Reply to Mike Fromm

We want to thank Mike Fromm for his very helpful questions and suggestions, which improved the quality of the manuscript.

Before we reply to the comments we briefly explain the overall changes to the manuscript since the original submission to ACPD.

Unfortunately, we found two small bugs in the code.
The first one was a mismatch in the look-up table used for the activation of the cloud droplets. Here, the aerosol concentrations were not correctly used.
-Instead of N_{CN}=1000 cm^{-3} a concentration of N_{CN}=200 cm^{-3} was used.
-Instead of N_{CN}=20000 cm^{-3} a concentration of N_{CN}=1000 cm^{-3} was used.
-Instead of N_{CN}=60000 cm^{-3} a concentration of N_{CN}=10000 cm^{-3} was used.
We repeated the simulations again with the correct aerosol concentrations. However, it turned out that there was no big difference between the simulations with N_{CN}=20000 cm^{-3} and N_{CN}=60000 cm^{-3}. Therefore, we decided to choose the following aerosol concentrations, to cover the full diversity of the results:

N_{CN}=200 cm^{-3}
N_{CN}=1000 cm^{-3}
N_{CN}=20000 cm^{-3}

With this new setup, the overall results concerning the influence of the aerosol concentration did not change.

The second bug was that the shutdown of the fire was not working in the model. We fixed this issue and do now see a significant effect of the fire shutdown.

Substantive Questions/Concerns

- The simulations presented differ in one respect: 3 loadings of aerosol number concentration, a "clean case" (1000/cm3), "intermediate case" (20000/cm3), and a "polluted case" (60000/cm3). All three are fed by a sensible heat source representative of an intense boreal forest fire. The "clean case" then becomes the apparent control experiment. However, it is not clear how this setup compares to a non-fire control setup, either in terms of the heat/buoyancy source or environmental aerosol loading. Have auth done a simulation of a "natural" thermal trigger and environmental CN loading? I would be interested to see a comparison of this convection as another control, with which to compare the "clean case."

  We did not conduct a "natural" thermal trigger case with environmental CN loading, because the dynamical evolution in such a scenario will not be comparable with the simulations of the pyro-clouds. For our assessment of the impact of the aerosol-cloud interactions on the evolution of a pyro-convective cloud we consider the 'clean' pyro-convective simulation as the "control" simulation, since the dynamical forcing of the clouds is identical and the aerosol effects can be assessed separately.
  However, as a test, we set up a small warm bubble by starting the fire as in the other simulations and turning it off after one minute. However, the ground and the atmospheric layers in the vicinity of the fire are still warmer after the shutdown of the fire than the

surrounding. This results in a small but constant updraft, which keeps, together with the non-existent background wind, the "bubble" alive.

(This was not clearly described in the manuscript for the sensitivity cases, therefore we added theses two sentences:

"Note, after switching off the fire forcing the location of the fire is still warmer than the surroundings. Therefore, the updraft region is still existing, but very small compared to the conditions during the fire.")

For this simulation we used an aerosol concentration of N_{CN}=200 cm^{-3} characteristic for very clean conditions.

Figure 1 shows the temporal evolution of the number of cloudy grid points including also the "warm bubble" case (blue). It is clearly visible that the behaviour of the warm bubble cloud is very different compared to the pyro-clouds. After about 14 minutes the growth of the cloud is slowed down. In contrast, the onset of the precipitation is much earlier.

