Reply to Anonymous Reviewer #1

We thank the Anonymous Reviewer for his helpful comments and questions, which improved the quality of the manuscript.

Before we reply to the comments of the Anonymous Reviewer #1 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.

- Abstract: the first two paragraphs do not really read like an abstract, but more of an introduction. I would suggest that it be re-written to contain the essence of the paper and the main findings.

We have shortened the abstract (first two paragraphs removed and reformulation of the first sentence) to show only the essence of the paper:

The dynamical and microphysical processes of pyro-convective clouds in mid-latitude conditions are investigated using idealized three-dimensional simulations with the ATHAM model and building upon a realistic parameterization of CCN activation. A state-of-the-art two-moment microphysical scheme has been implemented in order to study the influence of the aerosol concentration on the cloud development.… (the rest of the abstract is unchanged)

- Introduction, line 9: "air parcels to rise". You just mean convective instability. Air parcels rising is not really what is happening. The air parcel description is continued on line 11 and is an over simplification for essentially the movement / dynamics of a fluid.

We rewrote these sentences in a more precise way:

These clouds, known as pyro-cumulus or pyro-cumulonimbus convection (Fromm et al., 2010), can occur anywhere in the world with sufficient fuel density to produce enough heat to trigger convection, but are frequently observed in boreal forests (Nedelec et al., 2005; Rosenfeld et al., 2007) and tropical forests (Andreae et al., 2004). During the upward motion of the air due to the convective instability the lifted condensation level is reached and a cumulus cloud starts to form.

- Same page "this aerosol plume was observed for several months well within the stratosphere". Please provide a reference for this point.

The statement belongs not the Chisholm fire, but to a fire near Canberra, Australia in January 2003. We corrected this. The reference for this statement is: Fromm et al., Violent pyro-convective storm devastates Australia's capital and pollutes the stratosphere, Geophys Res. Let., VOL. 33, L05815, doi:10.1029/2005GL025161, 2006.

The injection of tropospheric aerosol into the stratosphere was also shown in measurements and model simulations of the Chisholm pyro-cumulonimbus of 2001 (Fromm and Servranckx, 2003; Trentmann et al., 2006; Rosenfeld et al., 2007; Fromm et al., 2010). Another aerosol plume from an Australian fire was observed for several months well within the stratosphere (Fromm et al., 2006). Again, for the Chisholm fire an extremely continental microphysical structure was documented, which lead to an efficient suppression of precipitation formation within the updraft region

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- Same page "continental microphysical structure was documented" what does this mean? Please elaborate.

We rewrote this part to be more precise:
Also, for this case an extremely continental microphysical structure was documented. This means that the high aerosol concentration led to a high number of small cloud droplets, which led to an efficient suppression of precipitation formation within the updraft region.

- Page 3 onto page 4: "sensible heat release by the fire was the most important parameter". I'd prefer to have some clearer explanation of what the context is here. What else was investigated, why was it so important, etc.

We rewrote this part:

In a sensitivity study by Luderer et al. (2006) several conditions influencing pyro-convective clouds were varied, such as sensible heat release by the fire, aerosol concentration and emission of water vapour by the fire. It was shown that the sensible heat release by the fire has the strongest effect on the development of the Chisholm pyro-cumulonimbus, which is also consistent with other studies (Penner et al., 1986; Lavoue et al., 2000).

- "is reaching higher altitudes" should be "reached higher altitudes", i.e. past tense not present tense. There are several examples of this kind of language in the text.

We have gone through the manuscript to correct this issue. However, we think in this particular case, describing a general mechanism, present tense is correct to use.

- Next sentence talks about a "positive feedback", but no details are given as to what you mean. Do you mean radiative effects? But you don't consider radiation in these calculations.

"Positive feedback" here describes the fact that more sensible heat by a fire results in higher cloud top heights which in turn intensifies the convection by additional latent heat release. However, we removed the misleading term "positive feedback"

When more sensible heat is available the cloud is reaching higher altitudes, thereby condensing and freezing more of the available water and releasing additional latent heat~~, which gives rise to a positive feedback~~.

- Line 17: "Thus, pyro-convective cloud are a unique form of atmospheric...an ideal test bed" I am not sure I follow exactly what makes them an ideal test bed. Does this really follow from what you said? I think you need to say why they are an ideal test bed.

