RESPONSE TO ANONYMOUS REVIEW 1

Z. J. LEBO, H. MORRISON, AND J. H. SEINFELD

We thank the anonymous reviewer for his/her thoughtful comment and criticism. Our responses to the specific comment are as follows:

(1) The reviewer is correct that by showing differences between the simulations at specific times, the results could potentially be biased since it is difficult to discern differences in the timeline of the development of the storm. However, we have shown both the cumulative precipitation (Fig. 2) and the change in the mean convective mass flux (Fig. 7) as time series plots. If a difference in the timeline of the storm development was causing the differences shown and discussed in the manuscript, this would most likely be evident in these figures. However, there is no evidence that there is a significant shift in the timeline of the development of the supercell. Moreover, for example, by showing mean vertical profiles at various times throughout the simulations, we can analyze how the the convective mass flux changes in the vertical with time (Fig. 8) in conjunction with changes in latent heating in the vertical (Fig. 9). These differences will likely be much more difficult to discern if only PDFs were shown.

To address the issues with Figs. 14 and 15, we have chosen to remove the figures and replace them with a scatter plot of the ambient supersaturation as a function of height at 4 different times (Fig. 1, herein) and a cumulative distribution function (CDF) of the condensational growth timescale (Fig. 2, herein). The former figure demonstrates that the supersaturation does in fact continue to increase substantially with height through the cloud (quite unlike that which is expected in less volatile scenarios like marine stratocumulus). The CDF shows that for both the bulk-explicit and bin model configurations, more than 50% of the model points containing cloud water have a condensational growth timescale that is larger than the model time step (i.e., 5 s). In these cases, the saturation adjustment assumption is invalid and will produce potentially significant errors.

Date: August 24, 2012.

Lastly, we have modified Sect. 5 to reflect these changes. It now reads (note that the figure references correspond to this response to the reviewer and are modified in the actual draft to reflect the position in the paper):

"We have demonstrated the sensitivity of simulated aerosol effects on a supercell storm to the use of a saturation adjustment scheme. It was shown that saturation adjustment in the bulk-original model leads to a small weakening of the average convective mass flux in polluted versus pristine conditions. In contrast, using an explicit calculation of the supersaturation evolution in the bulk-explicit, bulk-cond, and bin models leads to a small invigoration. The key difference between these model configurations is that the bulk-original model assumes that the condensational growth timescale is no larger than the model time step (i.e., 5 s in the present study). On the other hand, the bulk-explicit, bulk-cond, and bin models are capable of accurately representing the real condensational growth time scale. To represent the significance of the assumption that the condensation growth timescale is less than the model time step, Fig. (2) shows the cumulative distribution function (CDF) of the condensational growth timescale for the bulk-explicit and bin model configurations. To minimize the effect of the initial conditions on the CDF, only data from the last 1.5 hr of the simulations are included in the analysis. The vertical dashed line indicates the points at which the model time step coincides with the condensational growth time scale and the horizontal dashed line represents the 50th percentile (i.e., the median). While in both model configurations, the condensational time scale for some points does lie below the model time step threshold. However, most of the points lie beyond the model time step, where the saturation adjustment scheme (or the equilibrium assumption) is invalid. For the bin model, this constitutes between 65% and 80% for the "Clean" and "Polluted" conditions and for the bulk-explicit model, between 95% and 97% of the points lie beyond the model time step. Thus, in the majority of the cloud, the saturation adjustment scheme will overpredict condensational growth (and, consequently, the latent heat release aloft that ultimate leads to complex dynamical feedbacks).

Whether or not there is a net overprediction of condensation and latent heating over the depth of the cloud using saturation adjustment depends upon the equilibrium value of the explicit supersaturation. The net error increases with larger values of equilibrium supersaturation; if the equilibrium supersaturation is zero then there is no net error in the condensation rate using saturation adjustment, although there may still be errors in the vertical distributions of condensation and heating. All else being equal, equilibrium supersaturation will be higher for stronger updrafts and lower droplet concentrations. Thus, the net error will be greatest using saturation adjustment applied to strong updrafts in clean conditions, and smaller in weak updrafts or polluted conditions. This dependence on aerosol loading implies a different magnitude of error in the response of the condensation rate and hence latent heating to polluted and pristine conditions using saturation adjustment. This is consistent with differences in the response of the average convective mass flux using the bulk-original model with saturation adjustment compared to bulk-explicit or bin.

