Radiative Impacts on the Growth of Drops within Simulated Marine Stratocumulus. 
Part II: Solar Zenith Angle Variations

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ABSTRACT

The effects of solar heating at a variety of solar zenith angles (\( \Theta_0 \)) on the vapor depositional growth of cloud drops, and hence the potential for collection enhancement, is investigated. A large eddy simulation (LES) model is used to predict the evolution of marine stratocumulus clouds subject to changes in \( \Theta_0 \). During the course of each simulation, LES output is stored for 600 parcel trajectories and is used to drive an offline microphysical model that includes the influence of radiation on drop growth.

Smaller \( \Theta_0 \), such as when the sun is overhead, provide strong solar heating, which tends to confine circulations to the cloud layer and leads to long in-cloud residence times for cloud drops. At larger \( \Theta_0 \), when solar heating is weak, circulations are stronger and penetrate through the depth of the boundary layer, which causes much shorter in-cloud residence times for cloud drops. Simulations show that this leads to a more rapid collection process in strongly, as compared to weakly solar-heated clouds provided that the liquid water contents of each cloud are similar. When drop vapor growth includes radiative effects, three main results emerge: 1) Solar heating at smaller \( \Theta_0 \) (0° to 45°) dominates over longwave cooling effects causing a suppression of collection for lower drop concentrations (100 to 200 cm\(^{-3}\)). 2) At larger drop concentrations (>300 cm\(^{-3}\)) longwave cooling dominates over solar heating and collection is enhanced. 3) At large \( \Theta_0 \) (60° to 90°), solar heating is ineffective at modifying the drop size spectrum thus allowing longwave cooling to significantly enhance collection at all drop concentrations above approximately 100 cm\(^{-3}\).

1. Introduction

Radiative influences on the growth of cloud hydrometeors is an old, but relatively sparse, area of study. It is well known that radiative heating and cooling alters the thermal state of a water drop leading to changes in vapor depositional growth rates (see Pruppacher and Klett 1997). Many previous studies have been done that examine the influences of radiation on the growth of drops. Most of the early studies (e.g., Roach 1976; Barkstrom 1978; Guzzi and Rizzi 1980), and some later studies (e.g., Austin et al. 1995a) examined the influences of infrared [longwave (LW)] radiative cooling on drops isolated at cloud top. These studies showed that larger cloud drops (\( r \gtrsim 10 \mu m \)) have growth rates that are enhanced by radiative cooling. This tends to increase the breadth of the drop size spectrum, which can then enhance collection (Austin et al. 1995a). Other studies included the effects of radiation on vapor depositional growth within dynamic cloud modeling frameworks (e.g., Bott et al. 1990; Ackerman et al. 1995). These studies generally showed significant changes to cloud structure because of the radiative term. [See Hartman and Harrington (2005), hereafter Part I, for a full discussion of prior studies.]

In an attempt to bridge the gap between microphysical–dynamic models (like Bott et al. 1990; Ackerman et al. 1995) and the isolated-drop models (like Guzzi and Rizzi 1980; Austin et al. 1995a), Harrington et al. (2000) studied the impact of the radiative term on collection initiation using a trajectory ensemble model (TEM). The TEM is essentially a parcel model with binned microphysics, however the TEM is driven by parcel data derived from cloud model simulations. Harrington et al. (2000) analyses showed that drizzle enhancement may occur and that collection onset may be reduced by about one-half of an hour for typical drop concentra-
tions (≤200 cm$^{-3}$). Additionally, their results showed that radiation most strongly affected parcels that spend significant amounts of time at cloud top. Since these are the parcels that usually initiate collection anyway, Harrington et al. (2000) concluded that though radiation likely modulates drizzle production, it is perhaps not an initiating mechanism.

Because of the strong influence solar (shortwave, SW) heating has on stratiform clouds (e.g., Turton and Nicholls 1987; Loeb et al. 1998), one may think that these previous studies would have included the effects of solar [or shortwave (SW)] radiation. However, that is not generally the case. While Davies (1985) and Ackerman et al. (1995) included SW effects in their studies of drop growth, no previous studies included this important component of the radiative budget. [Harrington et al. (2000) included SW heating however the effect was almost negligible because the study was conducted for arctic clouds where $\Theta_o$ is quite large.] Because of this, Part I took the earlier work of Harrington et al. (2000) further by including maximum solar heating, or a solar zenith angle $\Theta_o = 0^\circ$ (overhead sun). Previous studies have shown (e.g., Bougeault 1985; Turton and Nicholls 1987; Duynkerke and Hignett 1993) that strong solar heating can stabilize stratiform cloud layers with respect to the subcloud layer. In Part I, we showed that this leads to parcel trajectories that are confined to the stratiform deck. The consequences being that in-cloud and cloud-top time scales for parcel trajectories are significantly lengthened and this has a positive influence on drop growth, and collection initiation. Unlike LW cooling, which is confined to a small region at cloud top, SW heating exists throughout much of the cloud deck. This leads to narrowing of the drop size spectrum throughout the cloud since large drop growth is strongly suppressed by SW heating. Furthermore, Part I showed that the largest drops ($r \approx 200$ µm) experience a net heating even at cloud top, leading to their evaporation. Finally, Part I used a larger range of drop concentrations (up to 400 cm$^{-3}$) than Harrington et al. (2000). These results showed that at larger drop concentrations, radiative cooling may significantly enhance the collection process even when SW heating is included. Such results are relevant given the potential importance of the drizzle process to stratocumulus cloud evolution, cloud patterns, radiative processes, and climate (e.g., Albrecht 1989; Ackerman et al. 1993; Austin et al. 1995b; Kogan et al. 1995; Feingold et al. 1997; Stevens et al. 1998, 2005; vanZanten et al. 2005).

