First of all, we appreciate the reviewer's comments and suggestions. In response to the reviewer's comments, we have made relevant revisions to the manuscript. Listed below are our answers and the changes made to the manuscript according to the questions and suggestions given by the reviewer. Each comment of the reviewer (in black) is listed and followed by our responses (in blue).

Review of "Aerosol as a potential factor to control the increasing torrential rain events in urban areas over the last decades" by Seoung Soo Lee et al.

The authors investigate the role of spatial gradients in aerosol concentrations on the formation o heavy precipitation from convective clouds. They use a series of high-resolution simulations with the ARW-model with either a spatially homogeneous aerosol concentration or a spatial gradient in the aerosol concentration. Heavy precipitation coincides with the boundary between the air masses with high- and low aerosol concentration, which is also marked by large convergence. In the simulations with a spatially homogeneous aerosol concentration the convergence zones remain weaker and are less organised. The authors argue that the difference in the convergence fields is a result of larger evaporative cooling in the high-aerosol airmass leading to stronger downdrafts and surface divergence.

While the role of spatial gradients for aerosol-cloud interactions has been little explored and is an interesting topic, there are several major issues with the current manuscript, most importantly the lack of an analysis of the meso-scale circulation (see general comments). Before the manuscript can be accepted for publication these issues need to be addressed by the authors and substantial changes to the manuscript are required.

1 General comments

1. Introduction: The authors claim that the temperature and humidity forcing are homogeneous across a MCS and that spatial variability in the dynamic forcing can not explain the spatial variability in MCS intensity. However, it is well known that meso-scale circulation such as sea-breeze fronts, lake-breezes, or cold-pools have a substantial impact on the evolution of convective clouds and MCS. Also a population of clouds in the same large-scale environment will produces cells of varying intensity and at various evolution stages, which leads to a complex and varied spatial distribution. This is not adequately reflected by the statements by the authors (p. 3, l. 79-86).

   As the reviewer stated here, for the same large-scale or synoptic-scale environment, there is the variability of cloud properties in a MCS and we emphasize that this study aims to understand this by focusing on how the aerosol variability creates the variability of cloud properties for the same synoptic-scale environment which is represented by the synoptic-scale forcings.

To state that this study focuses on aerosol variability to explain the variability of cloud properties for the same synoptic-scale environment by reflecting the comment here about mesoscale circulations or forcings, text is revised as follows:

(LL91-101 on p4)

The highly inhomogeneous distribution of precipitation means that there are highly inhomogeneous variables, processes and forcings which disrupt the synoptic-forcing-induced homogeneity of MCSs in urban areas. Some of those forcings are mesoscale forcings that show mesoscale variability and, for example, are related to phenomena such as sea-breeze fronts and lake breezes. In particular, in urban areas, due to strong heat fluxes at the surface, there is the urban heat island (UHI) effect as another example of those phenomena. Examples of those variables and processes are cold pool, rear inflow, wind shear, and mesoscale vorticity. Aerosol is also one of those variables which have large spatial variability. In particular, urban aerosol particles are produced by randomly distributed sources (e.g., traffic), which enables aerosol to have large variability in urban areas.

(LL139-144 on p5)

Motivated by the hypothesis and associated argument here, among the forcings, processes and variables which have spatial variability, this study focuses on aerosol. To examine aerosol effects on clouds and precipitation, numerical simulations are performed by using a cloud-system resolving model (CSRM) that resolves cloud-scale microphysical and dynamic processes and simulates the effect of the variability and loading of aerosol on precipitation.

2. Introduction / Conclusions (p. 4, l. 117 - p. 5, l. 123 / p. 24, l. 730 - 734) : The authors hypothesise that local variability in aerosol concentrations can drive spatial variability in precipitation. This should be more clearly highlighted as hypothesis. Also, I find this hypothesis highly unlikely as (i) convective clouds (in particularly strongly organised MCS) usually are not stationary and may ingest aerosol from various regions during their lifecycle and (ii) horizontal

gradients in aerosol are reduced by turbulent mixing during the transport to cloud base. The spatial variability discussed here appear to be of much smaller scale than those investigated with the simulations with two different aerosol-concentration air masses over an area of about 100 x 100 km.

