Reply to Anonymous Referee #1

We thank the reviewer for his/hers comments and remarks. Reviewer's comments are listed below in black, our replies (R) are written in blue.

General comment: This manuscript describes a new modeling approach in order to understand the formation of drizzle in stratocumulus fields. A unique feature of the model is the possibility to follow individual cloud parcels in a Lagrangian sense and to analyze which are the favor conditions for the onset of drizzle production and the further drizzle dynamics until the drizzle drops partly reach the ground. Before I start with my comments I have to point out that my personal background are in-situ cloud experiments and, therefore, I cannot make detailed/specific comments on technical aspects of this kind of modeling.

My overall impression is that this manuscript provides unique details of the development of drizzle production in Sc and can provides insight in the favorable conditions under which drizzle formation takes place which is terrific. In particular the different contributions of turbulent mixing on this procedure is evaluated in an interesting and clear way. From my point of view the manuscript is clearly written although at a few places careful rewording is needed. Furthermore, the part about the aerosol in Sec 4.5 is interesting but a little bit separated from the previous parts. If the manuscript should be shortened I suggest skipping this paragraph.

I highly recommend this manuscript for publication in ACP after my (minor) comments - which are given below - are considered/discussed.

We thank the referee for the positive remarks and recommendation.

Detailed comments:

Page 24134; Line 19: This sentence should be reworded – it is somewhat confusing. The two main questions are very important and maybe it is better to make shorter sentences.

(R) The sentence has been rewritten.

P24135; l 16: What metric is important from the second-order structure function? Do you assume inertial sub-range scaling and derive the energy dissipation? Be more precise here.

(R) The shape of the structure function characterizes the correlation properties of the turbulent velocity field. The relations between amplitudes of different harmonics were derived using the structure function. The structure function used in the model produces a -5/3 energetic spectrum in the horizontal direction. Intensity of turbulence is evaluated using measured root mean square values of vertical velocity fluctuations. The dissipation rate is set constant using a typical value of $10 cm^2 s^{-3}$.

P 24135, l 22ff: Can you briefly describe the input aerosol size distribution and number concentration of CCN

(R) The aerosol distribution is described in the following section 3. It is derived from measurements with a total concentration of $\sim 200 cm^{-3}$ in the radius range of $0.01 - 1.3\mu m$. The distribution is presented in Magaritz et al. (2009).

Magaritz, L., M. Pinsky, O. Krasnov, and A. Khain (2009), Investigation of Droplet Size Distributions and Drizzle Formation Using a New Trajectory Ensemble Model. Part II: Lucky Parcels, *J. Atmos. Sci.*, *66*(4), 781–805, doi:10.1175/2008JAS2789.1.

P 24136, l 22ff: 1st, during DYCOMS-II; was the energy dissipation rate measured? I assume you can estimate it at least as a mean value from the wind measurements? What was the value? A typo in Monin / Yaglom (see also reference list)

(R) In the model the dissipation rate has been set to a constant value below the inversion of $10 cm^2 s^{-3}$ which is typical of maritime Sc (Katzwinkel et al., 2011). Above cloud top the dissipation rate in the model diminishes linearly to zero at the height of $1100m$.

The reference has been corrected.

Katzwinkel, J., Siebert, H. and Shaw, R. A.: Observation of a Self-Limiting, Shear-Induced Turbulent Inversion Layer Above Marine Stratocumulus, Boundary-Layer Meteorol., 145(1), 131–143, doi:10.1007/s10546-011-9683-4, 2011.

Page 24137, l 6&7: I have no idea what you mean with this statement – please explain.

(R) The LEM is a 2D model. The 2D computational area can be considered as a cross-section perpendicular to the large-scale flow within the boundary layer. The large eddies that are simulated in the 2D model can be considered as a cross-sections of a roll vortices that are known to be elongated along the direction of the background large-scale flow. Such consideration was used in many studies (e.g. Ginis et al. 2004; Shpund et al. 2012, 2014). Since background flow is directed perpendicularly to the 2D computational area and all derivatives along the direction of the flow are equal to zero, the existence of such wind does not change the structure of the velocity field within the computational area. At the same time, the background wind increases the fluxes from the surface. The effect was taken into account assuming that the background wind is 10m/s near the surface.

Ginis I., Khain, A. P., and Morosovsky E., 2004: Effects of large eddies on the structure of the marine boundary layer under strong wind conditions. *J. Atmos. Sci*., 61, 3049-3063.

Shpund, J., M. Pinsky, and A. Khain, 2011: Microphysical structure of the marine boundary layer under strong wind and spray formation as seen from simulations using a 2D explicit microphysical model. Part I: The impact of large eddies. *J. Atmos. Sci*., 68, 2366–2384.

Shpund, J. J. A. Zhang, M. Pinsky, and A. Khain, 2014: Microphysical Structure of the Marine Boundary Layer under Strong Wind and Sea Spray Formation as Seen from a 2D Explicit Microphysical Model. Part III: Parameterization of Height-Dependent Droplet Size Distribution. *J. Atmos. Sci.*, 71, 1914–1934

Page 24137, Line 13 ff: You mention that there is no large-scale subsidence in your model but then you argue that this subsidence sharpens the gradients? Maybe I misunderstood your statement – please clarify in the manuscript.

(R) The paragraph has been rewritten more clearly in the revised text. In nature, the gradients of humidity and temperature above cloud top are affected by large-scale air subsidence. Stratocumulus clouds can have been observed to have a strong temperature jump and also a more gradual change of temperature. In the model the slope of the dissipation rate profile in this area determines the gradient seen in the simulation. In the simulations presented in the paper, the inversion is not very strong and turbulence induced entrainment leads to an increase of cloud top height.

On page 24135 you mention that the longitudinal structure function is taken as input, on page 24137 (l 23) you take the lateral component?

(R) The input for the model is the lateral structure function taken from Lothon et al. (2005). Corrected in the revised paper.

Lothon, M., Lenschow, D. H., Leon, D. and Vali, G.: Turbulence measurements in marine stratocumulus with airborne Doppler radar, Q. J. R. Meteorol. Soc., 131(609), 2063–2080, doi:10.1256/qj.04.131, 2005.

End of sec 3 on Page 24138: Up to here it is not clear to me if you take date from the cited literature as input for your model run or measured values. Where exactly does the mean dissipation rate mentioned on page 24138 (line 4) comes from? I suggest to change the reference "Siebert et al. 2006“ to Siebert et al 2010, JAS, Statistics of small-scale velocity fluctuations and internal intermittency in marine stratocumulus clouds. The 2006 paper is about shallow cumulus clouds.

(R) The input for the model includes:

- The lateral structure function D_{NN} taken from observations (Lothon et al., 2005)
- The vertical velocity variance profile taken from observations (Stevens et al., 2005)
- Aerosol distribution taken from measurement data. This distribution is set equal for all parcel in the boundary layer at t=0 min.
- Initial temperature and humidity profile selected to correspond to measured values once the boundary layer is well mixed.

The dissipation rate profile is set to a characteristic constant value in the boundary layer and sharply decreases above cloud top height to zero.

Reference changed to Siebert et al, 2010.

Fig 1: Axis labels are weak, mark the two discussed positions. I suggest for the x-axis: “x / m” and for y-axis “z / m”. Can you include up- and downdrafts into Fig. 1 Also the adiabatic LWC should be included for reference.

(R) The figure has been corrected

Page 24139, line 24: Is it helpful to include a figure to illustrate this feature?

(R) Figure 2 has been replaced and now includes the temperature and total water mixing ratio profiles as well.

Page 24139, line 26: "minor underestimation of temperature and humidity gradients“- Can you provide numbers? What is "minor“?

(R) Figure 2 now presents the vertical profiles allowing to evaluate the underestimation of the temperature and humidity gradients near the upper cloud boundary. As was stressed in the paper as a response to this comment, the gradients depend on the assumption of the height dependence of dissipation rate within inversion just above cloud top. Supplemental simulations indicate that comparatively low sensitivity of results to this choice. At the same time, we wanted to investigate effects of mixing at the cloud base and decides to, supposedly, overestimate the rate of such mixing by the choice of linear profile of dissipation rate within the inversion layer. Note that in many observations including RF03 in DYCOMS-II, the gradients of T and q are similar to those simulated by the model. As such our choice can be considerd realistic and typical for these clouds.

Page 24140, l5 ff: I feel that a somewhat more detailed explanation of the Paluch diagram would help the reader to follow your arguments.

(R) Since the Paluch diasgram was presented and discussed by Magaritz-Ronen et al. (2014), Figure 3 has been removed in the revised manuscript

In line 9 you write that the data is for cloud top but in the next sentence you write that it is for "in and near" the interfacial layer - this is confusing and I suggest to be more precise in your wording.

(R) As mentioned above, Figure 3 has been removed in the revised manuscript

Page 24140, Line 19: Can you quantify this statement? What does the slope exactly tells me about the mixing process?

(R) As mentioned above, Figure 3 has been removed in the revised manuscript

Page 24141, l3: Please provide numbers, what are large droplets?

(R) Large droplets are larger than 30 µm.

Page 24141, l 18ff: I understand that larger droplets close to cloud base can be a result of downward mixing of large droplet originally formed in cloud top regions but what is the effect of the ascending volume (line 18)? Maybe just a misunderstanding but please clarify.

(R) We clarify the sentence in the revised text. DSDs in ascending and descending parcels are not symmetrical (Pinsky et al., 2013), and larger drops can be found in descending parcels when they reach cloud base. The mechanism suggested by Korolev et al. (2013) proposes that these larger droplets near cloud base can laterally mix into ascending parcels at cloud base. The ascending parcels will have a wider DSD and will be more likely to produce large drops through collisions. In the model results (Fig. 3) we point to the existence of larger values of r_e near cloud base in the mixing case which could point to this mechanism. In addition, we stress the role of droplet collisions that increase the aerosol size within the drops. As a result, parcels containing larger haze particles at cloud base have more intense collisions.

Korolev, A., Pinsky, M. and Khain, A.: A New Mechanism of Droplet Size Distribution Broadening during Diffusional Growth, J. Atmos. Sci., 70(7), 2051–2071, doi:10.1175/JAS-D-12-0182.1, 2013.

Pinsky, M., Mazin, I. P., Korolev, A. and Khain, A.: Supersaturation and Diffusional Droplet Growth in Liquid Clouds, J. Atmos. Sci., 70(9), 2778–2793, doi:10.1175/JAS-D-12-077.1, 2013.

Page 24142, l 5: This sentence is difficult to understand, I suggest rewording.

(R) The sentence has been rewritten.

Page 24142, l 27: I like the phrase "lucky parcel" but I remember a paper by Alex Kostinski about "lucky droplets" and at some place you should definitively cite and discuss this paper in depth. Alexander B. Kostinski and Raymond A. Shaw, 2005: Fluctuations and Luck in Droplet Growth by Coalescence. Bull. Amer. Meteor. Soc., 86, 235–244. doi: http://dx.doi.org/10.1175/BAMS-86-2-235

(R) Yes, Kostinski and Shaw (2005) introduced the concept of lucky drops. Droplets in clouds experience different amount of collisions. Some rare droplets experience more collisions which result in formation of a small number of drizzle (or rain) drops. The formation of such lucky drops is a fully stochastic, random process.

However, lucky parcels (or lucky cloud volumes) are those which have favorable conditions for formation of largest LWC and drops. Formation of lucky parcels is a deterministic process, and we can predict which volume will become "lucky".

Page 24143, l 7: Maybe you could show the velocity field for a certain time step?

(R) The velocity field has been added in figure 1.

Page 24143, l 8ff: this sentence is quite complicate; do you just consider the integral time scale?

(R) In Magaritz-Ronen et al. (2014) the lifetime of a single parcel is determined by the time it takes a conservative property in the air volume (total water mixing ratio) to become equal to that of the air volume's environment value. It was found that this life time is on the order of 15-20 min. The sentence has been rewritten more clearly in the revised paper.

Page 24143, l 14ff: Does this make sense? You consider the ratio of ql at 150 min and

140 min but take the location at 15 min - probably a typo and you mean 150 min?

(R) Corrected

Page 24144, l 8: What do you mean with "..a slope forms.."?

(R) The sentace was unclear, corrected

Page 24145 l 1: This sentence is somehow incorrect..

(R) Corrected

Page 24145, l 20: Can you calculate the ratio of the droplet concentration in the considered height versus the cloud base which should be a better parameter showing how adiabatic the considered parcel is?

(R) The adiabatic properties of the parcels in zone 1 are demonstrated by the almost constant droplet concentration. Parcels near cloud base (~400 m, blue color) have the same concentration as parcels near cloud top (~700 m, yellow).

Page 24146, l 4ff: At this point the concept of inhomogeneous (and homogeneous) mixing should be introduced/discussed. As I understand this mixing concept the data is perfect to show that both, homogeneous and inhomogeneous mixing occurs in Sc but at different levels or more precisely in parcels with different history – right? Exciting result!