Note that there are complications to this general picture. In updrafts that substantially increase in intensity with height, as is generally the case for moist deep convection, supersaturation may increase with height even in the cloud interior well above cloud base (as demonstrated in Fig. 1). This effect will exacerbate the net overprediction of condensation rate and latent heating using saturation adjustment. Moreover, droplet concentration can decrease with height in the cloud due to collision-coalescence, increasing the supersaturation relaxation timescale. In the absence of additional droplet activation, this can lead to large values of supersaturation inside the cloud (*Clark*, 1973), which again increases errors in the net condensation rate and heating over the depth of the cloud using saturation adjustment.

We note that a similar situation occurs for moist downdrafts. If the supersaturation (evaporation) timescale is short compared to the model time step, conditions are near equilibrium and saturation adjustment is a good approximation. However, in non-equilibrium conditions, such as in an accelerating downdraft, saturation adjustment may produce noticeable error in the evaporation rates and hence latent cooling.

To briefly summarize, saturation adjustment produces errors in strongly non-equilibrium conditions, when the supersaturation relaxation timescale is much longer than the model time step. This occurs near cloud base, especially in strong updrafts, and in the cloud interior when convective updrafts increase in intensity with height or when droplet number concentration is reduced as a result of collision-coalescence. On the other hand, saturation adjustment is a good approximation in other circumstances. In models with a relatively large grid spacing and long time step or in environments with weak vertical motion, supersaturation will be closer to equilibrium through most of the depth of the cloud and hence errors in the vertical distribution of condensation/evaporation rate using saturation adjustment will be small. Moreover, equilibrium supersaturation will be close to zero in weak updrafts, implying little error in net condensation over the depth of the cloud. However, we note that even though there may limited error in the condensation rate using saturation adjustment in this situation, large errors can occur in the peak supersaturation (near cloud base) and hence droplet number concentration in models that explicitly predict droplet activation as a function of supersaturation. Without performing detailed simulations using the microphysics models presented herein applied to other cases, this discussion serves to provide a conceptual view of the applicability of saturation adjustment in models. Detailed analysis of situations for which saturation adjustment is expected to produce little error is beyond the scope of this paper."

(2) Please see our response to the first point above.

(3) Saturation adjustment is only applied to cloud liquid water at the end of the time step, after all other processes have been calculated. Deposition of ice hydrometeors is calculated explicitly during the time step based on ice particle characteristics and the ambient supersaturation with respect to ice.

(4) A discussion of the model resolution has been added to the manuscript as described in the response to Dr. Axel Seifert's comments.

(5) We have modified Figure 12 so that the x-axis has logarithmic spacing so as to accentuate the data that are most important (i.e., smaller supersaturations since there are a few orders of magnitude more points in which the supersaturation is 1% relative to those greater than 40%). Moreover, in the case the homogeneous nucleation were to become important, it would only be so at very few locations. Moreover, the supersaturation is accounted for in the ice nucleation algorithm in the bin model and is detailed in the references provided. We have excluded details

of the representation of ice nucleation processes as they are beyond the scope of this work and are still a topic of great uncertainty within the community.

References

Clark, T. L. (1973), Numerical modeling of the dynamics and microphysics of warm cumulus convection, *J. Atmos. Sci.*, *30*, 857–878.

