8 November, 2017

Dear Prof. Garrett,

Please find attached the revised paper "Theoretical analysis of mixing in liquid clouds. Part IV: DSD evolution and mixing diagrams", authored by Mark Pinsky, and Alexander Khain. All Your comments and remarks, as well as comments and remarks of reviewers are carefully addressed. Line-by-line responses are attached as well as the MS with the changes highlighted.

In considerations, the effective radius was replaced by the mean volume radius. Accordingly, seven figures were replotted. Explanations given in the responses to reviewers are given now in the text of the revised paper.

Sincerely yours,

Alexander

Prof. Alexander Khain

 Department of Atmospheric Sciences,

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Israel

Review of ACP-2017-508

In this manuscript the authors made theoretical assessment of how mixing of cloudy air with unsaturated clear air affects the evolution of cloud microphysical parameters in the mixed volume, using a one dimensional diffusion-evaporation model. Entrainment and mixing in clouds have been known to be an important but not well understood problem in cloud physics for several decades even though their effects on cloud microphysics critically affect further cloud development. In that sense, this type of study is highly needed for advancement of our understanding of the problem. The authors calculated droplet spectral evolution in a one dimensional horizontal column of 40 m length during the turbulent mixing of cloudy air and unsaturated clear air of different proportions. Mixing starts at the interface between cloudy and clear air and proceeds gradually throughout the whole length by turbulent diffusion. Cloud droplet spectrum in the mixed volume changes due to droplet evaporation until saturation is restored. All these processes are expected to occur during the entrainment and mixing and with the model they employed, the authors seem to have calculated these processes well. But the critical question is if indeed they occur in real clouds under the conditions provided in this manuscript. If not, it would be inappropriate to give so much credit to the arguments the authors made in this manuscript. Nevertheless, I think that this manuscript is worth the publication if the authors clearly specify the limitation and applicability of their results. English is definitely not up to the standard of ACP publication and therefore requires great improvement. Some specific comments are followed.

Major comments

© According to the model description, turbulent diffusion and evaporation of the droplets in the mixed volume occur simultaneously. The authors call this process inhomogeneous mixing because the degree of mixing is not uniform throughout the whole volume during the mixing. I am not sure if inhomogeneous mixing is the right term for this process.

® We state that mixing is inhomogeneous in a mixing volume because different droplets in the volume experience different subsaturations and evaporate with different rates. We believe that this definition is the logical and widely accepted.

© But I will stick to this definition for this review. In a one dimensional column, mixing may proceed only this way no matter what Damkohler number (Da) is. It seems that the model is capable of simulating homogeneous mixing as a special case for very small Da. How about the case of extremely inhomogeneous mixing, which is likely to occur when Da is very large?

® Yes, we agree that the diffusional-evaporation model can describe both homogeneous and inhomogeneous mixing. Effects of Damkohler number on mixing within the frame of diffusional – evaporation model is analyzed in detail in Part 2 and especially, in Part 3 of the study (Pinsky et al., 2016a,b). In particular, In Part 3 several types of mixing (homogeneous, intermediate, inhomogeneous and extremely inhomogeneous) are distinguished. In the present study we use parameters of mixing volume, turbulent diffusion and droplet size distribution, which as we suppose, are typical of **real** clouds. These parameters correspond to the values of Da of several hundred. Corresponding comments are included into the revised paper.

© In a 3-D space overturning of turbulent eddies during the mixing of cloudy air with clear air may create some portion of cloud volume remaining unaffected and some other portion of cloud volume losing all droplets due to complete evaporation. Is the model capable of simulating something similar to this 3-D reality when Da is very large? Or setting a different Da value just changes the speed of mixing and evaporation that occur in an in variably simultaneous fashion in the mixed volume? If so, this model does have intrinsic limitation.

® We do not describe formation of separate turbulent filaments. In the study we describe averaged effects of turbulent mixing by modeling of turbulent diffusion, characterized by a typical value of turbulent diffusion coefficient. This is specially stressed in the paper. In principle, the model allows consideration of penetration and mixing of separate filaments by setting the specific initial conditions. However, we suppose that spatial-time distribution of cloudy and droplet free filaments is not well known and require special consideration. Such investigations are out of scope of the present study.