Here, we want to emphasize that we prescribe background aerosol, its size distribution, chemical composition, and spatial gradient that are all based on observation, since for this study, we do not focus on and consider aerosol physical and chemical processes, and effects of clouds and associated convection and turbulent mixing on the background aerosol. By excluding those processes and effects, we can isolate effects of prescribed or background aerosol loading and its spatial distributions on clouds and precipitation with confidence. Note that our level of understanding of effects of background aerosol itself on precipitation in urban areas has been very low, and through the isolation, this study aims to enhance this understanding that acts as an important building block for more complete understanding of aerosol-cloud-precipitation interactions in urban areas. Yes, aerosol physical and chemical processes and effects of clouds, convection, and turbulent mixing on aerosol distributions need to be explored for the complete understanding. However, this study does not focus on those processes and effects, and instead, aims to gain the understanding of effects of background aerosol itself on clouds and precipitation, since we believe that fulfilling this aim acts as an important first stepping stone to the complete understanding of aerosol-cloud-precipitation interactions in urban areas and understanding of the processes and effects in urban areas merits future study as a next stepping stone.

Although the background aerosol is prescribed, its properties are based on observation. Thus, although physical and chemical processes and the effects of cloud, convection, turbulence on the background aerosol are not considered, overall background aerosol properties including its spatial gradient are not that deviant from observed counterparts. This enables the good consistency in the locations of heavy precipitation between the simulation and observations, demonstrating that the simulations here are not that unrealistic despite the neglected aerosol processes and effects of clouds on the background aerosol.

In this study, the cloud system is over two sectors: the first sector is on the western side of the low-aerosol/high-aerosol boundary and the second sector is on the eastern side of the boundary. Then, we show that the sector on the western side experiences higher aerosol concentrations than that on the eastern side. Due to higher aerosol concentrations, there are lower autoconversion rate and thus a larger amount of cloud liquid as a source of evaporation, leading to higher evaporation rate in the sector on the western side than in the sector on the east side. This higher evaporation rate in the sector on the western side is a key process to form the strong convergence field in the green rectangle. The sector of cloud system on the western side always experiences higher aerosol concentrations and produces higher evaporation rate than those on the eastern side until 19 LST when the strong convergence field in the green rectangle forms as shown in Figures 10 and 12. Basic cloud physics and dynamics (e.g., Rogers and Yau, 1991; Pruppacher and Klett, 1978) indicate that most of aerosol particles that are ingested into clouds are from around the surface just below those clouds. Hence, cloud cells of the cloud system on the western side are mostly affected by higher aerosol concentrations on the western side than those on the eastern side and this causes higher evaporation on the western side than on the eastern side. It is true that some of cloud cells on the western side can advect into the eastern side before they die. These cloud cells ingest higher (lower) aerosol concentration while they stay on the western (eastern) side; in other words, these cells ingest aerosol from various regions during their lifecycle as the reviewer phrases. However, these cloud cells produce lower (higher) autoconversion and higher (lower) evaporation rates, while they stay on the western (eastern) side. Hence, even these cells contribute to the higher evaporation rates on the western side and thus to the formation of the strong convergence line in the green rectangle, which is essential for the development of heavy precipitation as explained in the manuscript.

Considering the reviewer's comment here, the word "possibility" is replaced with "hypothesis" in Line 127 on p5.

Also, to reflect a point about the isolation of the effects of background aerosol in text, the following is added:

(LL291-298 on p10)

This assumption indicates that we do not consider the effects of clouds and associated convective and turbulent mixing on the properties of background aerosol. Also, above-explained prescription of those properties (e.g., number concentration, size distribution, and chemical composition) indicates that this study does not take aerosol physical and chemical processes into account. This enables the confident isolation of the sole effects of given background aerosol on clouds and precipitation in the Seoul area, which has not been understood well, by excluding those aerosol processes and cloud effects on background aerosol.

To remove the impression (pointed by the reviewer here) that "the spatial variability discussed here appear to be of much smaller scale than those investigated with the simulations with two different aerosol-concentration air masses over an area of about 100 x 100 km", we revised the corresponding text.

For the revision of text between line 117 and 123 in the old manuscript, we removed words like "district" and "city area", which give the impression, as follows:

(LL130-139 on p5)

For example, cloud cells (in an MCS) sitting on a significant portion of a metropolitan area with a higher aerosol concentration can be invigorated more than those cells on the rest portion of the area with a lower aerosol concentration. This can lead to enhanced precipitation and possibly torrential rain at the portion with the higher aerosol concentration, while in the rest portion, there can be less precipitation. This creates an inhomogeneity of precipitation distributions that can accompany torrential rain in the specific portion of the area. A further increase in aerosol concentration in the portion with the higher aerosol concentration will further enhance precipitation and torrential rain there and thus create a greater inhomogeneity of precipitation distributions.