(R) In the classical concept of homogeneous and inhomogeneous mixing the hypothetic final equilibrium stage of a cloud and environment volume pair is considered. Our approach differs from the classical approach in two main aspects. First, we consider the history of each parcel and look at changes in the cloud parcel and in initially dry parcel separately. Second, because the parcels move and their adjacent parcels change the final equilibrium stage is not reached.

The mixing between parcels in the model is inhomogeneous and gradients between neighboring parcels remain throughout the simulation. In case homogeneous mixing was represented all microphysical parameters in neighboring parcels would become identical during one time step and spatial gradients of all quantities between would tend to zero during this short time, this does not occur.

The model allows us to follow the history of each parcel. We suppose that such an approach better describes natural processes occurring in clouds than can be derived from standard mixing diagrams. The analysis in fig. 9 shows that all parcels can be separated into three groups with different LWC-N relationships. Formal application of such dependencies using the concept of the mixing diagrams to characterize the type of mixing imply that parcels belonging to group 2 mix homogeneously, while parcels belonging to group 3 mix inhomogeneousely. However, considering that the presented results are only a single time step in an ongoing process revels a different interpretation which is not limited by the assumptions of the mixing diagrams as mentioned above. In initially cloudy volumes mixing decreases the LWC but the concentration remains high through penetration of small droplets form the initially dry volume. Also, evaporation of droplets is only partial that leads to decrease LWC, but not droplet concentration.

Despite that the evolution of the DSD resembles the concept of homogeneous mixing the mixing is inhomogeneous. The apparent impression comes from simplifications of "classical" approach that assumes monodisperse DSD. In this case inhomogeneous mixing should not lead to change in the DSD shape. In our more realistic case, the width of DSDs in cloud parcels is quite wide and mixing leads to the DSD broadening. Such broadening was found in several recent studies of inhomogeneous mixing. Besides, in reality all of these features describe different stages in of inhomogeneous mixing process between cloudy and dry environment air. Corresponding comments are included into the revised paper.

Page 24146, l 7: Please define "spectral width“

(R) The spectral width here is the standard deviation of the droplet size distribution. Definition added in the text.

Page 24146: l 25 ff: I am a little bit confused at this point. Cloud base should be basically defined by the difference between the dewpoint and actual temperature at surface level - right? Does it mean that the water vapor and sensible heat fluxes decrease this difference? Maybe this point should be explained a little bit more detailed, although I think you are right.

How much is the upper boundary influenced by entrainment? Is it significant? Can you provide numbers?

(R) Yes, during the simulation sensible and latent heat fluxes from the ocean surface increase the humidity in the sub-cloud layer and alter the cloud base height. Entrainment-mixing leads to an increase of the cloud top height of ~100 m during the simulation. Both of these changes can be seen in fig. 4 (top panel). This has been written more clearly in the text.

Page 24147, l 4 ff: Do you really need lin and log representation in your Figures? Next sentence: delete one "peak“ (line 5)

(R) Only the log scale is presented in the revised figure, text corrected

Page 24147, l 13ff: can you specify - what is the humidity level of these lucky parcels? Are you talking about absolute humidity or relative humidity/supersaturation?

(R) Lucky parcels are characterized by high absolute humidity, and will be the most humid air volumes in the cloud. This feature of lucky parcels is demonstrated in fig. 6.

Page 24148, l 1 ff: Why is humidity maximal at surface – adiabatic implies well-mixed SCL - right?

(R) Humidity fluxes from the surface maximal values near the bottom of the domain (fig. 5). These fluxes lead to an increase in the parcels closest to the surface. The added humidity is mixed into the BL during the parcel’s ascent and the entire BL becomes more humid. The boundary layer is considered well mixed but still not all parcels have the same properties. In the mixing case (CON) adiabatic parcels are the ones that lose only a small portion of the humidity during their ascent in the boundary layer.

End of page 24149: you mentioned that increased turbulence (and turbulent fluxes) result in a moister SCL and the LCL is lower so there must be a further effect: drizzle has a shorter way in subsaturated air (LCL to surface) and this path is moister which should increase the drizzle rate at surface - right?

(R) Yes we agree, in a moister sub-cloud layer there will be less evaporation of drops and an increase of drizzle amount at the surface.

Page 24149, l26: Is this true? I thought that updrafts are smaller but with stronger vertical velocity compared to larger downdraft areas with smaller negative values of the vertical velocity (keeping the mass balance)? You mention that areas of up and down drafts are equally distributed?! Are there references?

(R) The sentence has been removed.

Page 24150, l 10: Why is aerosol size is increasing during droplet collisions? I don't understand this procedure or misunderstood... Do both nuclei stick together?

(R) For droplets with dissolvable aerosols, collisions lead to an increase in the mass of both the water and salt in the drop. If the drop evaporates a single larger aerosol releases. Actually, evaporation of droplets leads to formation of haze particles in equilibrium with environment. The increase in the aerosol mass by collisions leads to an increase in the radius of the equivalent "dry" aerosol. This problem was considered by Magaritz et al (2010). Corresponding comments are added into the text.

Magaritz, L., Pinsky, M. and Khain, A.: Effects of stratocumulus clouds on aerosols in the maritime boundary layer, Atmos. Res., 97(4), 498–512, doi:10.1016/j.atmosres.2010.06.010, 2010.

End of Sec 4.5: I have the feeling that this is a subsection which is a little bit speculative and if one wants to shorten this manuscript I suggest to remove this section. Is the formation of larger aerosol due to collision of cloud droplets a feature of the numerical model?

(R) The formation of large aerosols due to collisions is represented in the model. This is a specific feature of the advanced model microphysics. Most models are not able follow the drop salinity (salt mass) in the process of drop growth and collisions. The LEM tracks the aerosol mass also when it is inside the drops. A detailed study concerning the changes to the aerosol distribution during the cloud evolution and the effects of collisions on the maximum aerosol size has been presented in Magaritz et al. (2010).

Magaritz, L., Pinsky, M. and Khain, A.: Effects of stratocumulus clouds on aerosols in the maritime boundary layer, Atmos. Res., 97(4), 498–512, doi:10.1016/j.atmosres.2010.06.010, 2010.

Discussion section: Most of the "Discussion" section is a summary because many aspects have been discussed in the previous sections and no more discussion is added here. Why not combining Sec 5 and 6, shorten it and call it "Summary and conclusion"?

(R) Accepted

Page 24152, Sec 5.1: why do you introduce shallow Cu at this point - all the paper is about Sc? Fig 17 is nice but it lengthen the manuscript and I suggest to delete Fig 17 and completely focus on Sc - shallow Cu is a different story and I wouldn't mix them.

(R) The comparisson has been removed

Please check carefully the reference list in terms of typos.

<u>Reply to anonymous Referee #2</u>

We thank the reviewer for his/hers comments and remarks. Reviewer's comments are listed below in black, our replies (R) are written in blue.

In this manuscript, the author analyse the effect of turbulent mixing on drizzle formation in stratocumulus using a Lagrangian-Eulerian model. They find that mixing has two opposing effects: first mixing delays the initial formation of drizzle drops by diluting high LWC parcels, but later mixing is essential to create an environment in which drizzle drops are able to develop further and therefore reach the sub-cloud layer.

The Lagrangian-Eulerian model is a great tool to analyse drizzle formation and I think that the manuscript can contribute to better understand the puzzling role of mixing in drizzle formation in Sc. However, I have two general comments which should be taken into account before publication.

General comments

I understand that the LEM, which is used for this study, has been developed and described in earlier papers and that turbulent mixing has been included as a process in the LEM by the same group of authors (Magaritz-Ronen et al. 2014). In that 2014 study, the authors simulate and analyse a different research flight (RF01 instead of RF07) from the same field campaign (DYCOMS-II). Although RF01 is a non-precipitating case and RF07 develops more pronounced precipitation, in their 2014 paper the authors already conclude that "turbulent mixing leads to an increase in the effective radius and facilitates and accelerates drizzle formation" (this is from the 2014 abstract). I think that the current analysis shows some new results compared to the 2014 paper, especially concerning the opposing effects of mixing. However, some of the analysis overlaps, e.g., Fig.6 in the 2014 paper and Fig.3 in this manuscript. Please point out more clearly, where the currents study builds on (or reproduces) results from the earlier study and where it contributes new insights. Please skip overlapping analysis if necessary.

(R) The previous paper (Magaritz-Ronen et al., 2014) concentrated on the affects of turbulent mixing on the averaged properties of the stratocumulus cloud. It discusses the overall structure and variability of different parameters such as LWC, concentration and temperature inside the cloud. In the simulation presented in the paper it was seen that more large drops form more rapidly and that the effective radius seen in the cloud layer was higher in the case turbulent mixing was included. These results indicated that turbulent mixing and entrainment have an effect on the drizzle formation process in the cloud.

The current paper is a continuation of that work and aims at understanding the mechanism leading to the enhanced drizzle formation in the mixing case. Figure 3 has been removed.

In the manuscript, a collision parameter is defined as $N^2 r_e^5$. In the stochastic collection equation, the collision rate depends on the droplet concentration, the size of the droplets and on the velocity difference of pairs of droplets. Assuming that drops fall with terminal fall velocity, the velocity difference can be related to a size difference. Therefore, I would expect that a collision parameter should be highly sensitive to the DSD width, which characterises droplet size differences. However, in Fig.11 there is only a small dependence of the collision parameter on the spectrum width. Please discuss, how and why you define the collision parameter as you did. Which assumptions are in the formulation? Why does it not depend on the DSD width? How does the formulation effect the interpretation of the results?

(R) Collisions are described using the stochastic equation for collisions. The rate of collision is determined by the concentration of the colliding drops (N^2) and the collision kernel. In a study by Freud and Rosenfeld (2012) analysis of data from many field campaigns showed that the collision kernel is proportional to $\sim r_v^5$ ($r_v^{4.8}$). The relationship between the rate of collisions and the DSD width is discussed. It is shown that increase in the DSD width does not automatically lead to increase in the rate of collisions. Moreover, in our particular cases, DSD broadening due to mixing leads to decrease in the rate of collisions. The corresponding comments are included into the revised paper.

Freud, E. and Rosenfeld, D.: Linear relation between convective cloud drop number concentration and depth for rain initiation, *J. Geophys. Res. Atmos.*, 117(D2), D02207, doi:10.1029/2011JD016457, 2012.

Specific comments

1. Throughout the text, e.g., p.24132, l.20: If several references are listed to support one statement, they are usually sorted by year, not alphabetically.

(R) Corrected

2. p.24133: The first paragraph is hard to read because it jumps between different topics, please restructure. Maybe have two paragraphs: one about the processes that foster drizzle, and one about the difficulties of LES to simulate drizzle.

(R) The paragraph has been rewritten

3. p.24135, l.3: Is the model version used in this study exactly the same as described in Magaritz-Ronen et al. (2014)? Or are there differences to that version?

(R) The version used in this study is the same as the one used in Magaritz-Ronen et al., (2014), only different simulations are used.

4. p.24135, l.5: 2D turbulence is known to have a quite different structure from 3D turbulence. (See, e.g., Stevens, B., Feingold, G., Cotton, W. R., and Walko, R. L. (1996). Elements of the microphysical structure of numerically simulated nonprecipitating stratocumulus. Journal of the atmospheric sciences, 53, 980-1006.) What are the limitations of using a 2D model? What might be the effect on the results?

(R) The statistical properties of the simulated velocity field are as in 3D turbulence. For instance, the velocity field obeys the -5/3 law and as such we do not simulate 2D turbulence. Similarly, mixing between parcels is based on the Prandtl approach also developed for 3D turbulence.

The utilization of 2D geometry for the model means that the convective (large eddies) structure represent roll vortices elongated along the background wind. A great number of studies showed that such a structure provides the same heat fluxes and has the same critical Rayleigh numbers as in 3D geometry. At the same time, 2D geometry allowed us to use high resolution, and to use very accurate description of microphysical processes needed for description of such a fine feature as drizzle formation.

5. p.24136, l.6: Does the formulation of Pinsky et al. 2001 include turbulent enhancement in the collision efficiency? If so, I think it would be worth to state that here. If not, what is the effect of neglecting turbulent enhancement?

(R) No, the tables of the collision efficiency presented by Pinsky et al. (2001) present gravitational collision efficiencies. Our estimations showed that low dissipation rates used in the model do not lead to any significant increase in the collision rate. The turbulent-induced increase in collision rate in Sc clouds supposedly takes place in zones of imbedded convection. However, in this paper the turbulence-like wind field does not contains such convective elements. We showed in the study that even gravitational collision kernels can lead to drizzle formation and reasonable drizzle fluxes.

6. p.24136, l.21: In that formula, why is K a function of l? Is ε a function of l? Later, in section 3 it is said that ε is set constant (in the BL).

(R) We used the Richardson law to describe the turbulent coefficient. In the equation $K(l) = C\varepsilon^{1/3}l^{4/3}$: the turbulent dissipation rate ε is constant in the BL, and set at the beginning of the simulation; l is the distance between Lagrangian parcel centers and changes as the parcels are advected in the computational domain. The increase in K with increase in mixing length can be explained by the fact that at larger distances, turbulent vortices of larger size can participate in the mixing. The utilization of the Richardson law does not mean the increase in turbulent fluxes and the fluxes are determined by spatial gradients of the variables. The gradients decrease with the increase in the distance.