© Another important point is that it takes nearly 5 min to arrive at the equilibrium state in the model simulations. In reality the mixed volume of 40 m length would not remain as an adiabatic entity for that long time as is pointed out by the authors themselves in the Discussion and Conclusion section. Therefore, I am hesitant to give too much credit for the arguments based on the results obtained at the equilibrium state.

® We agree with Reviewer. Moreover, in this study and in some other our papers we show that mixing in real clouds does not reach equilibrium state and that the scattering diagrams observed in situ are just snapshots of the transient mixing process. However, since the classic mixing diagrams are plotted namely for equilibrium states, we investigate transition to such equilibrium assuming that the mixing volume remains adiabatic (i.e. isolated) during the entire period of mixing.
   This point is stressed in the revised paper (conclusion section).

© Narrow and wide DSDs are used as input to the model. It is shown that mixing and evaporation actually result in increase of r_e in the mixed volume when DSD is wide. However, assuming a wide DSD does not reflect the reality. In the argument of entrainment and mixing, we start with an adiabatic cloud parcel and see how entrain and mixing of clear air would affect cloud microphysics in this parcel. Importantly, droplet distributions in adiabatic parcels are intrinsically narrow. The wide DSD the authors used is therefore unrealistic. If a wide DSD is observed in a cloud parcel, it would indicate that this parcel has already been through severe entrainment and mixing and/or coalescence process but certainly not a parcel that will start entrainment and mixing just now.

® Indeed, pure diffusion growth leads to very narrow DSD. However, several other microphysical processes lead to DSD broadening. Mechanisms of DSD broadening in ascending adiabatic volumes are considered in several studies (e.g., Khain et al (2000), Pinky and Khain (2002), Segal et al. (2004), Prabha et al. (2011). These studies show the DSD broadening is caused by in-cloud nucleation of droplets within clouds as well as by collisions. It is shown that DSDs in adiabatic volumes can be wide and first raindrops or drizzle arise namely in non-diluted adiabatic cloud parcels (Khain et al. 2013), Magaritz-Ronen et al. 2016). We use wide DSD in the form of gamma distribution with parameters typically used in different bulk-parameterization models. We agree that mixing leads to additional DSD broadening. We also do not see any problem if the DSDs, which are used as initial DSDs in cloudy parcels were affected by mixing during by their previous history. It does not affect our analysis.

© RH of 60% is the lowest in the model calculation of this manuscript. What about the mixing of air with RH of~20%, which is a proper RH value for the air above the stratocumulus cloud top in the subtropics? Mixing will be more likely to be extremely inhomogeneous when this very dry air is entrained. Can this be simulated in the model?

© The authors claim that mixing diagrams are not capable of distinguishing between mixing types. Moreover, results are not distinguishably different for different RH values of entrained clear air (Fig. 11). However, distinction between inhomogeneous and homogeneous mixing seems so obvious in Fig. 9a. It is not so in Fig. 9b as the authors claim but here unrealistically wide DSD is used for the calculation and therefore giving too much credit is unjustifiable. Even in the traditional mixing diagram that uses normalized concentration (N/N_1) as in Fig. 11, distinction should be obvious between inhomogeneous and homogeneous mixing and also among different RH values for homogeneous mixing. The authors do not put the lines for homogeneous mixing in Fig. 11. If they do, I expect that the results would be distinctively different from those for inhomogeneous mixing.