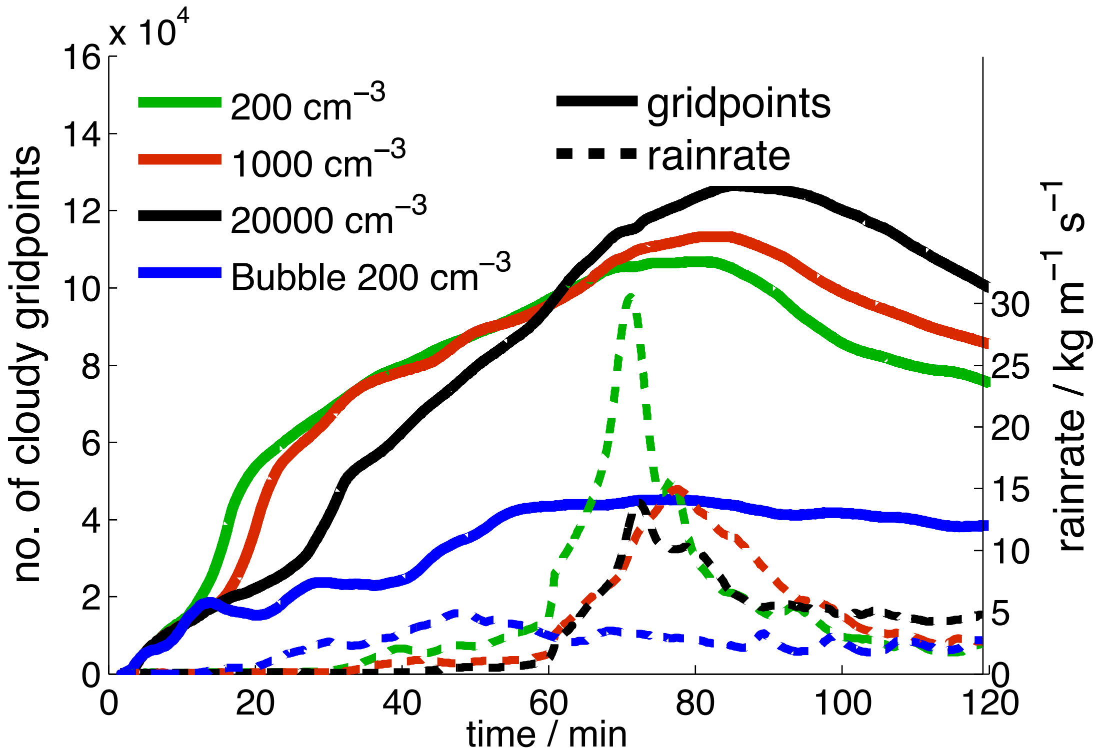


Figure 1: Temporal evolution of (solid lines) the number of cloudy grid points for aerosol concentrations (green) N_{CN}=200 cm^{-3}, (red) N_{CN}=1000 cm^{-3}, (black) N_{CN}=20000 cm^{-3} and (blue) the „warm bubble" run with N_{CN}=200 cm^{-3} and (dashed) for the rain rate (in kg m^{-2} s^{-1}) for simulations with the four specified aerosol concentrations

Figure 2 shows the spatially-averaged water content for each hydrometeor class in the "warm bubble" simulation. It is obvious that the rain formation in this case happens via the warm phase. After more than 30 minutes the glaciation of the cloud begins with graupel and hail. But the contribution in terms of water content is rather low.

