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Atmospheric
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Discussions

Interactive comment on "Physical controls on orographic cirrus inhomogeneity" *by* J. E. Kay et al.

J. E. Kay et al.

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Along with my co-authors, I thank both referees for their thoughtful reviews. Here, we address their comments and note the changes that we have made to our manuscript.

1 AUTHOR RESPONSES TO MAJOR COMMENTS:

1.1 Contribution of ΔZ to σ variability:

Both referees made a number of comments about the contribution of cloud physical thickness (ΔZ) variability and fallout zone processes to optical depth (σ) variability (Referee 1 main point 3, Referee 2 major comment). Here, we describe the text and

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calculation changes we made in response to both referees' suggestions on this topic. We also provide responses to individual referee comments regarding the feasibility of incorporating ΔZ variability and/or additional fallout zone processes into our study.

Changes to manuscript:

1. Following Referee 1's suggestion, we added text that further addresses the influence of ΔZ variability on σ variability. Text additions were made to: the description of our conceptual framework (pg. 4897), and the conclusions (pg. 4904).

   TEXT ADDED ON PAGE 4897: *...cannot always be justified. For example, observations show that ΔZ variability contributes to σ variability (Figure 2). Because we assume a constant ΔZ, we can only incorporate σ variability associated with variability in w and initial conditions such as N_{IN}. A more complicated model could be used to predict ΔZ and to assess the contribution of ΔZ variability to σ variability. The fidelity of ΔZ predictions derived from a more complex model will largely depend on the assumed vertical moisture profile.*

   TEXT ADDED ON PAGE 4904: *...would be interesting. It is important to note that using a more complex model to assess the influence of ΔZ variability on σ variability requires an accurate initial vertical moisture profile.*

2. We added a new panel to Figure 2 that contains a scatter plot of observed σ vs. observed ΔZ. This new panel illustrates that the observed ΔZ variability does not fully explain the observed σ variability. The scatter in the σ vs. ΔZ plot could be explained by microphysical variability or by errors in the estimated ΔZ and/or σ.

   TEXT ADDED ON PAGE 4893. ... *The lidar observations reveal that ΔZ variations contributed to the observed broad P(σ) (Figure 2). Although the lidar observations do not reveal the influence of N_{ice} and R_{eff} on the observed σ, the* *large amount of scatter in the observed relationship between σ and ΔZ shows that the observed ΔZ variability cannot explain a large fraction of the observed σ variability (Figure 2).*

3. As both referees point out, our modeled σ values (e.g., Figure 12) are smaller than the observed σ values (Figure 2). Both referees suggested that the small ΔZ used in our model σ calculations could explain this difference. We assumed $\Delta Z = 1000$ m, which is often smaller than the observed ΔZ. Using a cloud mask based on the lidar depolarization, we estimate that the average observed $\Delta Z = 3500$ m from 8 to 24 UTC. Therefore, we changed the ΔZ used for our σ calculations from 1000 m to 3500 m. Increasing ΔZ produced a uniform increase in σ (see Figure 12A, 12B). Increasing ΔZ resulted in a better match between modeled and observed σ above Lamont, OK (see Table 4).

   TEXT CHANGED ON PAGE 4896: *...by linearly scaling the ice formation region R_{eff} and N_{ice} over the entire cloud depth and by assuming* $\Delta z = 3500\,m$ *(the mean observed ΔZ from 08:00 to 24:00 UTC, see Figure 2).*

Responses to individual referee comments:

Although the referees provided many interesting suggestions and comments regarding the treatment of ΔZ variability and the fallout zone in our modeling, we did not change our modeling approach for reasons explained below.

1. **Change the representation of fallout zone processes:** Referee 1 suggested that microphysical processes in the fallout region (aggregation, diffusional growth, evolution of the size distribution) would tend to amplify heterogeneity in the formation layer. If true, this would call into question our assumption that microphysical processes occurring below the formation layer do not contribute to σ variability. We know and acknowledge in the text that assuming all σ variability is generated

in the nucleation zone is simplistic. A more complex model is needed to evaluate the contribution of the fallout zone microphysical processes to σ variability. Developing such a model is beyond the scope of this study.

Never-the-less, we maintain that fallout region processes are unlikely to drastically change P(σ) shape. For example, aggregation is not of great importance to most cirrus clouds because of the small size of most cirrus ice crystals. In addition, diffusional growth rates are a function of particle size, which in the absence of aggregation, are largely controlled by the N_{ice} that results from homogeneous or heterogeneous freezing.

To assess the effect of processes occurring below the nucleation zone on σ variability, we have simulated the processes occurring as individual cloud particles fall through a column with increasingly dry air. These simple 1D model runs suggest that ice particles may have near-uniform lifetimes below saturated layers. Large crystals fall quickly to drier air but grow/evaporate slowly while small crystals fall slowly remaining in moister air but grow/evaporate quickly. This result provides additional support to our assumption that processes occurring below cloud do not drastically change σ variability.