Their argument is based only on the results for inhomogeneous mixing. However, RH dependence of inhomogeneous mixing is not known to be significant anyway and has never been discussed in mixing diagram analysis (e.g., Burnet and Brenguier, 2007).
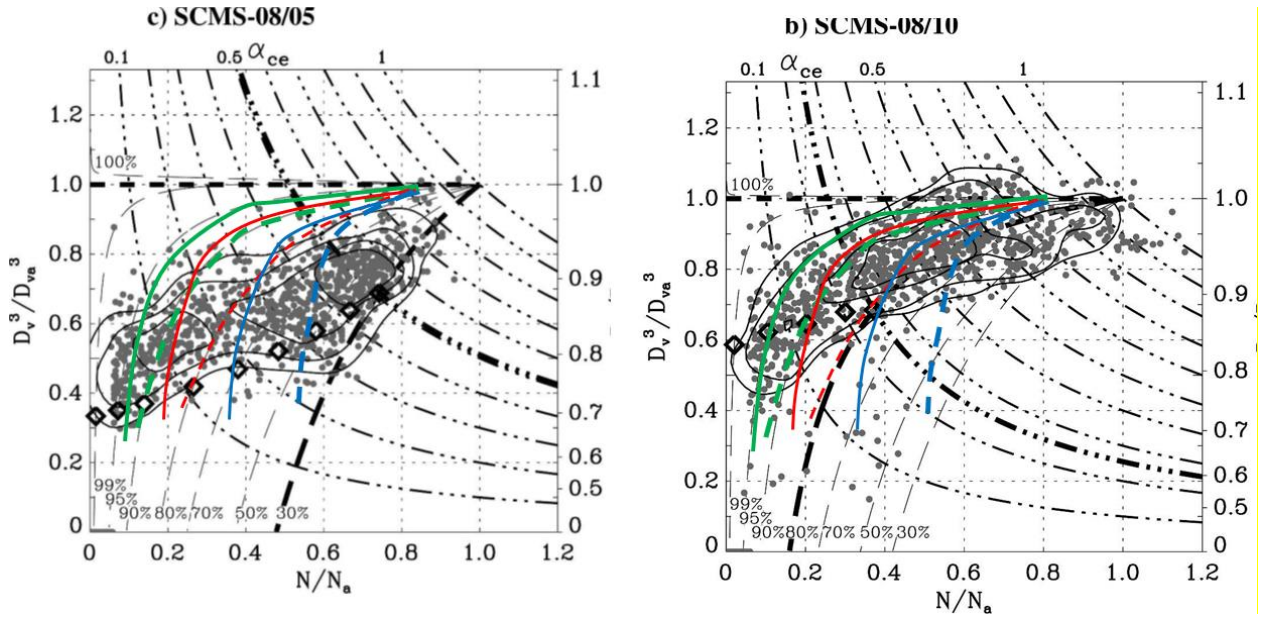
© Another thing to note is that in the traditional mixing diagram, y-axis is the cube of normalized mean volume radius (representing mean volume of the droplets), not the cube of normalized effective radius as is used in this manuscript. With the obvious relationship of $L = NV$, where L is the liquid water content, N is the number concentration and V is the mean volume of the droplets, L/L_a (i.e., normalized L, where L_a is the adiabatic value of L) = const lines can be drawn with rectangular hyperbolic lines in the mixing diagram, making the diagram somewhat like a 3 D field of N, V and L (Burnet and Brenguier, 2007). So I recommend the authors to use mean volume radius instead of effective radius.

® The mean volume radius is used in the revised paper in the analysis instead of effective radius. Seven figures were replotted accordingly.

Minor comments

© L28: It is not right to say that droplet concentration remains unchanged when mixing is homogeneous. It does reduce because of simple dilution of cloud volume by clear air. The total number of droplets in the whole mixing volume remains unchanged but not the concentration, which is the number of droplets in a unit volume.

® Yes, we agree. The corresponding sentence is corrected.

© In several Figure captions, it is stated that p = 8288 mb. Shouldn't it be 828.8 mb?

® Corrected

© Figures 9, 10 and 11: How are re/re0 values obtained? Are they averages for the whole mixed volume at the time when equilibrium is achieved? How about N/N1? Explain clearly.

® In these figures the mixing diagrams corresponding to the final equilibrium states are calculated. In the equilibrium state (about 300s) all quantities, including mean volume radii (and effective radius) and droplet concentration become uniform along x-coordinate.

© Inappropriate English expressions are found in many places in this manuscript. They need to be corrected.

® We have improved English whenever possible.