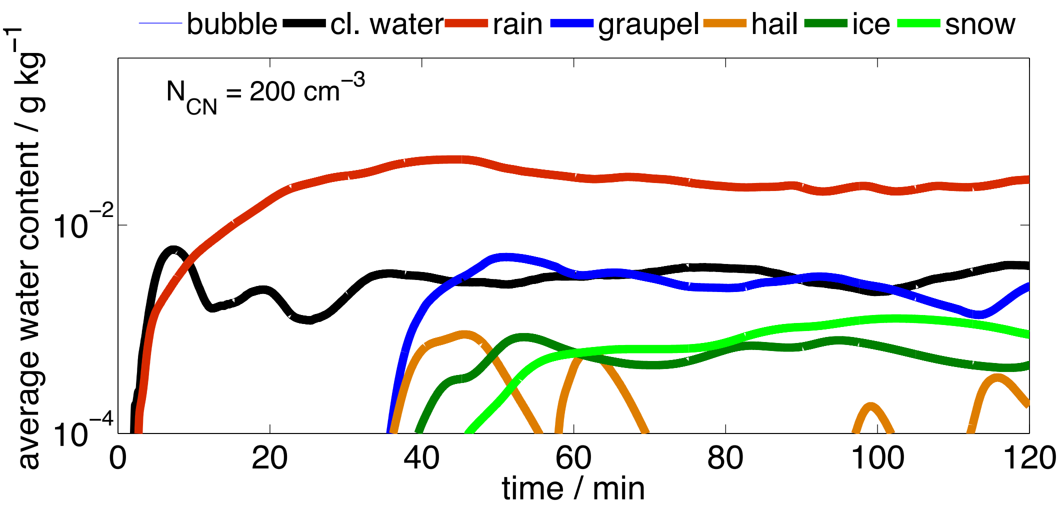


Figure 2: Temporal evolution of the averaged water content (g kg-1) in the model domain for the six hydrometeor classes (black) cloud water, (red) rain water, (blue) grauupel, (orange) hail, (dark green) ice and (green) snow for the „warm bubble" case. Time axis ends after 120 minutes.

Moreover, the fire effects have also been systematically investigated in a following study by varying the fire forcing from 1 × 10^3 to 3 × 10^5 W m^{-2} (Chang et al. 2014), which shows a strong dependence of aerosols effects on the intensity of fire forcing.

Ref: D. Chang, Y. Cheng, P. Reutter, J. Trentmann, S. Burrows, S. Nordmann, M. O. Andreae, U. Pöschl, and H. Su: Aerosol and Dynamic Effects on the Formation and Evolution of Pyro-clouds, ACPD, accepted, 2014

Overall, the main difference between the "warm bubble" case and the clean case mentioned in the manuscript is that the ice phase is playing a big role already during a very early stage of the cloud evolution in the latter case.

- Auth show a time series of cloud volume (number of cloud grid points) and rain rate for the 60 minutes of the fire and 30 minutes thereafter. Figure 1 shows that the pyrocloud is still growing (and precipitation increasing) at the end of the 90-minutes. To the extent that cloud lifetime indirect effect is a topic of this paper, it would be very informative to see the relative times of maximum cloud area and precipitation rate, both of which presumably occur after the 90-minute simulation shown. Would auth consider extending the time analysis to include the reduction of these quantities for all three simulations? Referring back to the prior question about a non-fire control scenario, the Figure 1 analysis would be even more informative with a comparison to this suggested control case.

Figure 1 in this reply shows the result for all cases during the full 2 hours. The decay of the cloud in all simulations is now obvious. In the new manuscript we also show the full 2 hours to show the decay. In our opinion, extending this further makes no sense, because the chosen setup without horizontal wind is mainly suitable for the investigation of the pyro-cloud during strong forcing but not during its decay.

Regarding the cloud lifetime effect: With the extension of the simulations to 2 hours we are now more precise and added the following to the manuscript:

"However, the maximum cloud size and the time when this maximum is reached differ for all three case. The maximum number of cloudy grid points reached during 2 hours of simulation is smallest for the clean case (106 858) after 79.5 minutes. In the intermediate case the maximum of 113 357 cloudy grid points is reached after 84.1 minutes, while the strongly polluted case reaches its maximum (126 682 cloudy grid points) one minute later (85.3 minutes). This means that with increasing aerosol concentration the maximum size of the cloud is bigger and the maximum occurs later. Note, due to the stretched grid the number of cloudy grid points is not directly proportional to the cloud size."

- A provocative finding in this paper is that the pyrocloud continues to expand, and rainrate increase, after the fire is turned off. This seems curious to me because there is no thermal forcing other than the fire, yet convective development apparently continues for at least 30 minutes in this state. However, auth do not explore the post-fire cloud dynamics or microphysics in sufficient detail. The suggestions above, to extend the simulation in the post-fire state and run a non-fire control case, also apply to this concern. And it would be valuable to see vertical views of the post-fire state and a discussion thereof.
  Due to a small programming error the fire was not turned off. However, we now see the clear response of the fire shutdown in the rain rate and later also in the size of the pyroCbs. We corrected this in the manuscript.
  Our focus in the manuscript is on the evolution of the pyroCb to its maximum size. However, due to the extension of the simulation to 2 hours, we now also describe the time after the shutdown of the fire, especially when discussing Figures 1 and 3.

