P1.26 RADIATIVE INFLUENCES ON THE GLACIATION TIME-SCALES OF ARCTIC MIXED-PHASE CLOUDS

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1. INTRODUCTION

The Arctic region is unique in many respects, including in the nature and characteristics of the ubiquitous stratiform clouds that frequently occur. The recent increase in relative interest in Arctic cloudiness has been garnered primarily because of the rapid warming (e.g. Chen et al., 2002; Stone et al., 2002) and decreasing sea-ice extent (e.g. Parkinson et al., 1999) that has been observed. Indeed, it had been hypothesized (e.g. Curry and Ebert, 1992), and evidence seems to suggest (e.g. Intrieri et al., 2002a) that Arctic clouds could have important impacts on the surface radiation budget, and hence, the climate of the Arctic region. Since the liquid phase dominates the radiative warming response of Arctic low-level clouds, and since the Arctic contains liquid clouds for much of the year, understanding the liquid partitioning in these mixed-phase clouds is of paramount importance from a climate perspective.

Be that as it may, assessing the internal processes of Arctic clouds is no easy task. During the short summer season, Arctic clouds can be primarily liquid and may also be found in layers, some of which are thermodynamically stable (Curry et al., 1996). During the two short transition (fall, spring) seasons and winter, these low-level stratiform clouds still contain an appreciable amount of liquid along with precipitating ice (e.g. Pinto et al., 1998; Hobbs and Rangno, 1998) with around 73% of all clouds containing some liquid (Intrieri et al., 2002b). Even though these clouds are precipitating, they can be quite persistent and can exist with multiple liquid layers interspersed with ice precipitation (Pinto et al., 1998; Harrington et al., 1999; Zuidema et al., 2005). These local processes are also linked to both meso- and synoptic scale dynamics which can strongly influence cloud evolution (e.g. Curry and Herman, 1986).

The abundance of liquid in Arctic clouds, even at low temperatures, along with their frequency and persistence, is not well understood. This is partially due to the fact that mixed-phase clouds are colloidally unstable since ice crystals grow rapidly to large sizes at the expense of liquid drops (the well-known Bergeron-Findeisen-Wegener process). As Pinto (1998) and Harrington et al. (1999) have pointed out, ice nuclei (IN) concentrations within Arctic clouds should be quite low, otherwise rapid ice nucleation and growth would dissipate the mixed-phase clouds. Given that the Arctic is a relatively pristine environment, with few in-situ sources of IN, this seems to be a reasonable hypothesis. Recent measurements during SHEBA and M-PACE appear to bear this out as IN concentrations tend to be quite low (less than 2 l^{-1}) in the Arctic during both fall and spring. Moreover, Harrington et al. (1999) and Jiang et al. (2000) illustrated that even small changes in IN concentrations can cause very rapid changes in cloud liquid water amounts suggesting that Arctic mixed-phase clouds may be quite susceptible to anthropogenic changes to the aerosol population (see Fig. 1). Additionally,

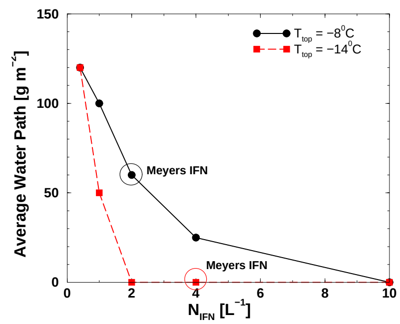

Figure 1. Average liquid water path (LWP) as a function of IN concentration for the mixed-phase Arctic stratus simulations of Harrington et al. (1999)

recent measurements suggest that some of the standard nucleation parameterizations (e.g. Meyers et al., 1992) produce ice concentrations that are too high for the Arctic. It is also quite possible that contact nucleation may play a role in mixed-phase cloud longevity (Morrison et al., 2005).