Theoretical analysis of mixing in liquid clouds. Part IV: DSD evolution
and mixing diagrams by M. Pinsky and A. Khain

This study present analysis of mixing in cloudy and clear air. Evolution of DSD has been analyzed using poly-disperse initial DSD and varying cloud fraction µ. A diffusion-evaporation model was considered for the analysis. The main findings are
   • Mixing diagram has multi-parameter characteristics.
   • In dry volume, mixing leads to a rapid increase in RH
   • DSD shape changes based on initial DSD chosen.
   • The critical cloud fraction μ_{cr} with respect to total droplet evaporation are same for any mixing type.
   • Mixing diagrams for homogeneous and in-homogeneous mixing for poly-disperse DSD do not differ much.

It was concluded that classical concept of mixing diagram is too crude to distinguish the mixing type in observation data.
® Thank you for the clear summary of the study

General comment: Overall, the manuscript is worth to publish after explaining questions below.

Major comments:

1.   Explain the reason for considering droplet concentration by averaging along X-axis only why not in whole domain? Also, why vertical velocity was neglected? Since, the analysis is done based on these assumptions, it is inappropriate to make strong general statement about mixing diagrams.

® The paper reconsiders the classical theory of mixing diagrams. In the classical theory two volumes (cloudy and droplet free) mix with each other within a given unmovable mixing volume (see review by Korolev et al., 2016). We *do not perform* averaging along X-direction. Instead, we calculate time dependencies of microphysical parameters along X-direction (e.g. figs. 2-7). Mixing diagrams are plotted for times when all variables become uniform within the mixing volume, i.e. when the equilibrium state is reached.
We plot the mixing diagram using the same simplifications used in the widely accepted (classical) mixing diagrams, namely: no vertical motions and no collisions are allowed. These assumptions allow to reveal better the microphysical effects of turbulent mixing. It is widely assumed that the mixing type is determined by the Damkohler number that depends only on drop relaxation time and mixing time. No averaged vertical velocity and no collision rate are included into this criterion.

 Aiming at reconsidering the classical theory, we use the same simplifications as regards to dynamical processes (i.e. mixing is assumed to be turbulent, and averaged vertical velocity is equal to zero). We extend the theory, however, in several important aspects concerning

microphysical effects: a) we consider time dependent process of mixing and b) initial droplet size distributions are assumed polydisperse.

These simplifications are clearly formulated in the paper and corresponding discussion is included to section 4 of the revised paper.

We agree that averaged vertical velocity, as well as collisions, affect DSDs, but these changes in DSDs are not related directly to mixing, and are described by other microphysical equations.

2. In this analysis, collision and coalescence was not considered which also contribute in broadening of DSD. Authors should make comments on this issue.

®. We agree that many microphysical processes lead to the DSD broadening. The new feature that we stress in the study is that any mixing leads to DSD broadening (in contrast to conclusions of classical theory, considering monodisperse DSDs.) The corresponding comment is added into the conclusion section.

3. The result shows that in dry volume large droplets do not change their size significantly. This is not the case in general because during mixing, droplet size starts decreasing as soon as they enter in dry volume. Authors should provide the reason for it.

® According to equation of diffusion growth/evaporation, in of sub-saturation the rate of droplet radii decreases is inverse proportional to droplet radius. It means that if, say, 2 μm radius droplet decreases twice during a certain time instance, the radius of 20 μm droplet will decrease by less than 0.1 μm. It means that the relative decrease in the sizes of large droplets is much lower than that of small ones. That is why, we wrote that the size of large droplets remains approximately unchanged.

Corresponding comments are included into the revised paper (see description of the DSD evolution).

4. Traditional mixing diagrams should be plotted for normalized values of cube radii vs. number concentration and then compare with mixing diagrams proposed in this study.

® All figures (seven figures) containing effective radius are replotted. The effective radius is replaced by the mean volume radius.

Minor comments:
1. All figure labels, legends should be bigger size to be visible enough.
® Figures 5 and 6 are replotted.

2. Some references related to recent numerical simulation of entrainment and mixing should be added.

® References to recent studies (Andrejczuk et al. 2006, 2009; Bera et al, 2016a,b; Kumar et al, 2014; 2017; Khain et al, 2017, Yum et al, 2016;) are included.