- Auth show an isoline of interstitial aerosol concentration on the vertical slices through the cloud, but there is no discussion of this. It seems like a valuable element of discussion, as to how the interstitial aerosol is affected by the simulations.
  We discuss the effects of the different aerosol concentrations on the vertical distribution of the aerosol mass in Figure 2 of the manuscript.
  We now also mention the differences in the isoline of the interstitial aerosol:

  "The shapes of the interstitial aerosol plumes for each case (red contour lines in Figs. 5 to 7) show differences on small scales after 60 minutes in addition to the differing vertical distributions of the aerosol mass (Fig. 2). The interstitial aerosol plume is rather narrow below an altitude of 7km for the clean and intermediate cases. In contrast, in the strongly polluted case it is broader between 4–6 km. However, the horizontal extension of the interstitial aerosol plume at an altitude of 9 km is slightly larger for the clean and intermediate cases than in the strongly polluted case. Note that these isolines denote the shape of the smoke plume. In terms of the vertical distribution of the aerosol mass, the differences between the three cases are very small."

- On page 19537, lines 20-23, auth conclude that precipitation onset in the clean case is via liquid-phase microphysics. However, I don't see how that can be determined by the figures they show.
  The reviewer is right - this is a misleading formulation. We reformulated this sentence:
  "Therefore, the earliest and strongest onset of precipitation is due to the large rain droplets and their influence on the larger frozen hydrometeors in the clean case."

- On page 19540, line 19-20, auth make a conjecture as to the radiative effects with respect to cloud evolution. They present no basis for this. I would suggest they consider dropping this sentence.
  We omitted this sentence.

- These simulations and the presented metrics in the figures are informative, but they made me wonder how updraft strength varied in the experiments. I suggest including an analysis of maximum updraft velocity (as function of time and altitude within the cloud).
  Due to the large amount of data we did not save the data in high enough resolution to do useful time series. However, the time series of the maximum up- and downdraft within the cloud (also for the warm bubble case) and the y-z-snapshots for the different cases indicate that the aerosol loading has only a minor influence on the updraft strength during the fire (see Fig.3 below). After the shutdown, there is still a temperature anomaly at the ground, which produces a significantly smaller updraft. However, significant differences occur only after 90 minutes. Then, in the strongly polluted case, a stronger updraft region at a height of 6 km can be seen, which is not present in the other cases.
  Nevertheless, we think that a more detailed investigation of the updraft strength should be addressed in a follow-on study with background wind.

