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The Power of Water: Examining Ice Crystal Nucleation’s Impact on Cloud Thermodynamic Properties

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ABSTRACT

Cloud systems demonstrate great influence on Earth’s climate with both radiative and precipitation processes. However, detailed convection can be poorly represented in global climate models. By resolving fine-scale features, like cloud ice crystal nucleation, an improved understanding of the microphysics involved with deep convection will aid to more accurate incorporations of cloud systems into climate models. The purpose of this study is to analyze the differences in certain cloud thermodynamic properties, including mixing ratios and latent heat budgets, as a result of various ice nucleation cases. The Clark-Hall Cloud-Resolving Model (CRM) was initialized with observations from the 1997 Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) field campaign. Three model runs were completed, one for each of the following ice crystal nucleation types: primary, secondary, and artificial. The compositions of the cloud systems expressed interesting variations; artificial nucleation created the most Type A ice, small ice crystals that grow through deposition, while secondary nucleation had the most Type B ice, larger hydrometeors formed via collisions between Type A ice and water droplets. The artificial nucleation case experienced the greatest latent heating and cooling due to deposition and sublimation. Primary and secondary nucleation differed most greatly during latent heating phase changes at levels higher in the cloud system. In addition, the size of each cloud system, in part determined by its composition and latent heating characteristics, affected its radiative properties, thus creating precipitation differences between the three cases. These results provide greater insight into how various ice nucleation types ultimately modify atmospheric stability and precipitation trends in their environment. With this understanding, large-scale precipitation and radiative processes in future climate scenarios can be better addressed in climate modeling.
1. Introduction

Cloud systems play an essential role in the global climate system (Chou 1999). They produce various types of precipitation and distribute water resources around the planet. Not only do clouds transport water far from their source region, but they are also influential in regulating Earth’s temperature. Incoming shortwave radiation is reflected to space by clouds in the atmosphere, thus aiding to cool the planet. Yet, outgoing longwave radiation is absorbed and reemitted back to the surface by clouds, which produces a warming effect. It can be noted that cloud systems play a vital role in many atmospheric processes that govern the daily weather and long-term climate of the planet.

Despite their importance to the climate system, cloud systems have been difficult to incorporate accurately into climate models (Zhao 2014). One reason for this complication results from the various phases of water, including ice crystals, supercooled liquid droplets, and water vapor, that make up mid-latitude cloud systems. Specifically, the importance of ice crystal nucleation in the cloud system has traditionally been studied under very small timescales (Wu et al. 1999). Due to limited observational datasets of ice crystal concentrations within clouds, the influence of these small particles on the overall cloud system over longer time periods is still relatively unknown when compared to liquid droplets. By using cloud-resolving models, an increased understanding of the interaction between ice crystal nucleation and the thermodynamic structure of clouds can be deduced. The accuracy of global climate models would then benefit from a finer representation of convection.

2. Background

Cloud-resolving models (CRM’s) treat small-scale dynamic processes within cloud systems according to governing equations to create detailed analyses of convection. Their purpose is to reproduce observed cloud systems using datasets from intensive field campaigns. Multiple instrumentation methods, including radiosondes, surface observations, and aircraft, are used to collect data over short time intervals. Fine horizontal and vertical resolutions allow CRM’s the ability to simulate individual cloud features while general circulation models (GCM’s) often parameterize clouds with a very coarse spatial resolution (Grabowski et al. 1996). CRM’s are a powerful tool to utilize for an accurate understanding of microphysical processes in the atmosphere.