7. p.24136, last paragraph: Do inconsistencies arise from those "two kinds" of diffusional growth?

(R) There are difference between resolved and subgrid processes of diffusion growth. Cloud resolved diffusion growth takes place in a parcel that ascends or descends with time. This process is accompanied by transport of air mass (parcels) upward or downward. Subgrid (small scale turbulent) diffusion growth has no net updraft or downdraft. It represents small scale fluctuations up and down. It is equivalent to introduction of small-scale fluctuations of vertical velocity around the mean updraft or downdraft.

8. p.24137, l.3: Is SST fixed? At what value?

(R) Yes. SST is set to $19°C$

9. p.24137, l.11: Please add references here or skip that sentence.

(R) Removed.

10. How long is the simulation? What is the timestep?

(R) The simulation is for 8 hours. There are several timesteps used in the model. For diffusion growth a small time step of 0.01s is used, collisions and mixing is calculated using 1s time step.

11. It might be my personal taste of style so please ignore this comment if you feel strongly about it: I think figure caption should not be repeated in the text, e.g., Fig.3. on p. 24140, l.9-13 or Fig.11 on p.24146, l.8-11. Skipping them would shorten especially section 4, which is sometimes a bit lengthy to read.

(R) Accepted, changed throughout the text

12. p.24140: This paragraph is hard to follow. At several points I am not sure how the sentences are relating to each other: l.7 what kind of changes in the variable field? l.17 How does homogenisation making the processes (which?) adiabatic? l.17 Which two limits? Cloudy and inversion layer from two sentences ago? l.20 What do you mean by magnitude of q_t and θ_l?

(R) The paragraph has been rewritten.

13. p.24144, l.14-15: I think the statement of the second half of the sentence is too strong. Looking at the last panel of Fig.7a, it is not the parcels with the highest initial humidity that have the highest LWC, but the parcels with the highest LWC that preferable start from the highest initial humidity.

(R) Agreed, not all parcels with high humidity will have maximum LWC. Corrected in the text.

14. p.24144, l.24: What is "the maximum value of the DSD"? Maximum re?

(R) It is the peak of the distribution, corrected in the text.

15. p.24145, l.3: It would be interesting to see how much LWC a parcel loses through sedimentation. Looking at Fig.8b the contribution might be small.

(R) Sedimentation is mostly effective for the larger drops at the right tail of the DSD, and yes, the fraction of LWC lost should not be very large.

Most of the drops are lost by sedimentation at the next stage of cloud development when drizzle falling from above collects smaller droplets in parcels located below.

16. p.24146, l.22-23: This sentence does not makes sense to me. Why would drizzle drop formation continue because something has happened before?

(R) The sentence was unclear and has been rewritten. If in the parcel that mixes with the inversion air collisions were already sufficiently strong, larger drops will be present. In this case efficient collision can continue also after the parcel mixes with the dry air and the smaller drops in the spectrum evaporate.

17. p.24150, l.25-27: This paragraph/sentence appears somehow unrelated. Please skip or relate to the following text.

(R) Removed

18. p.24151, l.2-17: The recirculation of aerosols and the importance of large aerosols for the drizzle drops seems somewhat speculative to me. Please back this up with analysis or skip it.

(R) The full analysis of this mechanism and its effects on the cloud microstructure has been previously presented in Magaritz et al., (2010). In the study it was shown that collisions also lead to larger aerosol particles in the cloud layer and that subsequently the largest drops contain these large aerosols.

Magaritz, L., Pinsky, M. and Khain, A.: Effects of stratocumulus clouds on aerosols in the maritime boundary layer, Atmos. Res., 97(4), 498–512, doi:10.1016/j.atmosres.2010.06.010, 2010.

19. p.24151ff: Section 5 is rather a summary of section 4 than a discussion. Although I like the conclusion section 6 in its current (concise) form, please think about combining section 5 and 6 (or section 4 and 5).

(R) Accepted

20. p.24152, l.10-18: The comparison of Sc and Cu appears here out of the blue. I would recommend to skip it because Cu are not the topic of the manuscript. If you want to keep it, a thorough discussion of literature on lucky parcels in shallow cumulus is needed (e.g. studies by Lasher-Trapp, Cooper, etc.).

(R) The comparison has been removed

21. p.24153, l.29f: Larger compared to what? Fig. 13 does not show spectrum width.

(R) In the cloud layer, larger values of spectrum width are seen in CON case than in the NoMI. This is seen in fig. 11 (corrected in the text)

22. Fig.1: Please use the same color scale to make the figs comparable.

(R) Corrected

23. Fig.2: Labels of the x-axis are wrong. Is concentration the concentration of cloud droplets?

(R) Labels corrected. The concentration is total droplet concentration (added)

24. Fig.3: Why do you show data for different height layers from the model and the observation?

(R) The figure has been removed.

25. Several figure (e.g., 2, 3, 5, ...) show model data from different point or periods in simulation time. For what reason did you chose those (different) time frames? It seems a bit arbitrary to me.

(R) There are many processes described in the model which affect the microphysical structure of the cloud and the investigated mechanisms described in the paper are at times masked by one another. The time steps selected for the different figures are the ones in which the discussed affect is most clearly presented.

26. Throughout the text and e.g. in Fig.6 and Fig.7: Is humidity and qt the same in manuscript? Please clarify.

(R) Humidity in figures 6 and 7 (and in the text) refers to the water vapor in the parcel. q_t is the total water mixing ratio and is the sum of the humidity and LWC. q_t is a conservative value in adiabatic processes and its average profile is constant in the BL.

27. Fig.8b: Please explain the y-axis. M is never mentioned.

(R) This figure presents the mass distribution in the parcel. Changed to LWC.

28. Fig.11: How do you calculate the spectrum width?

(R) The spectral width here is the standard deviation of the droplet size distribution.

Technical corrections

1. p.24132 l.25: comparatively to what? - *corrected*

2. p.24134, l.12: of the droplet size distribution - *corrected*

3. p.24137, l.3: Lagrangian-Eulerian Model (LEM). - *corrected*

4. p.24137, third paragraph: Stay in present tense for the model description. - *corrected*

5. p.24139, l.29: model by using - *corrected*

6. p.24140, l.13: Concentration of cloud droplets? - *Yes, corrected in the text*

7. p.24142, l.11: Insert a paragraph break here. - *corrected*

8. p.24143, l.5: layers - *corrected*

9. p.24143, l.16: t = 150 min? - *corrected*

10. p.24144, l.27: g m−3 - *corrected*

11. p.24145, l.14: to investigate - *corrected*

12. p.24146, l.4: substantially, leading - *corrected*

13. p.24152, l.20-22: This sentence is grammatically not correct, please rephrase. - *corrected*

14. p.24153, l.23: as a result of - *corrected*

15. Fig.16: Add "in cloudy parcels" to the caption. - *corrected*

Drizzle Formation in Stratocumulus Clouds: Effects of Turbulent Mixing

L. Magaritz-Ronen[1], M. Pinsky[1] and A. Khain[1]

[1] {Department of Atmospheric Sciences, The Hebrew University of Jerusalem, Isra

Correspondence to: L. Magaritz-Ronen (leehi.magaritz@mail.huji.ac.il)

Abstract

The mechanism of drizzle formation in shallow stratocumulus clouds and the turbulent mixing on this process are investigated. A Lagrangian-Eularian model of th topped boundary layer is used to simulate the cloud measured during flight RF0 DYCOMS-II field experiment. The model contains ~2000 air parcels that are adve turbulence-like velocity field. In the model all microphysical processes are described Lagrangian air volume, and turbulent mixing between the parcels is also taken into ac was found that the first large drops form in air volumes that are closest to adiab characterized by high humidity, extended residence near cloud top, and maximum liquid water content, allowing the formation of drops as a result of efficient collisi first large drops form near cloud top and initiate drizzle formation in the cloud. D developed only when turbulent mixing of parcels is included in the model. Without the cloud structure is extremely inhomogeneous and the few large drops that do for cloud evaporate during their sedimentation. It was found that turbulent mixing can process of drizzle initiation but is essential for the further development of drizzle in th

1 Introduction

Understanding the mechanism of drizzle formation in stratocumulus clouds (Sc) is standing problem in cloud physics. Formation of drizzle in the cloud leads to chang radiative properties of Sc (Nakajima and King, 1990; Gerber, 1996; Feingold et a Brenguier et al., 2000; Rosenfeld et al., 2006, 2012). Sc cover large areas of the glob a result microphysical processes occurring within them have a profound effect o

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Deleted: . Sc cover large areas of the globe, and as a result microphysical processes occurring within them have a profound effect on global radiation balance. The problem of drizzle formation is also interesting from a theoretical point of view, because drizzle forms within these narrow cloud layers of a few hundred meters, which contain comparatively little liquid water radiation balance. The problem of drizzle formation is also interesting from a theoreti of view. In Sc, drizzle forms within narrow cloud layers of a few hundred meter contain only little liquid water compared to more developed cumulus. Studies hav that both an increase in cloud depth (Pawlowska and Brenguier, 2003; Kostinski, 2(an increase in the drop residential time in the cloud (Feingold et al., 1996; Magari 2009) foster drizzle formation.

Warm stratocumulus clouds were investigated numerically using Large Eddy Sin (LES) with different levels of complexity to describe microphysical processes (Steve 2003b, 2005; Ackerman et al., 2009). Among these, LES models of Sc with spe microphysics were used to parameterize the rates of auto-conversion and drizzle f (Khairoutdinov and Kogan, 1999). These parameterizations are widely used in la models (Randall et al., 2003). And still, many LES models fail to reproduce the structure of Sc. Specifically, LES tend to substantially underestimate values of liqu content (LWC) near cloud top (Stevens et al., 2005). Stevens et al. (2005) attribut results to uncertainties in the description of small-scale turbulent motion in LES mod study concluded that a realistic structure of Sc can be simulated only if the LES has resolution as low as 1m, i.e. in configurations in which most turbulent motions are c explicitly.

Pinsky et al. (2008) and Magaritz et al. (Magaritz et al., 2009) described a new Sc m can be referred to as a Lagrangian-Eulerian model (LEM). In the model several adjacent parcels (Lagrangian) move within a turbulence-like flow, with statistical pa measured in the Stratocumulus-Topped Boundary Layer (STBL). The initial mode (Pinsky et al., 2008; Magaritz et al., 2009) did not include turbulent mixing of parcels and did not consider the effects of mixing and entrainment at the upp boundary. Nonetheless, the model successfully simulated many observed properties LWC, droplet size distribution, and drizzle formation. It was found that drizzle forms in 'lucky' parcels that ascend from the ocean surface and spend the most time near c Such lucky parcels were estimated to comprise about 1% of all air parcels. The large falling from 'lucky' parcels trigger collisions and drizzle formation in parcels locate them. It was found that drizzle tends to fall in downdrafts created by large eddie STBL.

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Pinsky et al.

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In the previous model version, consideration of a more realistic STBL geometry, characterized by a dry and warm inversion layer above the cloud top led to the formation of an unrealistic cloud structure. The extremely inhomogeneous structure was caused by entrainment of dry and warm air volumes into the cloud layer. The radius of correlation of all microphysical variables became equal to parcel size selected in the model, which is much lower than the radii of correlation calculated from observed data.¶ ...

In the previous model version, consideration of a more realistic STBL g characterized by a dry and warm inversion layer above the cloud top led to the forn an unrealistic cloud structure. The extremely inhomogeneous structure was ca entrainment of dry and warm air volumes into the cloud layer. The radius of correlati microphysical variables became equal to parcel size selected in the model, which lower than the radii of correlation calculated from observed data.

In order to make cloud structure realistic and represent processes resulting from in with the inversion layer, it was necessary to take into account processes of entrainn mixing of adjacent parcels (Magaritz-Ronen et al. 2014). It was shown that turbulen of parcels leads to realistic spatial variability of microphysical quantities characteri spatial correlation scale of ~200 m. It was also shown that mixing increases the wid droplet size distribution (DSD). The characteristic time period during which an a maintains its identity was found to be 15-20 min. Magaritz-Ronen et al. (2014) suc simulated the structure of a non-drizzling stratocumulus maritime cloud observe research flight RF01 of the Second Dynamics and Chemistry of Marine Stratocumu study (DYCOMS-II).

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In the present paper we simulate a slightly drizzling cloud observed during resear RF07 of the same field campaign. The study presented here addresses two questi first, given that turbulent mixing limits the life-time of separate cloud volumes, concept of 'lucky' parcels as triggers of drizzle formation remains valid? The second is what is the role of mixing in this process? Especially, what is the effect of mixir and warm air from the inversion on drizzle formation in the cloud? We also adc question whether DSD broadening caused by mixing at the cloud top favors drizzle fc or delays the process.

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2 Model description

The model used in this study was first described in Pinsky et al. (2008) and Magaı (Magaritz et al., 2009). It has been modified since the first studies were described papers. New processes such as surface fluxes, radiative cooling from cloud top, a important, turbulent mixing of air parcels, have been incorporated. Some mai developments, as were first presented in Magaritz-Ronen et al. (2014), are further c below.