Since Part I included only the effects of maximum SW heating (overhead sun), herein we examine the important influence of varying the solar zenith angle ($\Theta_o$), which controls the degree of SW heating, on drop growth. In particular, Part I noted that in-cloud time scales are drastically altered by solar heating. Since cloud time scales are quite important for the initiation of collection (e.g., Feingold et al. 1996; Part I), our main goal is to examine how $\Theta_o$ alters these cloud time scales and how this influences collection. To capture the entire drizzle process, simulations with a cloud model including explicit microphysics would be necessary. Because of this, and since parcel models like the one used here can, at best, capture the early evolution of the drop size spectrum (e.g., Harrington et al. 2000; Part I), we limit our analysis to the initial development of collection, or collection initiation.

2. Numerical models

The influences of solar radiation on drop growth are examined using a trajectory ensemble model that includes bin microphysics, which is forced by parcel data generated from the large eddy simulation (LES) option (Stevens et al. 1999) of the Regional Atmospheric Modeling System (RAMS; Pielke et al. 1992; Cotton et al. 2003). The LES, trajectory datasets, and the TEM are described in Part I and in the references given therein. As in Part I, the input data for the TEM is generated during an LES simulation in which 600 point parcels are placed randomly below cloud base. These parcels are advected in a Lagrangian fashion throughout the cloud for 2 h and the output is then used as input to the TEM (see Part I for a full description.) An example of these trajectories for two LES simulations is provided by Fig. 1. The disadvantages of this approach are discussed in detail in Part I and in Harrington et al. (2000). However it is perhaps important to state that the main disadvantage is that drops cannot sediment and that microphysical changes do not feedback to the dynamics (though this is also an advantage.) The main advantage of this approach over traditional parcel models is that the modeled drops experience cloud time scales and dynamic influences that are in accord with three-dimensional (3D) LES simulations. For example, Fig. 1 shows not only a great deal of variability of the in-cloud time scales for each parcel, but also that solar zenith angle ($\Theta_o$) strongly influences these trajectories and time scales.

3. Cases and parcel input

a. Case description

The case used for this study, and the setup of the LES model is the same as that used in Part I. Part I showed that the addition of maximum SW heating (overhead
sun, or $\Theta_0 = 0^\circ$) stabilizes cloud base to such an extent
that the Lagrangian parcels never dip far below cloud base (Fig. 1a), whereas at large $\Theta_0$ (90°, or nocturnal) the parcels travel far below cloud base (Fig. 1b). Obviously, parcel trajectories and cloud time scales, which indirectly affect drop growth, depend greatly on the amount of SW heating, or $\Theta_0$. To examine this dependence, we conducted four more LES simulations at a variety of solar zenith angles ($\Theta_0 = 30^\circ$, 45°, 60°, and 90°, or nocturnal). In each simulation, the solar zenith angle was fixed at one value of $\Theta_0$ so that any alterations in cloud dynamics due to a time-varying $\Theta_0$ are removed. Although this simplification is artificial, it leads to steady cloud dynamics and allows us to more easily separate effects than if $\Theta_0$ were allowed to vary over the 2-h simulation period. For instance, Fig. 2 shows time series of the cloud-top liquid water content (LWC) maximum and the maximum of the resolved vertical component ($w'w_{\text{max}}$) of the turbulent kinetic energy (TKE, a measure of circulation strength) over the last hour for three of the LES simulations. (The $\Theta_0 = 30^\circ$ and 60° cases show similarly steady fields and, for simplicity, are not shown.) The quasi-steady state of the $LWC_{\text{max}}$ and $w'w_{\text{max}}$ fields for each simulation is advantageous since we ultimately wish to intercompare the results of our parcel model run for each of the five $\Theta_0$ LES datasets. If these fields varied strongly with time, our intercomparisons would be much more difficult.

b. Influences of $\Theta_0$ on cloud time scales

The growth of cloud drops, and whether or not collection occurs, is dependent on cloud time scales (Feingold et al. 1996; Harrington et al. 2000; Part I). However, these time scales are intimately connected to the cloud dynamics (Feingold et al. 1996). As Fig. 2 indicates, decreasing $\Theta_0$ (increasing SW heating) causes subsequent reductions in cloud-top LWC and cloud circulations ($w'w_{\text{max}}$), results, which are in accord with previous studies (e.g., Bougeault 1985; Turton and Nicholls 1987; Duynkerke and Hignett 1993). Reductions in LWC are due to the fact that the increased SW heating through decreases in $\Theta_0$ (Fig. 3c) cause increases in the equilibrium vapor pressure, which lowers LWC amounts. The reduction in $w'w_{\text{max}}$ for decreasing $\Theta_0$ is due to the fact that SW heating reduces cloud-top
As one might imagine, such changes in circulation structure will strongly alter the amount of time a given parcel spends within the cloud layer, which is importantly related to drop growth and collection initiation (Feingold et al. 1996). For instance, compare the overhead sun (\(\Theta_o = 0^\circ\)) and nocturnal (\(\Theta_o = 90^\circ\)) parcel traces shown in Fig. 1. It is quite evident that parcels in the \(\Theta_o = 0^\circ\) case spend much more time within cloud. This is important for the reasons discussed in Feingold et al. (1996) and in Part I: 1) Longer time periods within updrafts, and within the cloud overall, extends the amount of time drops have to grow to sizes that may initiate collection. 2) Longer time periods at cloud top, where LWC is a maximum, significantly shortens the time for collection onset through classical, and radiatively enhanced, growth. Given these two points, it is advantageous to introduce time scales that will be useful in our later analyses. The cloud-top residence time, \(\tau_{cldtop}\), is the average amount of time a parcel spends in the region of high LWC. We calculate \(\tau_{cldtop}\) by looking for the region (about 75 m deep) where cloud-top LW cooling occurs since this is collocated with high LWC. This time scale, therefore, is also advantageous in determining the importance of cloud-top LW cooling on drop growth. The in-cloud residence time, \(\tau_{incld}\), is the average amount of time a parcel spends within the cloud layer during the 2-h simulation. The cloud-top transit time, \(\tau_{trans}\), is the average amount of time it takes a parcel to rise from cloud base to cloud top. This last time scale is important because updraft rise rate plays a role in determining the initiation of collection, as we shall see.