Koenig and Murray (1976) first began to incorporate specific ice categories into two-dimensional CRM’s. Type A ice (primary nucleation) represents very fine ice crystals which grow directly from water vapor depositing onto a microscopic ice nucleus (heterogeneous deposition) or from the instantaneous freezing of small, pure liquid droplets around -40°C. These ice crystals tend to initialize at a small size and grow rather slowly in size. In contrast, Type B ice (secondary nucleation) describes larger ice crystals that form through various versions of contact freezing at warmer temperatures within the cloud system. Whenever a very small ice crystal collides with a supercooled liquid droplet, the droplet instantly freezes to the ice crystal due to its unstable nature, thus instantly enlarging the ice crystal.
The relationship between the number of ice crystals and temperature within a cloud system is illustrated in Figure 1 (Koenig and Murray 1976). It can be noted that Type A ice is more prevalent under much colder cloud temperatures. Yet, Type B ice can be identified at warmer temperatures (around 0°C) and slightly colder temperatures, thus indicating that Type B ice is present through the vertical dimension. The quantity of Type B ice is much larger than Type A ice at temperatures above -10°C.

Although the location and size of various types of ice crystals were well represented in early CRM experiments (Koenig and Murray 1976), issues involving the effects of ice crystals on unique cloud properties were not well understood. Intensive field campaigns have been completed during the past few decades in order to utilize observational data to recreate cloud systems with the aid of CRM’s.

One such project was the Global Atmospheric Research Program Atlantic Tropical Experiment (GATE). Cloud-resolving model simulations from GATE observations modeled tropical convection well, and it handled cloud system transitions accurately (Grabowski et al. 1996). For example, distinct changes in the large-scale cloud features, like going from cumulus convection to intense squall lines, were signaled by the CRM (Grabowski et al. 1996). While larger cloud dynamics improved in CRM studies, there was still an issue of how to treat the moisture and condensed water in the cloud system (Grabowski et al. 1996). A high moisture bias was common in past field campaign studies, thus indicating a lack of cloud condensate forcing in the model (Grabowski et al. 1998). The need to further analyze the impact of water particles, specifically ice crystals, on cloud thermodynamic properties is still a forefront issue in cloud modeling.

In addition to GATE, the Tropical Ocean Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) was completed. This field campaign covered a 39-day period in the tropical Pacific in 1993. Major results from
CRM experiments with this observational dataset concluded that the amount and size of cloud ice crystals impact the cloud system's albedo and therefore radiative properties (Wu et al. 1999). Covert and Wu (2016) also found that slower ice crystal fall speeds tend to produce larger cloud systems which have a greater influence on cloud-radiation processes. Both of these studies analyzed the role of clouds in the climate system through their influence on shortwave and longwave radiation. Also, a bulk cloud microphysics scheme, which included ice parameterizations, was implemented into the Colorado State University General Circulation Model and produced cloud radiative properties consistent with observations in the tropics (Fowler and Randall 1995). As can be noted, much research has been invested into the interaction of large cloud systems on radiation schemes and general climate. Again, little research has stayed within the cloud system to understand ice crystal nucleation's role in the thermodynamic and energy budgets of clouds themselves.

The purpose of this study is to investigate the impact of ice crystal nucleation on cloud systems’ thermodynamic properties and evolution. More specifically, several thermodynamic properties, including ice mixing ratios and latent heat budgets, are analyzed to discern their spatial variability in the cloud system as a function of primary, secondary, and artificial ice nucleation. Connecting the microphysics variations within a cloud system to larger climate impacts is also a focus of this research. Observational data will be used to understand the representation of both ice nucleation processes in the real atmosphere. Primary ice nucleation mostly involves the phase change of water vapor into ice (deposition) while secondary ice depends heavily on liquid droplets aiding ice crystal growth through instantaneous freezing. Therefore, this study hypothesizes that the physical processes of deposition and freezing, both related to latent heat, will experience the greatest spatial and magnitude changes as a function of different ice crystal nucleation mechanisms.

Going forward, Section 3 of this paper introduces the data, model, and procedures that were completed to answer the research objectives. Then, in Section 4, temperature and moisture vertical profiles from the CRM and observations are compared in order to initially assess the CRM's bias in recreating the observed cloud systems. Section 5 goes into results regarding the analysis of cloud liquid and ice mixing ratios and latent heat budgets between primary, secondary, and artificial ice nucleation. In Section 6, a discussion of the results and limitations of the study are presented, thus leading to the study’s conclusions in Section 7.