We think they are an "an ideal test bed" because the unique characteristics of pyro-convective clouds provide the opportunity to study the influence of the aerosol concentration on the pyro-convective cloud. Especially using a broad range of aerosol concentrations (N_{CN} =200 cm^{-3} to N_{CN} = 20000 cm^{-3}) together with a fixed and intense dynamical trigger of the cloud (sensible heat of the fire) enables us to attribute differences in the simulations to the aerosol concentration. On the other hand, aerosol effects on the cloud formation have been suggested to be regime-dependent, e.g. depending on both updraft velocities and aerosol concentrations (Reutter et al. 2009; Stevens and Feingold, 2009). The extremely high concentration of aerosols and strong updrafts in pyro-convective clouds provide a specific regime which can be used to test and improve our current understandings through comparison with other contrasting regimes and environments.
We added a sentence

Thus, pyro-convective clouds are a unique form of atmospheric convection in terms of microphysical and dynamical properties, which makes them an ideal test bed for investigations of aerosol-cloud interactions using high resolution modeling. Using a broad set of different aerosol concentrations from very clean to very polluted together with a fixed and intense dynamical trigger for cloud formation (sensible heat of the fire) offers the opportunity to attribute the differences in the simulations to the aerosol concentration.

- Page 5, line 5: "within a pyro-convective clouds" should remove "a" or use "cloud" instead of "clouds"

We corrected it.

For the first time, the interaction between microphysics and dynamics within a pyro-convective cloud~~s~~ can be studied in detail within a three-dimensional high resolution model.

- Line 17: "supersonic flow around the vent of a volcano" can you provide a reference that this is the case?

The reference comes from:
Herzog, M., Graf, H.-F., and Oberhuber, J. M.: A prognostic turbulence scheme for the nonhydrostatic plume model ATHAM, J. Atmos. Sci., 60, 2783–2796, 2003: *"Since the flow close to vent can be supersonic, sound waves cannot be excluded from the dynamic equations."*

The reference is added in the text.

- Page 6, line 8: "indirect aerosol effects". I note that in the new IPCC report the authors are not referring to indirect effects anymore and have a new definition. Should this be adopted here?

We rewrote this sentence and replaced the term "indirect aerosol effects" with aerosol-cloud interactions. The new IPCC definition has its focus on the radiation, which is not in the scope of this manuscript.

The information on the number and mass of the hydrometeors is essential for this study in order to simulate the aerosol-cloud interactions in pyro-convective clouds properly

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- Line 11: "nucleation of cloud drops". It is not nucleation as nucleation implies a new phase. It is activation as liquid water exists in the aerosol below water saturation.

We replaced the misleading term "nucleation" by "activation"

For the activation of cloud droplets the model uses a look-up table based on the aerosol activation study by Reutter et al. (2009), which investigated the formation of cloud droplets under pyro-convective conditions using a parcel model with detailed spectral description of cloud microphysics.

- Line 14: "It was found that, depending on the ratio. . ." I suggest either removing this sentence or explaining it in more detail. It doesn't give the reader much at present.

The sentence was rewritten:
It was found that the cloud droplet activation shows different dependencies on updraft velocity and aerosol concentration, depending on the ratio between the latter two variables.

- Page 6, last para. It does seem odd that your definition of cloud base is an updraft velocity of 0.1 m/s, but that the look up table only has the smallest updraft equal to 1 m/s. How does this affect the calculations? Do you thus interpolate between 0 (i.e. no activated drops) and 1 m/s? Is there any potential to misrepresent the number of activated drops?

Yes, indeed. The lookup table interpolates between 0 m/s and 1 m/s. However, we think that the error in our study is rather small, because the majority of cloud base grid points shows an updraft velocity of >> 0.1 m/s. However, for studies regarding "calmer" cloud systems, more entries smaller than 1 m/s would be necessary in the look-up table.

- Section 3.1: number of cloudy grid points. I presume there is a threshold above which a grid point is counted as "cloudy". It is important to state what this criterion is so that people can repeat your analysis. Also does "cloud" include ice cloud? Does "cloud" include rain water?

Every grid point is counted as a cloudy grid point as soon as one hydrometeor category has a water content larger than $3*10^{-7}$ g kg^{-1}. We clarified this in the text.

- Rainrate in figure 1. Is this rainfall at the surface or the precipitation through the atmosphere?

In this case we refer to the precipitation that reaches the surface. We clarified this in the manuscript.