All three of these time scales are strongly linked to \(\Theta_o\) impacts on cloud dynamics, and this is evident in Fig. 4a. The time scales are averages for all 600 parcels from each of the \(\Theta_o\) LES simulations. At small \(\Theta_o\), when SW heating is strong, parcels spend an average of over 60 min inside the cloud layer, which is because of the stabilization of the cloud layer with respect to the subcloud layer. At large \(\Theta_o\), when SW heating is weak to nonexistent, circulations are strong and parcels dip below cloud base, which reduces the average \(\tau_{incld}\) to around 30 min. The stronger dynamics of the large \(\Theta_o\) cases necessarily means that the transit time to cloud top (\(\tau_{trans}\)) will be reduced. Indeed, for large \(\Theta_o\), it takes, on average, around 8 min for a parcel to reach cloud top. For strong SW heating cases (small \(\Theta_o\)) it takes an average of 25 min before a parcel reaches cloud top. Cloud-top residence times are also strongly linked to the cloud dynamics. At small \(\Theta_o\) when SW heating is strong, parcels spend a long time in the vicinity of cloud top with \(\tau_{cldtop} > 20\) min. Furthermore, a larger percentage of all 600 parcels, up to 80%, actually make it to the cloud-top region (Fig. 4b) when the SW heating is strong. For weaker SW heating (large \(\Theta_o\)), \(\tau_{cldtop}\) drops to around 12 min and the percent of parcels that make it to cloud top decreases to less than 60%. Note that the decrease in all time scales, and in the percent of parcels that make it to cloud top, is very rapid between \(\Theta_o = 30^\circ\) and 60°, a result that is consistent with the fact that solar heating drops rapidly between these two \(\Theta_o\).

The main conclusion to be drawn here is that many more drops are exposed to the LWC-rich cloud-top re-
gion for longer periods of time when solar heating is strong than when it is weak. This radiation–dynamic link has microphysical repercussions that will be discussed shortly.

4. Average parcel results

Given the discussion of the preceding section, it is apparent that if we wish to successfully separate the dynamic/radiative influences on collection initiation for the various LES simulations that we must consider the following: 1) that LWC varies between the LES simulations. Smaller $\Theta_o$ simulations have lower LWC, which necessarily means weaker collection rates (Pruppacher and Klett 1997); and 2) that smaller $\Theta_o$ simulations have longer in-cloud time scales, which may mean stronger collection rates. It is important to note that 1) and 2) act in an opposing sense. Clouds with stronger dynamics have larger $\Theta_o$ and larger LWC, but also shorter in-cloud time scales.

To separate these effects, we begin by examining the behavior of average parcels for each of the LES simulations and then proceed to ensemble simulations that include all 600 parcels. For each of the five LES simulations ($\Theta_o = 0^\circ, 30^\circ, 45^\circ, 60^\circ$, and $90^\circ$) we derived a single, average parcel with behavior that is representative of that cloud system. This is done by computing an average updraft path, cloud-top path, and downdraft path using all 600 parcels for each simulation. The thermodynamic, dynamic, and radiative information are averaged to produce the single, average path. We can then use the bin microphysical model described in section 2, and in more detail in Part I, for each average parcel. Starting with a single, average parcel for each LES simulation has certain advantages, such as separating cloud dynamic effects from LWC increases. Separating these effects for all 600 parcels of each $\Theta_o$ simulation is a difficult task that is made easier by using average parcels.

Figure 5 shows the average parcel trajectory for each of the $\Theta_o$ simulations. Because smaller $\Theta_o$ leads to weaker cloud dynamics (Fig. 2) the rise time of a parcel from cloud base to cloud top is lengthened. Note that the average parcel updraft trajectory changes rapidly between $\Theta_o = 30^\circ$ and $60^\circ$, which is consistent with the time scales shown in Fig. 4. This is also true for the cloud-top LWC maximum values, given on Fig. 5, which are larger because of the larger LW cooling and because the average cloud depth increases between $\Theta_o = 45^\circ$ and $60^\circ$. The main reason for the greater cloud depth is the stronger, deeper circulations and weaker SW heating (Fig. 3).

The rise time of a parcel ($\tau_{\text{trans}}$) from cloud base to top is important for drop growth as Fig. 6a illustrates. Plotted on this figure is $\sigma_{\text{cdtop}}$, which is the standard deviation of the drop number concentration spectrum when the average parcel reaches cloud top. The value

Fig. 4. (a) In-cloud, cloud-top, and cloud-top-transit time scales plotted as a function of solar zenith angle ($\Theta_o$). (b) Percent of all (600) trajectories that make it to cloud top at least once during the 2-h simulation as a function of $\Theta_o$.

