Reply to comment by W. Grabowski

We greatly appreciate the reviewer's efforts to carefully review the paper and the insightful comments. We have addressed the questions and concerns indicated in the reviews and believe that the revised version meets the journal's requirements. In the following, blue italic letters denote the reviewer's comments and black regular font letters denote our responses. All the page numbers and line numbers in the response refer to the location in the revision (P=page, L=line)

1. I found it surprising that the impact of turbulent collisions between similar-sized droplets overwhelms the gravitational collisions between droplets with different sizes. I do not say I do not believe the effect, I just think this should be emphasized more in the manuscript and perhaps supported by additional arguments. Yes, I agree that turbulence dominates the enhancement for equally-sized droplets simply because gravitational collisions vanish in that limit. This is the major problem when showing the turbulent enhancement. However, it is not clear to me why turbulent collisions between equally-sized droplets should outnumber gravitational collisions between droplets of different sizes. The argument presented in the paper, that is, narrowing of the droplet spectra through condensational growth leading to more collisions when turbulence is added, hinges on this conjecture. I think this is the crux of the argument and it should be appropriately stressed in the manuscript. Moreover, one may ask why it is so? Is this because droplets of different sizes tend to cluster in different regions of the turbulent flow (as shown by Lain-Ping Wang in some of his papers), but droplets of the same size should cluster in the same region? Is this the collision efficiency effect? I think it would be appropriate to expand the analysis and maybe come-up with a hand-waving argument to provide some additional support for the key argument.

The similar-sized collisions outnumbered the different-sized collisions only when both condensational process and strong turbulence are present. By comparing the PDF of droplet collision with and without condensation at different flow conditions (see Fig.3), one can note that the major contributor of similar-sized collisions results from the interaction between the condensational process and the collisional process. When condensation is absent, the number of similar-sized collisions is always small regardless of the intensity of the turbulence (Fig.3, left column). With strong turbulence, the PDF (Fig.3(e)) becomes flattened but the number of different-size collisions remains dominant. This feature ruled out the explanation that the outnumbered similar-sized collisions were purely produced by the clustering effect, the collision efficiency effect, and the transport effect (i.e., by increasing the droplet relative velocity). In contrast, when condensation is present, the intensification of turbulence increases similar-sized collisions (Fig.3, right column or Fig.4, right column), indicating that the enhancement of similar-sized collisions is mainly contributed by the condensation-mediated collisions. In addition, the condensation-mediated collisions only become outnumbered when the turbulence is strong. However, it should also be noted that the large number of similar-sized droplets generated by condensation can further reinforce the clustering effect. Droplet pairs with similar sizes tend to cluster in the same regions of the flow because of similar droplet inertia and terminal velocities. This effect has been confirmed previously in a number of studies (e.g., Ayala et al. 2008a; Franklin et al. 2005) and is especially pronounced for large droplets. The reason is that small droplets have small Stokes numbers, and they adjust very quickly to changes in the flow and therefore behave more like fluid tracers than inertial droplets.

On the other hand, condensational process tends to narrow the droplet size spectrum and create more similar-sized droplets. We include Figure 5 in the revision (also shown below) to illustrate the time evolution of the pair combinations of droplet with similar sizes (r/R>0.7) and with different sizes (r/R<=0.7). With the presence of condensation, the number of different-sized pairs significantly decreases in the condensation-collision experiment in the first 2 minutes (Fig. 5 (b)). This reduction is caused by the rapid condensational growth for droplets with r <15microns. Simultaneously, the number of similar-sized droplets significantly increases during the first 2 minutes and steadily decreases thereafter (Fig. 5 (d)). In contrast, when condensation is absent as in the collision-only experiment, the number of different-sized droplet pairs stay relatively constant (Fig. 5 (a)) while the number of similar-sized pairs undergoes only a mild decay (Fig. 5 (c)). The large increase of similar-sized pairs in the collision-condensation experiments during the first 2 minutes significantly increases the number of turbulent-enhanced similar-sized collisions. After 2 minutes, the condensational effect diminishes, and the collision-coalescence process takes over in modulating the droplet pair population. The subsequent decline in the number of similar-sized pairs and the increase in the number of different-sized pairs mainly arise from the collision-coalescence process. We also include a detailed description and explanation of this point in the revision (from P9 L5-P10 L24).