For the revision of text between line 730 and 734 in the old manuscript, we removed words like "traffic" and "sudden", which give the impression, as follows:

(LL781-786 on p26)

For example, in a place such as a large-scale industrial complex within an urban area away from an urban boundary, there can be an increase in aerosol concentrations and thus high aerosol concentrations. These high aerosol concentrations can advect, as exemplified in the case adopted in this study, and a boundary between a place with low-aerosol concentrations and a place with high aerosol concentrations can vary spatiotemporally within the urban area.

References:

Rogers, R. R., and M. K. Yau, A short course in cloud physics, Pergamon Press, 293 pp, 1991.

Pruppacher, H. R. and J. D. Klett, Microphysics of Clouds and Precipitation, 714pp, D. Reidel, 1978.

3. Description of the model: The description of the model and the simulation set-up is scattered across section 2 and 3. In particular, many parts of section 3 detail the set-up of the model domains and the cloud microphysics instead of discussing the investigated case. The model description should be provided in one single section. The authors also say they developed a module to represent the spatial variability of

aerosol (p. 7, l. 193-194). It is not clear from the manuscript at this point what processes this entails. Please provide a better description of what processes are included.

The description of model, simulations and their set-up is now provided in one single section, which is Section 3.

The aerosol module simply interpolates the observed background aerosol properties such as $PM_{10}$ at observation sites to model grid points and time steps. There are no other functions of the aerosol module other than this. The interpolated $PM_{10}$ is used to calculate aerosol number concentration at each grid point and at each time step as explained in Section 3.2 by following assumptions on aerosol size distribution and composition as elaborated in Section 3.2.

More description of the aerosol module is now provided as follows:

(LL225-228 on p8)

For this, we develop an aerosol module that is able to represent the variability of aerosol properties. This aerosol module interpolates observed background aerosol properties such as aerosol mass (e.g., $PM_{10}$) at observation sites to model grid points and time steps. This aerosol module is now implemented to the ARW model.

3. Results: The analysis of the differences between the simulations, the physical mechanism driving these changes and the presented conclusions are not very convincing to me. While there are certainly differences in the convergence patterns between the runs, the physical mechanism is not clear. From the presented figures, I find it hard to believe that the difference in surface wind between the two air masses with different aerosol concentrations are a result of different latent cooling rates in the two areas, in particular as the convective systems are rather small compared to the extend of the wind field anomaly in the high-aerosol air mass during the initial stages of the simulation.

   As shown in Weisman and Klemp (1982) and Newton and Fankhauser (1975) that are well-known classic studies in the field of convection, the extension of the wind field anomaly, caused by evaporative cooling, is much greater than that of the area where cloud cells and associated evaporative cooling are located. It is well-known that the outflow from evaporation-driven downdrafts spreads out from cloud cells to surrounding much larger areas, leading to a situation where the extension of the wind field anomaly is much greater than that of the area where cloud cells and associated evaporative cooling are located as in classic textbooks (e.g., Houze, 1993; Emanual, 1994). Consistent with those studies and textbooks, this study shows the extension of the wind field anomaly much greater than that of the area where cloud cells and associated evaporative cooling are located, particularly, in the part of the domain to the west of the strong convergence line in the green rectangle. In fact, the ratio of areas occupied by cloud cells to those occupied by the wind anomaly in those studies and textbooks is similar to that in this study.

References:

Emanuel, K., Atmospheric convection, Oxford University Press, 580 pp, 1994.

Houze, R. A., Cloud dynamics, Academic Press, 573 pp, 1993.

Newton, C. W., and J. C. Fankhauser, Movement and propagation of multicellular convective storms, Pageoph, 113, 747-764, 1975.

Weisman, M. L., J. B. Klemp, The dependence of Numerically Simulated Convective Storms on Vertical Wind Shear and Buoyancy, Mon. Wea. Rev., 110, 504-520, 1982.

Just looking at the wind fields in Fig. 9, it appears that there are significant differences in the wind field at the lateral boundaries. It would be interesting to investigate whether the changes in the wind field are due to cold pool formation in an upstream area of the domain 3. This is particularly important as the system at least in the initial and mature phase is located very close to the northern domain boundary (e.g. Fig. 7). Along these lines, it would be also important to assert that the meso-scale circulation patterns in the outer domains are similar in the additional sensitivity simulations the authors present. Is it possible that the large differences in the convergence and the lack of organization is related to changes in the meso-scale circulation in the outer domains?