Fig. 5. Height as a function of time for the five average parcels. Included are the cloud-top LWC maximum values for each of the $\Theta_o$ LES simulations.
of $\sigma_{cldtop}$ is plotted for a variety of drop number concentrations ($N_d'$; see Part I, section 5d, for how we control this parameter), which ranges from 50 to 400 cm$^{-3}$. The upper value of $N_d'$ was chosen as 400 cm$^{-3}$ because larger concentrations do not initiate collection during the 2-h period for many of the ensemble simulations we conducted (see section 5). Examining any of the $\Theta_o$ simulations shows what we should have anticipated. As $N_d'$ rises, $\sigma_{cldtop}$ decreases meaning that the drop size spectrum is narrower when cloud top is reached. Additionally, one might expect that shorter $\tau_{\text{trans}}$, such as those for larger $\Theta_o$, would lead to narrower drop spectra, but this is not the case. Instead, $\sigma_{cldtop}$ varies weakly with $\Theta_o$, showing only a small increase in $\sigma_{cldtop}$ as $\Theta_o$ increases. The reason for this variation has to do with the fact that larger $\Theta_o$ have larger LWCs, which compensates for the shorter cloud-base-to-top transit time. To show the LWC compensation, we artificially reduce the LWC in each $\Theta_o$ simulation so that they all match the $\Theta_o = 0^\circ$ case. This is done by reducing the total parcel mixing ratio until the cloud-top LWCs match. From this point forward we call these reduced LWC simulations whereas the nonreduced cases will be referred to as standard LWC simulations. When the LWCs are equal, the large $\Theta_o$ cases have much smaller $\sigma_{cldtop}$ (Fig. 6b) and therefore narrower drop spectra. Note the large decrease in $\sigma_{cldtop}$ between $\Theta_o = 45^\circ$ and $60^\circ$, which is due to the large LWC reduction and much shorter $\tau_{\text{trans}}$. Hence, we should anticipate that cases with stronger dynamics (weaker SW heating) but similar LWCs will have narrower size spectra when the drops reach cloud top.

Lastly, we have plotted on Fig. 6 the standard deviation at which collection typically initiates ($\sigma = 1.27 \mu m$). This number was arrived at using the definition of collection initiation given in Feingold and Chuang (2002), which we used in Part I and employ throughout the remainder of this paper. That is, collection initiation appears to occur in explicit microphysics models when the concentration of 20 $\mu m$ drops (this size is called $r_{\text{max}}$) reaches a value of $10^{-3}$ cm$^{-3}$. Our analysis (Part I) indicates that this is a good measure of collection onset for our model and, furthermore, that $\sigma$ is typically around 1.27 $\mu m$ when this occurs. As Fig. 6 illustrates, collection initiates before cloud top has been reached only at $N_d' \approx 100$ cm$^{-3}$. All other $N_d'$ require that the parcel spend at least some time at cloud top before collection can begin.

The dependence of collection initiation on the cloud-top residence time of our average parcels is shown in Fig. 7. In this figure, $\tau_{\text{topcol}}$ is the amount of time the parcel spends at cloud top before collection is initiated. In general, as $N_d'$ increases more time in the vicinity of high LWC is required before collection begins. At the highest $N_d'$, greater than 60 min at cloud top may be required, and such long $\tau_{\text{topcol}}$ occur in the smaller $\Theta_o$ simulations (Fig. 4a). At larger $\Theta_o$, shorter $\tau_{\text{topcol}}$ are required before collection starts (Fig. 7a). This is because the breadth of the drop size distribution is not significantly different between the various $\Theta_o$ simulations when the parcel reaches cloud top (Fig. 6a). Therefore, when cloud top is reached, less time is required for collection initiation because LWCs are higher in the larger $\Theta_o$ cases. The situation changes when the clouds have the same LWC (Fig. 7b). Although difficult to see, $\tau_{\text{topcol}}$ does not change drastically as $\Theta_o$ increases from $0^\circ$ to $45^\circ$. The reason is that in each of these cases, the $\sigma$ of the size distribution is quite similar when cloud top is reached (Fig. 6b). How-

![Fig. 6. Std dev of drop number spectra as a function of total drop concentration ($N_d$) for each $\Theta_o$ case. (a) Standard LWC and (b) LWC reduced to $\Theta_o = 0^\circ$ case.](image-url)
ever, for the \( N_o = 60^\circ \) and \( 90^\circ \) cases, cloud top is reached much more quickly and the size distribution is narrower than the smaller \( N_o \) cases, and therefore longer time at cloud top is required. Since larger \( N_o \) cases have short \( \tau_{\text{cloud}} \), we expect that similar LWC clouds will show a significant reduction in collection onset.

These analyses provide us with an important framework that we can use to understand the results for the ensemble of parcels (e.g., all 600) for each \( \Theta_o \) case. However, one must keep in mind that the above results are for an average parcel trajectory through each of the \( \Theta_o \) cloud cases. And though the above-described behavior roughly mimics the overall cloud behavior, it misses one very important feature. That is, each of 600 parcels in a given \( \Theta_o \) case takes a different trajectory through the cloud. As Fig. 1 indicates, some parcels follow the simplified, average parcel behavior of entering an updraft and then following cloud top for some period of time. Many other parcels, however, oscillate in smaller updrafts and downdrafts inside the cloud, and some for significant lengths of time. This should be borne in mind as we proceed with our analysis.