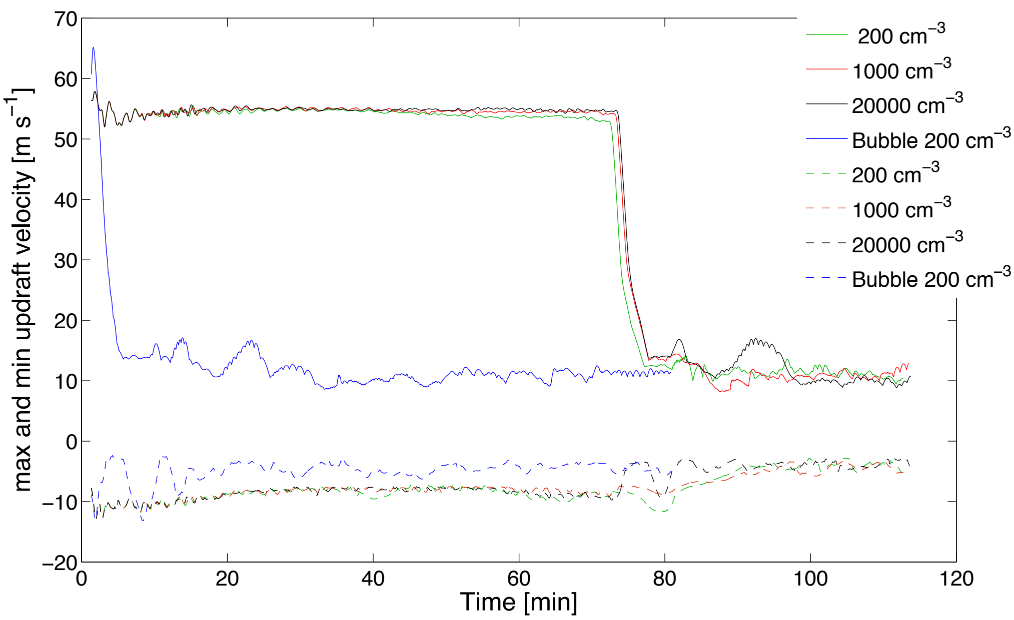
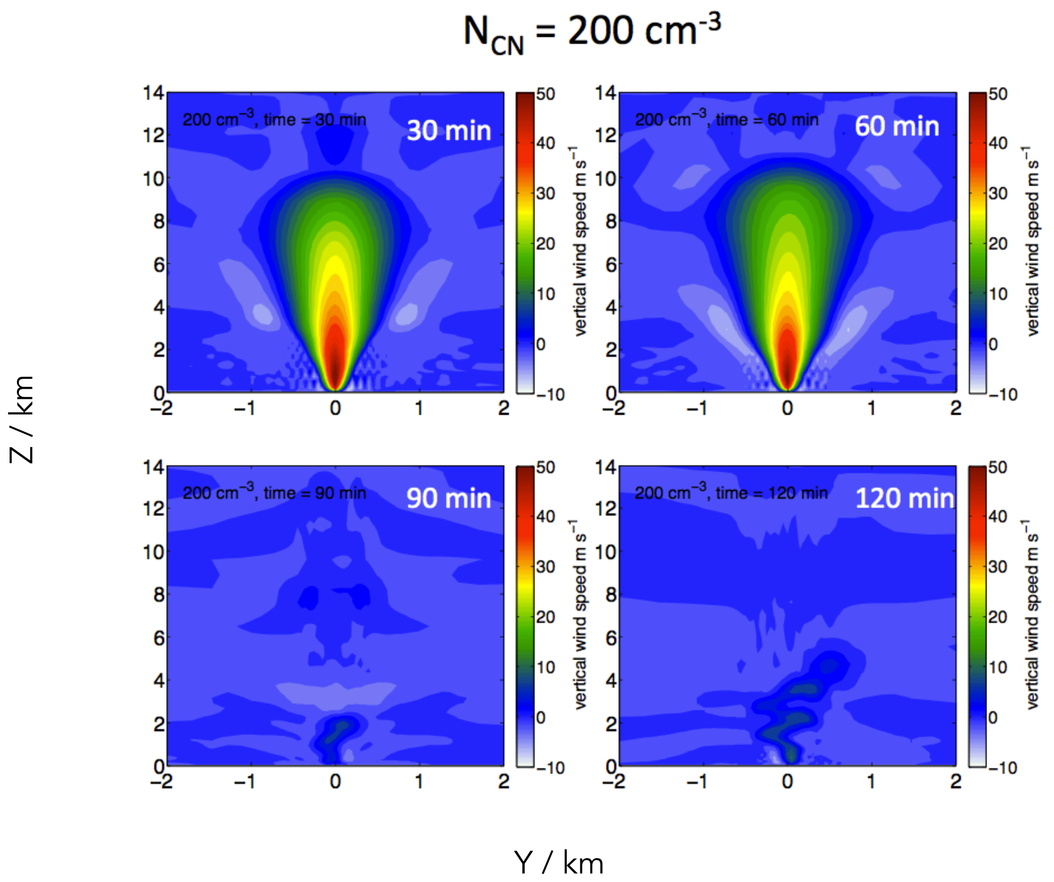
