, the $S_{u,eq}$ curves decrease with drop radius, as Roach (1976) showed (e.g. Fig. 1). As explained above, this reduction with radius is due to the fact that the LW cooling effect in Eq. 3 increases with drop radius. Thus, drops with r > 8-10 µm can exist in equilibrium at subsaturation. This becomes more significant as the drop size increases with r = 80 µm drops having an $S_{u,eq}$ of 0.4%.

However, for drops with r > 80 µm $S_{u,eq}$ begins to increase again, crossing $S_{u,eq}$ = 0 at around 180 µm. This effect is due to the fact that LW absorption coefficients for liquid drops asymptote at much smaller sizes than do those for SW absorption. Hence, as drops increase in size, they absorb increasingly greater quantities of solar radiation (this is not new, see Wiscombe et al., 1984). At some point, SW absorption overpowers the effects of LW cooling and the drops experience a net warming. This occurs around r = 180 µm in this case, but depends on any factor that influences the radiative fluxes (cloud morphology, N, LWC, distribution breadth, etc.).The minimum (80 µm) and cross-over point (180 µm)

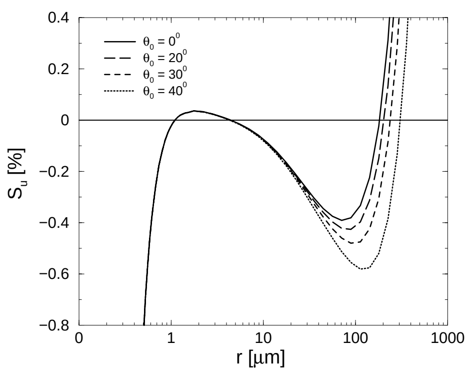

Figure 5. $S_{u,eq}$ for r_{salt} = 0.1 µm and a variety of θ_0.

have interesting implications for drop growth at cloud top that we discuss later and explore in a companion paper (Hartman et al., 2002).

Of course, one of the most important variations is that of SW heating with solar zenith angle (θ_0) Since, as Fig. 4 shows, the SW influence on $S_{u,eq}$ does not depend strongly on the salt mass, we plot the influence of θ_0 for only one r_{salt} (Fig. 5). As θ_0 increases (lower sun elevation), the minimum and the cross-over point both shift to larger sizes. At θ_0 of 40^0, the minimum now occurs near 120 µm whereas the cross-over point occurs at around 320 µm.

3.2 Cloud Depth

Since LW cooling is confined to a layer near cloud top whereas SW heating is distributed throughout the cloud (Fig. 3), we would expect a significant variation of $S_{u,eq}$ with depth below cloud top. Figure 6 shows this variation from cloud top

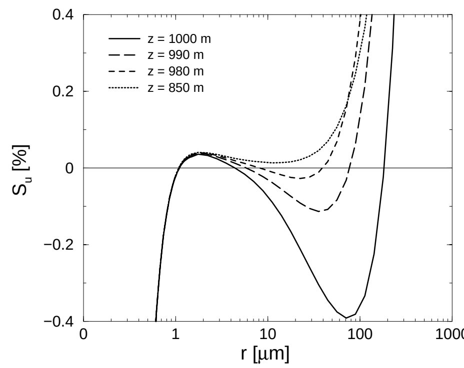

Figure 6. Variation of $S_{u,eq}$ with depth (1000m = cloud top) for $\theta_0 = 0^0$ and r_{salt} = 0.1 µm.

to mid-cloud where net radiative heating tends to be the strongest. Because LW cooling decreases rapidly as the distance below cloud top increases, the minimum $S_{u,eq}$ rises quickly with depth. Hence, LW effects on drop equilibrium, and drop growth, are confined to the top 20 m or so of the cloud. Consequently, SW heating dominates the radiative influence on $S_{u,eq}$ a relatively short (about 50 m) distance below cloud top. Below 50 m depth, subsaturated equilibrium conditions no longer occur and all drops, regardless of size, require supersaturated conditions. At mid-cloud (850 m) drops have only a small range of supersaturations over which they can grow before they reach the rapid increase in $S_{u,eq}$.

3.3 Cloud Base Heating

Surface temperature differences with the overlying air (ΔT_{sfc}) can cause significant LW heating of cloud base. As Fig. 3 shows, this influence is not confined to a shallow layer like cloud top LW cooling because the vertical gradient in LWC near cloud base is much weaker. Hence, cloud base LW influences are typically spread throughout the lower portion of the cloud. Surface temperature differences of as little as 5C can cause enough cloud base warming to significantly influence $S_{u,eq}$. This has immediate consequences since most CCN are nucleated in the vicinity of cloud base.