5. Ensemble parcel results

A single, average parcel trajectory can in no way encompass the behavior of the parcel ensemble and, consequently, it is not entirely representative of the average behavior of the cloud. However, the average parcel results are useful as a guide in the interpretation of the microphysical model output for our ensemble simulations. These simulations, as in Harrington et al. (2000) and Part I, use the binned microphysical model with radiative influenced growth for every one of the 600 parcels for each \( \Theta_o \) case. The simulations provide a wealth of data and because of this we present mainly averaged results. We begin by discussing the influence of SW heating on drop growth through modifications to cloud dynamics (i.e., cloud time scales) and LWCs. This is followed by an analysis regarding how SW and LW radiative effects modify collection initiation through vapor diffusion.

a. No radiative influence on drop growth

Since we are primarily interested in how SW heating affects collection initiation, and since each \( \Theta_o \) case is comprised of 600 parcels, we need some aggregate method to describe the initiation of collection. Following Feingold and Chuang (2002) and Part I, we use \( r_{\text{max}} \) and define a time scale for collection initiation (\( \tau_{\text{max}} \)). This \( \tau_{\text{max}} \) is the amount of time required before \( r_{\text{max}} = 20 \mu m \), or in other words, when collection is effectively initiated in each parcel. To compare the overall, cloud average results for each \( \Theta_o \) simulation, we compute the average of \( \tau_{\text{max}} \) over all parcels that initiate collection. We exclude parcels that do not initiate collection since we have no way to appropriately include these parcels in our average. The consequences of this type of selective averaging are fairly obvious: If a long time is required for collection initiation, as is the case for large \( N_o \), then only a few parcels out of the full 600 may initiate collection. Therefore, \( \tau_{\text{max}} \) alone is an insufficient measure of collection initiation for the entire cloud. Because of this, we compute the percent of all parcels out of 600 that initiate collection \( \left(P_{\text{col}}\right)\) during the 2-h simulation (see Part I). This provides a better overall measure of collection initiation for the entire cloud during the simulation. Together, these two vari-
variables are typically sufficient to characterize collection initiation for the ensemble of parcels for each $\Theta_\alpha$ simulation.

To provide a common basis of comparison for all of the $\Theta_\alpha$ simulations, we first start by examining the two extreme cases, that is $\Theta_\alpha = 0^\circ$ (maximum SW heating) and $\Theta_\alpha = 90^\circ$ (no SW heating, or nocturnal). These cases provide the largest difference in cloud dynamics and LWCs, and are therefore an appropriate place to begin our analysis (Fig. 8). Similar to our average parcel results, and Part I, as $N_d$ is increased from 50 to 400 cm$^{-3}$ the time for collection onset ($\tau_{\text{max}}$) increases while the percent of all parcels that initiate collection ($P_{\text{col}}$) decreases. Generally, $\tau_{\text{max}}$ increases from around 20 min to almost 120 min while $P_{\text{col}}$ drops from nearly 100% to almost 0% as $N_d$ is increased. The time for collection initiation is always longer for the $\Theta_\alpha = 0^\circ$ case, which according to our average parcel analysis, is due primarily to the fact that the LWCs are larger in the $\Theta_\alpha = 90^\circ$ case. Even though $\tau_{\text{max}}$ is shorter for $\Theta_\alpha = 90^\circ$ (collection initiates faster) fewer parcels initiate collection during the 2-h simulation for intermediate values of $N_d$. This is due to two factors, the first being that cloud-top residence time is much longer for the $\Theta_\alpha = 0^\circ$ simulation and the second being that more parcels actually reach cloud top in the $\Theta_\alpha = 0^\circ$ than in $\Theta_\alpha = 90^\circ$ simulation (Figs. 4a and 4b). Since, as Fig. 7 shows, more time at cloud top is required for collection initiation at larger $N_d$, fewer parcels have the requisite $t_{\text{cloud}}$ as $N_d$ increases in the $\Theta_\alpha = 90^\circ$ simulation. That this is the case can be seen in Fig. 9, which provides a histogram of $\tau_{\text{max}}$ for $N_d = 200$ cm$^{-3}$. Note that even though it takes longer to initiate collection in the $\Theta_\alpha = 0^\circ$ case, many more parcels participate. Most of the parcels in the $\Theta_\alpha = 0^\circ$ case require approximately 60 min before collection occurs. Because the strong SW heating confines parcels to the cloud layer, many parcels have the requisite, long in-cloud residence times (see Fig. 4a and Part I). Conversely, the $\Theta_\alpha = 90^\circ$ simulation has parcels with much shorter in-cloud residence times. So, it is not surprising that most of the parcels that initiate collection have $\tau_{\text{max}} \leq 40$ min. Few parcels initiate collection at $\tau_{\text{max}} \geq 40$ min since they do not possess the requisite cloud-top residence time. This means that the stronger dynamics of the $\Theta_\alpha = 90^\circ$ simulations lead to fewer parcels reaching cloud top and these have shorter cloud-top residence times. So, even though $\tau_{\text{max}}$ is shorter, fewer parcels initiate collection than in the strongly SW-heated case.

As one might imagine, there is little difference in $P_{\text{col}}$ for the $\Theta_\alpha = 0^\circ$ and $90^\circ$ simulations when $N_d \leq 100$ cm$^{-3}$ and when $N_d \geq 300$ cm$^{-3}$. At the lower $N_d$ values, collection is typically initiated rapidly and frequently before parcels reach cloud top (see section 4), hence almost all parcels initiate collection and drizzle is easily formed. At the larger values of $N_d$, very long cloud-top residence times are necessary before collection is initiated (nearly 2 h). Few parcels in any from the $\Theta_\alpha$ simulations have such long $t_{\text{cloud}}$.