It is important to keep in mind that feedbacks between the microphysics and dynamics of mixed-phase cloud layers have important consequences for mixed-phase cloud structure and longevity. Stronger updrafts, and smaller crystal sizes, tend to increase the lifetime of liquid water within a mixed-phase cloud layer (e.g. Rauber and Tokay, 1991; Korolev and Isaac, 2003). Furthermore, the longevity of mixed-phase clouds may be strongly linked to the cloud top radiative cooling that drives the dynamics of the cloud layer (Harrington et al., 1999). Hence, alterations in the aerosol population changes the liquid water at cloud top which is ultimately responsible for driving the dynamics of the cloud layer. In fact, Harrington and Olsson (2001a) showed that alterations in IN can even affect the dynamics of strongly surface-driven Arctic mixed-phase

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clouds. These studies hint at the interplay between microphysics and dynamics within mixed-phase layers, however since few studies have been done these interactions are poorly understood at present.

In this paper, we add a further wrinkle to the discussion of mixed-phase cloud longevity. It is well known that radiative cooling and heating can alter the growth of liquid water drops substantially (e.g. Roach, 1976; Hartman and Harrington, 2005a). It therefore seems likely that radiative processes may alter the growth of ice crystals with a consequential influence on the longevity of mixed-phase clouds.

2. METHODS

In order to estimate the potential importance of radiative heating and cooling to mixed-phase cloud longevity, we follow the approach discussed in Korolev and Isaac (2003). Namely, we use a box model and numerically compute the amount of time required for ice crystals to completely evaporate a given amount of liquid (the so-called glaciation timescale, or τ_g). The model is initialized with a given liquid water content (LWC), a small amount of ice with a known ice concentration (N_i), and a given temperature. The saturation state is assumed to be that of liquid. We then compute τ_g by integrating the vapor growth equation for ice until all of the liquid has been depleted. When radiative effects are included, the growth equation for ice becomes,

$$\frac{dm_i}{dt} = 4\pi C_i G_i(T,P)[s_{ui} - R(L_i)E_d(L_i)] \quad (1)$$

$$E_d = \sum_j F_j Q_{a,j}(L_i)$$

In the above equation, C_i is the capacitance for a given crystal, s_{ui} is the ice supersaturation, $R(L_i)$ is a function of the ice crystal maximum dimension, and E_d is the net flux absorbed by the crystal. Note that E_d simply the sum of the net radiative flux (F_j) and the absorption efficiency ($Q_{a,j}$) for each wavelength interval, j, which ranges across the longwave (LW) and shorwave (SW) spectra. The radiative contribution to growth is negative (positive) for cooling (heating) which means that vapor growth is enhanced (suppressed).

Since the radiative effect depends on size, the above equation must be solved numerically. Furthermore, the growth equation now depends on the net radiative flux experienced by the ice crystal which depends on the location of the crystal within the cloud layer. As a consequence, we compute the net radiative fluxes through a simple, adiabatic stratiform cloud layer which is embedded in an Arctic atmosphere (Fig. 2). In order to make the profile slightly more realistic, a constant in-height ice water content (IWC) is added which tends to zero at cloud top, and at the surface. The LWCs, IWCs and cloud depth were constrained to follow the available observations (e.g. Pinto 1998). These profiles are then used in the radiative transfer model described in Harrington and Olsson (2001b) to compute the radiative fluxes which are shown in Fig. 3 below. As is typical of most stratiform cloud layers, the longwave (LW) cooling is confined to the upper 100 m of the cloud with a maximum of nearly 6 K h^{-1}. The solar heating, which was computed for a solar zenith angle, $\theta_0 = 40^0$, extends throughout the cloud layer. This means that Fig. 3 shows the approximate maximum potential heating of an Arctic mixed-phase stratiform cloud deck by solar heating. (Realize that low-level mixed-phase clouds can and do occur during the summer months in the Arctic.) The total radiative heating profile (not shown), therefore shows that the cloud cools over the top 75m, but warms throughout the remainder of the cloud deck.

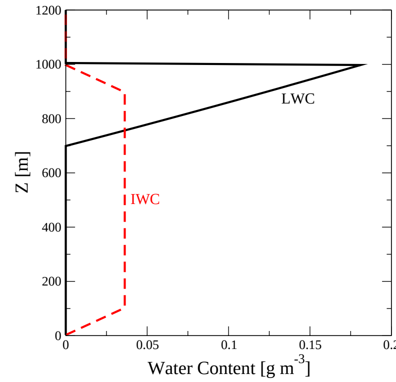

Figure 2. Adiabatic LWC and IWC for an idealized arctic mixed-phase stratiform cloud.