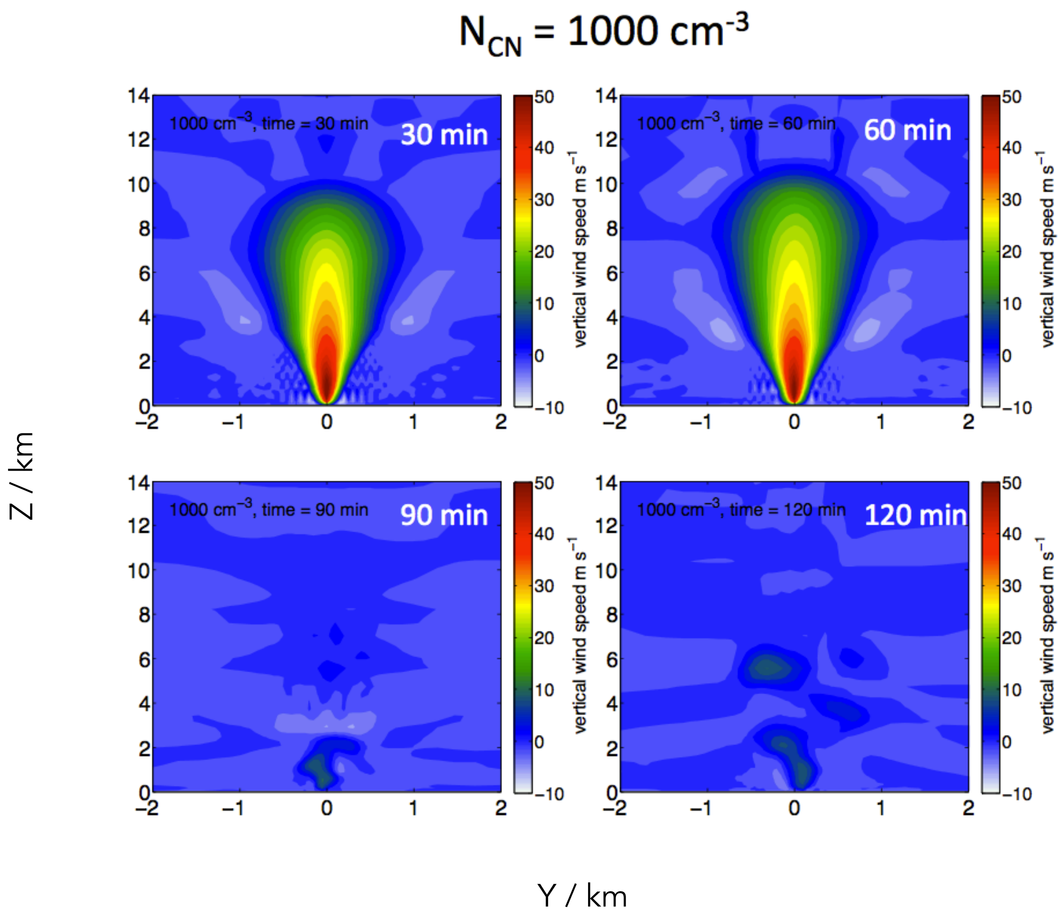