In order that we may isolate the influences of differing cloud time scales that are due to the drastically different cloud dynamics of the $\Theta_\alpha = 90^\circ$ and $\Theta_\alpha = 0^\circ$ cases, the LWC in the $\Theta_\alpha = 90^\circ$ case was reduced so that it matches that of $\Theta_\alpha = 0^\circ$. (Compare the results shown in Fig. 8 to Fig. 10.) When the LWC is the same, $\tau_{\text{max}}$ is quite similar between the $\Theta_\alpha = 0^\circ$ and $\Theta_\alpha = 90^\circ$ cases. This, again, follows from our average parcel results (Fig. 7). There are some notable differences in $\tau_{\text{max}}$ between $N_d = 200$ and 300 cm$^{-3}$; however these are primarily due to trajectories that do not follow the simple average parcel model of the previous section. In fact, as Fig. 9 shows, the influence of reducing LWC in the $\Theta_\alpha = 0^\circ$ case is due primarily to a reduction in the number of parcels with $\tau_{\text{max}}$ between 20 and 40 min. That this is the case is hardly surprising. Most trajectories in the $\Theta_\alpha = 90^\circ$ case have shorter cloud-top residence times (Fig. 4) and so reducing the LWC from 0.71 to 0.55 g m$^{-3}$ effectively stops many of the short $t_{\text{cloud}}$ time-scale parcels from initiating collection. This is further corroborated by the fact that there are much larger differences between $P_{\text{col}}$ for the $\Theta_\alpha = 0^\circ$ and $\Theta_\alpha = 90^\circ$ cases when the LWCs are the same (Fig. 10b). Note that between $N_d = 100$ and 300 cm$^{-3}$ there can be as much as a 40% difference in $P_{\text{col}}$. So, when LWCs are the same, the fact that nocturnal clouds have stronger
and deeper boundary layer (BL) dynamics, and consequently shorter cloud time scales, may hamper the initiation of collection at moderate drop concentrations.

When the other \( \Theta_\alpha \) cases are included, a more complete picture of how SW heating alters collection emerges. Consider Fig. 11, which shows \( \tau_{\text{max}} \) and \( P_{\text{col}} \) for all of the cases. For most values of \( N_d \), there is a consistent decrease in \( \tau_{\text{max}} \) by as much as 20 min as \( \Theta_\alpha \) increases from 0° to 45°. Between \( \Theta_\alpha = 60° \) and 90°,

\( \tau_{\text{max}} \) does not change much. Even though LWC increases with \( \Theta_\alpha \), the transit time of parcels from cloud base to top decreases, which leads to similar \( \Theta_\alpha \) at cloud top (Fig. 6b) and therefore similar cloud-top residence times are required for collection initiation in the \( \Theta_\alpha = 60° \) and 90° cases. Consequently, it stands to reason that the time scale for collection initiation (\( \tau_{\text{max}} \)) should be similar for these two cases.

Unlike \( \tau_{\text{max}} \), the percentage of all parcels that initiate collection (\( P_{\text{col}} \)) is much more sensitive to changes in \( \Theta_\alpha \) (Fig. 11b). As with previous results, there is little influence of \( \Theta_\alpha \) on collection initiation at low and high \( N_d \). However, between \( N_d = 100 \) and 300 cm\(^{-3} \), \( P_{\text{col}} \) actually increases from \( \Theta_\alpha = 0° \) to 30°, remains constant at 45°, and then experiences a rapid drop to \( \Theta_\alpha = 60° \) and 90°. The primary reason that more parcels initiate collection in the \( \Theta_\alpha = 30° \) and 45° cases is the larger LWCs. In the \( \Theta_\alpha = 30° \) case, LWCs are slightly larger than the \( \Theta_\alpha = 0° \) case, while the cloud time scales are similar (Fig. 4). The combination of these factors leads to a larger percentage of parcels initiating collection. At \( \Theta_\alpha = 45° \), the parcel cloud-top residence time is significantly shorter than \( \Theta_\alpha = 0° \) (Fig. 4a), which should lead to a smaller number of parcels initiating collection. However, LWCs are significantly larger and this leads to a greater number of parcels initiating collection in \( \Theta_\alpha = 45° \) than in the \( \Theta_\alpha = 0° \) case.

That higher LWCs is the primary controller of this behavior is immediately apparent if cases with reduced LWC are examined (Fig. 12). Not only are the values of \( \tau_{\text{max}} \) now within about 5 min of each other for almost all \( \Theta_\alpha \) cases, but \( P_{\text{col}} \) now decreases as \( \Theta_\alpha \) increases.
This illustrates how changing cloud dynamics through altered SW heating affects collection initiation for clouds with similar LWCs. As \( \Theta_o \) increases from 0° to 45°, a decrease of around 5% in \( P_{\text{col}} \) occurs. This is due almost entirely to the two factors discussed in the average parcel section: Shorter cloud-base-to-top transit times lead to narrower size spectra and, therefore, larger cloud-top residence times are required before collection can begin. But, as \( \Theta_o \) increases, \( \tau_{\text{cidrop}} \) decreases (Fig. 4a) and so fewer parcels can participate in the collection process. It is important to note that the biggest drop in \( P_{\text{col}} \), from values of about 53% to about 20% with \( N_d = 200 \text{ cm}^{-3} \), occurs between 45° and 90°, respectively. This large decrease is due to the fact that the \( \Theta_o = 60° \) and 90° cases not only have shorter cloud time scales but also suffer a further set back, namely that fewer parcels actually make it to the LWC-rich region of cloud top (Fig. 4b). Therefore, for similar LWC clouds, the combination of decreasing cloud-top residence times and the number of parcels reaching cloud top as \( \Theta_o \) increases leads to a significant reduction in collection initiation for large \( \Theta_o \) clouds.

b. Radiatively influenced drop growth

The previous section dealt exclusively with how SW heating alters collection initiation though dynamics-induced changes to cloud time scales. Our picture of radiatively influenced collection initiation would be incomplete if we did not include the effects of radiation on the vapor diffusion growth of the drops, which was the primary purpose of (Harrington et al. 2000; Part I).