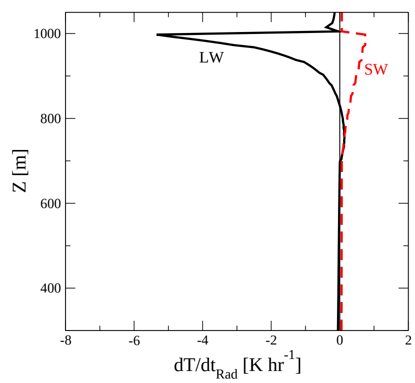

Figure 3. Longwave (LW) and shortwave (SW) cooling and heating profiles for the cloud in Fig. 1.

3. Radiative Influences on Ice Supersaturation

Given the heating profiles in Fig. 3, we might expect that ice crystal growth, and thus glaciation, will be enhanced at cloud top but suppressed throughout the remainder of the

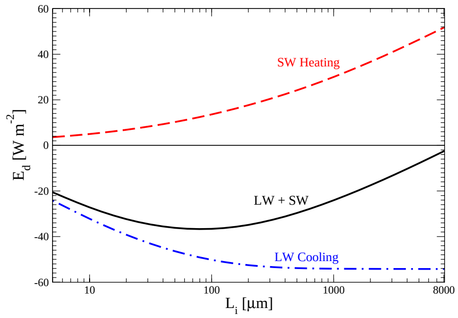

Figure 4. Net absorbed flux (Ed) at cloud top for the radiative profiles in Fig. 2 as a function of ice crystal size (plate diameter).

cloud. While this is generally true, the results at cloud top are a bit more complex. As Hartman and Harrington (2005) point out for water drops, and this is also true for ice crystals (Fig. 4), the net LW flux emitted by the particle rapidly asymptotes with size. However, the absorbed net SW flux continues to rise with crystal size because Q_a is a slowly varying function of size at solar wavelengths (Fig. 4).Small crystals, therefore, experience a strong net cooling whereas this cooling weakens for larger crystals as the amount of SW absorption rises. For very large crystals, it is even possible for a net warming to occur even at cloud top. These results suggest that, at cloud top, we should expect the strongest enhancement of ice crystal growth for intermediate crystal sizes. As a crystal becomes larger, increased solar heating should slow the crystals growth.

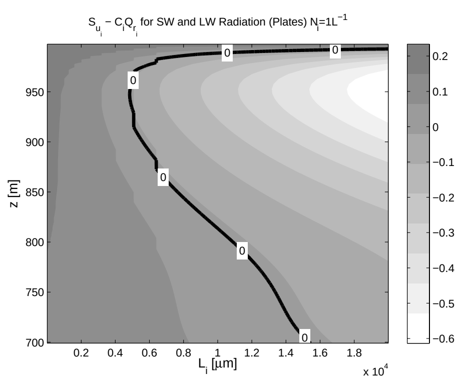

Figure 5. s_{ui}-R(L_i)E_d(L_i) as a function of height for the cloud, and radiative profiles, shown in Fig. 1 and 2. Cloud top T = -15C and $\theta_0 = 40^0$.

The above result becomes more clear if plotted for the entire cloud layer. Instead of showing E_d, however, we have plotted, $s_{ui} - R(L_i)E_d(L_i)$ in Fig. 5. Hence, when the above difference is positive (negative), net deposition (sublimation) should occur. Though it is hard to see in the figure, ice crystals in the upper 50m of the cloud layer will experience strongly enhanced growth. In fact, the ice supersaturation, which is ~ 15% without radiative influences, is effectively increased to nearly 30%. Of course, the influences of LW cooling rapidly diminish as one moves from cloud top toward cloud base. In fact, lower in the cloud, the ice supersaturation is effectively reduced due to the influences of net SW heating. For instance, at 900m, plate crystals with diameters greater than 1 mm experience a reduction in effective supersaturation from ~ 15% to as little as a few percent. Hence, as crystals grow larger, SW absorption continues to rise effectively slowing the net depositional growth of the crystals. The largest crystals in the cloud (~ 1 cm in diameter) may even experience a net heating and, therefore net sublimation.