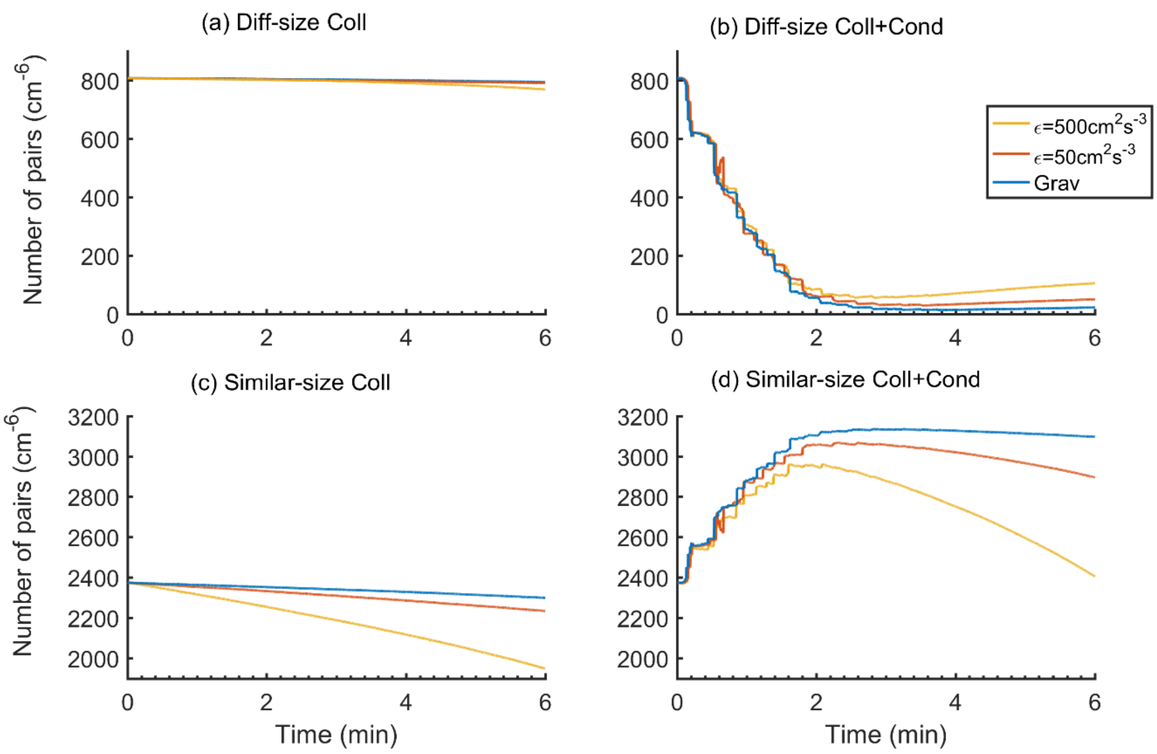

Figure 5: Time evolution of the number of pair combinations for (a) the different-sized droplets (r/R \<= 0.7) and (c) the similar-sized droplets (r/R>0.7) in the collision-only experiments, and (b) the different-size droplets and (d) the similar-sized droplets in condensation-collision experiments. The pair combination is computed using the droplet number concentration (cm^{-3}), therefore the unit is cm^{-6}. The color denotes the three different flow conditions which are shown in the legend.

2. I am little concerned with a small size of the computational domain used in the simulations. The size limits the range of scales that the simulations can cover, but this is not what I am worried about. There are some suggestions in the literature that claim the problem also depends on the Reynolds number, that is, the size of the domain, but I feel this is of secondary importance. I am worried about the number of droplets that simulations include. Assuming the total concentration is somewhere around 100 per cc, then you carry around about 10^5 droplets in your 1 liter domain. To create one 100 micron droplet out of a cloud of droplets with mean size of, say 10 microns, takes of the order of 1000 collisions. Thus, the number of droplets you carry has to significantly decrease with time. Is this a problem? Of course, this also means that you underestimate the impact, correct? I feel one should discuss this issue in the paper (e.g., show how the number of droplet changes with time) and suggest some improvements. One is to run ensemble of simulations to provide confidence intervals on Fig. 1 (the oscillations for radius larger than about 40 microns are a result of a single realization, correct?). The other possibility is to add droplets, for instance, create a new droplet, but keep the colliding droplets in the domain (perhaps re-positioning them randomly). The support for such an approach may come *from the following argument: larger droplets fall faster and they simply fall out from the volume you consider and find themselves in the environment that has the same droplet population as before the collision. Such a methodology would provide an upper bound of the impact, correct? I feel it would worthwhile to discuss this aspect in the paper.*

In all the simulations, the total number of collisions remains below 10% of the total number of droplets. Specifically, the number of collisions is below 9% of the total number of droplets at EDR = 500 cm^2s^{-3}, below 3% at EDR = 50 cm^2s^{-3} and below 2% in the purely-gravitational case. Overall, this is a relatively small proportion, and therefore the impact of decreasing droplet number is expected to be secondary. Statistically, the proportion cannot be reduced by either increasing the number concentration or by expanding the domain size. However, it is possible to reduce the statistical uncertainty by doing so. We also agree on the alternative way suggested by the reviewer to reduce the impact of decreasing droplet number by creating new, randomly located droplets after each collision so that the total droplet population is conserved. The justification of this treatment is that larger droplets fall out from the volume and new droplets enter. However, what size of droplets should be introduced remains contentious and needs further justification. We included the above argument and description in the revision (P4, L22-28).

Minor specific comments (P – page, L – line):
1. The text uses the word "observation" and "observe" in several places. I suggest to replace with different words to avoid confusion. This is a numerical not observational study.

Thanks for the suggestion. We have replaced the words that may lead to confusion in the manuscript.

2. P2, L26: What you mean by the "large-scale flow" here? Is that the eddy hopping idea as suggested by Grabowski and Wang (the ARFM review) and studied in Grabowski and Abade (JAS 2017)?

Yes, we have included the references to further clarify the statement.

3. P4, L15: The 100 micron drop is an arbitrary choice. You can argue it comes from the traditional separation between cloud droplets and drizzle drops, correct? Arguably, one should select a smaller size because the Stokes flow solution that you apply in hydrodynamic interaction calculations is only valid for droplets up to about 50 microns in radius. A comment on that would be desirable here.

Thanks. Yes, we choose 100 microns as the largest droplet size in accordance of the traditional definition of drizzle drops. We agree that 50 microns is a safe threshold to render the hydrodynamic interaction calculation valid. Droplets larger than 50 microns have particle Reynolds number of order one, which will cause certain inaccuracy of the disturbance flow. However, since the collision efficiency of the droplets over 50 microns is very close to unity due to the large Stokes number, it is argued that this assumption would not impact much of the collision statistics. We have addressed this issue in the article. (P4, L18-22)

4. P. 10, L15. I think there should be R^2 *on lhs of Eq. B1, correct?*

Thanks. We have corrected Eq. B1.