Atmos. Chem. Phys. Discuss., 11, C2975–C2981, 2011
www.atmos-chem-phys-discuss.net/11/C2975/2011/

Atmospheric
Chemistry
and Physics
Discussions

Interactive comment on “Theoretical basis for convective invigoration due to increased aerosol concentration” *by* Z. J. Lebo and J. H. Seinfeld

Z. J. Lebo and J. H. Seinfeld

zachlebo@caltech.edu

Received and published: 9 May 2011

We thank the anonymous reviewer for his/her thoughtful comment and criticism. Our responses to the major points are below. The points correspond, in order, to those in the review.

1. The Method of Moments technique introduced by *Tzivion et al.* (1987) is an adequate method for performing collision calculations. The kernels are mass-weighted and thus are adjusted on each time step to represent the mass and number within each bin. Moreover, the moment conserving technique has been used recently in numerous studies (e.g., *Hill et al.*, 2008; *Xue et al.*, 2010).

2. We agree with the reviewer that limiting the model to 32 bins for each hydrometeor category presents a physical limitation on the validity of the numerical results. We have modified the hydrometeor distributions to include 36 mass doubling bins. The paragraph detailing the distributions has been changed to: “The mixed-phase bin microphysics scheme divides each hydrometeor spectrum into 36 bins (i.e., $x_{j_1}, x_{j_2}, \ldots, x_{j_{36}}$, where j corresponds to the hydrometeor type: c, i, s, and g for liquid cloud droplets, pristine ice, snow, and graupel, respectively, and x is the mass) with mass doubling between bins such that

   $$x_{k+1} = 2x_k \tag{1}$$

   in which k corresponds to the lower boundary of bin number k. The mass of the smallest bin is defined to be 1.598×10^{-14} kg (*Reisin et al.*, 1996), which, for liquid droplets (with density $\rho_{\mathrm{l}}=1000\,\mathrm{kg\,m^{-3}}$) corresponds to a diameter of 3.125 μm. Additionally, we assume fixed bulk densities for the frozen species, i.e., $\rho_{\mathrm{i}}=900\,\mathrm{kg\,m^{-3}}$, $\rho_{\mathrm{s}}=200\,\mathrm{kg\,m^{-3}}$, $\rho_{\mathrm{g}}=500\,\mathrm{kg\,m^{-3}}$. The choice of 36 bins allows hydrometeors to attain appreciable sizes for precipitation to occur while minimizing the risk of creating numerical instability due to very large particles falling through grid boxes within a single time step. With these assumptions, the droplets, pristine ice, snow, and graupel can grow to 10.1 mm, 10.5 mm, 17.3 mm, and 12.8 mm, respectively. These sizes are adequate to accurately represent the formation of hail and the changes in hail formation due to aerosol perturbations that has been shown to be important in previous studies (e.g., *Andrejczuk et al.*, 2004; *Khain et al.*, 2011).” The suite of simulations have been rerun and the figures have been updated accordingly in the revised manuscript.

3. In regard to the shortcomings of the model described in the original manuscript, please refer to point (2) above. We have replaced “demonstrate” from statements in the manuscript in which the word is not fully appropriate

Below, we list our responses/modifications/etc. regarding the specific comments. The comments here are preceded by the line number given in the anonymous review:

- Page 2776, line 3: “Cold rain” has been replaced with “mixed-phase”.

- Page 2776, line 4: The statement pertaining to collision-coalescence has been clarified. It now reads, “not directly by collision-coalescence of liquid droplets into larger, rain drops”

- Page 2776, line 6: *Koren et al.* (2005) has been moved to the end of the sentence in which the observational studies are listed.

- Page 2776, lines 13-14: We have added the following statement to clarify the comment in reference to *Rosenfeld et al.* (2008): “*Rosenfeld et al.* (2008) suggest that a decrease in invigoration of deep convective may occur due to the direct effect of aerosols acting to limit the downward shortwave radiative flux at the surface, mitigating surface warming and leading to weaker convection.”

- Page 2776, line 16: The statement regarding previous studies in the previous paragraph now reads: “Recently, the potential effects of polluted environments on the formation and development of deep convective clouds have received attention via both modeling studies using a 3D CRM with bulk microphysics (e.g., *Van den Heever et al.*, 2006; *Van den Heever and Cotton*, 2007), 3D CRM with bin microphysics (e.g., *Khain et al.*, 2008; *Khain and Lynn*, 2009), 2D CRM with bin microphysics (e.g., *Fan et al.*, 2009) and, less commonly, observational analyses (e.g., *Koren et al.*, 2005, 2010).” We have also included the model used by *Van den Heever et al.* (2006). Moreover, *Van den Heever et al.* (2006) and *Van den Heever and Cotton* (2007) are now cited correctly.

- Page 2776, line 25: The details regarding the dynamic framework have been added.

- Page 2776, line 27-28: The reference has been included in the revised manuscript.

- Page 2777, line 7: The details of *Fan et al.* (2009) have been changed as discussed in the response to Dr. Fan’s comments.

- Page 2777, lines 17-19: The statement regarding the results of *Koren et al.* (2010) now reads: “By broadening the anvil, the cloud becomes thinner and thus reduces the cloud albedo while the outgoing longwave radiation is relatively unchanged since the cloud top temperature does not change much. In turn, this combination results in an increase in the solar radiation reaching the surface.”

- Page 2780, lines 7-8: The statement regarding CAPE now reads: “...can increase the released gravitational energy, which is equivalent to changing the effective convective available potential energy (CAPE) of the parcel by >1000 J kg^{-1}.”

- Page 2780, line 10: We have added the following statement: “*Rosenfeld et al.* (2008) also discussed that the increase in evaporative cooling within the downdrafts near the surface provides additional additional upward heat transport leading to convective invigoration.”