- Figure 2: I am not clear what the point of aerosol mass is since you say previously that you use the same Ncn everywhere. Can you be explicit about how the aerosol mass is used? It makes a difference to the interpretation of the results. Is it just a passive tracer emitted by the fire?

ATHAM is releasing smoke according to the fire emissions. However, in our setup the smoke acts like a passive tracer and is not visible to the cloud microphysics in ATHAM. For the cloud microphysical scheme we prescribe the number of aerosol particles N_{CN} to conduct the sensitivity studies.

We clarified this in the manuscript.

Note that the aerosol released by the fire is not used as CCN. However, it is used as a passive tracer to illustrate the behaviour of the smoke plume.

- Figure 4: on page 11, line 6 you compare the maximum liquid water content altitude. But clearly the fields are time-dependent, so I feel this should be noted. The point is that it may be that the situation looks a little different later or earlier in time.

Yes, we point that out in the manuscript now.

Please note that these figures are snapshots after 60 minute of time-dependent variables.

- Similar argument applies for figure 5: you are comparing y-z profiles at 60 minutes, whereas the fields are time dependent (see Figure 1) and the clouds are at different stages of development. You could perhaps just note this and say you are saying that the more polluted cloud takes longer to glaciate?

Yes, we changed it in the proposed way in the manuscript.

- Page 12, line 5: you talk about ice forming by freezing of cloud droplets AND by nucleation AND deposition freezing. Surely all of these are ice nucleation processes? A minor point is that deposition nucleation isn't really freezing as liquid water isn't involved at all in deposition ice nucleation.

We reformulated these sentence to be more precise

This is consistent with the results for the liquid particles, because in this case freezing of cloud droplets forms cloud ice. Nucleation of ice crystals from the gas phase does not play a significant role here due to the abundant cloud droplets.

- I think what is happening is that homogeneous nucleation of ice in the supercooled droplets is leading to high concentrations in the polluted case. You don't actually mention this but I think it is crucial to say whether or not this is the process responsible for the high concentrations (you do mention the freezing temperature of water, do you mean the temperature for homogeneous nucleation?). Otherwise why would increasing the number of biomass burning aerosol (organic aerosol, which current literature would suggest are not ice nuclei) result in an increase in the number of ice crystals in the cloud?

Yes, you are right, we clarified this in the text – see below:

When the aerosol concentration is increased the cloud droplet concentration is also increased and therefore more cloud droplets are transported to heights where they can homogeneously freeze and form cloud ice.

- Page 14, line 16: radiative effects: obviously the question of the spatial coverage of pyro-convective clouds is raised when the discussion turns to radiative effects and some discussion on this point would be welcomed.

We added a short discussion and a reference.
However, due to the different microphysical properties of the different cases, a significant change of the radiative effects can be expected (cloud albedo effect). ~~On the other side,~~ The emitted smoke and its influence on the microphysical structure and the subsequent radiative effects can have significant consequences on a larger scale. Although a climatology for intense pyroCbs is missing, the year 2002 showed at least 17 pyroCbs in North America alone (Fromm et al, 2010). Therefore, one can assume that pyroCBs are frequent phenomena in boreal regions, with an even higher occurence of the weaker pyro-cumulus clouds. This shows that pyroCbs are an important aspect when investigating the influence of clouds and aerosols on the climate.

- I would expect to see a conclusions section which states the main findings of the study succinctly. If there are no definite conclusions then it throws into question whether the paper is of worthy scientific merit to be published in ACP. I do believe it is of high enough scientific merit, but still feel the authors should make the effort of writing down the conclusions.

The main results are listed shortly at the beginning of the conclusion section as "take away messages".

In this study the influence of the aerosol concentration on the dynamical and microphysical evolution of a pyro-convective cloud has been investigated. The main achievements and finding of the study are:

- *A first investigation has been presented of the influence of aerosol particles on the evolution of a pyroCb using a realistic description of the activation of cloud droplets.*
- *Clear and distinct differences in the microphysical evolution of pyro-cumulonimbus clouds are found depending on the aerosol concentration.*
- *No clear influence of aerosol particles on the dynamical evolution and the smoke transport was documented.*

In the following, the main methodology and results are summarized and discussed. *To investigate the aerosol-pyroCb interaction a sophisticated two-moment microphysical scheme (Seifert and Beheng, 2006) has been implemented into the cloud-resolving model ATHAM. To study the influence of different aerosol concentrations on pyro-convective clouds a lookup table based on the results of a cloud droplet activation study (Reutter et al., 2009) was included into the microphysical scheme.*