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The model contains about 2000 adjacent Lagrangian parcels with a characteristic linea 40m. The parcels cover the entire 2D model domain of $2500x1250\ m^2$ and describe of an STBL, from the ocean surface, where latent and sensible heat flux is calculate top of an approximately $300\ m$ deep warm and dry inversion layer. Parcels are throughout the domain by a turbulence-like velocity field.

The velocity field is represented as the sum of a large number of harmonics with time-dependent amplitudes. The velocity field is assumed quasi-stationary during t simulation, statistically uniform in the horizontal direction and obeys the Kolmogoro law. Energetic and statistical properties of the velocity field are taken from observatio two measured quantities, the vertical profile of r.m.s. of velocity fluctuations, $\langle w'^2\rangle^{1/2}$ (where w' are the fluctuations of vertical wind velocity and brackets horizontal averaging) and the lateral structure function (Pinsky et al., 2008; Magari 2009). Microphysical processes such as diffusion growth, collisions, and sediment calculated in each individual parcel. At t = 0 min, each Lagrangian parcel conta wetted aerosols (haze particles) and the entire boundary layer (BL) is cloud-free. Pa advected in the velocity field, so that some parcels may cross the lifting condensat (LCL) and become cloudy. These parcels will contain drops as well as wetted During the parcels' motion droplets may continue to grow or evaporate, resuming to of haze particles. Aerosol and drop distributions are calculated using a single 500-l grid with a 0.01μm to 1000 μm radius range. The single bin grid allows explicit se between haze particles in equilibrium with the environment and cloud drops specialized nucleation parameterization. Nucleation, diffusion growth, and partia evaporation are described by the full diffusion growth equation, with a small time $0.01s$ to accurately describe the growth of the smallest particles (Pinsky et al., 2008; et al., 2010). Diffusion growth of droplets is calculated on a movable mass grid, in wh bin shifts along the mass axis, according to the solution of the equation. The use of bins eliminates numerical spectrum broadening, while increasing the accuracy of dro distribution calculations.

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Droplet growth by collisions is described using the stochastic equation for collisions resolution tables for collision efficiencies presented by Pinsky et al (2001). Collis performed on a regular 500-bin mass grid using the Kovetz and Olund method (19 great number of bins assures a high degree of accuracy in the calculation of collisio of droplets.

One of the most prominent features of this model is that parcels are not isolated and two types of interaction between Lagrangian parcels: droplet sedimentation and mixing. Droplet sedimentation through parcel boundaries allows larger droplets tha cloud parcels to act as drop collectors during their fall and reach the surface as dr calculate sedimentation the entire computational area is covered by an auxiliary reg with a 5m resolution. Droplet flux is calculated through each of 5m grid in separating adjacent parcels.

Turbulent mixing between adjacent Lagrangian parcels is described using an expansi theory for cases of mixing of conservative and non-conservative values (such as DS on a non-regular spatial grid formed by parcel centers. The algorithm was first pre Pinsky et al. (2010) and applied by Magaritz-Ronen (2014). The turbulent coeffici calculated as $K(l) = C\varepsilon^{\frac{1}{3}} l^{\frac{4}{3}}$ (Richardson's law), where l is the distance betwee centers, ε is the turbulent kinetic energy dissipation rate taken from observations, and (Monin and Yaglom, 1975).

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To calculate mixing of DSDs, droplet flux is calculated between parcels. Because I not conservative variables, the increase or decrease in droplet size during transport parcel to another is taken into account according to the equation of diffusion grow mixing at sub-grid scales is accompanied by latent heat release. This process diff latent heat release at the resolvable scales, where supersaturation is determined by the vertical motion and droplet concentration.

Since the parcels move within an Eulerian coordinate system and droplet sedimer performed at the regular Eulerian finite-difference grid, the model is regard Lagrangian-Eulerian Model (LEM).

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Sensible and latent heat surface flux is calculated using the bulk-aerodynamic formu a Dalton number of $C_E = 0.002$ (Smith, 1988) and background wind at 10 m of 1 The model's computational area is assumed perpendicular to the background win wind affects only the surface flux.

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Parameterization of long wave radiative cooling based on the two-stream appro following Khvorostyanov (1995) and Khvorostyanov et al. (2003) is used in the mode

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The model has periodic boundary conditions in the horizontal direction. There is no air subsidence above cloud top in the model. In the STBL large-scale subsidence gradients of temperature and humidity at the upper cloud boundary and can reduce th increase of cloud top height. In the model, the rate of mixing and entrainment at clo determined by the slope of the ε profile. With the profile used in the simulations p here, mixing of cloud and inversion air increases cloud top height, indicating a process of turbulence-induced entrainment.

3 Design of simulations

For this study the cloud observed during flight RF07 of the DYCOMS-II field c (Stevens et al., 2003a) was simulated in the model. The stratocumulus cloud measure this night flight was ~500 m thick and capped by a strong inversion at 825 m. Drizz the surface in this flight was evaluated at 0.6 mm/day (VanZanten et al., 2005).

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Measurements of the vertical profile of $\sigma_w(z) = \langle w'^2 \rangle^{1/2}$ (Stevens et al., 2005) and th structure function (Lothon et al., 2005) were implemented in the model to gen turbulence-like velocity field, with observed statistical properties. The $\sigma_w(z)$ maxin equal to $0.5 m/s$ at z = 500 m and zero in the inversion layer, above z=800 m. The m determining parameters of the turbulence-like model using these observed values is d by Pinsky et al. (2008) in detail.

The dissipation rate of turbulent kinetic energy (ε) was used to calculate mixing of The dissipation rate is set to a constant value of $10\ cm^2 s^{-3}$ in the BL and decreas cloud-top. The profile and values are typical of the stratocumulus clouds under cons (Lothon et al., 2005; Siebert et al., 2010; Katzwinkel et al., 2011).

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Initial aerosol distribution was derived from observations (total concentration 200 radius range 0.01-1.3μm) and assumed to be the same for all parcels at t = 0 mi boundary layer (Magaritz et al., 2009). Initial concentration of aerosols in parcels w inversion layer was set to zero. Initial temperature and humidity profiles are assum horizontally uniform at t=0. Initial relative humidity (RH) is set to approximately 90 the inversion level. It decreases rapidly at heights above that level.

In this study we investigate the formation the first large-sized drops and drizzle in stratocumulus clouds and the role of turbulent mixing in this process. To this enc simulations were preformed. The control run (CON) included all processes and simu cloud measured during flight RF07. Supplemental simulations included a simulation turbulent mixing between the parcels (NoMI), a simulation with no sedimentation the parcels (NoSd), and a simulation without mixing and sedimentation (Measurements from flight RF07 of the DYCOMS-II field experiment were used for v of the model results.

4 Results and discussion

4.1 Mean cloud structure

Turbulent mixing at cloud boundaries and inside the cloud layer has a strong effe macroscopic properties of the cloud and drizzle formation, especially homogeniz clouds in the horizontal direction, as discussed in detail by Magaritz-Ronen et al. (201

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A snapshot of the field of LWC at t = 270 min in the CON and NoMI simulations is p in Fig. 1. The time instance in the figure corresponds to the time just before drizzle fo In the CON simulation, LWC increases with height but decreases at cloud top be mixing with the dry and warm air above.

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It is seen that in some parcels LWC exceeds $1g\,m^{-3}$.The cloud is continuous in the h direction, and mixing leads to a clear cloud base at ~400m. The velocity field presented in Fig. 1, it can be seen that in areas of updraft cloud thickness is larger. velocity reaches $1.5\ m\ s^{-1}$ in updraft areas (x=1100m) and $-1.5\ m\ s^{-1}$ in downdr (x=500m). In the study by Magaritz-Ronen et al. (2014) the spatial correlation le several microphysical properties was calculated and found to be on the order of a few meters. This value agrees with the correlation length calculated from observations same case.

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In the NoMI case, the LWC field is highly inhomogeneous throughout the cloud, ind smaller radius of correlation on the order of the linear size of one parcel. Su inhomogeneity is also seen near cloud base, indicating a high variability in the separate parcels. One can see that in CON cloud is thicker than in NoMI, with high top and lower cloud base. This difference is the result of turbulent mixing between pa

Figure 2 compares the profiles of LWC, concentration, temperature and total humidit the model and observations. On average the profiles are in close agreement with obse

The inversion is well preserved for single time step and cloud and BL properties are s correctly. Total humidity (q_t) and temperature increase in the model in a layer that i than seen in observations between cloud top and the inversion. As mentioned, chang cloud top gradient are caused by turbulence-induced mixing. Supplemental sin indicate that minor underestimation of temperature and humidity gradient above t layer does not change the description of the physical mechanism of drizzle formation temperature and q_t gradients can be achieved in the model by using a sharper gra dissipation rate just above cloud top. Our choice of linear profile is based on the forn a realistic mixing (Paluch) diagram. Note that smoother transition between cloud l inversion is often observed in Sc, including during the DYCOMS-II field experin instance, RF03).

4.2 Initiation of drizzle - lucky parcels

Fig. 3 shows the evolution of the median profile of the effective radius (r_e) simulations, CON (top) and NoMI (bottom). Only parcels with $LWC > 0.01\ g/m^3$ w for the calculation of the median. In CON, large values of r_e are first seen near clo ~120 min. The median of the effective radius increases in the lower levels of the clo following time steps. The development of the median r_e is seen throughout the cloud drops first form near cloud top and then initiate the formation of larger droplets in th the cloud. After 300 minutes, large values of r_e below cloud base indicate the pre drizzle in the BL. Drizzle formation begins when r_e at cloud top reaches ~11-12 μ value corresponds with measurements (VanZanten et al., 2005).

Examination of profiles of the median r_e at individual time steps in the CON case another effect of turbulent mixing. The effective radius does not increase monotonica cloud and larger values of r_e can be seen close to cloud base (for example t = 100-1 These larger values are not evident in the NoMI case and are a result of turbulent mix of the mechanisms able to lead to larger r_e near cloud base is lateral mixing descending volumes containing droplets of larger sizes with ascending volumes co smaller droplets (Korolev et al., 2013; Pinsky et al., 2013). Effects of turbulent mixin the cloud on drizzle formation are further described in section 4.5 and in the dis below.

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Deleted: To characterize the process of mixing between the cloud and the inversion layer above, mixing diagrams (Paluch diagrams) are commonly used (Burnet and Brenguier, 2007; Paluch, 1979). In the diagram, two parameters that are conservative in moist adiabatic processes are used as coordinates. As mixing is a non-adiabatic process, changes in this variable field indicate the amount of mixing in the air volume. Total water mixing ratio (q_t) and liquid water potential temperature (θ_l) are both conserved in moist adiabatic processes. Figure 3 presents the Paluch diagram for cloud top in the model simulation CON (left) and as it was calculated from observations (right). The points in the diagram represent parcels/samples in and near the interface layer of the cloud and inversion. Points in the diagram are separated into cloudy (black circles) and non-cloudy (gray triangle), using a $3cm^{-3}$ concentration limit. In the diagram, two areas are identified at the tips of the scatter: at the cloud layer where θ_l is lower and q_t higher, and at the inversion on the opposite side. A comparatively small dispersion of parcels within the cloud layer indicates that mixing leads to homogenization, making the processes within clouds close to adiabatic. Between these two limits a mixing line forms as a result of inversion air entering the cloud, where it cools and becomes humid, and vice versa. The mixing process is illustrated in the diagram by the slope of the mixing line and the magnitudes of q_t and θ_l formed as a result of this process. The diagram plotted from the model appears to be in close agreement with observations, indicating a proper representation of the turbulent interface layer in the model. When the same Paluch diagram is plotted for the NoMI case a clear mixing line does not form and it is evident that mixing plays a crucial role in the formation of a realistic cloud structure in the model (see comparison for flight RF01 in Magaritz-Ronen et al.,(2014)). In observations somewhat higher values of q_t are seen. This was to be expected, as stated previously, because the gradient of the jump in q_t in the model is not as sharp as it was in observations leading to somewha ...

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The evolution of the r_e median profile in the NoMI case is presented in Fig. 3 (bottor In the NoMI case the change in the r_e profile throughout the simulation is quite (Parcels in this simulation are almost adiabatic; they do not mix with each other affected only by sedimentation of the largest droplets. Microphysical properties of ea in this case are determined by its initial conditions and trajectory in the BL. Using t as a limit for the calculation of the median, dry parcels penetrated from the inversi (Fig. 1) are excluded from consideration. The profile from NoMI resembles th expected from an ascending adiabatic parcel where the effective radius is de primarily by the distance above the LCL. In the NoMI case, cloud base is on averag than in CON, and maximum values of r_e in NoMI do not exceed $10\mu m$, indicating t drops and drizzle do not form in this case.

