Comment on “Long-resident droplets at the stratocumulus top” by Alberto de Lozar and Lukas Muessle

The authors quantified the time that droplets stay at the top of a cloudy mixed layer using direct numerical simulations (DNS). Lagrangian particle tracking method has been applied in the large eddy simulation (LES) results during the recent years. One of their purpose is to complement past Lagrangian studies by LES. The advantages of using DNS are (1) resolving the turbulent dynamics explicitly by DNS (2) tracking more cloud droplets and getting better statistics. They found that about 15% cloud droplets can escape the stratocumulus large-scale convective motions, and reside at the cloud top region for a time longer than the convective eddy time. They argued that those long-resident droplets might broaden the droplet size distribution, thus speed up the rain formation in stratocumulus with middle scale turbulence.

This paper is clear and easy to follow. However, I have one concern about their Lagrangian tracking method. If I understand correctly (Line 144), their model does not include the droplet sedimentation. But I think it might be important, especially for large droplets. Even for small cloud droplet, I think, sedimentation might affect its trajectory after a long resident time. Please justify it clearly that why this study neglected the gravitational settling on the droplet movement. Otherwise, I think, sedimentation should be considered in the method.

Overall, this manuscript is well written and the results are interesting. It is worth to publish on ACP, if my concern above and minor comments below are addressed properly.

Answer: Thank you very much for your positive comments. We decided to neglect sedimentation in order to investigate if turbulence alone can produce long trajectories at cloud top. We think that this is an important first step to understand cloud droplets dynamics, which are mostly driven by the mean flow. Rain droplets with larger sedimentation velocities might behave differently. Besides, neglecting sedimentation allows us to compare our results to past LES that neglect sedimentation (Kogan (2006) and Stevens and Feingold (1996)), which is one of the objectives of this paper.

Please notice that including sedimentation in the calculations is not completely straightforward, because Lagrangian cloud droplets sediment with similar settling velocities as the Eulerian liquid water. Sedimentation thus needs to be modeled both in the Lagrangian and in the Eulerian evolution equations. We are currently implementing the Eulerian sedimentation model in order to investigate how sedimentation alters the entrainment dynamics (publication in preparation). In the future we would like to couple the new Eulerian scheme to the Lagrangian part of the code to investigate how sedimentation alters the residence time of small droplets.

We have added a sentence to the introduction to make clear that the investigation is restricted to droplets without sedimentation (see below). Besides, we also discuss that the pattern of long-resident droplets (Fig. 4) is only expected for low sedimentation velocities (see answer to comment 8).

Page 2, line 35: As in these past studies, we restrict to small cloud droplets and neglect sedimentation, which could have a relevant effect for larger droplets.

Comments: 1. Line 83: “Todays” should be “Today’s”?

Answer: Thanks. Changed.

2. Line 92: There are two papers from de Lozar and Mellado in 2015, should be cited clearly a) or b).

Answer: We are sorry for that. Changed.

3. Line 100: The author only consider one-way coupling in this study. However, I think the latent heat release duo to evaporation of huge amount of cloud droplets might be significant. Is it because the authors already consider the condensation/evaporation process in the DNS, e.g., Eq. 1?

Answer: Condensation/evaporation is calculated in the DNS, and the Lagrangian droplets follow the DNS tendencies. Please notice that the ratio of cloud droplets to Lagrangian droplets is still approximately 20 millions to one, so that latent heat release from the Lagrangian droplets is insignificant. Besides, in order to consider the latent heat release from the Lagrangian droplets we would need a different mixed Eulerian-Lagrangian formulation.

4. Eq. 1: reference is Lozar and Mellado JAS 2015 or GRL 2015? I think it is JAS.

Answer: The reference has been corrected in the text. It is indeed to the JAS paper.

5. Eq.A5: I derive s_{eva} as an interest, but get a different result:

$$s_{eva} = \kappa_T (\frac{df}{d\xi}) \nabla^2 \xi$$

I might make some mistakes somewhere, but I can’t figure it out. Please put the derivation in the response file. Thanks.

Answer: Please find the derivation of s_{eva} at the end of this document.

6. Line 160: “...with changing height” should be “...with changing size”? I think the whole paragraph is talking about the assumption that the growth of droplets are almost independent of their sizes. And I don’t understand this sentence “because this term is identically zero in a mixed layer with constant pressure.” What does “this term” mean?

