UNDERSTANDING ICE SUPERSATURATION, PARTICLE GROWTH, AND NUMBER CONCENTRATION IN CIRRUS CLOUDS

Jennifer M. Comstock\(^1\), Ruei-Fong Lin\(^2\), David O’C. Starr\(^3\)

1 - Pacific Northwest National Laboratory, Richland, Washington, USA
2 - Goddard Earth Sciences and Technology Center, University of Maryland, Baltimore County, Baltimore, Maryland, USA
3 - Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

1. INTRODUCTION

Many factors control the ice supersaturation and microphysical properties in cirrus clouds. We explore the effects of dynamic forcing, ice nucleation mechanism, and ice crystal growth rate on the evolution and distribution of water vapor and cloud properties in cirrus clouds using a detailed microphysical model and remote sensing measurements obtained at the Department of Energy’s Atmospheric Radiation Measurement (ARM; www.arm.gov) Climate Research Facility located at the Southern Great Plains (SGP) site near Lamont, OK, USA (36° 36.30’N, 97° 29.10’W).

2. MODEL DESCRIPTION

We use the one-dimensional (1D) time-dependent cirrus model with size resolved microphysics described in Lin et al. (2005). In this version of the model, the prognostic variables are the dry static energy, \(s = C_pT + gz\), the water vapor mixing ratio, \(q_v\), and the number concentration of aerosols and ice crystals per unit mass of air for each bin, \(N_k\). The model is also coupled with large-scale forcing data derived using the constrained variational analysis approach (Zhang and Lin, 1997; Zhang et al. 2001). The model takes into account the horizontal advection of \(s\) and \(q_v\), but neglects advection of condensate, as in a single column model.

Homogeneous nucleation of sulfuric acid droplets is simulated following Sassen and Dodd (1988) and Heymsfield and Miloshevich (1993). We also include the classical theory heterogeneous nucleation scheme for immersion freezing and deposition (Khvorostyanov and Curry 2000, 2004) to compare with empirical representations (e.g. Meyers et al. 1992). The diffusional growth of ice crystals follows the analytical expression including both kinetic and ventilation effects (e.g. Pruppacher and Klett 1997) and treats the direct radiative effect on the growth of ice crystals.

3. MEASUREMENTS

We compare model simulations with lidar and radar measurements from the ARM SGP site. The ARM Raman lidar (RL) transmits a laser pulse at 355 nm using a Nd:YAG laser and detects Raman shifted photons at 387 nm and 408 nm due to the rotational-vibrational Raman scattering off nitrogen and water vapor molecules, respectively (Goldsmith et al. 1998). The extinction at 355 nm and water vapor mixing ratio can be derived directly from these measurements. The ARM RL also measures the depolarization ratio at 355 nm, enabling the distinction between aerosols and cloud phase (ice/liquid) in the atmosphere. We use the ARM RL water vapor profile along with radiosonde temperature measurements to initialize the model simulations.
In addition to the RL extinction (αe), we use radar reflectivity (Ze) measurements from the 35 GHz millimeter cloud radar (MMCR) for model evaluation. Note that simulated αe and Ze are computed directly from the predicted ice crystal size distributions. The ice water content (IWC) and effective radius (reff; assuming hexagonal columns) are computed from measured αe and Ze using the radar-lidar retrieval algorithm of Wang and Sassen (2002), which are also compared with model results.

In addition to Ze, the MMCR measures the Doppler velocity (VD), from which we compute the mesoscale vertical velocity using a method similar to that of Orr and Kropfli (1999). To summarize, we use a conditional averaging approach where VD is binned then averaged according to Ze and altitude. If a particular altitude-Ze bin has insufficient samples, we interpolate between bins with sufficient samples. Each altitude-Ze bin should represent volumes that contain similar PSDs and thus similar fall speeds (Vi). This method assumes that if the samples of VD in each altitude-Ze bin are averaged, then the random turbulent motions are removed, and the mean VD then represents the crystal fall speed for that population of ice crystals. We then compute the cloud mesoscale velocity (Vm) by subtracting Vi and the large-scale velocity (VLS) from the observed VD (Vm=VD-Vi-VLS). We then compute the mean “in-cloud” mesoscale velocity between cloud base and top and force the model with these values, which are updated every 5 sec in the simulations. The value of VLS~2 cm s⁻¹ for this case is derived from the variational analysis produced by the ARM program (Zhang and Lin 1997; Zhang et al. 2001).