Larger values of r_e in the CON case are also a result of increasing cloud dept simulation. During the simulation, surface fluxes lead to an increase in humidit subcloud layer and a lower cloud base height. In addition cloud top height increase the CON simulation. This is a classic manifestation of the entrainment process 1992). These two processes increase cloud depth and result in larger r_e near cloud refer to parcels in which large droplets first form as ‘lucky’ parcels and seek to form conditions leading to their formation.

Several studies have shown that for the formation of large droplets in the DSD, collisions are crucial (Pinsky and Khain, 2002; Khain et al., 2013). The rate of collis be characterized by the product of the square of droplet concentration and collisio This product represents the gain integral in the stochastic equation of collisions (Pr and Klett, 1997). Evaluations of the collision kernel conducted by Freud and R (2012) found that the kernel is proportional to ${r_e}^5$. Accordingly, for a given DSD the rate can be characterized by a collision parameter in the form of $N^2{r_e}^5$. Figure 4 desc dependence of the collision parameter on LWC. Each parcel during 200-220 mi simulation is represented by a dot on the diagram; colors denote the height of th There is clear dependence between the two parameters and as LWC increases s collisions in the parcel. An increase is also seen as the height of the parcel in t increases. This is expected, given the strong LWC-height correlation. According t presented in Fig. 4, as LWC increases the probability of the formation of lar increases. The importance of maximum LWC values in the formation of drizzle

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stressed by Khairoudinov and Kogan (2000) and Magaritz et al (Magaritz et al., 200 the first characteristic of a ‘lucky’ parcel.

Figure 5 illustrates the mechanism of formation of parcels with maximum v LWC. This figure shows the field of humidity at t = 150 min (top panel). The dry i and the well-mixed BL are clearly seen. Moisture flux from the ocean surface le increase in humidity in parcels located at the lower levels of the domain. These high l areas expand upwards towards the cloud in updrafts related to large eddies (convect rolls). Large eddies are a typical feature of marine boundary layers (Stevens et al. 2005; Ginis et al., 2004) and are reflected in the velocity field of the model. The velocities in such cells can exceed $2m\ s^{-1}$ and the width of the updraft can be as la few hundred meters.

A previous study (Magaritz-Ronen et al., 2014) found that with turbulent mixing the of a single 40 m parcel is on the order of ~15-20 min. The lifetime of a parcel is defi as the time it takes for a parcel to mix with its environment and conservative properti parcel become similar to those in its surrounding. During this time period the parce distinguished from surrounding parcels, and can be tracked and analyzed. But changes occur during its lifetime. Examination of a conservative value such as to content (q_t) enables us to evaluate the extent to which an air volume mixes neighboring parcels. The middle panel in Fig. 5 presents the ratio between $q_t(15($ $q_t(140min)$ for all parcels in the model. Parcel locations in the figure are according location at $t = 150min$. Parcels mix with their environment at different rates, as a fu the gradient between the parcel and its immediate environment. For some of the par the surface q_t increases during this period. The ascending branch of humidity, as ide the top panel, is wider than a single parcel, allowing the parcels in the center of the l lose less q_t than adjacent parcels. During their ascent (here of 10 min), parcels may l 10% of q_t. These ascending parcels also have a lower lifting condensation leve (bottom panel). Parcels with high q_t will later have a high LWC in the cloud. The t of a single parcel between 140-150 min is marked in black in the middle panel. The t of the same parcel between 150-160 min is marked in gray. After a rapid ascent, the parcel moves along the cloud top. As emphasized in the following sections th preferred trajectory for a ‘lucky’ parcel forming the first large drops in the cloud.

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Field Code Changed

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The process of lucky parcel formation is further illustrated in Fig. 6*a*. All parcels l the bottom of the domain, near sea surface at t = 145 min, were selected. These parc varying humidity values, depending on flux from the ocean surface and the histo parcel. This is the x- axis of the plot. The y-axis is the LWC marked at 5-min increm colors denote the height of the parcel. After 5 min, small values of LWC are seen parcels. The LCL of these parcels is about ~300m, although the cloud base has an height of ~400m. These parcels have maximum values of humidity. Parcels of this similar to the one marked in Fig. 5. After another 5 min, more parcels ascend and reaching 600m have largest LWC. Parcels with the highest initial humidity will highest LWC as well. This trend also continues for a further 5 min. As expected, dependence on the height of the parcel is evident in the scatter. In the last panel, afte of simulation, the clear slope disappears and the LWC is determined mostly by the l the parcel in the boundary layer. Only parcels with maximum values of LWC are s panel *b*. In the figure it is shown that even with the strong dependence on the heig parcel, parcels with maximum LWC at cloud top have maximal initial humidity valu mechanism described can be summarized as follows. In adiabatic (or close to a parcels LWC increases inside the cloud as adiabatic LWC. For maximum LWC cloud top, the LCL should be minimal for such a parcel. The low LCL is determinec RH in the parcel. Such high RH can be obtained from the ocean surface.

Figure 7 presents the evolution of microphysical parameters of a single parc parcel, which is marked in Fig. 6*a* by black circles in all panels, ascends from clou 800m in 13 min (panel *b*). The effective radius in the parcel increases to $12\mu m$ du time. The formation of drizzle-sized drops (droplets with radius exceeding 25 - substantially accelerates at t=160 min, when $r_e = 11\mu m$ and LWC reaches $1g\ m^{-}$ DSD (panel *b*) an elongated tail of largest droplets is formed. Towards t = 166 min, t contains drizzle droplets with radii as large as $40\mu m$ (Fig. 7b). A tail of large drops reported in observations (VanZanten et al., 2005). The concentration of these drops small and does not increase r_e significantly. The peak of the DSD appears at $r \approx 11$ - After the time steps shown in the figure, large droplets are lost from the sedimentation.

In Fig. 8 we examine only those parcels that reach a value of LWC greater than 0. Along the x-axis, the time each parcel retained the high LWC value is plotted. The m

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collision parameter value during this period is shown along the y-axis in the diagı color denotes the maximum value of LWC during the same time period. As the lengtl the parcel has high LWC increases, the collision rate in the parcel increases as well. F after the parcel has a residence time of more than 10-12 min with high LWC, the parameter no longer increases. Sedimentation of the larger drops forming in th reduces the LWC and collision parameter. Not all parcels can retain the high L intense collisions for the duration presented in Fig. 8. For this to occur a parcel neec be located near cloud top, where LWC is maximal, but not too close to the inversi where mixing with dry air may lead to loss of LWC.

4.3 Interaction between cloud top and inversion

The first large droplets form near cloud top, where mixing with dry environment pronounced. Inhomogeneous mixing is often suggested as a mechanism leading to in the maximum drop size in ascending cloud volumes mixing with the environn cumulus clouds (Baker et al., 1980; Baker and Latham, 1982; Lasher-Trapp et a Cooper et al., 2013), it is therefore of interest to investigate the possibility that mixing at cloud top of Sc may accelerate the formation of these droplets.

Fig. 9 shows a scatter diagram of droplet concentration and LWC (LWC-N). Each po diagram marks a single parcel at t = 185 min. Colors denote the height of the parcels. in the diagram can be separated into three zones. In zone 1 air parcels are close to a as indicated by the high droplet concentration. Parcels in this zone are ascending in t and droplets grow by diffusional growth. Droplet concentration in the parcels remaiı the same, but LWC increases with height. In zone 2 cloud parcels are located near c for longer periods of time. Turbulent mixing of these parcels with parcels from the i layer leads to a decrease in droplet concentration and LWC. However, LWC decrea substantially than concentration, indicating partial evaporation of droplets in the I penetration of small droplets from neighboring initially dry parcels. The decrease iı concentration is only on the order of 10%. In zone 3 the slope of the relationship cha this zone parcels initially from the inversion layer become cloud parcels, due to mix adjacent cloud parcels. Both droplet concentration and LWC in these parcels are sma in the initially adiabatic cloud parcels. Since LWC and concentration are initially zerc parcels, every droplet that enters the parcel and does not evaporate completely increa values substantially, leading to the larger slope of data points in zone 3. Changes iı

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concentration also lead to changes in the DSD spectrum width, which is demonstrate 10.

Figure 10 compares DSD widths (standard deviation of the distribution) as a function in simulations with (CON, panels *a*, *c*) and without mixing (NoMI, panels *b*, *d*). In t case the spectrum width values are higher than in the NoMI case. In CON, DSD maximal in zone 2, where mixing leads to the formation of small droplets and broac DSD. These parcels correspond to the parcels in zone 2 in Fig. 9, where the decrease is seen to be greater than the concentration. As mentioned above, partial evapo droplets in these parcels is the principal process leading to broadening of DSD towar drops and increasing spectrum width. While spectrum width is greatest in parcels at c the strongest collisions are in the most adiabatic parcels with the largest LWC (zone parcels may have lower DSD width, because they contain fewer small droplets. In pa interact with the inversion air, mixing with dry environmental air increases spectru towards smaller drops and decreases the rate of collisions. If sufficiently large drop in the parcel before it mixed with the dry inversion air, collisions can still be effic drizzle-size drops may form.

In adiabatic parcels, the spectrum width is determined by a combination of th spectrum at cloud base and the path of the parcel in the cloud. The initial DSD is a fu the supersaturation at the LCL and the aerosol distribution. Further ascent of the accompanied by diffusion growth and, if conditions permit, the beginning of collis widening of the DSD towards large drops. Variability of spectrum width values i when the parcels are not adiabatic (Fig. 10). In the case of turbulent mixing, the wi individual spectrum is not a direct result of the parcel's history but also of the h adjacent parcels. These wider DSD may expedite drizzle formation in the cloud general, we see that the DSD width is not the main factor that fosters intense collisio our case first drizzle drops. Diffusion growth leads to DSD narrowing in the space radius, in the space of r^2 DSDs are shifted to large sizes without change in the sha distribution. Since relative velocities between droplets are proportional to r^2, growth leads to increase in the collision kernel and collision rate despite DSD narr the radii space. The main conclusion from this analysis is that maximum drop size are in parcels close to adiabatic, but not in parcels with wide DSD formed under e mixing.

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It is interesting to note that in addition to a higher collision parameter, LWC m values are greater in the CON case than in the NoMI case as well. These higher LW indicate a deeper cloud. During the simulation, sensible and latent heat fluxes f surface increase the humidity in the boundary layer and lead to a decrease in cl height as was mentioned above. These changes result in an increase of the LWC n cloud top.

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Conclusions inferred from the previous figures regarding the shape of the I supported by Fig. 11, where DSDs at 100m layers near cloud top are presented. The I separated by LWC value and averaged in the horizontal direction. For all presented I distribution peak is located at similar radii. The concentration of drops around 10μm i with the increase in the LWC at each height. In addition, DSDs with lower LWC higher concentration of small droplets. DSDs in this figure all come from near clouc the decrease in LWC, decrease in the larger drop concentration, and formation of droplets result from turbulent mixing with the dry inversion air. These DSDs corre the parcels in zone 2, in figures 9 and 10. So, according to our results, mixing does no the formation of superadiabatic droplets that trigger collisions. On the contrary, dr maximum size arise in parcels close to adiabatic (undiluted).

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Note that mixing between parcels in the model is inhomogeneous, because significant time (15-20 min) for homogenization (according to homogeneous homogenization is instantaneous). At the same time mixing leads to DSD broadeni contrasts with the classical theory that assumes the shape of DSD unchangeable ir extreme inhomogeneous mixing. We attribute this difference to simplifying assum about monodisperse DSD in the classical mixing concepts.

4.4 The dual role of turbulent mixing in formation of drizzle

In previous sections we discussed the properties of 'lucky' parcels where first c formed. 'Lucky' parcels have high absolute humidity. They originate from near th and reach the upper levels of the cloud quickly, not allowing sufficient time for mix the surrounding air. In these parcels collisions lead to the formation of drizzle foll sedimentation of the largest drops.

In this section we wish to observe the effects of turbulent mixing on the formation o parcels as well as on the further development of drizzle in the cloud. Figure 12 pr

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accumulated mass (left) and accumulated number (right) of drops larger than 20µ parcels in the domain. Several different simulations are compared: the control (CON mixing (NoMI) cases and two simulations in which sedimentation is switched o model, one for the CON case (NoSD) and one for the NoMI case (NoMISD).

Large droplets first form in cases where drop sedimentation is removed. In these sin drops become very large and grow by collisions to unrealistically large sizes, and provide insight into the process of first drizzle drop formation.