2. **Use Monte Carlo methods to incorporate cloud depth variability:** Referee 1 suggested using the mean and standard deviation of observed ΔZ to define model ΔZ at each time step using a Monte Carlo approach. The statistical assignment of observed cloud ΔZ at each time step could produce σ variability from ΔZ variability. Yet, statistical assignment of ΔZ at each time step would not increase our understanding of the physical processes that generate σ variability. Given our modeling tools and observations, we think the best way to assess the influence of ΔZ variability on σ variability is to use the observations (see above changes to manuscript 3 above). Future studies could investigate the physical mechanisms generating ΔZ variability and the influence of ΔZ variability on σ variability.

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3. **Run multiple parcel models:** Referee 1 suggested running multiple parcel models to simulate processes occurring at different levels. Although this approach could be informative, our goal was to use a simple model to quantify interactions between dynamics and cirrus microphysics. With a more complex modeling set-up, we would need new modeling tools to extract Lagrangian w profiles from MM5 and a new set of physically-based assumptions to relate the parcel models to each other and to cirrus in the atmosphere.

4. **Use MM5 to diagnose cloud thickness:** Given the moisture biases evident in the MM5 simulation, we do not think the MM5 humidity fields would provide useful information to diagnose ΔZ. In many cirrus, ΔZ and fallout zone processes depend on the vertical moisture profile. Initializing upper tropospheric moisture fields in models is difficult given the paucity of good observations. Uncertainty in moisture initialization remains a major limitation of current cirrus cloud process models.

1.2 Referee 1 Main point 1:

Referee 1 remarked that the model-observation comparisons were distracting. We re-examined our presentation and we do not agree with referee 1's assessment. We have indicated that the MM5 simulation had a moisture bias which complicated direct comparison with observations. We feel that a detailed explanation of why the model and observations diverge is useful for our readers. We also explain why our modeling results are representative even though direct comparison of modeled and observed P(σ) was not possible.

The temporal evolution of σ is presented in Figure 10. We do not wish to add another figure showing the temporal evolution of P(σ) because it can be inferred from Figure 10.

1.3 Referee 1 Main point 2:

Referee 1 requested that the coupling of the parcel model runs and MM5 be more fully described. Table 3 already indicates that the parcel model was initialized with the MM5 moisture, temperature, and pressure fields. We added an additional sentence to Table 3 to clarify that we are using an adiabatic model and therefore, we did not nudge the parcel model humidity to the MM5 humidity (pg 4909). We also added adiabatic as a descriptor of the parcel model in the abstract, in section 4.2 (pg 4897), and in the conclusions (pg 4902).

TEXT ADDED ON PAGE 4909: *... were derived from the indicated MM5 domain. All parcels were assumed to be adiabatic, which implies that no mixing or nudging to the MM5 fields was included.*

2 AUTHOR RESPONSES TO MINOR COMMENTS:

Referee 1: p4890 line 25. It can be seen that sigma is more dependent upon Reff than Nice.

Mathematically, σ does depend more on R_{eff} than on N_{ice}, but at a constant ice water content (i.e., a constant temperature), N_{ice} and R_{eff} co-vary. As N_{ice} is determined by the nucleation processes and R_{eff} responds to N_{ice}, we are comfortable with stating that σ depends primarily on N_{ice}.

TEXT ADDED ON PAGE 4891 *...are primarily determined by N_{ice}. At a fixed ice water content (temperature), R_{eff} is largely determined by N_{ice}.*

Referee 1: I suggest moving the last para on p4891 ahead of this statement, so that the reader can see how w controls Nice which to some extent controls Reff.

We think adding a statement that that $N_{\rm ice}$ and $R_{\rm eff}$ co-vary at a constant ice water content (temperature) will clarify the influence of $N_{\rm ice}$ upon $R_{\rm eff}$. We did not change the order of the presentation.

Referee 1: section 5.1 Do the comments about the effects of adding IN include the both the addition of 0.03 cm-3 and introducing the Meyers et al. scheme?

In section 5.1, the described effects are only for typical background IN (N_{IN}=0.03 cm^{-3}).

TEXT ADDED ON PAGE 4898 ...*In contrast, the addition of typical background* N_{IN} *(*N_{IN}*=0.03 cm*$^{-3}$)

Referee 1: section 5.3 I think you should briefly describe how the Reisner scheme predicts Nice.

We added the requested description.

TEXT ADDED ON PAGE 4893 ...interesting because the Reisner II scheme neglects the influence of w on Ci N_{ice}. In fact, the N_{ice} predicted by the Reisner scheme at Ci formation temperatures (T $<$ -30 degrees C) is a constant N_{ice}=0.1 cm^{-3}.

Referee 1: section 5.3 It could be argued that eq 1 is directly (if ice particle mass is proportional to size squared) proportional to ice water path. It would be nice to see P(IWP) as well as P(sigma) and P(Nice).

Because we are assuming a fixed ΔZ in these figures, we hope the reader can obtain a rough estimate of IWP using Table 4. We do not want to add additional figures.

Referee 1: fig13 and associated discussion. Although the grid box mean RH is below ice saturation there is an implicit pdf of humidity, if the mm5 has a

cloud fraction parameterization. Therefore, some parts of the grid box will be significantly more moist.