Figure 3: Time series of the maximum (solid) and minimum (dashed) vertical velocity in the pyro-clouds for the four different cases.

In the following, snapshots of the vertical velocity after 30, 60, 90 and 120 minutes shown. For the warm bubble case, snapshots are only available after 60 and 120 minutes after the start of the simulations due to data storage reasons.

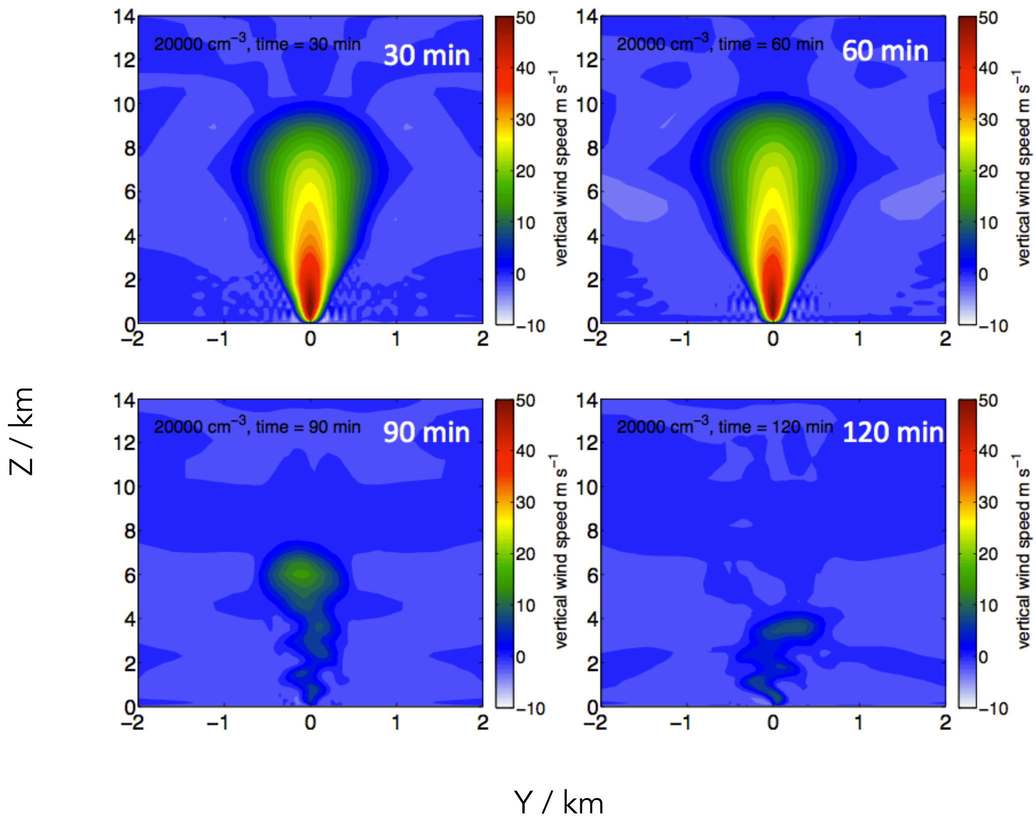


N_CN = 200 cm^-3
200 cm^-3, time = 30 min
30 min
200 cm^-3, time = 60 min
60 min
200 cm^-3, time = 90 min
90 min
200 cm^-3, time = 120 min
120 min
vertical wind speed m s^-1
Z / km
Y / km