3. Data and Methods

Observations taken from a field campaign in the Southern Great Plains are used to initialize the Clark-Hall CRM. Three model runs are performed, each for a specific ice nucleation case, using the observational data. Analysis is broken into two main parts: overall model biases and a detailed comparison with latent heating and cooling between the three ice nucleation types.
a. Observational Data

The observational dataset used in this study to initialize the Clark-Hall CRM is from the Department of Energy’s Atmospheric Radiation Measurement (ARM) 25-day field campaign in the Southern Great Plains (SGP) domain in 1997. The SGP site covers nearly 600 km$^2$, and it spans from central Kansas southwards through central Oklahoma (Figure 2). The Central Facility for the ARM SGP field site is located near Lamont, Oklahoma, which is in the north central region of the state. Atmospheric data collected from the field campaign include temperature, moisture, precipitation, wind velocity, and aerosol concentrations. Various instrumentation methods were utilized to collect data, including radiosondes, surface weather station networks, radars, and aerosol detection equipment. These observations have been averaged temporally to three hourly data.

Figure 2: ARM SGP domain (area within red box) located in central Kansas and Oklahoma

b. Model Set-up

The Clark-Hall CRM, from the Research Applications Laboratory (RAL) at the National Center for Atmospheric Research (NCAR), is used to simulate the convection during the 1997 ARM campaign at the SGP field site. The model is two-dimensional (x,z) as it represents space as a straight horizontal line along the surface (x-axis) with a vertical coordinate (z-axis). The entire 600 km$^2$ SGP domain is included in the model. The horizontal resolution of the Clark-Hall CRM has been set to 3 km, so the model depicts the domain as 200 separate 3 km square grids. Vertically, a stretched grid format is used with 34 individual levels in the atmosphere. By using a stretched vertical scale, lower levels are represented with a much finer resolution, nearly 100 m, while the resolution decreases as one nears the tropopause. The model outputs data every fifteen seconds, and the data is then averaged to 15 minute intervals and stored in separate files.

c. Description of Ice Nucleation Model Cases

A Koenig-Murray (1976) ice parameterization scheme is utilized in the Clark-Hall CRM. Type A ice represents fine ice crystals which increase in size by heterogeneous deposition at very cold temperatures, indicative of primary ice nucleation. Type B ice refers to heavily rimed ice particles, and these crystals are often formed at warmer temperatures (around 0°C) when they collide with supercooled liquid droplets in the cloud system, indicative of secondary ice nucleation. The third representation of ice particles in the Koenig-
Murray scheme comes from artificial ice nuclei formed by cloud seeding experiments.

For this study, primary ice nucleation, represented with Type A ice, is the dominant category in Case 1. With Case 2, Type B ice caused by secondary ice nucleation is the main focus in the ice parameterization scheme. Finally, the ice forcing mechanism is artificially nucleated ice crystals throughout the cloud system in Case 3. A summary table of the maximum ice nuclei concentration for each case in the Clark-Hall CRM is provided below (Table 1).

<table>
<thead>
<tr>
<th>Ice Nucleation Type</th>
<th>Maximum Concentration (# nuclei/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1: Primary</td>
<td>100</td>
</tr>
<tr>
<td>Case 2: Secondary</td>
<td>21.5</td>
</tr>
<tr>
<td>Case 3: Artificial</td>
<td>21500</td>
</tr>
</tbody>
</table>

The greatest ice concentration occurs with the artificially-induced ice nucleation present in Case 3. The amount of ice crystals per liter is roughly five times greater with primary ice nucleation with Case 1 in comparison to secondary ice nucleation with Case 2. In addition to the changes in maximum ice crystal concentration, each ice crystal forcing mechanism treats the growth and decay of ice crystals differently depending on the values of two constants, which have been changed according to the nucleation type, in the ice parameterization subroutine.