4. Radiative Influences on Glaciation

4.1 Cloud Top

The results presented above suggest that at cloud top we may expect much more rapid glaciation due to LW cooling of ice crystals, however this will depend to some degree on whether or not SW heating is significant. For large SW heating, we expect that ice crystal growth will slow as the crystal gets larger which may then offset any enhancement of the glaciation process caused by LW cooling. Within the center of the cloud, we expect glaciation to be slowed due to net SW heating.

These general results are borne out in Fig. 6 which shows

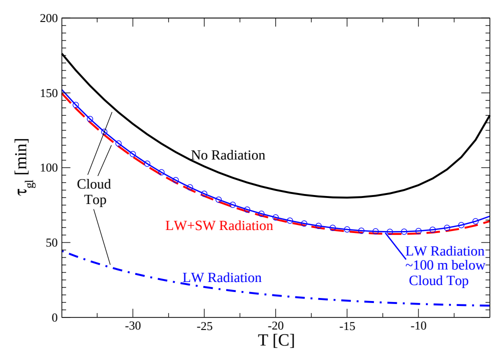

Figure 6. Glaciation time-scale (τ_g) at cloud top (and 100 m below cloud top) with and without radiative influences on depositional growth.

the glaciation time-scale (τ_g) computed by numerically solving Eq. 1. The initial values assumed in this calculation are: LWC of 0.1 g m^{-3}, plate ice crystal concentration (N_i) of 1 l^{-1}, cloud top T of -15C, and $\theta_0 = 40^0$. These values were chosen so as to mimic those typical of Arctic mixed-phase clouds. Without radiative influences our numerical solution produces results that are very similar to those shown by Korolev and Isaac (2003). Glaciation times tend to range from ~ 100 to 180 min with the shortest times occurring around -15C, which is expected. For nocturnal clouds, when LW cooling alone is active, note that τ_g is reduced drastically since LW cooling strongly enhances net depositional growth. Furthermore, the minimum in τ_g is displaced towards higher T. This is to be expected since LW cooling decreases the temperature of the ice crystal below that incurred through steady-state growth. As one moves deeper into the cloud, the LW cooling influence is reduced but is still significant even 100 m below cloud top (Fig. 6). Solar heating, of course, offsets these effects. Note that when SW heating is included at cloud top τ_g is increased by a large amount. In fact, the curve is almost the same as that 100m below cloud base when only LW cooling is included. Even though SW heating is included, τ_g is still reduced by 20 to 40 min by radiation.

As a consequence of these results, one might expect that ice at cloud top would rapidly deplete the cloud top region of liquid. However, one must keep in mind that sedimentation is not included in a simple box model like this. So, as crystals quickly grow large due to LW enhanced growth, they will settle out of the cloud top region. These influences will be explored further in more detailed studies.

4.2 Mid-Cloud

In the middle and lower regions of the cloud, SW heating dominates the radiative processes. Since ice crystals in this region are heated, we expect ice crystal growth rates to be largely suppressed. However, the numerical computation of τ_g has no limitations on ice crystal size and so ice crystals can become unrealistically large. This typically is not a problem for the computations like those presented in Korolev and Isaac (2003) because the ice growth equation is only used as a first order estimate of the rate at which liquid is depleted through ice crystal growth. (If anything, τ_g will be too short since larger crystals have much larger mass growth rates.) Alas, in our case, as crystals become large SW heating increases rapidly. Ice crystals will eventually reach sizes where the SW heating will be comparable to s_{ui} and growth of the crystal will stop and the glaciation process will come to a halt. This result may be realistic for a very small portion of the ice crystal population that are fortunate enough to attain very large sizes (~ 0.5 to 1cm or so). However, most crystals in the cloud have smaller sizes and, therefore, positive growth rates. Hence, the result that glaciation will never occur when τ_g is computed with a straightforward integration of Eq. 1 is not realistic.