As those previous works show, LW cooling and SW heating can significantly alter the collection rates. For example, consider Fig. 8, which shows how \( \tau_{\text{rmax}} \) and \( P_{\text{col}} \) change with \( N_d \) for the maximum SW heating (\( \Theta_o = 0° \)) and nocturnal (\( \Theta_o = 90° \)) cases (see section 5a). When LW cooling is allowed to influence vapor growth, the time for collection initiation (\( \tau_{\text{rmax}} \)) decreases markedly whereas the percent of parcels that initiate collection (\( P_{\text{col}} \)) increases. As one might imagine, LW cooling does not significantly alter the initiation of collection when \( N_d \) is small (\( \leq 100 \text{ cm}^{-3} \)) since the cloud is already prolific at starting the collection process. This is not the case for larger \( N_d \) as \( \tau_{\text{rmax}} \) is reduced by almost 40 min at \( N_d = 400 \text{ cm}^{-3} \), which causes collection initiation in parcels that previously could not initiate collection (Fig. 8b). In fact, at \( N_d = 400 \text{ cm}^{-3} \), 20% (10%) of all parcels in the \( \Theta_o = 0° \) (\( \Theta_o = 90° \)) case now initiate collection whereas without radiative influences on drop growth nearly none did. Moreover, a larger number of parcels initiate collection in both the \( \Theta_o = 0° \) and 90° cases when \( N_d \geq 200 \text{ cm}^{-3} \). Note that cloud time scales still strongly influence the results as \( P_{\text{col}} \) is typically 10% greater in the \( \Theta_o = 0° \) case because of the longer cloud time scales.

When both cases have similar LWCs, only small changes in \( \tau_{\text{rmax}} \) occur (cf. the LW results of Figs. 10 and 8) whereas significant changes are observed in \( P_{\text{col}} \). The general trend with \( N_d \) is the same as that of the standard LWC case, except that now the difference in \( P_{\text{col}} \) between the \( \Theta_o = 0° \) and 90° cases is typically 20%. Thus, we expect that LW cooling should have its strongest influences on collection initiation in clouds with \( N_d \geq 100 \text{ cm}^{-3} \) and that the influences should be strongest in clouds with long cloud-top residence times, or clouds with convection confined primarily to the cloud layer. That this is the case is shown in Fig. 13. The addition of LW radiation to cloud drop growth reduces the time for collection onset by a roughly similar amount in all \( \Theta_o \) cases, ranging from a 10- to 40-min reduction between \( N_d = 200 \) to 400 \text{ cm}^{-3} \). That the reduction in \( \tau_{\text{rmax}} \) is somewhat similar for all \( \Theta_o \) cases is due to the fact that LW cooling affects only parcels that spend time at cloud top and these parcels are affected similarly by LW cooling.

The influence of LW radiation on \( P_{\text{col}} \) however, is not similar between the \( \Theta_o \) cases. As stated above, \( \Theta_o = 0° \) shows the strongest influence of LW radiation on drop growth with fully 30% more of all 600 parcels initiating collection (\( \Delta P_{\text{col}} \); Fig. 13b). The increase of \( \Delta P_{\text{col}} \) between \( N_d = 300 \) and 400 \text{ cm}^{-3} \) is due to the fact that collection initiation naturally decreases as drop concentrations rise. Hence, the LW influence has its strongest effects at intermediate concentrations. As \( \Theta_o \)}
rises, the LW effect on drop growth does not enhance $P_{\text{col}}$ as strongly. Note that at $\Theta_a = 90^\circ$ (nocturnal) the percentage of parcels initiating collection increases by only 10%. The main reason for this is that larger $N_d$ have shorter cloud-top residence times (Fig. 4a) and this means that less time is available for LW cooling to enhance drop growth and initiate collection at larger $N_d$. Results with LWCs reduced to the $\Theta_a = 0^\circ$ case are not shown as they are qualitatively similar to the results shown in Fig. 13.

Though LW radiation appears to most strongly enhance collection initiation in small $\Theta_a$ cases because of the long cloud-top residence times, we must keep in mind that these clouds are also those that are affected by SW heating. As Part I has shown, SW heating significantly suppresses drop vapor growth and collection initiation by heating the cloud interior and reducing the cloud-top LW cooling maximum. That these effects are significant for the various $\Theta_a$ cases can be seen in Fig. 14. Shortwave heating effectively reduces (negative $\Delta r_{\text{max}}$) the collection onset time by a few minutes for $N_d = 50$ to 150 cm$^{-3}$. These concentrations are typically those that rapidly initiate collection even in the absence of LW radiatively influenced drop growth because of their broader drop size spectra. When SW heating is included, as Part I has shown, drop heating throughout the cloud deck significantly narrows the drop size spectrum causing a suppression of collection. Furthermore, not only do the $\Theta_a = 0^\circ$ to 45° cases have stronger SW heating rates, but they also have longer in-cloud residence times and cloud-base-to-top transit times. As a consequence, parcels in these clouds spend more time within the region of strong SW heating (Part I) and this leads to a reduction in $P_{\text{col}}$ of up to 10% (Fig. 14b) between $N_d = 100$ and 200 cm$^{-3}$ for the $\Theta_a = 0^\circ$ to 45° cases.

Once drop concentrations exceed approximately 300 cm$^{-3}$, however, $P_{\text{col}}$ is enhanced for every simulation. At high drop concentrations, not only are drops smaller, which means that they are less strongly influenced by SW heating, but the drop size spectra are already quite narrow (Part I). Because of these two factors, SW heating produces less extra narrowing of the size spectrum. So, upon reaching cloud top, the SW radiatively influenced size spectra are not much more narrow than when radiatively influenced growth is ignored. Therefore, the cloud-top LW cooling maximum positively influences collection in all of these cases (Fig. 14b). Our results suggest that collection initiation is suppressed at lower $N_d$ (100 to 200 cm$^{-3}$) and enhanced at higher $N_d$ (≥300 cm$^{-3}$) in clouds that experience moderate to strong SW heating.