d. Analysis Procedures

Initial analysis involves understanding overall model temperature and moisture biases for each of the three cases. With an overview of how the model performed against the ARM SGP observations, the bulk of the results will investigate key differences in the cloud systems’ composition in addition to diabatic heating from latent heat processes. A combination of vertical profiles and time series is used to graph changes in the key variables: mixing ratios, latent heat budgets, radiation, and precipitation. The model output is averaged both temporally and across the horizontal domain for vertical profile plots in order to produce a snapshot of the vertical structure of the cloud systems. For time series, the model output is only averaged spatially.

4. CRM - Observations Comparisons

Before specific ice nucleation cases are compared to each other, an overall evaluation of the CRM’s performance is conducted against ARM SGP observations. Understanding the model's temperature and moisture biases in each of the three cases provide context into which later analysis can be placed. Vertical profiles of temperature and water vapor mixing ratios are used to see how the model compares to the observations. For Case 1, indicative of primary ice nucleation, the model is roughly 3.5°C warmer than the observations very near to the surface (Figure 3a). The air in contact with the surface exhibits the greatest amount of bias. The difference between the model and observational temperatures quickly decreases near 1 km in height. The model is then only, at maximum, 1°C warmer through the rest of the vertical dimension, thus aligning more with observations in the middle to upper troposphere. The water vapor mixing ratios for the model and observations tend to
display better agreement throughout most of the vertical profile (Figure 3b). Again, the lowest 2 km have the largest difference, with the model being 2 g kg\(^{-1}\) more moist at a height of 1 km.

When comparing Case 2 with observations, several of the same biases appear as with Case 1. Warmer near-surface temperatures, by roughly 2-3\(^{\circ}\)C, exist in the model before the difference quickly diminishes for the middle to upper cloud (Figure 4a). Similar water vapor mixing ratio biases are noticed between Cases 1 and 2 (Figure 4b).

The largest temperature and moisture biases exist in the Case 3 simulation with artificial ice nucleation. The model simulates the convection to be roughly 5\(^{\circ}\)C too warm when compared to observations at the surface (Figure 5a). The model bias decreases to 2\(^{\circ}\)C by 2 km above the surface, yet the model continues to overestimate the cloud temperature as the bias continues to increase through a 12 km depth in the troposphere. The model run is too moist throughout the entire depth with a maximum of 3 g kg\(^{-1}\) near a height of 2 km (Figure 5b). Because of the artificial supply of ice crystal nuclei, it is expected to notice these warm and moist biases in the model simulations. The deposition that occurs when water vapor freezes on the additional ice nuclei induces greater heating in the cloud system aloft, which will be further explored.

**Figure 3:** Vertical profile of the difference (model - observations) in (a) temperature and (b) water vapor mixing ratio throughout a depth of 16 km for Case 1 (primary nucleation). Horizontal bars represent standard deviations at each of the 34 levels.
Figure 4: Vertical profile of the difference (model - observations) in (a) temperature and (b) water vapor mixing ratio throughout a depth of 16 km for Case 2 (secondary nucleation). Horizontal bars represent standard deviations at each of the 34 levels.

Figure 5: Vertical profile of the difference (model - observations) in (a) temperature and (b) water vapor mixing ratio throughout a depth of 16 km for Case 3 (artificial nucleation). Horizontal bars represent standard deviations at each of the 34 levels.

