Reply

We thank both reviewers for their reviews and suggestions to improve the manuscript. We have thoroughly considered all of them, and have modified the enclosed the manuscript accordingly. For your convenience, we have put reviewers' comments in italic and our replies in regular fonts.

Dr. Khain's comments:

The paper shows that the gradient of pressure fluctuations increases vertical velocity in the front of the ascending volume, which can lead to increase in relative humidity and droplet nucleation near cloud base. The simulations performed for short time period showed that in developing clouds droplet nucleation may take place near cloud top that can lead to droplet spectrum broadening near cloud top. The results are of interest and this study is worth to publish.

Reply: We would like to cordially thank Dr. Khain for the helpful comments and suggestions.

1. In the conclusion the text says: " This finding can explain why the observed liquid water content and the temperature of cumulus clouds in the early stage are less than the adiabatic values of air parcels ascending from the cloud base". To my understanding, the authors want to say that the cloud volumes near cloud top ascend not from the cloud base level, but from higher levels (higher lifting condensation levels) being forced to ascend by the pressure fluctuations caused by volumes ascending from lower levels. As a result, the volumes near cloud top have LWC lower that the adiabatic value calculated for the parcels ascending from the cloud base. If this statement is correct, it would be important to include it into the article.

Reply: We appreciate this comment. We added the following sentences in the modified version of the manuscript:
"The cloud volumes in the upper part of cumulus clouds result from moist air being forced by the pressure gradient force generated by the dynamic perturbation pressure and then ascending from different altitudes above the cloud base. As a result, the upper parts of cumulus clouds contain lower liquid water contents than those of adiabatic values of cloud air ascending from the cloud base."

2. It would be important to add some discussion about possible consequences of the effects discussed in the study, for instance: a) decrease in liquid water fraction with height is not always a result of a dilution with environment, but can take place in adiabatic volumes just because of different lifting condensation levels of parcels ascending within a cloud. b) small droplets observed near cloud edges can be formed not because of evaporation caused by the mixing with dry environment, but due to in-cloud nucleation. c) this process leads to the DSD broadening toward smaller sizes.

Reply: We appreciate this comment. We added the following sentences in the modified manuscript:

The decrease in liquid water content with height at the upper parts of cumulus clouds has often been observed (Pruppacher and Klett, 1997; Rauber et al., 2007; Heymsfield et al., 2009). Entrainment of unsaturated air into clouds and subsequent cloud dilution have been applied to explain this phenomenon by means of boundary mixing either from the interface of the cloud top (Squires, 1958; Paluch, 1979) or from the periphery of the main updraught with vortex-like structures in the upper parts of cumulus clouds (Grabowski, 1993; Carpenter et al., 1998a,b; Zhao and Austin, 2005). However, our study shows that this phenomenon need not be always explained by entrainment and mixing because cloud air adiabatically ascending from different lifting condensation levels can also lead to a decrease of liquid water content with height.

The existence of small cloud droplets near cumulus cloud edges has always been considered as a result of homogeneous mixing of dry environmental air (Warner, 1969, 1973; Baker and Latham, 1979; Small and Chuang, 2008) and subsequent cloud droplet evaporation (Telford et al., 1984). Cloud droplet nucleation instead of droplet evaporation can also result in the formation of small cloud droplets at the cloud-environment interface. Furthermore, the entrained air from a subsiding cloudy shell in the late development stage of cumulus clouds will be driven upwards by the pressure gradient force generated by the dynamic perturbation pressure (Zhao and Austin, 2005). This expansion cooling process can also lead to entrained air to be supersaturated. The numerical simulations for deep convective clouds showed that small droplet nucleation occurs at the cloud periphery (Khain and Pokrovsky, 2004， Slawinska et al., 2011). The main physical mechanism for small cloud droplet formation may be the nucleation process rather than the evaporation process in the developing stage of cumulus clouds. Therefore, the phenomenon of cloud droplet spectrum broadening toward small sizes may be mainly attributed to dynamically driven microphysical processes of cloud lateral-interface nucleation, cloud top-interface nucleation and even in-cloud nucleation (Pinsky and Khain, 2002; Segal et al., 2003; Prabha et al., 2011; Khain et al., 2012).

The formation of sufficiently large cloud droplets (diameter around or greater than 50 μm) is key to the initiation of precipitation (Beard and Ochs, 1993). Inhomogeneous entrainment of unsaturated air into clouds (inhomogeneous mixing) (Baker et al., 1980) has been considered as one of important physical mechanisms to form collision-coalescence initiators (Small and Chuang, 2008). However, entrainment and mixing cannot occur in the early developing stage of cumulus clouds. The role of inhomogeneous mixing in large cloud droplet formation may be overestimated.

3. It would be interesting to see a discussion how the effects found in the study can be distinguished from the effects of mixing and entrainment.

Reply: We appreciate this comment. We are very thankful for your fair comments. We discussed distinct effects of our finding and of mixing and entrainment from line 509 to line 544 in the new manuscript.