Figure 7 shows $S_{u,eq}$ for a large salt particle, one that would nucleate a 15 µm drop in the presence of a slight supersaturation and no radiative effects. However, when LW radiation is included and for a case in which ΔT_{sfc} = 0C the Köhler curve changes drastically. (Cloud base is still warmed in this case because the temperature of the surface is significantly greater than that of the base of the cloud.) Note that even in

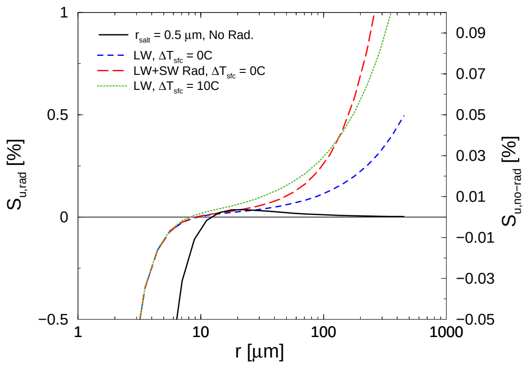

Figure 7. $S_{u,eq}$ 50 m above cloud base (750 m) for four cases including SW heating with $\theta_0 = 0^0$.

this weak LW heating case, which should also be very common in low-level clouds, there is a significant increase in $S_{u,eq}$ with size. In fact, note that for larger salt particles, there is no longer a maximum in the $S_{u,eq}$ curves. Haze drops such as these may never nucleate in a radiatively warmed environment. When SW heating, or a greater surface temperature, is included the effect on $S_{u,eq}$ is even greater. Of course, the shapes of the above curves depend on r_{salt}. We find that $S_{u,eq}$ does not have a maximum for r_{salt} > about 0.2 µm for most heating rates. For salt sizes smaller than this, a maximum still appears in $S_{u,eq}$ however the minimum is usually above 0% and is quite small in depth.

3.4 A Cloud-Scale View

The individual plots presented above are useful, however they tend to make it difficult to get an overall view of $S_{u,eq}$ in a stratus cloud. Figure 8 show $S_{u,eq}$ for the upper half of a stratus

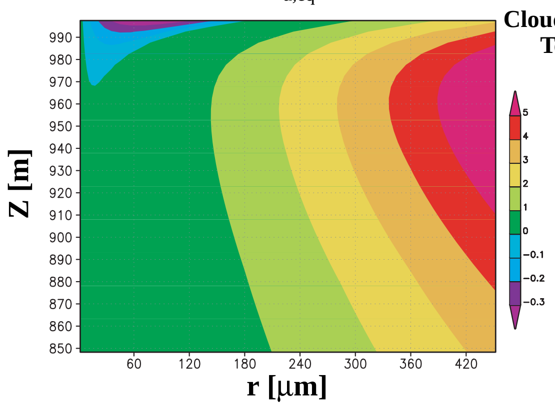

Figure 8. $S_{u,eq}$ for r_{salt} = 0.1 µm through the upper half of a 300 m deep stratus layer with $\theta_0 = 0^0$.

cloud using 0.1 µm salt particles in the solution term. Note that negative values of $S_{u,eq}$ are confined to the upper 30 m of the cloud and to drop sizes generally smaller than 180 µm (note that this size rapidly decreases with distance from cloud top). The lower portion of the cloud (including cloud base) show equilibrium at $S_{u,eq}$ up to 5% for the largest drops (about 500 µm). Thus, we expect strong suppression of vapor growth for medium to large size drops that are more than 30 m from cloud top. The maximum in $S_{u,eq}$ corresponds to the region of maximum radiative heating as shown in Fig. 3. This result has significant implications for the prediction of the cloud-drop size spectrum, has we discuss in Hartman et al. (2002)

A similar view is shown in Fig. 9 for a larger salt particle (0.5 µm). In this case, slight subsaturations occur only at cloud

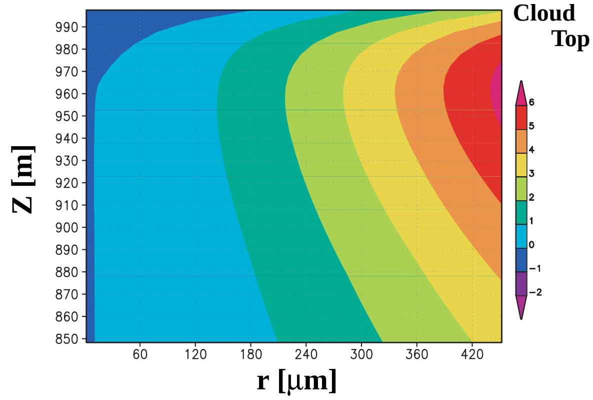

Figure 9. $S_{u,eq}$ for r_{salt} = 0.5 µm through the upper half of a 300 m deep stratus layer with $\theta_0 = 0^0$.

top and at the smallest drop radii. However, unlike with the case of the smaller salt particle (Fig. 8), no minima in $S_{u,eq}$ is observed at cloud top for small drop sizes. Instead, and this occurs throughout the cloud, $S_{u,eq}$ continually increases with drop radius. Hence, salt particles of this size and greater would never seem to nucleate in a stratus cloud that is significantly heated by solar radiation. This result could have implications for studies which suggest that giant CCN may enhance the collision-coalescence process (e.g. Feingold et al., 1999). Future work will examine the implications of this process in a detailed cloud model.

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