RESPONSE TO COMMENT BY DR. AXEL SEIFERT

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We thank Dr. Seifert for his thoughtful comment and criticism. Our responses to the specific comments are as follows:

(1) Discussion of supersaturation – The manuscript does include a detailed description of the statistics of the supersaturation fields in the bin and bulk-explicit models (last paragraph of Sect. 4.2), including figures of the supersaturation PDFs (Fig. 12a) and mean in-cloud supersaturation (Fig. 12b). Figure 12a shows that the models often predict supersaturations less than 5%. But, in very rare instances (i.e., probability is less than 0.01%), supersaturations above 10% can be found. In the rarest cases, the models suggest supersaturations as high as 30-50%. Unfortunately, there are essentially no observations of supersaturation within the convective core of supercells. However, we can use parcel model simulations as a sanity check for the predicted supersaturations in the 3D simulations. Parcel model simulations using the updraft velocity profiles predicted for the convective core were performed offline and corroborate the relatively high supersaturations; thus, they are not a result of numerical artifacts. Figure (1) shows a profile of supersaturation using a Lagrangian bin parcel model simulation with a fixed updraft velocity and relative low CCN concentration to mimic the effect of collection on the ambient number of particles. The parcel model simulations corroborate the high supersaturations predicted in the 3D CRM.

The supersaturations are capable of reaching such high values in regions with low droplet/ice number concentrations and with high updraft velocities (at least 50 m s^{-1}). This occurs in regions with high collection/riming efficiency. In the absence of an aerosol source, as is the case in the current study, one ought to expect the number concentrations to be somewhat lower than in the case where aerosols are produced at the surface or by gas-to-particle conversion and thus the supersaturations presented here should serve as upper estimates.

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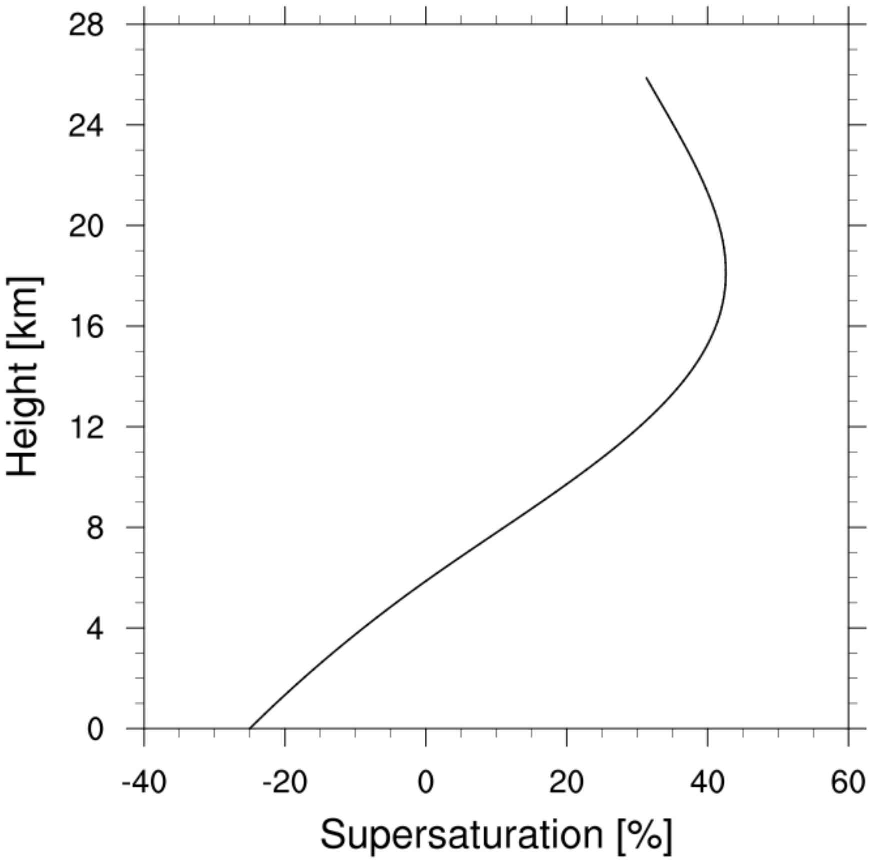

FIGURE 1. Supersaturation as a function of height using a detailed parcel model with a constant updraft velocity of 50 m s^{-1} and a relatively low CCN concentration of 25 cm^{-3} to mimic the effect of collection on the total number concentration.