4. In my opinion, it would be reasonable to include references to a set of studies, where process of in-cloud nucleation and formation of small droplets at the upper levels is discussed (e.g., Pinsky and Khain 2002; Segal et al. 2003; Prabha et al, 2011; Khain et al. 2012). In these studies small droplets arise by nucleation of small cloud condensational nuclei ascending within cloudy volumes when vertical velocity of the parcels increases (or droplet concentration decreases) leading to supersaturations exceeding the values that took place in the volumes earlier. Such acceleration can be reached both due to buoyancy and the pressure fluctuations.

Reply: We appreciate this comment. We added these references in the new manuscript.

5. Note that friction between ascending volumes and neighboring volumes can lead to acceleration of the latter volumes and to nucleation of small droplets. Such effect was simulated by Khain and Pokrovsky (2004).

Reply: We appreciate this comment. We addressed this issue in the new manuscript from line 520 to line 525, and have now referenced Kahin and Pokrovsky (2004) and Slawinska et al., (2011) to the reference list.

Anonymous Referee #1

General comments:
This article uses a 1.5 dimensional cylindrical model and a LES version of the WRF model to study the role played by pressure perturbations in creating regions of local expansion and cooling near the top of an ascending cloud turret. They show that the 1.5D model produces a thin region of enhanced supersaturation near cloud top due to these pressure effects, and a similar supersaturation maximum also occurs in the WRF simulation. These results are novel and of general interest, and I recommend publication subject to addressing the minor points below.

We would like to thank the referee for above helpful comments and suggestions. We have revised the manuscript according to his suggestions. We hope that the revised manuscript can be suitable for publication.

Specific comments:
1) There are some general organizational problems that make reading the paper harder than it needs to be. The discussion makes multiple passes through the figures, first mentioning figures 1a, 2a-c, 1a again, then 1b, 3a, 3b, then back to 1c and 1d before finishing the section with 3c and 3d. This saves space, but there needs to be some warning at the beginning of section 3 about the fact that the discussion will first look at the pressure perturbation results in multiple figures before returning to discuss the

nonpressure perturbation run. Similarly the fact that it's a 1.5 D cylindrical model needs to be mentioned earlier when the "special Eulerian model" (what's special about it? WRF is also Eulerian, isn't the distinguishing feature the 1.5D approximation?) is mentioned (line 26, p. 1725). The bin microphysics scheme is described in detail for the WRF model, but not at all for the cylindrical model. If they are identical then why not move this up to the beginning, if they are different, how do they differ?

Reply: We appreciate this comment. We have addressed all of the above comments and made clarifications in our new manuscript.

a. We added warning sentences at the beginning of section 3 from line 139 to line 145 about the fact that the discussion will first look at the pressure perturbation results in multiple figures before returning to discuss the nonpressure perturbation run.
b. We added words “firstly” in line 75 and “further” in line 81 to make the manuscript easier to read. We also added one sentence from line 72 to line 73 to explain “special Eulerian model”.
c. We added two sentences from line 135 to line 139 to describe bin microphysics scheme for the cylindrical model. We also added one sentence from line 366 to line 369 to show the different microphysics treatment between WRF and the cylindrical model.

2) The reader needs more guidance about what to look for in Figure 1B (line 28, p. 17728) i.e. something like "the 25 meter thick band of elevated supersaturation that occurs at cloud top between 25 and 50 minutes". Similarly the sentence on line 6, p. 17734:"The temporal and spatial evolution of the saturation ration indicates that the parabolic feature liquid water of the liquid water content is due to the new activation of cloud droplets" occurs in a discussion of figure 4, but seems to be referring back to figures 1 and 2. And the only obvious parabola in figure 4 is in the number density (4c) not the liquid water content?

Reply: We appreciate this comment. We modified our paper according to the above suggestions. We added one sentence from line 201 to line 204 and another sentence from line 407 to line 409. The parabolic feature of liquid water content means the change tendency of liquid water content with height.

3) Grabowski and Morrison (2008) solved the spurious supersaturation problem by writing a new monotonic advection scheme for supersaturation, and then diagnosing thermodynamically consistent water and temperature fields using that prognostic supersaturation. The solution described on p. 17729 instead simply limits the rate of change of temperature when evaporation and condensation are "excessive" (line 19) What is the quantitative definition of excessive? and does this approach conserve en ergy and water? Are you satisfied that the more sophisticated approach of Grabowski and Morrison is overkill?

Reply: We appreciate this comment. Dr. Grabowski had done pioneer works to mitigate spurious cloud-edge supersaturation. Grabowski and Morrison (2008) argued that supersaturation predicted by the supersaturation equation with a monotonic advection scheme can mitigate the problem of spurious supersaturation. Meanwhile, they also demonstrated that such a scheme can results in stronger oscillations for temperature and water vapor mixing ratio near the interface than another scheme in which supersaturation is diagnosed by temperature and water vapor mixing ratio. The feedback of such oscillations on dynamic fields may result in negative impact on simulations with Eulerian models.