Answer: We refer to the condensation/evaporation of droplets as they ascend/descend through the cloud. This condensation/evaporation does not occur in a mixed layer with constant pressure. We have added two sentences to the text to this paragraph to clarify this point:

Droplets grow as they ascend through the clouds and shrink when they descend, due to the change of temperature in the atmospheric boundary layer. Equations 1 and 3 neglect the condensation/evaporation of droplets with changing height, because this ~~term~~ is identically zero in a mixed layer with constant pressure. We decided not to include this process, because its effect on the cloud-top DSD of a well-mixed stratocumulus is also negligible when assuming that all droplets follow the mean condensation/evaporation. The reason is that this assumption implies that condensation/evaporation affects equally all droplets independently of their size, *and all of them grow by the same amount when they reach the cloud top*. In reality larger droplets 15 condensate/evaporate faster than smaller ones leading to some broadening of the DSD (Cooper, 1989; Lanotte et al., 2009), but this mechanism is not considered in this study.

7. Figure 4: Results here are for one specific time? End of the simulation? Please add more description for this figure.

Answer: The results are for the end of the simulation at t =11.1t^*. This information has been added to the caption.

8. Line360-364: Results here show that long-resident droplets prefer the downdraft regions which is contrary to my feeling. I thought droplets in the downdraft region might be quickly moved out, while in the updraft region might be suspended. Is it because you neglect the inertial and sedimentation for the droplet's movement in this study?

Answer: This finding also initially surprised us, but it is the same tendency as in Kogan (2006). We think that updrafts, which are mostly composed by "young" in-cloud droplets, push "older" droplets into the downdraft regions. We think that small-scale turbulence allows some of the older droplets to escape from the downward movements, thus creating long-resident droplets.

Sedimentation increases the residence time in the updrafts and reduces the residence time in the downdrafts Therefore it is likely that more and more long-resident droplets appear in the updrafts as the sedimentation velocity is increased. In the limiting case of ice crystals (very strong sedimentation) long-lived crystals cluster on the updrafts (Yang et al. (2015)). We have added a sentence to the conclusions to state that the pattern is only expected for small sedimentation velocities, and that the opposite pattern can be expected for high sedimentation velocities (page 16, line 13):

The agreement suggests that the tendency of long-resident cloud droplets to be preferably placed in downdrafts is ~~quite~~ generic *for droplets with relatively small sedimentation velocities (in the other extreme, long-lifetime ice crystals with much higher sedimentation velocities cluster in the updrafts regions (Yang et al. (2015))*.

The liquid equation

From Eq.(A3) it can be derived:

$$d\ell = -\left(\frac{d\ell}{d\xi}\right)\left[\frac{d\chi}{\chi_s} + \frac{d\psi}{\psi_s}\right]. \tag{1}$$

Using Eq. (1) in the evolution equations Eq.(A2) leads to:

$$\frac{d\ell}{dt} = -\left(\frac{d\ell}{d\xi}\right)\left[\frac{\kappa_{\mathrm{T}}}{\chi_s}\nabla^2\chi + \frac{\kappa_{\mathrm{T}}}{\psi_s}\nabla^2\psi - \frac{r}{\psi_s}\right]; \tag{2}$$

where d/dt is the convective derivative. Now we need to relate the Laplacian of ℓ to the Laplacians of χ and ψ.

Again using Eq. (1) we find:

$$\nabla\ell = -\left(\frac{d\ell}{d\xi}\right)\left[\frac{\nabla\chi}{\chi_s} + \frac{\nabla\psi}{\psi_s}\right] = \left(\frac{d\ell}{d\xi}\right)\nabla\xi; \tag{3}$$

and using again the gradient operator:

$$\nabla^2\ell = \left(\frac{d^2\ell}{d\xi^2}\right)|\nabla\xi|^2 - \left(\frac{d\ell}{d\xi}\right)\left[\frac{\nabla^2\chi}{\chi_s} + \frac{\nabla^2\psi}{\psi_s}\right]. \tag{4}$$

Combining Eq. (2) with Eq. (4) we obtain the evolution equation for ℓ:

$$\frac{d\ell}{dt} = \kappa_{\mathrm{T}}\nabla^2\ell + \left(\frac{d\ell}{d\xi}\right)\frac{r}{\psi_s} - \kappa_{\mathrm{T}}\left(\frac{d^2\ell}{d\xi^2}\right)|\nabla\xi|^2; \tag{5}$$

where the second and third terms of the r.h.s are the condensation and evaporation functions described in the paper.