Moreover, unlike the case in stratocumulus, or even warm cumulus congestus, the supersaturation maximum ought not to occur within $\sim$ 100 m of cloud base in a supercell. The reason for this dichotomy is that the updraft continues to increase in intensity for several kilometers above cloud base, thus providing a very large source in the supersaturation equation. This can increase the supersaturation well above cloud base despite the presence of significant cloud water, leading to additional droplet activation. In Fig. (1), we see that the peak supersaturation occurs about 10 km above the cloud base predicted by the parcel model.

In order to minimize the influence of the model initialization (i.e., inclusion of a warm bubble to instigate the convective updraft core), the PDF of supersaturation and the time evolution of the mean in-cloud supersaturation (Fig. 12) are generated by excluding the first 30 minutes of the simulations. After 30 minutes, the system has little memory of the initial perturbation and thus by excluding all data prior to 30 minutes, we minimize the influence of the strength of the initial perturbation on the conclusions. This is included in the caption to Fig. (12).

Lastly, we chose a supercell case for demonstrating the influence of the saturation adjustment scheme due to recent publications (e.g., *Khain and Lynn*, 2009; *Lebo and Seinfeld*, 2011) that show significant differences between predicted supercells and their response to aerosol loading using bin and bulk microphysics. This is discussed in the introduction.

We have enhanced the discussion surrounding supersaturation in Sect. 4.2 with the above details and now reads:

"With the addition of an explicit representation of supersaturation in the bulk-explicit model configuration, we are able to compare directly the predicted supersaturation fields between the bulk-explicit and bin models. Since the bulk-original model adjusts the supersaturation to 0 % at the end of every time step, no points in the domain have supersaturation (with respect to liquid water) following calculation of the microphysical process rates. Thus, in Fig. 12 both the probability distribution function (PDF) and mean supersaturation as a function of t are plotted for only the bulk-explicit and bin model configuration. Note that only positive values are shown and that all points between $z = 2.1$ and 9.1 km and $t = 30$ and 120 min are used in computing the PDFs (by excluding all data from the first 30 minutes of the simulations, we minimize the influence of the initial perturbation strength on the generated PDFs). The large supersaturations seen in Fig. 12 result from very large updraft velocities that are typical of supercell thunderstorms and low droplet/ice number concentrations; these values of supersaturation are confirmed by parcel model simulations (not shown). However, to date, no reliable detailed observations of in-cloud supersaturation for supercells exist. The PDFs portrayed in Fig. 12a show that for both the bulk-explicit and bin models, except at small supersaturations (i.e., <2 %), there is a consistent reduction in the PDF from "Clean" (solid) to "Polluted" (dashed) conditions. Figure 12 is consistent with previously discussed results regarding latent heating and invigoration since the decrease in the supersaturation PDF in "Polluted" compared to "Pristine" corresponds to an increase in condensation and consequently an increase in latent heating aloft (Fig. 9). Figure 12b shows that the magnitude of the mean supersaturation differs between the bin and bulk-explicit model configurations, but the change in supersaturation from an increase in aerosol number concentration is quite similar. The bulk-original model cannot represent these changes in the supersaturation field resulting from increased aerosol loading, which limits its ability to predict the small invigoration simulated by the bulk-explicit and bin models (Fig. 7).

In stratocumulus or shallow cumulus clouds, supersaturations often peak near or just above cloud base (*Pruppacher and Klett*, 1997). This is a direct result of relatively weak vertical velocities and thus a small source term in the supersaturation equation. Thus, the rapid increase in condensed liquid outweighs the supersaturation source due to rising air motion. On the other hand, in a supercell, the vertical velocity often increases substantially with height, reaching a maximum value several kilometers *above* cloud base. Since the vertical velocity can exceed 50-60 m s^{-1} within the strongest updrafts at mid- to upper-levels, there is a large supersaturation source that allows supersaturation to increase as parcels rise above cloud base. Moreover, in regions aloft where the number concentration of droplets/ice is reduced due to very efficient collection processes, the sink of water vapor due to condensation/deposition is limited. This further enhances the large increase in supersaturation above cloud base."