The spurious supersaturation diagnosed by temperature and water vapor mixing ratio occurs prominently in numerical simulations without dynamic fields for the evaporation process of water droplets. The magnitude of the spurious production of supersaturation is highly related to initial relative humidity (Stevens et al., 1996). Physically, evaporation cannot result in unsaturated air to become supersaturated. Relative humidity changes at any moment in response to temperature variation and water vapor mixing ratio in the evaporation process. However, finite-difference numerical methods assume them constant within one time step. As a result, it is possible that the air will become supersaturated due to evaporation cooling only after one time step if the time step is large enough. The difference between this time step and the time step needed to evaporate the air so that the relative humidity reaches 100% can be defined as excessive evaporation time. In order to avoid this situation and make simulations more accuracy, the time steps for microphysical processes should be as small as possible. If the spurious supersaturation occurs even with the time-splitting method, we have to stop the simulation for microphysical processes within a dynamic time step. Obviously, this approach cannot conserve energy and water. But just as Stevens et al. (1996) argue that the spurious supersaturation only occurs under the presence of sharp gradients of relative humidity in Eulerian Models. The impacts of this approximation on the simulation accuracy may be ignored for the case of the low gradients of relative humidity in the vertical direction if we consider perturbation pressures in the simulations with Eulerian models.

4) On p. 17734 the authors state that "the low liquid water content at the cloud summit cannot be explained by the entrainment mechanism for the simulation" Why not? (for example, are the thermodynamic variables in this region inconsistent with cloud environment mixtures of conserved variables?)

Reply: We appreciate this comment. Since the wind field shows that the environment air only entrains into cloud air from cloud base in the early developing stage, we can conclude that the low liquid water content at the cloud summit does not result from entrainment and mixing. Moreover, two conserved variables, the wet equivalent potential temperature and total water mixing ratio (Figure 1), in the upper part of the cloud always decrease with height in the early developing stage, which also indicates that there is no environmental air mixing with cloud air from lateral sides because these two conserved variables are not equal to the mixtures of those variables from environment and from the cloud base.

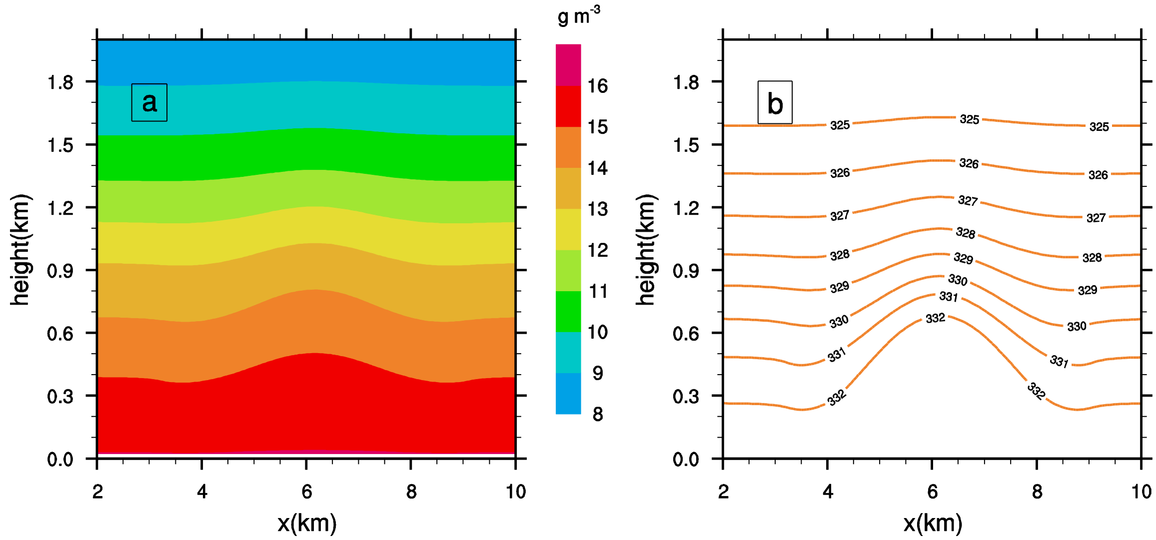

Figure 1. The vertical cross section of the simulation at 5.5 min. a. Total water mixing ratio (g/m^3), b. Wet equivalent potential temperature (^{o}C).

Technical corrections:
Figure 1b – supersaturation colorbar has units of g/mˆ3
Figure 3 – I'm assuming that (Lnm) means natural log of the mass of the bin, but there should be a mention (especially if I'm wrong).
Spelling/Grammar – "Eulerain", "from basic state", "all great than", "should keep spatially continuous",

Reply: We revised all mistakes above, and we appreciate your proofreading.

We would like to thank again the reviewers and the editor for their time, constructive comments and suggestions.

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