4. SIMULATIONS USING LARGE-SCALE FORCING AND MESOSCALE WAVES

<table>
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<th>Run</th>
<th>Vertical Velocity Forcing</th>
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<td>HOM</td>
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<tr>
<td>LS-2</td>
<td>Large-Scale +4 cm s⁻¹</td>
<td>HOM</td>
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<tr>
<td>LS-4</td>
<td>Large-Scale +4 cm s⁻¹</td>
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<tr>
<td>MS-M92</td>
<td>Meso-Scale HET-M92+ HOM</td>
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We simulate a cirrus cloud observed at the ARM SGP site on 7 December 1999. The cloud top temperature is -53°C and the peak RHI is ~130% in the initial profile. The baseline large-scale vertical velocity is ~2 cm s⁻¹.

First, we compare time series of simulated bulk properties with observations to understand how well simulations capture
the evolution of the cloud structure. Figure 1 compares large-scale and mesoscale forcing simulations (see Table 1 for an explanation of simulation specifics and nomenclature). The simulation using the baseline large-scale forcing (LS-0) grossly underestimates the bulk properties and delays cloud initiation until \( \sim 5 \) hr. Next, we uniformly increase the LS forcing by \( \sim 2 \) cm s\(^{-1}\) (LS-2) and then \( \sim 4 \) cm s\(^{-1}\) (LS-4). Although simulations are improved, the timing of cloud initiation is still delayed for both LS-2 and LS-4. The optical depth \((\tau)\), is somewhat underestimated (overestimated) for LS-2 (LS-4). IWP is generally underestimated for both LS-2 and LS-4, although LS-4 tends to overestimate IWP at the beginning of the simulation. \( r_{\text{eff}} \) is grossly overestimated for both LS-2 and LS-4, although cloud thickness \((\Delta z)\) is somewhat reasonable. Forcing the simulation using the mean mesoscale air velocity (MS-HOM) derived from the radar Doppler velocity measurements appears to overall improve the simulation, although \( \Delta z \) is smaller than observed and \( \tau \) is larger than observed at the end of the simulation. The timing of cloud initiation is still delayed until \( \sim 1.3 \) hr. Note that for MS-HOM the mean \( V_m \) is added to the background large-scale velocity, which is \( \sim 2 \) cm s\(^{-1}\).

Next, we compare the Probability Density Function (PDF) of measured and modeled “in-cloud” relative humidity with respect to ice (RHI), \( r_{\text{eff}} \), IWC, \( Z_e \), and \( \alpha_\varepsilon \) to understand if the distribution of simulated quantities is similar to measurements. Although measurements of ice crystal number concentration \((N_i)\) are not available for this case, we include \( N_i \) in the PDF plots to better understand what a reasonable order of magnitude is for this quantity. Our approach in evaluating the PDF figures are 1) a “good” simulation is one that captures both the location of the mode and the width of the distribution, and 2) if both \( Z_e \) and \( \alpha_\varepsilon \) are simulated well, then we infer that \( N_i \) is likely correct. The latter condition is rendered using the knowledge that radar wavelengths are sensitive to the large particle mode, whereas lidar wavelengths are sensitive to the small particle mode.

All runs using large-scale forcing (LS-0, LS-2, LS-4) have a higher frequency of large RHI and \( r_{\text{eff}} \) compared with observations (Fig. 2). This is caused by the small number of ice crystals nucleated, which grow quickly to large sizes. Since the particles are primarily large, the \( Z_e \) comparison is reasonable (although somewhat larger for LS-2 and LS-4). The distribution of \( \alpha_\varepsilon \) for LS-0 is much smaller than observed. As the large-scale vertical velocity increases (LS-2 and LS-4), the
number of ice crystals nucleated increases, and thus the total surface area available for uptake of water vapor increases. This causes the RHI to be drawn down (relative to LS-0). Note that for LS-2 and LS-4 the frequency of \( r_{\text{eff}} > 50 \, \mu\text{m} \) is still much larger than observed, and thus the PDF of \( Z_e \) is skewed to large values. On the other hand, the mode value of \( \alpha_e \) is much closer to observations, implying that the number concentration of small crystals is comparable; however, LS-2 and LS-4 underestimate the frequency of small \( r_{\text{eff}} \) compared with observations. The mesoscale forced simulation (MS-HOM) produces the largest \( N_i \) and largest frequency of small ice crystals, which shifts the mode \( \alpha_e \) toward larger values than observed. This is somewhat inconsistent with the results in Fig. 1. It is possible that the observed \( \tau \) is underestimated due to attenuation of the lidar beam, which could account for an overestimation of \( r_{\text{eff}} \).