(2) Vertical resolution – This is a good point. Certainly, vertical grid spacing of ~ 300 m would be deemed too course for simulations of stratocumulus or shallow cumulus, where vertical velocities are relatively weak and maximum supersaturation typically occurs near cloud base as discussed above. However, in deep convection generally, and supercells in particular, vertical velocity increases substantially with height above cloud base. Thus, extremely fine vertical grid spacing (of order 10 m) is likely *not* required to resolve the vertical structure of supersaturation in convective cores (having high vertical resolution near cloud base is not likely to be as important in supercells). In this case, the key is to correctly simulate the vertical structure of vertical velocity, i.e., resolve the supercell dynamics; grid spacing of order few hundred m has been used typically for modeling supercells in previous studies (e.g., *James and Markowski*, 2010). While sensitivity to vertical (and horizontal) resolution would certainly be interesting to investigate, it is beyond the scope of this paper.

Figure 14 is included to serve solely as a conceptual model of the supersaturation. However, to make the discussion of the applicability (or lack thereof) of the saturation adjustment scheme presented in Sect. 5 more clear, we have removed both Fig. 14 and Fig. 15 and replaced them with a scatter plot of the ambient supersaturation as a function of height at 4 different times and a cumulative distribution function (CDF) of the condensational growth timescale. For more detailed information regarding this change, refer to the response to the first anonymous reviewer.

We have included more details regarding the chosen resolution in the paper according to the above comments. The first paragraph of Sect. 3 now reads:

"The bin and bulk microphysics models described in Sect. 2 are coupled to the Weather Research and Forecasting (WRF) model Version 3.3 (*Skamarock et al.*, 2008) as a 3-D CRM. The model is compressible and nonhydrostatic. The domain extends to $200 \times 200\,\mathrm{km}^2$ in the horizontal and 24 km in the vertical. The grid spacing is 1 km in the horizontal and 343 m in the vertical (i.e., 70 levels). Unlike the case of stratocumulus and shallow cumulus, for which high vertical resolution (i.e., grid spacing of order 10 m) is required to resolve peak supersaturations near cloud base and cloud-top entrainment (e.g., *Stevens et al.*, 2005), vertical velocities are large and tend to increase substantially in strength above cloud base in supercell storms. Thus, using high vertical resolution to resolve the detailed supersaturation structure near cloud base is less likely to be important when simulating these storms. The model time step is chosen to be 5 s to ensure numerical stability, and the duration of the simulations is 2 h. Rayleigh dampening is applied in the top 5 km of the grid, and open lateral boundary conditions are employed. For the purposes of this idealized study, we exclude radiation, surface fluxes, and Coriolis force. All scalars are advected in the horizontal and vertical using 5th and 3rd order positive-definite advection schemes, respectively."

(3) *Seifert et al.* (2006) presented a thorough comparison of bin and bulk microphysics schemes in regard to their prediction of deep convective storms. The emphasis of this study was on the direct inter comparison of bulk cloud properties predicted by the two model types. In contrast, we are looking specifically at how the aerosol effects on simulated supercells are dependent upon major assumptions in

the models. Moreover, we look to more closely analyze how aerosol perturbations impact convective characteristics and supercell dynamics. We have included a reference to *Seifert et al.* (2006) in the introduction:

"*Kogan and Martin* (1994) discussed the error of bulk condensation schemes, but not in comparison detailed bin microphysics. Moreover, *Seifert et al.* (2006) did a thorough comparison for bin and bulk model simulations for predicting single-cell convection and squall line development in 2D, finding that the assumptions about ice microphysics and warm-rain autoconversion are most significant in attaining a good agreement between models. However, both of these studies did not examine the treatment of condensation in the light of aerosol effects on supercells."

(4) The suggested references have been added to the paper.

References

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