- Page 2790, line 7: The text has been changed as discussed in the response to Dr. Fan’s comments

- Page 2791, line 11: We have clarified the statement regarding the sedimentation of cloud particles to now read: “...the downward flux of condensed water integrated over a timestep is dependent upon the timestep. In other words, a longer timestep may allow more cloud water to fall of a particular gridbox before other relevant microphysical processes can occur (i.e., collisions).

- Page 2792, line 9: Our statement regarding model resolution has been clarified to ensure that we discuss only similar modeling frameworks. The statement now reads: “We understand that even at the resolution used in the current work, although higher than that of previous studies in which 3D CRM simulations using bin microphysics was used...”.

- Page 2793, line 15: The statement regarding model resolution has been changed to “First, we simulate the evolution of deep convective clouds at a much higher resolution than previous studies using a comparable CRM.”
- Page 2793, lines 24-25: The units have been changed to ’m’.
- Page 2796, lines 7-9: As per point (2) above, we have modified the microphysics scheme to better capture the sedimentation of the cloud mass. We have also modified the text to include the fact that the results here suggest a decrease in precipitation (even though, under high RH conditions, the lower levels of the cloud may be invigorated) due to increased aerosol loading is reduced in the bin microphysical framework.
- Page 2802, line 26; Page 2803, line 28; Page 2805, line 21: These points have been addressed by increasing the number of bins to 36 in each hydrometeor category.
- Page 2807, line 21: According the *Meyers et al.* (1992) parameterization of freezing, the freezing rate is dependent upon the supersaturation. Thus, if more droplets freeze at warmer temperatures and subsequently grow rapidly via vapor diffusion, the ambient supersaturation is reduced, and thus the freezing rate at colder temperatures is reduced. This ought to lead to an environment in which more supercooled water exists.

References

Andrejczuk, M. O., D. Rosenfeld, P. Artaxo, A. A. Costa, G. P. Frank, K. M. Longo, and M. A. F. Silva-Dias (2004), Smoking rain clouds over the Amazon, *Science*, *303*, 1337–1342.

Fan, J., T. Yuan, J. M. Comstock, S. Ghan, A. . Khain, L. R. Leung, Z. Li, V. J. Martins, and M. Ovchinnikov (2009), Dominant role by vertical wind shear in regulating aerosol effects on deep convective clouds, *J. Geophys. Res.*, *114*(D22206), doi:10.1029/2009JD012352.

Hill, A. A., S. Dobbie, and Y. Yin (2008), The impact of aerosols on non-precipitating marine stratocumulus. model description and prediction of the indirect effect, *Quart. J. Roy. Meteor. Soc.*, *134*, 1143–1154, doi:10.1002/qj.278.

Khain, A., and B. Lynn (2009), Simulation of a supercell storm in clean and dirty atmosphere using weather research and forecasting model with spectral bin microphysics, *J. Geophys. Res.*, *114*(D19209), doi:10.1029/2009JD011827.

Khain, A., N. BenMoshe, and A. Pokrovsky (2008), Factors determining the impact of aerosols on surface precipitation from clouds: An attempt at classification, *J. Atmos. Sci.*, *65*, 1721–1748.

Khain, A., D. Rosenfeld, A. Pokrovsky, U. Blahak, and A. Ryzhkov (2011), The role of ccn in precipitation and hail in a mid-latitude storm as seen in simulation using a spectral (bin) microphysics model in a 2d dynamic frame, *Atmos. Res.*, *99*, 129–146.

Koren, I., Y. J. Kaufman, D. Rosenfeld, L. A. Remer, and Y. Rudich (2005), Aerosol invigoration and restructuring of atlantic convective clouds, *Geophys. Res. Let.*, *32*(L14828), doi:10.1029/2005GL023187.

Koren, I., L. A. Remer, . Altaratz, J. V. Martins, and A. Davidi (2010), Aerosol-induced changes of convective cloud anvils produce climate warming, *Atmos. Chem. Phys.*, *10*, 5001–5010, doi:10.5194/acp-10-5001-2010.

Meyers, M. P., P. J. DeMott, and W. R. Cotton (1992), New primary ice nucleation parameterization in an explicit model, *J. Appl. Meteor.*, *31*, 708–721.

Reisin, T., Z. Levin, and S. Tzivion (1996), Rain production in convective clouds as simulated in an axisymmetric model with detailed microphysics. part i: description of the model, *J. Atmos. Sci.*, *53*(3), 497–519.

Rosenfeld, D., U. Lohmann, G. B. Raga, C. D. O’Dowd, M. Kulmala, S. Fuzzi, A. Reissell, and M. O. Andreae (2008), Flood or drought: How do aerosols affect precipitation?, *Science*, *321*, 1309–1313.

Tzivion, S., G. Feingold, and Z. Levin (1987), An efficient numerical solution to the stochastic collection equation, *J. Atmos. Sci.*, *44*(21), 3139–3149.

Van den Heever, S. C., and W. R. Cotton (2007), Urban aerosol impacts on downwind convective storms, *J. Appl. Meteor. Clim.*, *46*, 828–850.

Van den Heever, S. C., G. G. Carrió, W. R. Cotton, P. J. DeMott, and A. J. Prenni (2006), Impacts of nucleating aerosol on florida storms. part i: Mesoscale simulations, *J. Atmos. Sci.*, *63*, 1752–1775.

Xue, H., A. Teller, R. Rasmussen, I. Geresdi, and Z. Pan (2010), Effects of aerosol solubility and regeneration on warm-phase orographic clouds and precipitation simulated by a detailed bin microphysics scheme, *J. Atmos. Sci.*, *67*, 3336–3354.

Interactive comment on Atmos. Chem. Phys. Discuss., 11, 2773, 2011.