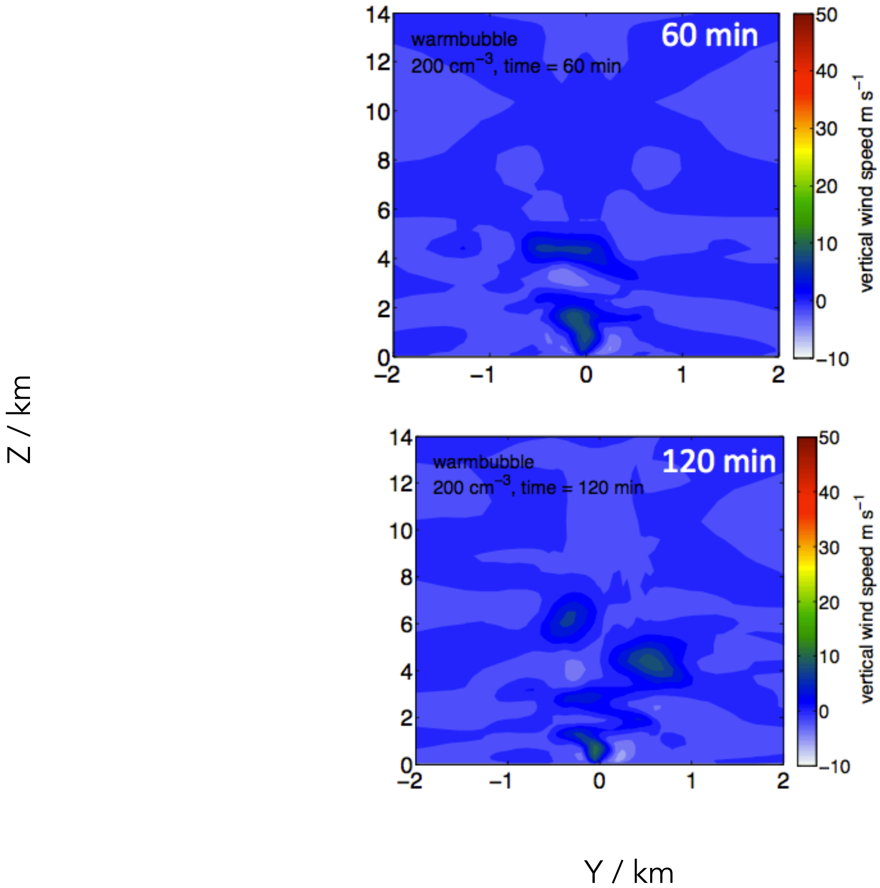


N_CN = 1000 cm^-3
1000 cm^-3, time = 30 min
30 min
1000 cm^-3, time = 60 min
60 min
1000 cm^-3, time = 90 min
90 min
1000 cm^-3, time = 120 min
120 min
vertical wind speed m s^-1
Z / km
Y / km

N_{CN} = 20000 cm^{-3}



Warm Bubble 200 cm^{-3}



Minor / Technical Issues

- P19529, L 24. Fromm et al. (2010) should be Fromm et al. (2008) (Part I or II, dealing with the Chisholm pyroCb)
  We corrected this.

- P19529, L26. Change "which lead to" to "which led to."
  Done.

- P19529, L25-27. Sentence beginning "Also, for this case. . ." requires a citation.
  The reference is from:
  Rosenfeld, D., Fromm, M., Trentmann, J., Luderer, G., Andreae, M. O., and Servranckx, R.: The Chisholm firestorm: observed microstructure, precipitation and lightning activity of a pyro-cumulonimbus. Atmos. Chem. Phys., 7, 645–659, 2007.
  We included this reference in the text.

- P19530, L5. The statement "The sensitivity simulations. . .weakly affected by the aerosol loading" needs a citation.
  The reference is:
  Luderer, G., Trentmann, J., Winterrath, T., Textor, C., Herzog, M., Graf, H. F., and Andreae, M. O.: Modeling of biomass smoke injection into the lower stratosphere by a large forst fire (Part II): sensitivity studies, Atmos. Chem. Phys., 6, 5261-5277, 2006.
  We included this reference in the text.

- P19532, L9. What is auth's modification to the Seifert and Beheng scheme mentioned here?
  We included the look-up table into the scheme, which was obtained by the parcel model studies (Reutter et al., 2009). We have rewritten these sentences to make more clear what we have done

  "*For the activation of cloud droplets the SB scheme uses a look-up table, which is not suitable for pyro-convective conditions. Therefore, a new look-up table was introduced, which is based on the aerosol activation study by Reutter et al. (2009). This study investigated the formation of cloud droplets under pyro-convective conditions using a parcel model with a detailed spectral description of cloud microphysics*."

- P19533, L23-25. Does this last sentence of the paragraph need a citation?
  We added the original reference form 1928(!):
  Courant,R., Friedrichs, K., and Lewy, H.: Über die partiellen Differenzengleichungen der mathematischen Physik, *Mathematische Annalen*, 100, 32-74, 1928.

- P19533, L4-5. "This rapid evolution is triggered by the latent heat release. . .form ice crystals, snow, and hail." Is this evident in the figures presented? If so, please point out.
  This can be seen in Figure 3, where the temporal evolution of the average water content of each hydrometeor is shown. The rapid evolution coincides with the time when significant amounts of frozen water are available. This is the case when graupel comes into play. Therefore, we replaced hail, which was wrong, with graupel. We also indicated this more clearly in the text.

- P19537, L20-23. "Nevertheless, in order to form graupel and especially hail, a sufficient amount of rain droplets is crucial. Therefore, the onset of precipitation in the clean case occurs via the liquid phase." I do not see where this is shown in Figure 5. Please clarify.
  The reviewer is right - this is a misleading formulation. We reformulated this sentence:
  "Therefore, the earliest and strongest onset of the precipitation is due to the large rain droplets and their influence on the larger frozen hydrometeors in the clean case."

- P19543, L3. "actiation" should be "activation"
  done.

- Figure 1 and 2. To me the colors of the 1000 and 60000 cases are too similar. Please consider more distinctive coloring.
  The new colouring is now:
  200 cm^{-3} = green, 1000 cm^{-3} = red, 20000 cm^{-3} = black