5. Results

a. Distribution of Water Phases in Cloud Systems

Various types of water particles compose cloud systems. The composition of the cloud system affects other properties, like albedo, radiative effects, and precipitation rate. Each of the three model cases was initialized with varying ice nucleation modes, thus altering the cloud systems’ water distribution throughout the vertical dimension.
Beginning with Case 1, which initiated with primary ice nucleation, a spatially and temporally averaged vertical profile of various mixing ratios is shown in Figure 6. Neither of the two ice types offers a sizeable contribution to the cloud system until a height of 4 km is reached. At this level, both Types A and B ice particles start to increase in amount, but the Type A ice mixing ratio (Q_a) continues to increase to roughly 0.04 g kg\(^{-1}\) by 8 km in height. Type B ice (Q_b) is present at a much smaller magnitude, nearly half of Type A ice’s mixing ratio, when primary ice nucleation is the dominant process for ice crystal generation. Note that both ice categories are at their maximums nearly 7-8 km in height. The condensate (Q_c) and rainwater (Q_r) mixing ratios are both fairly limited throughout the vertical profile and do not exceed 0.01 g kg\(^{-1}\), which is below either of the ice mixing ratios in the higher portion of the cloud system.

For Case 2, representative of secondary ice nucleation, the overall pattern of water particle mixing ratios does not change drastically from Case 1 (Figure 7). However, Q_a now has a decreased maximum near 8 km of approximately 0.025 g kg\(^{-1}\), which fell to roughly 62.5% of the maximum value for Q_a in Case 1. Also, Q_b slightly increased throughout the cloud system. As expected, the cloud system present in Case 2 is composed of less Type A ice than Case 1, thus decreasing the disparity between the two ice types. Since Type B ice forms via contact with supercooled liquid water droplets, there is an indication that more water in the liquid phase exists in this cloud system as opposed to Case 1.

Lastly, the water content is analyzed for Case 3, the cloud system with artificial ice nucleation. The most extreme mixing ratios occur in this model case with the largest values of Q_a and the smallest values for the other three mixing ratios (Figure 8). Because
of this distribution, most of the water particles that compose this cloud system are heavily those of Type A ice, whereas the amount of Type B ice particles is significantly reduced. With artificial ice nucleation, it seems as though heterogeneous deposition of small ice crystals high in the cloud system greatly outperforms the liquid phase. There appears to be a large influence from the extra Type A ice in the system.

All six of water’s phase changes are incorporated in the Q1 heat budget for the cloud system. The fusion term takes into account both melting and freezing processes. The purpose of this budget is to understand the combination of heating and cooling effects from the various phase changes. A positive Q1 budget indicates net heating while a negative Q1 budget implies net cooling in the cloud system.

For the three ice nucleation cases, the Q1 budget vertical profiles are consistent with each other (Figures 9, 10, 11). At levels above 2 km, all three cases experience positive Q1 budgets, thus indicating the presence of deep convection due to latent heating. Levels closer to the surface undergo a net cooling effect most likely due to the evaporation or sublimation of liquid droplets or ice crystals, respectively. For heights below 7 km, the model run overestimates the latent heating rates in all three cases by as much as 1.5 K day$^{-1}$ at maximum. However, both the observational and model profiles are largely within the model’s standard deviation of each other at each of the 34 vertical levels. Therefore, the observational heating rates are within the variability of the model cases. There is evidence that a significant difference between the observational and model Q1 budget profiles does not exist.

![Figure 8: Mean vertical profiles of mixing ratios within cloud system for Case 3 (A = type A ice, B = type B ice, C = condensate, R = rainwater)](image)

**b. Latent Heat Profiles**

During phase changes of water, latent heat is either released, heating the cloud system, or absorbed, cooling the cloud system, by hydrometeors. These temperature effects are a result of diabatic heating influences from the energy associated with changes in state. To quantify the overall influence from all the phase changes, the Q1 heat budget, adapted from Grabowski et al. 1996, is shown below:

$$Q1 = \text{con} + \text{eva} + \text{dep} + \text{sub} + \text{fus}$$  \hspace{1cm} (1)
With an examination of the overall Q1 heat budgets complete, analysis into each of the microphysical terms individually is provided. Of special consideration will be how each phase change contributes to the overall heating of the cloud systems and the differences observed between the three ice nucleation cases.