5.0 NUCLEATION MECHANISM

All simulations in Sec. 4 were performed assuming homogeneous nucleation. It was shown that using MS forcing greatly improves the evolution of the cloud development (Fig. 1); however there remains some issues in the PDF comparisons. Next we examine the effects of allowing heterogeneous as well as homogeneous nucleation to occur in the MS simulations. Figure 3 depicts the evolution of the bulk properties (as in Fig. 1) assuming homogeneous nucleation only (MS-HOM), using the Khvorostyanov and Curry (2000; 2004) approach (MS-KC), and the Meyers et al. (1992) parameterization (MS-M92). Note that in the latter two simulations, homogeneous nucleation is allowed to occur if the critical supersaturation is reached. Only the MS-KC run achieves RHI large enough for this to occur. The RHI for MS-M92 remains below 140%, which is below the 145-150% required to form crystals homogeneously in this case.

![Figure 3](image3.png)

The figure shows the evolution of the bulk properties (as in Fig. 1) assuming homogeneous nucleation only (MS-HOM), using the Khvorostyanov and Curry (2000; 2004) approach (MS-KC), and the Meyers et al. (1992) parameterization (MS-M92). Note that in the latter two simulations, homogeneous nucleation is allowed to occur if the critical supersaturation is reached. Only the MS-KC run achieves RHI large enough for this to occur. The RHI for MS-M92 remains below 140%, which is below the 145-150% required to form crystals homogeneously in this case.

![Figure 4](image4.png)

Figure 4. Time evolution of the vertical profile of \( \log(N_i) \) (left panels in \( L^{-1} \)) and RHI (right panels in %). Simulations use mesoscale forcing and vary with nucleation mechanism (MS-HOM on top, MS-KC in the middle and MS-M92 on the bottom).
The MS-M92 run improves the timing of cloud formation and the magnitude of all bulk properties compares favorably with observations, with the exception of the 3-4 hr time period when $\tau$ and IWP decrease significantly, which is also seen in MS-KC (Fig. 3). This is related to the fact that ~10 times fewer ice crystals are nucleated in MS-M92 and MS-KC as compared to MS-HOM during the initial pulse that begins at ~1 hr (see Fig. 4), and these crystals are generally larger and fall out quicker than in MS-HOM. It is also notable that $\tau$ is overestimated in all MS runs (Fig. 3) compared to observations. The lidar is somewhat attenuation limited for a short time period near 0500 UTC, which causes an underestimation of $\tau$. Since large particles tend to dominate the IWP, we don’t see a significant difference between model simulations and observations during that same time period.

We also compare the PDFs for these simulations (Fig. 5). Although the variation between PDFs in Fig. 5 is smaller than in Fig. 2, there are some differences worth noting. First, the MS-KC RHI has a secondary peak near 130% (Fig. 5). This occurs because nearly all the ice crystals generated during the first cloud pulse sublimate before the last cloud pulse initiates (MS-KC; Fig. 4). During this time period (~3.5-5 hr) the RHI increases substantially until the homogeneous nucleation threshold is reached (just before ~5 hr; MS-KC RHI in Fig. 4).

The second notable difference in the PDFs (Fig. 5) is that the MS-KC $N_i$ has a secondary peak as well. This is caused by a strong pulse that occurs at ~5 hrs due to homogeneous nucleation. This pulse generates ~10 times more crystals in the MS-KC run than in the MS-HOM run at that same time step.

Finally, it is notable that in each of the MS-HOM simulations, the $Z_e$ is simulated well, and the $\alpha_e$ is only slightly overestimated compared with observations.

Figure 5. As in Fig. 2 but for simulations comparing the effects of nucleation mechanism.

6.0 DISCUSSION

We have presented simulations analyzing the effects of dynamic forcing and nucleation mechanism on cirrus formation and evolution. All simulations performed and displayed here assume a deposition coefficient ($\alpha_D$) of 1.0, which causes ice crystals to grow quickly. We have also performed a similar set of simulations assuming $\alpha_D=0.006$, which effectively causes ice crystals to grow much more slowly, increasing the number concentration of small ice crystals by a factor of 10-100. Interestingly, we found that the sensitivity to the growth assumption ($\alpha_D=1$ vs $\alpha_D=0.006$)
are affected by the characteristics of the vertical velocity forcing. When mesoscale forcing was used, the increase in N$_i$ was dampened somewhat.

In summary, the simulations that are the most consistent with ground based observations of cirrus clouds are those that include the mesoscale variability. This result is consistent with previous results of Kärcher and Ström (2003) and Jensen et al. (2005). We also find that the Meyers et al. (1992) parameterization for deposition nucleation performs slightly better than other nucleation mechanisms for nearly all parameters. These results emphasize the need to better understand and parameterize nucleation and the effect of subgrid variability within global climate models. We have demonstrated the potential for using radar Doppler velocity measurements to improve cirrus simulations. We plan to further exploit the $V_D$ measurements to characterize and parameterize cirrus variability on the scale of a GCM grid box.

7.0 BIBLIOGRAPHY