In order to provide some estimate of how strongly SW heating at mid-cloud levels will alter τ_g we fix the ice crystal depositional growth rate at that for a particular size. We then compute how quickly the liquid water is depleted. Since the crystal size is fixed, our calculation provides a lower estimate of τ_g. Figure 7 shows τ_g computed for the same cloud water contents used to produce Fig. 6. Without the influences of

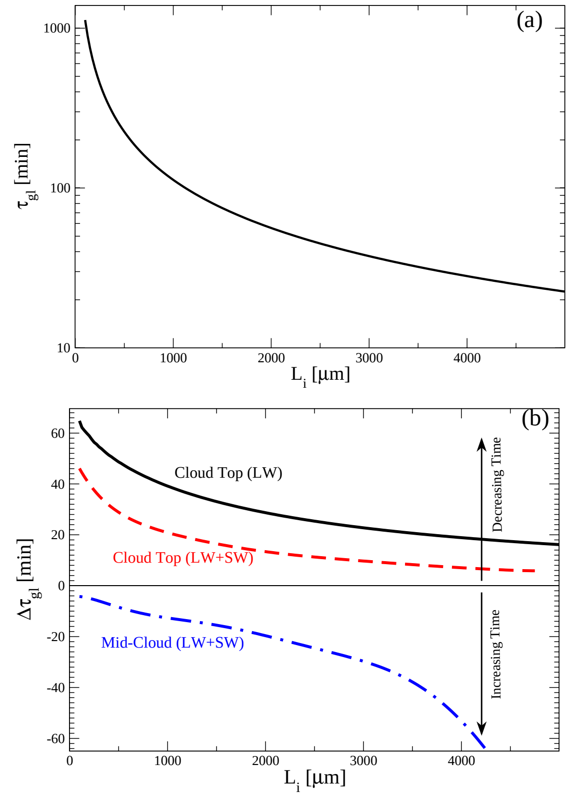

Figure 7. (a) τ_g plotted as a function of crystal size (Li) for LWC = 0.1 g m^{-3}, N_i = 1 l^{-1}, and T = -15C, without radiation. (b) Differences in τ_g between radiation and no-radiation cases are plotted for LW only and LW+SW with $\theta_0 = 40^0$. Positive differences indicate reduced (faster) glaciation times whereas negative differences indicate increased (slower) glaciation times.

radiation (Fig. 7a) τ_g decreases as L_i increases since the number of ice crystals is fixed. This result is not surprising since growth rates increase rapidly with size. Hence, clouds with a low number of small crystals glaciate relatively slowly whereas clouds with a low number of large crystals should glaciate relatively quickly.

When radiation is included (Fig. 7b), changes to τ_g occur. Since our previous discussions covered the cloud top region, we have included these calculations as a useful reference. Note that at cloud top, changes in τ_g are the greatest for small crystals. However, τ_g is already quite long for such situations and, therefore, it would appear that radiatively altered growth has little influence. For larger crystal sizes (L_i > 500 µm), the reduction in τ_g at cloud top can be comparable to the glaciation time-scale without radiation. This implies that radiative alterations to τ_g are likely to be most important for large crystals. Most measurements, however, (e.g. Pinto, 1998; Hobbs and Rangno, 1998) suggest that cloud top contains relatively small crystals. Thus, it may be the case that radiative influences at cloud top have little effect on cloud top glaciation. However, this does not preclude important radiative influences on the evolution of the ice size spectrum at cloud top. Such a calculation is beyond the scope of this study.

At mid-cloud levels (850 m), note that SW heating causes increases in τ_g (Fig. 7b). When ice crystals are small, little SW heating of the crystals occurs and, hence, there is only a slight suppression of depositional growth. However, as crystals become larger (L_i > 500 μm) the increase in τ_g reaches 20 to 60 min. At these sizes, τ_g without radiation is typically between 30 and 100 min. Consequently, we expect that the radiative suppression of the growth of larger crystals may be important for the glaciation of the lower regions of mixed-phase Arctic clouds.. Though we present results for only a single solar zenith angle, our calculations show suppression occurs for θ_0 down to 75^0. Hence, this increase in τ_g may be important for mixed-phase clouds that occur during part of the Arctic transition seasons and during the warm (summer) season.

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