The 25-day mean condensation vertical profiles for the three cases are provided in Figure 12. The greatest overall latent heating with this phase change comes from Case 2 while the smallest heating is observed with Case 3. Both Cases 1 and 2 exhibit maximum heating rates from condensation of roughly 6 K day$^{-1}$. Some upper-level heating occurs between 7 and 10 km, which is the largest difference in the heating profiles between Cases 1 and 2. Meanwhile, Case 3 consistently experiences lower heating rates throughout the profile, with a maximum of 5 K day$^{-1}$. For all three cases, the largest
heating influence due to condensation occurs near 4 km in height. Overall, the vertical profiles for mean condensation in the cloud system do not appear to differ greatly.

Figure 12: Vertical profiles for latent heating due to condensation for all 3 cases.

In contrast to condensation, evaporation is an atmospheric cooling process as water changes state from liquid to vapor. It can be noted that similar features appear as in the condensation profiles (Figure 13). Again, Case 2 demonstrates the greatest cooling effect due to evaporation while Case 3 is least influenced. All three cases have their most significant cooling taking place around a height of 3 km. A cooling rate of almost 4 K day\(^{-1}\) is evident with Case 2, but Case 3 only experiences maximum cooling of around 3 K day\(^{-1}\). Case 1 falls in between the other two cases. Both the absolute values of cooling rates and the differences between the three cases are smaller than they were in the condensation profiles.

Figure 13: Vertical profiles for latent cooling due to evaporation for all 3 cases.

The pattern of the results changes once the ice phase is included in the latent heating profiles. With deposition, the greatest heating stems from Case 3 while the lowest heating rates come from Case 2 (Figure 14). The greatest heating influence from deposition takes place higher in the cloud system around 7 km for the three cases. The profiles exhibit more variance from one another. Case 3 has a maximum heating rate of 6.5 K day\(^{-1}\), yet Cases 1 and 2 do not have heating effects larger than 4 K day\(^{-1}\) with their profiles. As noted with condensation, another latent heating process, Cases 1 and 2 vary more at upper levels within the cloud system and tend to move towards agreement at lower levels. The amount of heating from Case 3 is consistently larger than the other two cases everywhere in the profile above 4 km, where ice starts to become present.
Sublimation, the process of changing state from solid to vapor, is the counterpart of deposition. The profiles are in the same general pattern as deposition with Case 3 having the greatest cooling due to sublimation and Case 2 having the least cooling (Figure 15). The maximum latent cooling for the three cases occurs lower in the cloud system. Case 3 experiences a maximum cooling rate of 4 K day$^{-1}$ while Cases 1 and 2 cool at a rate of around 2 K day$^{-1}$ at this level. The difference in cooling rates between Cases 1 and 2 is smaller than with deposition, similar to how evaporation differences were less than with condensation. Again, Case 3 involves greater sublimation cooling throughout the vertical profile.

Finally, the 25-day mean fusion profiles are analyzed (Figure 16). When fusion results in positive heating, latent heat is being released through the process of freezing. On the other hand, negative heating (cooling) occurs via fusion when latent heat is being absorbed by the hydrometeors through the process of melting. There exist only slight differences between the three cases for latent heating effects due to freezing and melting. All three cases experience latent heating (freezing) or cooling (melting) less than 1 K day$^{-1}$. Case 2 does produce the greatest effects while Case 3 has minimal influence from fusion. The difference between Case 1 and 2 profiles is less than the difference between those two cases and Case 3. These microphysical processes do not seem to contribute to the overall Q1 budgets as much as the latent heating or cooling from the other four phase changes.
c. Implications for Radiative and Precipitation Processes

Moving towards larger scale climate processes, the total net radiative heating is shown for each case (Figure 17). All three cases exhibit net radiative cooling below 4 km. This exists since longwave radiation emitted by Earth’s surface is moving upwards through the atmosphere and cools the near-surface environment. However, Case 3 has net radiative heating aloft while Cases 1 and 2 continue to experience net cooling effects. This atmospheric heating profile for Case 3 is representative of a more stable atmosphere with heating occurring above low-level cooling.