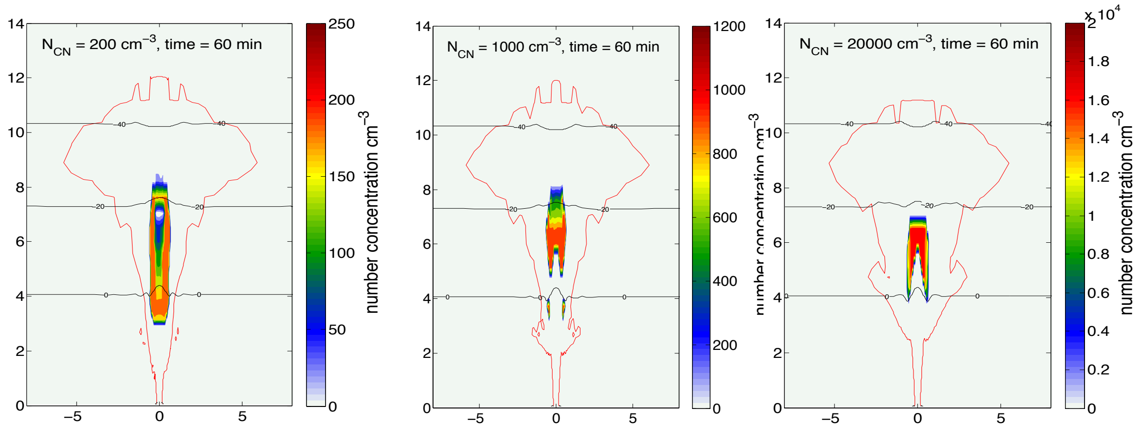
- Fig A1, A2 and A3 are only referred to in the appendix and not described at all.

We refer to these figures when discussing the mean volume radius. However, we will move these figures to the supplement area in ACP together with the figures concerning the number concentrations (see next remark)

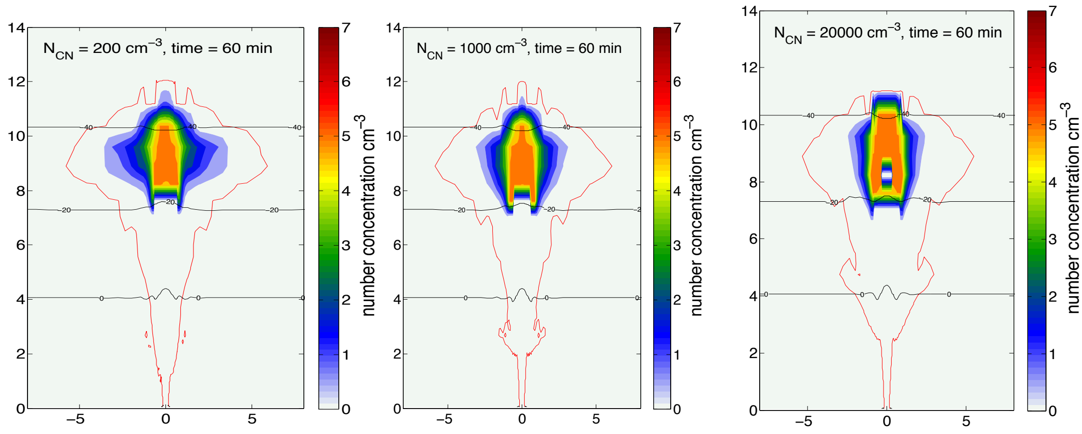
- It would be really useful to know what the droplet number and ice number concentrations were in the clouds. I did not see any of this information but is it relevant to assess whether the microphysical schemes are producing realistic cloud fields. For instance with 60,000 /cc of aerosol particles it is somewhat surprising that

We will add these figures in the supplements. The numbers are reasonable for the used numbers of CCNs.

Cloud droplet number concentration



Ice crystal number concentration



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Reutter, P., Su, H., Trentmann, J., Simmel, M., Rose, D., Gunthe, S. S., Wernli, H., Andreae, M. O. and Pöschl, U.: Aerosol- and updraft-limited regimes of cloud droplet formation: influence of particle number, size and hygroscopicity on the activation of cloud condensation nuclei (CCN), Atmos. Chem. Phys., 9, 7067-7080, doi:10.5194/acp-9-7067-2009, 2009.

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