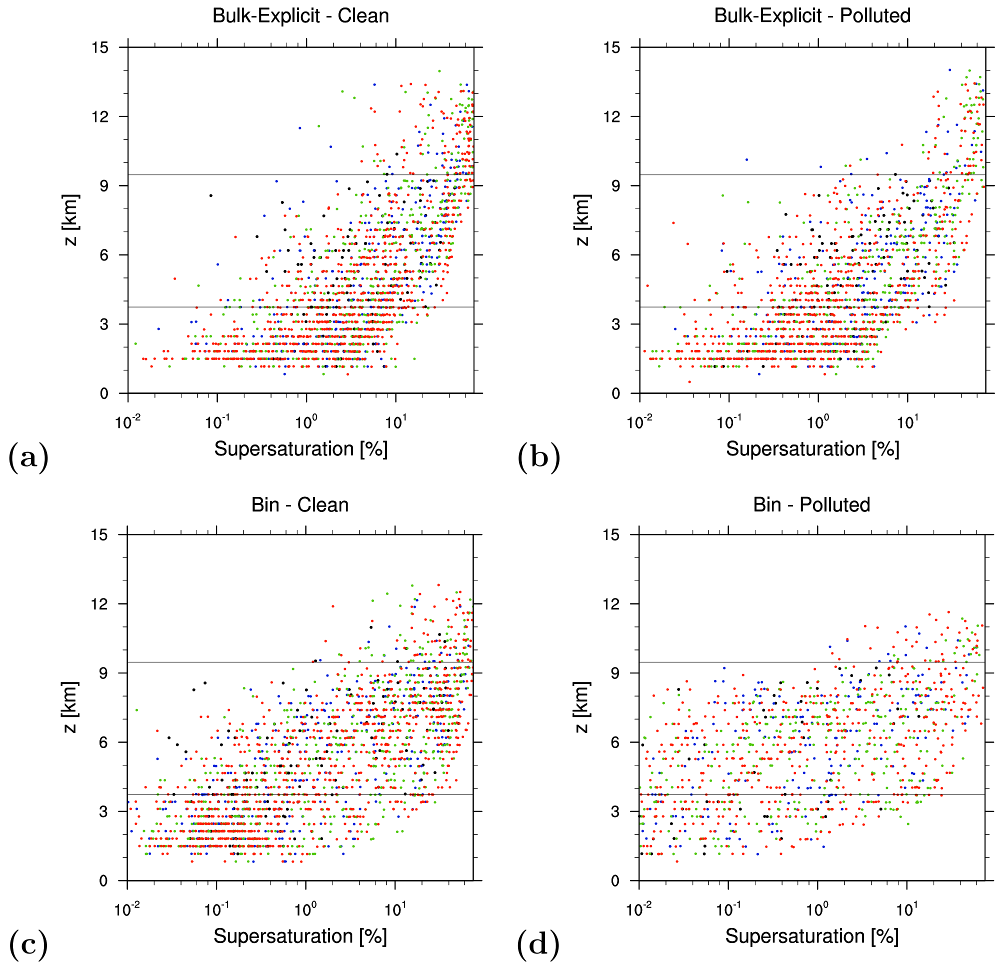

FIGURE 1. Scatterplot of ambient supersaturation as a function of height and time. Due to the large data sets, only every 40th point is shown. The colors correspond to 30 min (black), 60 min (blue), 90 min (green), and 120 min (red) into the simulations for the bulk-explicit and bin model configurations. The horizontal lines at 3.4 and 10.5 km are shown for referencing the mean height of the 0°C isotherm and the height at which homogeneous freezing of droplets occurs (i.e., about -38°C).

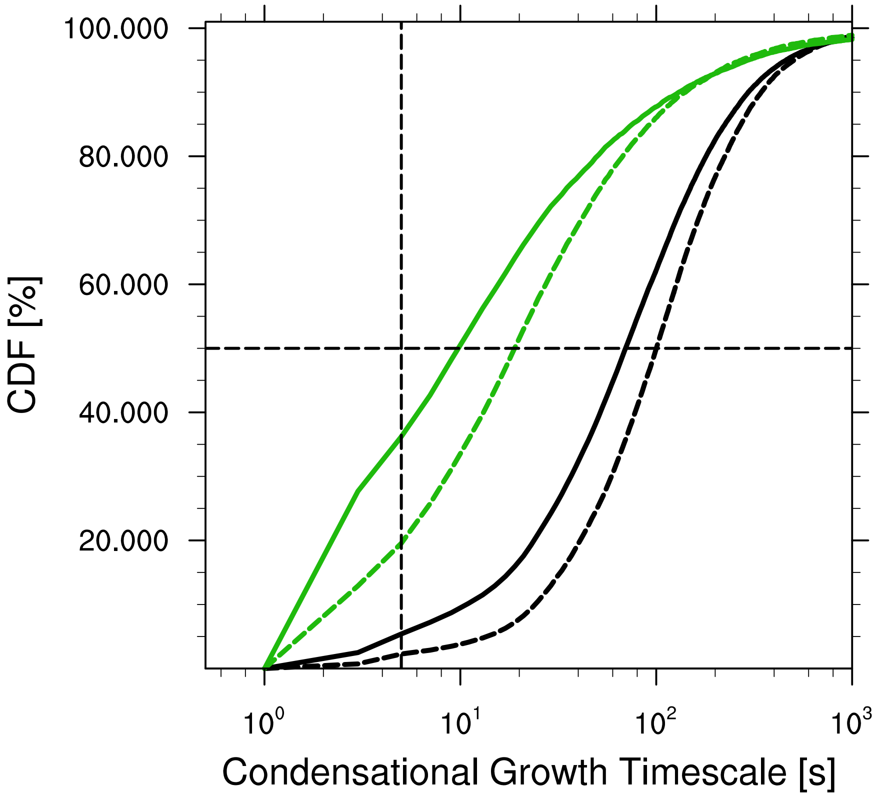

FIGURE 2. Cumulative distribution function (CDF) of the condensational growth timescale. The horizontal and vertical dashed lines correspond the the 50th percentile (i.e., median of the distribution) and the model time step, respectively. Colors correspond to those used in Fig. 12.