Atmospheric heating profiles alter the static stability of the environment. The average precipitation rate for each case during the 25-day campaign is provided (Table 2). Note that the smallest average precipitation rate comes from Case 3, roughly 65% of the two other cases. Although initially the difference in the precipitation rates appears rather small, the amount of precipitation received in this region would start to diverge for the three cases over time.

<table>
<thead>
<tr>
<th>Case</th>
<th>Precipitation Rate (mm hr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1: Primary</td>
<td>0.21</td>
</tr>
<tr>
<td>Case 2: Secondary</td>
<td>0.20</td>
</tr>
<tr>
<td>Case 3: Artificial</td>
<td>0.13</td>
</tr>
</tbody>
</table>

6. Discussion

a. Interpretation of Results

As noted previously, each case is composed of various types and amount of hydrometeors. Primary ice nucleation (Case 1) results in approximately double the amount of Type A ice as does secondary ice nucleation (Case 2). However, Case 2 has the largest Type B ice mixing ratio, thus signaling that the liquid phase is most prevalent under secondary ice nucleation. Artificial ice nucleation (Case 3) has by far the greatest amount of Type A ice but the least amount of Type B ice. Therefore, Case
3 has a great proportion of Type A ice crystals to the liquid droplets.

The latent heating and cooling for each ice nucleation case described in Section 5 can be explained in terms of each cloud system's composition. For condensation and evaporation, these phase changes involve the transition of water from the vapor and liquid states. Case 2 experiences the greatest latent heating and cooling due to these two processes since the largest amount of liquid water droplets exist with secondary ice nucleation. In Case 3, limited liquid water is present, so the phase changes involving the liquid phase do not contribute to the overall Q1 budget for artificial ice nucleation.

Regarding deposition and sublimation, the direct transition between the vapor and solid phases is the driving mechanism. Since artificial ice nucleation provides so many additional ice nuclei on which water vapor can easily deposit, the amount of Type A ice is greatly exaggerated in comparison to Cases 1 and 2. The drastic increase comes at a cost as the amount of Type B ice stems from the presence of liquid water droplets and vastly decreases to compensate. With this composition, most of the latent energy in Case 3 comes from the deposition and sublimation phase changes. As Case 2 has the lowest amount of Type A ice, it receives the least latent energy from these two processes. Also, due to the drastic difference of Type A ice between the three cases, the greatest differences in latent energy profiles come from deposition and sublimation.

While Case 3 differs most substantially from the other two cases during deposition and sublimation, the difference between Cases 1 and 2 is more subtle. For any phase change, the absolute difference is not large; yet, there exists a pattern. When analyzing processes that release latent heat into the cloud system (primarily condensation and deposition), a larger difference between the Case 1 and 2 vertical profiles appears. Note that this more noticeable difference happens at higher levels within the cloud system. Meanwhile, for latent cooling processes (evaporation and sublimation), Cases 1 and 2 are in more agreement. There is a wider gap between the two profiles for condensation over evaporation and with deposition over sublimation. Thus, it seems that phase changes associated with latent heating are slightly more variable due to ice nucleation type as opposed to those associated with latent cooling.