In the NoMISD case the mass increases faster and earlier in the simulation than in tl case. When the parcels are adiabatic, parcels initially located near the surface where is maximal will have the lowest LCL and maximum LWC. In the NoMISD these retain their extreme values of humidity and large drops form earlier. Inclusion o between the parcels leads to a reduction of maximum values, homogenization of the a subsequent delay in the formation of large droplets (NoSd, left panel). From these can be seen that the first large droplets will form in adiabatic parcels with initia humidity. The accumulated number of large drops (right) further supports this concl NoMISD the number of large drops increases until ~150 min and then remain constant. Following the formation of large droplets in parcels with appropriate cond more parcels are able to reach these conditions. In contrast, the number of large dro NoSD run continues to increase after 150 min of simulation. The absence of turbulen is the only difference between the two simulations and yet the changes in the n number of larger drops are significant. Results indicate that the direct effect of m parcels with initially high humidity and low LCL is to retard the formation of large dr

When sedimentation is included in the simulations, after some drops become large they may fall through the cloud. In the NoMI case large drops forming in a small nu parcels sediment through the cloud and evaporate in other parcels, especially in dry a parcels penetrated from the inversion (Fig. 1). As a result, the amount of large drop form in the cloud remains very low and the mass of these large drops is negligil evaporation process prevents the formation of drizzle at the surface in the NoMI case. simulation, when mixing is included, the cloud structure changes dramatically. As droplets falling from parcels close to adiabatic do not evaporate but grow by collision the cloud. In this simulation drizzle develops and reaches the surface. After th formation of large drops in the most humid parcels in the cloud, the number of large the CON case continues to increase, indicating that turbulent mixing facilitates the f of drizzle in the cloud.

In general, Fig. 12 shows the two main phases of drizzle formation in Stratocumulu First, larger droplets form in the most adiabatic parcels in the cloud layer. Second, mixing leads to further formation of more large droplets and drizzle-sized drops. In t phases turbulent mixing plays a contradicting role, delaying the first while enhan second (see further detail in the discussion).

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4.5 Further drizzle development in the cloud

In the cloud's latter stages of drizzle development, large drops forming in 'lucky sediment through the cloud, leading to further development of drizzle. In Fig. 3 this p first seen as an increase of r_e throughout the cloud layer. The horizontally-averag distribution in the simulated cloud at the drizzle stage (t = 360 min) is shown in Fi this time drizzle drops reach the surface. Figure 13 shows that large drops form first a (700-800m) and then sediment through the cloud. During their descent the drops g their relative proportion in the mass distribution increases. As the droplets from c sediment through the cloud they act as drop collectors, growing in size through collis coalescence. Near the surface (100-200m) there are only large drops in the distributio were large enough to reach these levels and not evaporate in the sub-cloud layer. Tl of drizzle drops ranges from 40 µm to 350 µm, with a peak at 200 µm. These radii ag observations (Pinsky et al., 2008).

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The dynamic structure of the BL and the presence of large eddies effect the contin drizzle development in Sc clouds as well. They determine areas of updraft and down are the controlling factor in the preferable trajectory of 'lucky' parcels. As larger dr along cloud top, droplets in parcels reaching areas of downdraft are more sedimentation. Drizzle does not develop in the entire cloud simultaneously so that more intense drizzle flux form. These areas coincide with downdraft areas in the clou 14 presents the averaged rain flux near cloud base (450 m) throughout the simulati bar shows the drizzle flux separated into downdraft and updraft areas. It can be seen t of drizzle falls in these areas. Areas of enhanced drizzle were seen in observations of well (VanZanten et al., 2005).

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In Fig. 14 it was shown that the mass and number concentration of larger drops increa turbulent mixing is taken into account – far beyond those seen with no mixing. In ad the inhibiting effect mixing has on the initiation of drizzle, turbulent mixing is ne continued drizzle development in the cloud.

Among possible mechanisms able to lead to this effect we first consider change aerosol size distribution. One of the specific features of the model used in this accounting for the aerosol distribution in each parcel. In addition to accounting for when the parcel is sub-saturated and all aerosols are in equilibrium with the environ model tracks aerosols in the drops themselves. Aerosol size does not change during p of diffusion growth or evaporation, but in cases of collisions aerosol size grows reach larger sizes than initially found in the BL. Figure 15 presents the development time of the maximum aerosol size in cloud parcels. The median profile of the m aerosol size in each parcel for the CON (top) and NoMI (bottom) cases is presented.

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First, it is clear that the changes in the maximum aerosol size are very different in cases. In the NoMI case, largest aerosols are present at the beginning of the simulatio aerosols have an average size of 1.3μm, corresponding to the largest aerosol in t spectrum. As the largest aerosols in the spectrum they will be in the largest drops in t After about 150 min, aerosol size diminishes. In NoMI, sedimentation of the largest from parcels with the lowest LCL results in the largest aerosols in drier and warmer These parcels do not have the conditions required for larger drop formation in the f time steps. Because of the comparatively small number of parcels with appropria conditions, sedimentation of the largest drops renders the largest aerosols unavai further collisions.

As seen in the previous section, initial conditions are a governing factor in the form large drops when the parcels are adiabatic, and drop formation will be much mo without mixing than in the case of mixing.

As the development of the cloud progresses in the CON case the maximum aero increases and reaches an average of more than 3μm. When turbulent mixing is maximum values of humidity and LWC are reduced and initial droplets forming in t are somewhat smaller. These drops do not sediment to the surface, but evaporate in cloud layer. The aerosols can now be advected back into the cloud in ascending bra large eddies. As aerosols recirculate in the BL, their size increases when they a droplets growing by collisions and coalescence. The mechanism for aerosols size in presented in a study by Magaritz et al. (2010) showing that the evolution of large dro leads to a corresponding increase in the aerosol size distribution as a result of collisio the cloud.

Mixing between parcels gives rise to the recirculation of aerosols in the cloud. Collis to the formation of increasingly large droplets and aerosols during the recirculati result, the maximum size of aerosols at cloud base increases which fosters the forn larger droplets at cloud base (large haze particles) and above in ascending parcels. W that the droplets formed on the largest aerosols contribute to the formation of th largest droplets in lucky parcels shown in Fig. 7b. After initiation of drizzle in th enhanced collisions and formation of drizzle leads to a rapid increase in aerosol size a shown in Fig. 15. Larger aerosols continue to circulate in the BL, fostering furthe formation at the drizzle stage of cloud evolution.

Spectral broadening and formation of the largest droplets in Sc due to turbulent mixir vertical recycling of cloud air is discussed in a study by Korolev et al. (Korolev et al In that study it is suggested that mixing of the DSD of parcels ascending and desce the cloud should lead to the presence of larger droplets in the ascending branch of t near cloud base and result in more efficient collisions as the parcel ascends. The res in fig. 15 can also foster formation of larger droplets in ascending parcels, during th of diffusion growth and collisions. In combination with the increased spectral widtl Fig. 10 and the increase in the median profile of r_e near cloud base that is shown in F believe that lateral mixing near cloud base and inside the cloud layer can have a stro on the drizzle formation process in Sc.

5 Conclusions

The process of drizzle formation in stratocumulus clouds is investigated using LEM accurate description of microphysical processes. The new version of the model process of mixing between parcels and surface flux of heat and moisture. Lightly stratocumulus clouds observed during flight RF07 of the DYCOMS-II field campa successfully simulated.

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<#>**Discussion** ¶

The study discussed in this paper separates the drizzle formation process in stratocumulus clouds into two parts. First, formation of the first largest drops in the cloud layer, initiating the process; second, the development of drizzle in the entire cloud until it reaches the surface. It is seen that turbulent mixing, both in the cloud and at the boundaries, plays two different and opposite roles in these two parts of the process. ¶

<#>**First large droplet formation**¶

The first large cloud droplets form in only a handful of 'lucky' parcels. These differ from the rest of the cloudy parcels by retaining their adiabatic properties. They are the most humid, ascending relatively quickly from the ocean surface and mixing only partially with the environment. 'Lucky' parcels remain at the upper levels of the cloud yet do not strongly interact with the inversion layer. With their high LWC their very efficient collisions lead to the formation of a tail of large drops with large effective radius. Turbulent mixing is only an inhibitor in the formation of 'lucky' parcels and the first large drops, reducing the humidity and LWC in the parcel during its ascent. ¶

Figure 17 compares the mechanisms of formation of the first large drops in warm cumulus clouds (Cu) and stratocumulus (Sc) clouds. In both cases collisions occur initially in nearly adiabatic parcels, in which effective radius critical value of about 15μm in cumulus (Khain et al., 2013) and 12μm in Sc. In Cu, the first large drops form near cloud top, but at larger distances above cloud base than in Sc clouds. We attribute this to the fact that the process of drizzle formation by collisions requires time to evolve. In Cu during this time parcels ascend in the cloud and r_e increases. In Sc 'lucky' parcels reaching cloud top continue along the upper ...

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Clouds observed in flight RF07 were simulated by an earlier version of LEM, wh was no mixing between parcels and no inversion layer above cloud top (Magari 2009). In that study the hypothesis that first drizzle forms in a small number of air near cloud top in which LWC is maximal was expressed and justified. The considera more realistic geometry of the STBL with an inversion layer required the implemen turbulent mixing between the Lagrangian parcels. The question arose, whether the hy of 'lucky' parcels can also be justified under conditions of mixing. Results of the study show that the hypothesis of 'lucky parcels' remains valid also when turbulent r taken into account.

It was further shown that mixing creates a realistic structure of stratocumulus clouds not prevent the appearance of nearly adiabatic LWC values at cloud top. Among volumes in the cloud 'lucky' parcels are the most humid and have the highest LWC most intense collisions.

It is shown that without mixing taken into account drizzle cannot form in strato clouds. Maximum LWC values are not as high and large drops can form only in a portion of the parcels that reach cloud-top. Effective radius in the cloud is lower and profile remains nearly constant throughout the lifetime of the cloud.

In conclusion, turbulent mixing plays a dual role in the process of drizzle formation one hand, the formation of the first large drops in Sc is an adiabatic process in which mixing is an inhibiting factor. It reduces maximal values of humidity and delays the f of the first drops. On the other hand, turbulent mixing leads to the creation of favorable background conditions and increased aerosol size within clouds, allowin growth and development during drop sedimentation. In addition, mixing leads to an in the drop size (haze size) at cloud base leading to faster formation of largest dro ascending nearly adiabatic cloud volumes.

Acknowledgments

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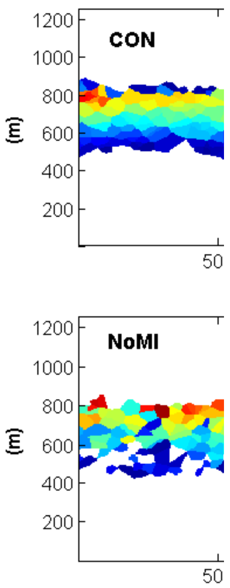

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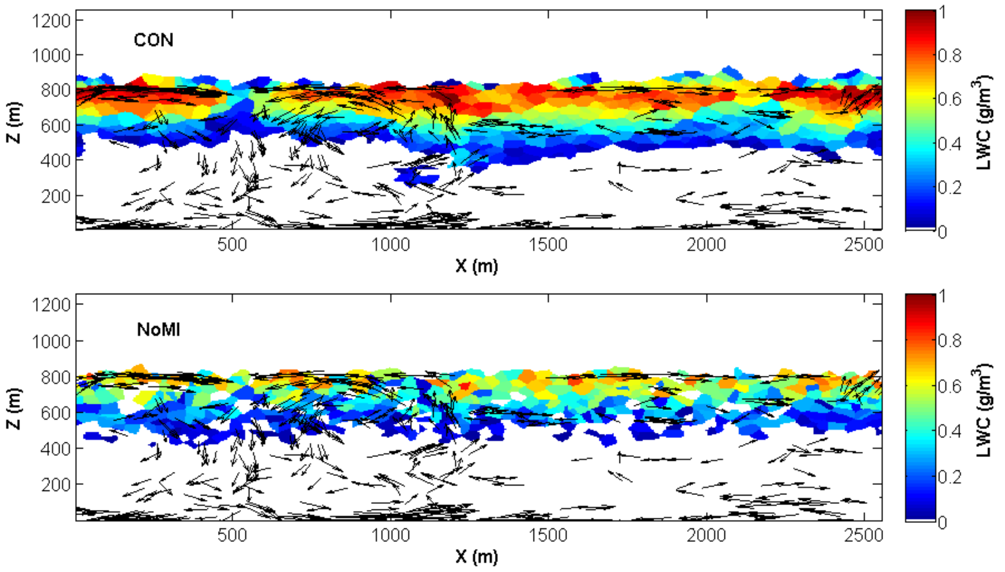


Figure 1. Fields of LWC in the CON and NoMI simulations plotted at t = 270 r
velocity field at the same time step is presented as well

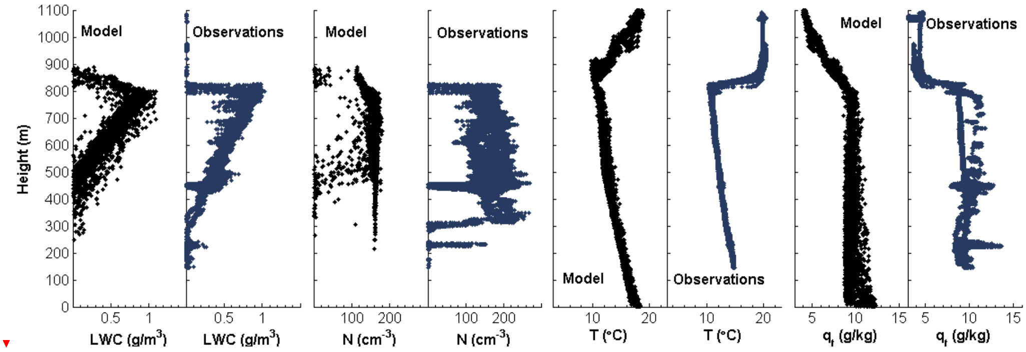
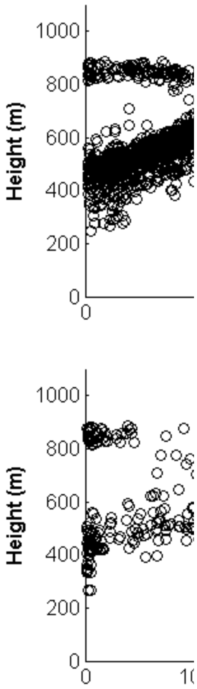


Figure 2. Profiles of LWC, droplet concentration (N), Temperature (T) and total wate ratio (q_t) from the model simulation and observations. From the model all parcels fr time steps between 270-280 min are presented. All observations between 0845-1135 presented.