The Reisner II scheme does not include a sub-grid cell distribution of humidity or a cloud fraction parameterization. All cloud and moisture values are assumed to be uniform over the entire MM5 grid cell. We agree that the humidity of a mesoscale model grid box with 4 km resolution may not capture all of the relevant variability in humidity. That being said, it is hard to maintain widespread cirrus cloud cover if the model RH_{ice}=80%.

Referee 1: What were typical values for Reff? Perhaps there should be some discussion about how Reff might be expected to evolve in the fallout section and how this would affect the estimates of sigma.

Typical values of modeled R_{eff} were provided in original Table 4. The evolution of R_{eff} is discussed in the author response to major comments (see responses to individual referee comments in 1.1 above).

Referee 2: It would be worth noting that vertical motions in wave clouds are typically much larger than in other types of cirrus, such as synoptically-forced cirrus.

We added the requested information.

TEXT ADDED ON PAGE 4892 *...are often missed by climate models (Dean et al., 2005). We note that orographic Ci typically form in environments with larger w than non-orographic Ci.*

Referee 2: Although the parcel model is described in detail in Kay et al. [2006], I think a bit more detail should be included here. In particular, it would be nice to have some description of how the ice fallout timescale is calculated. Presumably,

it is sensitive to the assumed parcel and cirrus depths.

The fallout timescale is only sensitive to the parcel depth, not ΔZ. A description of the K06 model processes has been added at the top of page 4896.

TEXT ADDED ON PAGE 4896 *the K06 parcel model and a simple conceptual framework (Fig. 8). The K06 model includes heterogeneous and homogeneous freezing, vapor diffusion, and fallout. Fallout is calculated by assuming that a fraction of the ice particles fall out of the parcel in each time step. This fallout fraction is determined individually for each bin using the particle fall speed, the timestep, and the assumed parcel depth.*

Referee 2: page 4896, lines 24-26 The authors state that w and T control the maximum homogeneous nucleation rate and the resulting ice concentration. I do not think this statement is quite correct. Jhom is controlled by ice supersaturation and temperature.

Yes, Jhom is controlled by the supersaturation with respect to ice. w controls the ice supersaturation but stating that w directly influences Jhom is not strictly correct.

MODIFIED TEXT ON PAGE 4896 *...If homogeneous freezing begins, the supersaturation with respect to ice largely controls the maximum homogeneous nucleation rate...*

Section 5.3 To what degree are the simulated cirrus lifetimes controlled by tau fallout versus subsidence-driven heating? Following on comment 2 above, the fallout times in a parcel model are somewhat arbitrary, and it would be interesting to know how sensitive the simulated cloud lifetimes are to the assumed fallout time specification.

K06 and Kay (2006) have done calculations which help address this comment. We briefly review their results here. In the K06 parcel model, cirrus fallout timescales are sensitive to the specified parcel depth, however, P(σ) shape is unaffected by reasonable choices for the parcel depth. In Kay (2006) pg 51, simple calculations are presented that suggest that the sublimation timescales for typical cirrus undergoing typical subsidence rates (w = -2 to -5 cm/sec) are multiple hours. Fallout timescales found in K06 approach these sublimation timescales when cirrus form by homogeneous nucleation at large w (w=100 cm/sec) and low T (T=-60 C). Therefore, subsidence-driven heating timescales can probably approach fallout timescales for cirrus with large N_{ice}. We note that when subsidence is present along the MM5 trajectories, subsidence-driven heating is included in our calculations and will affect P(σ).

It is stated that the Meyers et al. [1992] parameterization gives unreasonably large IN concentrations and the simulations using this parameterization are not atmospherically relevant. This is an important point. In fact, I might argue for removing the Meyers et al. simulation just to avoid confusion.

We agree that this is an important point. In order to emphasis the difference, we made the Meyers results dashed in Figure 12 and added a note to Figure 12's figure caption stating that the Meyers results are not relevant for the upper troposphere.

TEXT ADDED ON PAGE 4922 ... *were calculated for σ >0.1. The Meyers P(σ) and P(N_{ice}) are dashed because the large N_{IN} predicted by Meyers are not relevant for the background upper troposphere.*

3 ADDITIONAL CHANGES

We modified the abstract to improve clarity and focus.

Optical depth distributions (P(σ)) are a useful measure of radiatively important cirrus (Ci) inhomogeneity. Yet, the relationship between P(σ) and underlying cloud physical processes remains unclear. In this study, we investigate the influence of homogeneous *and heterogeneous freezing processes, ice particle growth and fallout, and mesoscale vertical velocity fluctuations on P(σ) shape during an orographic Ci event. We evaluate Lagrangian cirrus evolution along kinematic trajectories from a mesoscale weather model (MM5) using an adiabatic parcel model with binned ice microphysics. Although the presence of ice nuclei increased model cloud cover, our results highlight the importance of homogeneous freezing and mesoscale vertical velocity variability in controlling Ci P(σ) shape along realistic upper tropospheric trajectories.*

We added a more accurate estimate of the observed cloud top height based on the lidar deplorization.

TEXT CHANGED ON PAGE 4893 ... *The lidar-observed Ci had a constant cloud top height of approximately 12.7 km, ...*

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