The location within the cloud system at which ice crystals nucleate is an important factor. Type A ice usually forms higher in the cloud system, but it can be present anywhere within the system. In contrast, Type B ice normally occurs strictly at lower levels with warmer temperatures. The creation of ice crystals thus occurs at two different parts of the system. Since limited Type B ice will form aloft, Case 2 will have minimal heating due to deposition there. Yet, Case 1 will experience most of its heating aloft. Lower in the atmosphere, both ice types are being created and thus deposition induces latent heating in both cases and decreases the profile differences. Therefore, primary and secondary ice nucleation exhibit the greatest difference higher in the cloud system.
A connection can be made between the latent heating profiles and large-scale radiative and precipitation features. For Case 3, the addition of artificial ice nuclei into the cloud system induced greater levels of depositional heating and cooling from sublimation as compared to Cases 1 and 2. This effect, as well as the vast amounts of Type A ice present, indicate that the cloud system from Case 3 is the largest spatially. With this information, low-level longwave radiative cooling is restrained most significantly in Case 3 because of the absorption and reemission of energy by the large cloud system in all directions. Thus, low-levels continue to cool at a smaller rate than Cases 1 and 2, yet upper levels are warmed further by increased longwave emission from the larger cloud system. With radiative heating aloft and cooling below, atmospheric stability in the environment increases and therefore drives down further precipitation formation.

b. Limitations

This study uses observational data from the ARM SGP field campaign in 1997. The findings are therefore confined to mid-latitude cloud systems similar to the observations taken from the campaign domain in the south central United States. Extrapolation of these results to other climates around the globe may not be appropriate.

Secondly, the ARM SGP field campaign was completed during June and July of 1997. More than two decades have now passed, so advances in observational technology have developed. Meteorological instrumentation during the 1997 campaign would most likely have larger error associated with manual techniques and precision during data collection.

Lastly, the Clark-Hall CRM has a two-dimensional grid system. Instead of resolving the entire three-dimensional atmosphere, it only accounts for data in one horizontal direction in addition to the vertical axis. With this setup, emphasis is placed on understanding how atmospheric parameters vary in the vertical dimension. Comprehending cloud systems’ horizontal depth is not a major focus with this model.

7. Conclusions

The influence of ice crystal nucleation on the cloud system’s composition and latent heat budgets has been examined throughout this study. Further, an understanding of the latent heating effects on large-scale processes, like net radiative fluxes and precipitation, have been explored. Three types of ice generation were used in the Clark-Hall CRM in order to highlight key differences within the cloud system’s thermodynamic properties. The major findings are presented below:

- Noticeable differences exist in cloud system composition between the three cases, particularly with the additional Type A ice in artificial nucleation
- Largest overall heating differences noted in deposition and sublimation profiles
- Largest differences between primary and secondary nucleation occur in latent heating processes aloft
- Artificial nucleation produces the least precipitation over the 25-day
campaign due to greater atmospheric stability with additional heating aloft. These model results line up with cloud physics theory quite well. Based on the composition of each cloud system, the expected placement of the three cases relative to each other in the latent heating profiles was followed. Thus, it is important to understand the variation of liquid and ice particles within a cloud in order to comprehend the impact on heating budgets.

The most widespread heating differences between all three cases were noted in the phase changes involving ice, namely deposition and sublimation. This result makes sense as the amounts of Types A and B ice varied across each case. Further, latent heating differences between primary and secondary nucleation were noticed higher aloft in the cloud system under heating processes. While not as extreme as artificial nucleation, it is still worth meaningful discussion.

The significance of these results within a single cloud system is displayed in atmospheric stability and precipitation patterns. Ice crystal nucleation plays a role in the composition and growth of cloud systems via latent heating, thus influencing the cloud systems’ interaction with their environment. Long-term differences in precipitation accumulations develop as a result of various ice crystal nucleation processes and could alter a region’s climate.

Research on the subject of ice crystal nucleation will continue to increase the understanding of microphysical effects on convective systems. With better representation of convection in larger climate models, a more accurate depiction of future climate scenarios for the planet will aid society’s preparation for coming changes. Cloud systems exhibit powerful influences on the planet’s temperature and precipitation patterns and thus need to be fully understood.

**Acknowledgements**

I would like to thank my mentors, Dr. Xiaoqing Wu and Justin Covert, for all their guidance during this project. Dr. Wu was instrumental in seeing the bigger picture and leading me towards comprehensive analysis. Both Dr. Wu and Justin aided my use of the Clark-Hall CRM but also encouraged me to develop my own skills with modeling.

**References**