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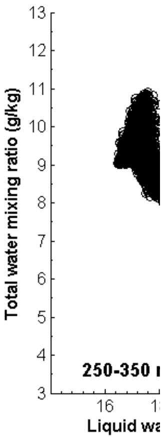

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Figure 3. Paluch diagram for the model simulation CON (left) and data from flight RF07 (right). From the model all parcels located in the layer between 700-1000 m during 100 min of simulation are presented. From observations all measurements in the layer between 700-850 m during 0845-1135 UTC are presented. A concentration limit of $3cm^{-3}$ is used to separate cloudy (black circles) and non-cloudy (gray triangles) samples.

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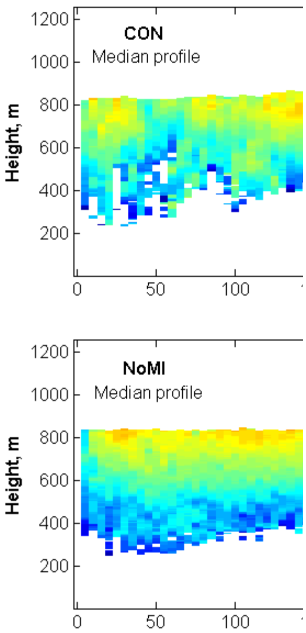

Figure 4.

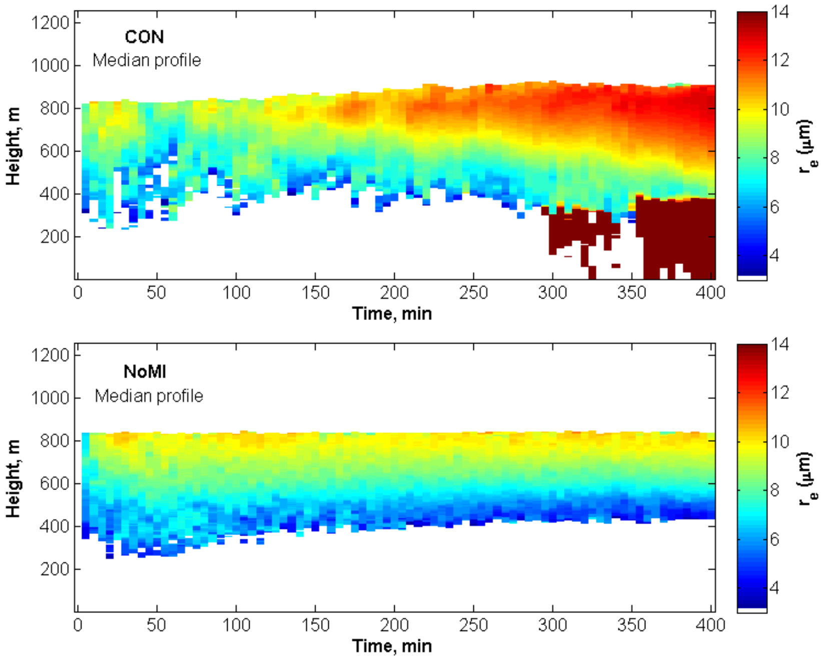

Figure 3. Changes in the effective radius median profile in the CON (top) and NoMI simulations.

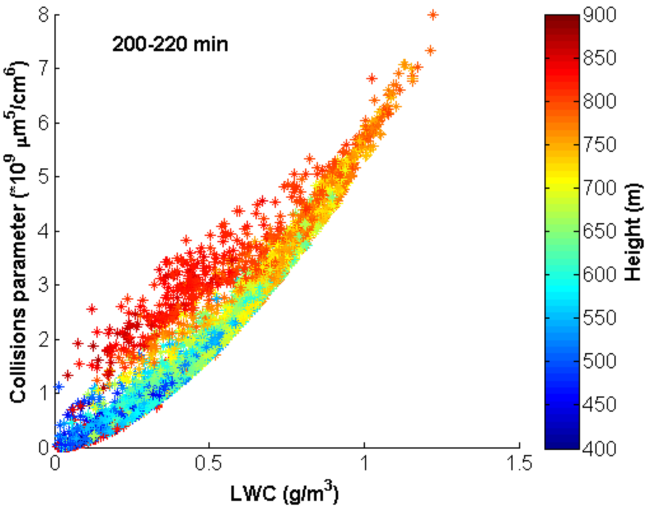

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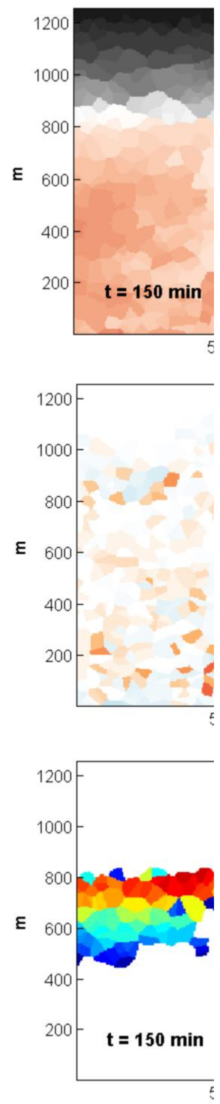
Figure 4. LWC – collision parameter scatter plot for all cloud parcels at 200-220 simulation in the CON case. Color denotes the height of the parcel.



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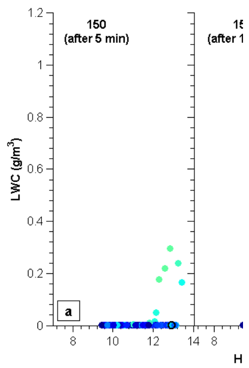

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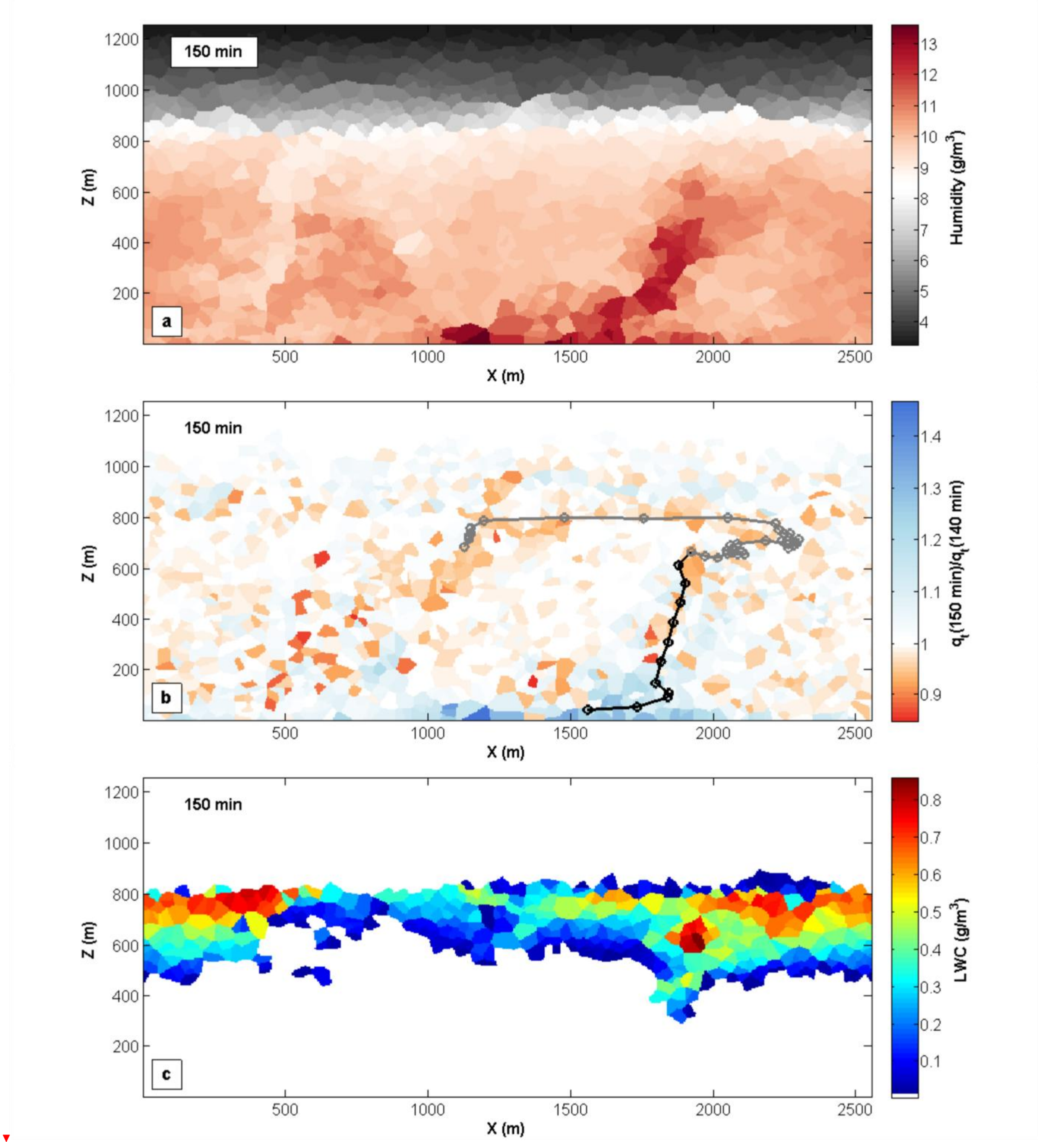

Figure 5. Fields of different parameters plotted at t = 150 min. (a) humidity (b) ratio water mixing ratio: $q_t(150\ \text{min})/q_t(140\ \text{min})$ (c) LWC.

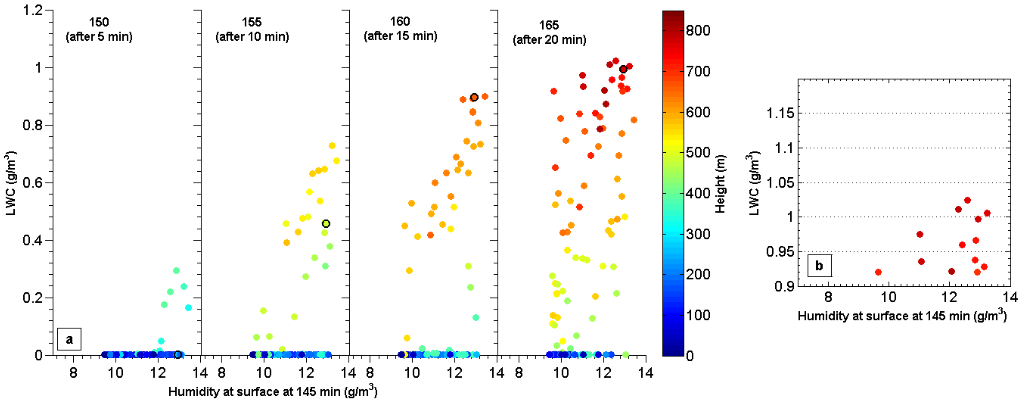

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Figure 6. (a) LWC as a function of humidity at the surface at 5 min intervals, startir min of simulation in the CON case. A single selected parcel used in Fig. 8 is marked in all panels. (b) Magnification of the top part of the last panel in (a).

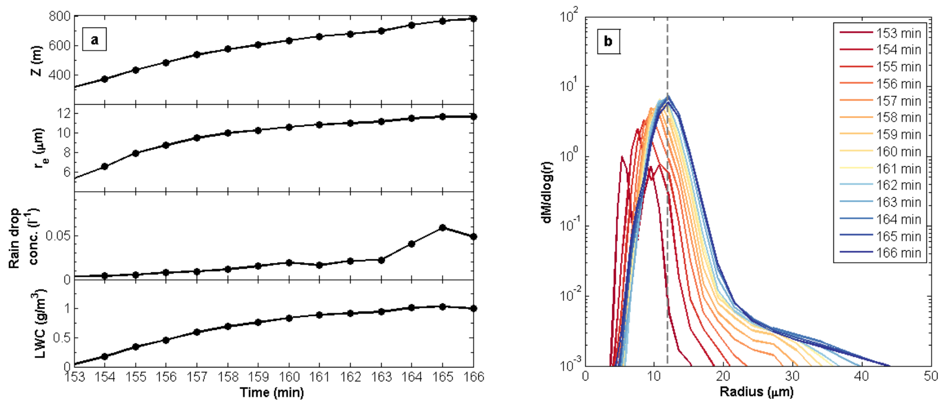

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Figure 7. History of a single parcel marked in Fig. 6. (a) Change in the height, radius, rain drop concentration and LWC of the parcel. (b) Changes in the mass distril the parcel.