At larger $\Theta_a$ (60° and 90°) SW heating is weak or nonexistent. In these cases, cloud-top LW cooling has a strong, positive impact on collection initiation even at intermediate drop concentrations (100 to 250 cm$^{-3}$). For nocturnal cases (90°), LW influences on the vapor
growth of drops increases the number of parcels that initiate collection \[(P_{\text{crit}})\] by up to 15%. This influence maximizes around \[N_d = 200 \text{ cm}^{-3}\] and then drops slowly as \[N_d\] increases.

6. Summary and concluding remarks
This work focused on the influence of shortwave (SW) heating and longwave (LW) cooling on the initiation of collection in stratiform clouds. Part I of this paper showed that maximum SW heating affects drop growth through: 1) alterations to the cloud dynamics that affects cloud time scales important for drop growth, and 2) SW heating significantly slows drop growth, and is especially strong at large drop sizes, since that heating is distributed throughout the stratiform cloud layer. Because Part I focused on maximum \((\Theta_o = 0^\circ)\) SW heating, the current paper examined how altering \(\Theta_o\) influences the two effects enumerated above, and how this modifies the initiation of collection. We examined this issues using the same modeling construct from Part I. A large eddy simulation (LES) model was used to simulate boundary layer stratocumulus for five different solar zenith angles \((\Theta_o = 0^\circ\) or overhead sun, 30°, 45°, 60°, 90°, or nocturnal). When the cloud dynamics were relatively steady, 600 point parcels were released below cloud base and advected through the cloud layer with thermodynamic, dynamic, and radiative information written out to a file at every time step (2 s). These data were then used to drive a parcel model with explicit, bin resolving microphysics that include the influence of both LW and SW radiation on the vapor growth of water drops.

The main results of our study can be summarized as follows:

- Clouds with smaller \(\Theta_o\) (stronger SW heating) tend to have weaker circulations that are confined to the cloud layer whereas larger \(\Theta_o \approx 60^\circ\) have stronger circulations that penetrate throughout the BL. This necessarily leads to longer in-cloud, cloud-top, and cloud-base-to-top transit times in the smaller \(\Theta_o\) cases. These cloud time scales are important as they represent the amount of time that drops have to grow to sizes that may initiate the collection process.

When radiation is not allowed to influence drop vapor growth, our results showed the following:

- Since cloud-base-to-top transit times are longer for small \(\Theta_o\) these clouds tend to have size spectra that are broader when cloud top is reached if the LWC is similar for each cloud. This means that less time is required in the LWC-rich region of cloud top before collection is initiated at smaller \(\Theta_o\).

- When LWCs vary, larger \(\Theta_o\) cases have larger LWCs. Because of this, drop size spectra have similar breadths after the transit from cloud base to cloud top. This necessarily means that less total time is required in cloud before collection initiates at larger \(\Theta_o\).

- Though this is the case, larger \(\Theta_o\) simulations tend not only to have much shorter cloud-top residence times but they also have fewer parcels reaching cloud top. These two factors conspire to cause collection initiation in many fewer parcels as \(\Theta_o\) increases at intermediate drop concentrations (100–300 cm\(^{-3}\)).

When LW and SW radiation are allowed to influence the vapor growth of drops, the above results are modified in the following way:

- In all \(\Theta_o\) cases, clouds with high drop concentrations \((\geq 300 \text{ cm}^{-3})\) effectively did not initiate collection without radiative effects. With SW and LW radiative influences on drop growth as many as 20% of all parcels initiated collection even at the largest drop concentrations (400 cm\(^{-3}\)).

- Even with SW heating, the high drop concentration simulations \((\geq 300 \text{ cm}^{-3})\) with small \(\Theta_o\) had 10%–15% more parcels initiating collection than the large \(\Theta_o\) cases. As described above, this is due to the fact that the large \(\Theta_o\) cases have short cloud-top residence times and fewer parcels reaching cloud top.

- Also, SW heating effectively reduces the number of parcels initiating collection for intermediate drop concentrations (100–250 cm\(^{-3}\)) and for \(\Theta_o = 0^\circ\) and 30°. This is due to the fact that SW heating occurs throughout the cloud deck and significantly narrows the drop size spectrum before cloud top is reached (see Part I). Since the small \(\Theta_o\) simulations have long cloud-base-to-top parcel transit times, this means that SW heating has a significant amount of time to retard drop growth and narrow the drop size spectrum.

In general, these results suggest that stratiform clouds with circulations that are confined to the cloud layer may start the collection process in a larger fraction of the cloud layer than in clouds with deeper circulations, as long as the LWCs are similar. Stratiform clouds with deeper circulations that penetrate significantly below cloud base have shorter cloud time scales (especially cloud-top time scales), which reduces the time available for drops to grow to collection sizes. This result does not require SW heating as the cloud-base stabilization mechanism. For example, arctic stratus clouds can, and do, exist frequently in stable environments even during the arctic summer when the clouds are predominantly liquid (e.g., Curry et al. 1996). In
such cases, one may expect an enhancement of the drizzle process through cloud-scale circulation confinement.

Of course, the above results have a significant drawback in that changes to the microphysics, the initiation of collection, and the subsequent drizzle process, cannot feed back to the cloud-scale dynamics. Furthermore, changes in terminal fall speeds once drops become large will alter the in-cloud time scales for drizzle drops. Though beyond the scope of our current studies, in the future, we plan to use full LES simulations with bin-resolving microphysics including the radiative influences on drop growth (e.g., Harrington et al. 2000) to examine these issues.

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