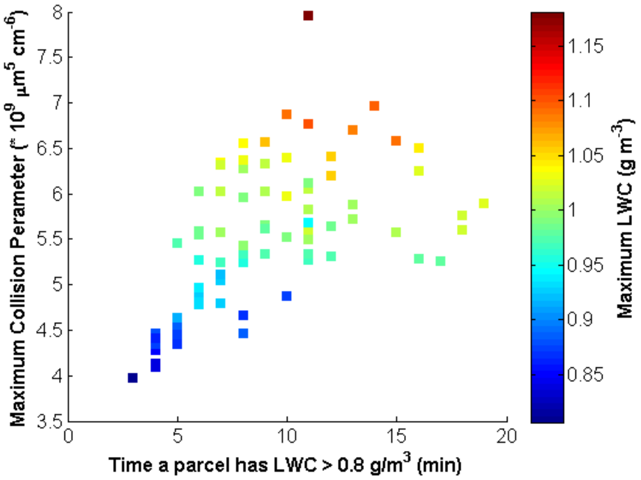

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Figure 8. Maximum collision parameter as a function of the accumulated time a pa $LWC > 0.8 g/m^3$. Colors denote the maximum value of LWC during the same time p

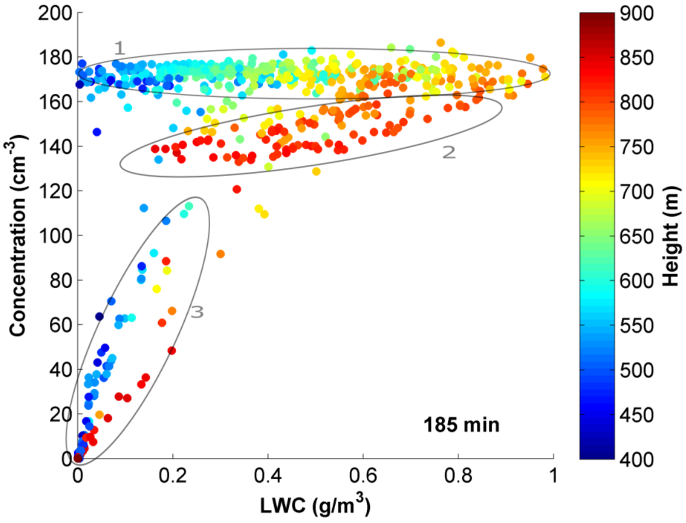

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Figure 9. LWC-N scatter plot at t = 185 min. Colors denote the height of the parcel.

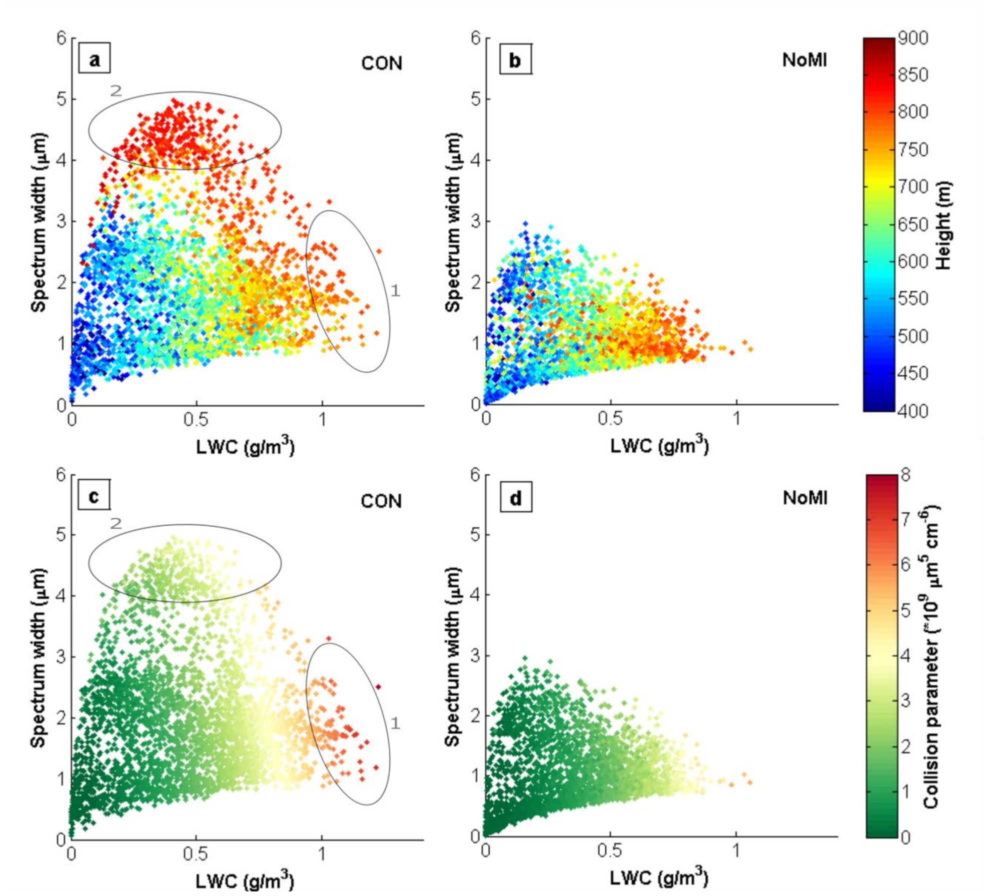

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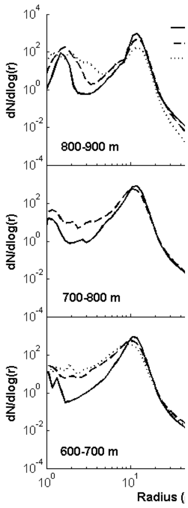
Figure 10. LWC-spectrum width scatter diagrams for the CON (left) and NoMI (righ
Each dot represents a parcel during 195-220 min of simulation. In the top row (a,
denote the height of the parcel. In the bottom row (c, d) colors denote the collision pa



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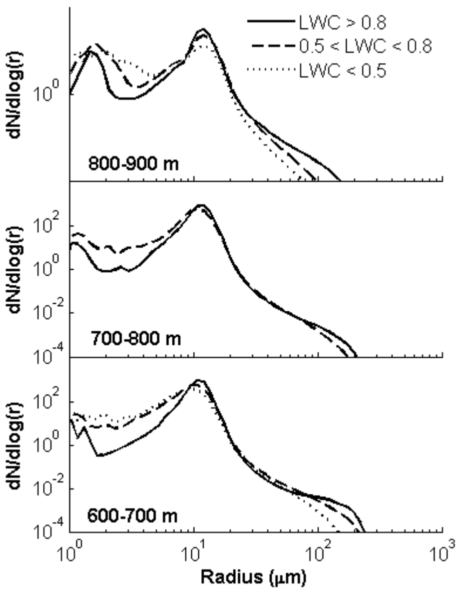

Figure 11. Averaged DSD at three layers near cloud top. At each level DSD is

according to LWC value.

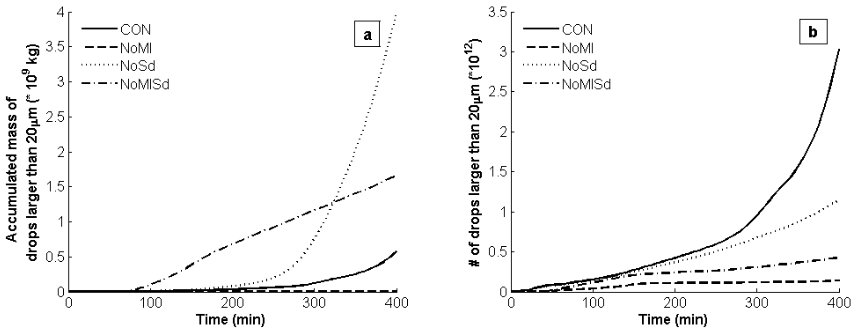

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Figure 12. Accumulated mass (a) and concentration (b) of drops larger than 20μ simulations are presented: control (CON), no-mixing (NoMI), control and no sedin (NoSd) and no-mixing and no sedimentation (NoMISd).

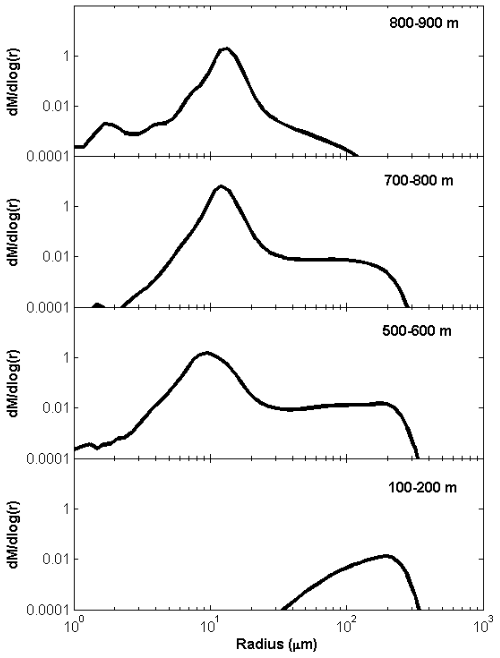

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Figure 13. Averaged mass distribution for 100m layers, plotted at t = 360 min in t simulation.

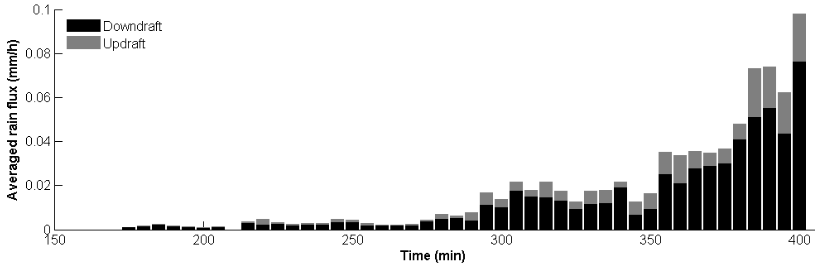

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Figure 14. Averaged rain flux at 450 m near cloud base, separated into downdraft (bl updraft (gray) areas.

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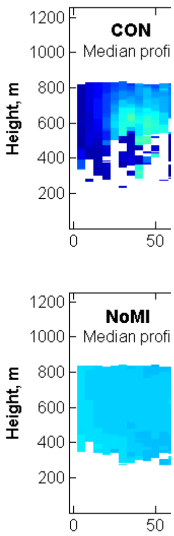

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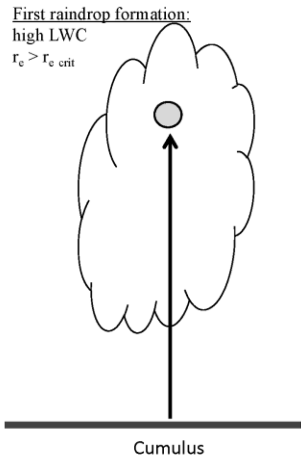

Figure 17. Schematic diagram of 'lucky' parcels and first drizzle-size drop formation.

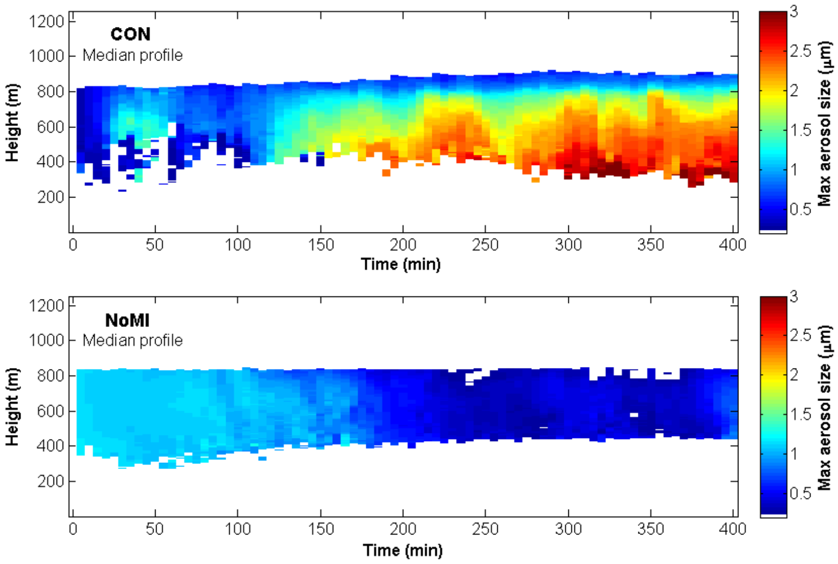

Figure 15. Change in the median profile of the maximum aerosol size in cloud parc
CON (top) and NoMI (bottom) case.