Note that initial atmospheric fields including the temperature field, the wind field and circulation patterns over all of the three domains are identical between the control run and the low-aerosol run. Due to differences in aerosol spatial distribution and loading in Domain 3, after the initial time step and after clouds start to form, the differences in evaporative cooling and associated wind field in Domain 3 between the runs start to appear first; note that there are no differences in aerosol spatial distributions and loading between the runs in Domain 1 and Domain 2. Then, these differences in Domain 3 induce differences in wind in the other two domains, considering two-way interactive triple-nested domains which are adopted by this study. Hence, differences in wind in Domain 1 and Domain 2 are results of those differences in Domain 3. These differences in Domain 2 in turn cause differences in wind around the boundary between Domain 2 and Domain 3. Hence, we want to emphasize that the differences in wind around the boundary are the subsequent result of the differences in aerosol and evaporative cooling in Domain 3 between the runs.

As seen in Figure 9 in the old manuscript, those differences (between the runs) in wind around the boundary (between Domain 2 and Domain 3) that corresponds to 0-100 km in the x direction and 70-180 km in the y direction of Domain 3 are amplified as wind moves southward and/or eastward from the boundary toward the inner part of Domain 3, since during this movement of the wind or outflow from the downdrafts, the wind or outflow is accelerated more due to more evaporation (and associated greater negative buoyancy) on the path of the movement in the control run than in the low-aerosol run. These amplified differences enable the large differences in the convergence field in the green rectangle between the runs. In particular, around the northern boundary that corresponds to 0-100 km in the x direction, there is stronger wind in the low-aerosol run than in the control run, which favors stronger convergence in the low-aerosol run in case the stronger wind in the low-aerosol run is maintained during the wind movement to the inner part of Domain 3. However, due to the amplification process during the wind movement, wind in the control run becomes stronger, leading to the stronger convergence in the rectangle in the control run. Here, we emphasize that the amplification, resulting in much stronger wind in the control run, occurs in Domain 3 BUT NOT in Domain 1 and Domain 2.

In summary, although there are differences in wind field or circulations in Domain 1 and Domain 2, these differences are caused by differences in aerosol and evaporative cooling between the runs in Doman 3. The differences in wind around the boundary between Domain 2 and Domain 3, which are caused by differences in Domain 2, are not able to explain the formation of the strong convergence field in the green rectangle. When those differences around the boundary are amplified via differences in evaporative cooling in Domain 3, the amplified differences eventually generate the large differences in the convergence field in the rectangle between the runs. This summary demonstrates that differences in aerosol and evaporative cooling in Domain 3 are the cause of differences in wind field in all of the three domains, and the differences in wind field in Domain 1 and Domain 2 are not able to explain the large differences in the strong convergence field in the rectangle between the runs. When the difference in wind in Domain 2, after wind in Domain 2 enters Domain 3, is amplified by differences in aerosol and evaporative cooling in Domain 3, the large difference in the convergence field in the rectangle is generated. This summary also demonstrates that without differences in aerosol and evaporative cooling in Domain 3, there is no formation of the strong convergence field in the rectangle. Stated differently, differences in aerosol and evaporative cooling in Domain 3 are a main cause of the large difference in the convergence field in the rectangle between the runs but not differences in circulations or wind fields in Domain 1 and Domain 2.

The following is added:

(LL568-572 on p19)

The outflow in the area with high-value aerosol concentrations accelerates, due to evaporation on its path, as it moves southeastwards from the northern and western boundaries of the domain. The outflow accelerates until it collides with surrounding air that has weaker horizontal movement in the area with low-value aerosol concentrations.

Another factor that is not at all mentioned are radiative effects of the aerosols that could impact the stability between the air masses with different aerosol concentrations. The authors say in the model description, that the aerosols interact with the radiative fluxes. These aspects need further investigation before any firm conclusions about the physical mechanism for the differences between the simulations can be drawn.

After aerosol particles are activated or cloud particles such as droplets are nucleated, aerosol-induced changes in the properties of cloud particles such as the effective size of droplets affect raditation in this study as described in text. However, before aerosol particles are activated, aerosol particles do not affect radiation, since observations do not show that strong radiation absorber such as black carbon is included in aerosol particles. Hence, in this study, we do not consider aerosol radiative effects that are the effects of aerosol particles on radiation before their activation.

The following is added:

(LL249-252 on p9)

Since the mixture includes chemical components that absorb solar radiation insignificantly as compared to strong radiation absorbers such as black carbon, we assume that the mixture does not absorb solar radiation and thus do not simulate the solar absorption of aerosol and attendant effects on stability.

Results: It is mentioned in the model description that ice- and mixed-phase processes are included in the microphysics module of the model. However, the discussion exclusively looks at warm-phase processes, i.e. using condensation/evaporation, autoconversion/accretion. If the simulations include mixed-phase processes, these need to be included in the analysis as well.

The following is added:

(LL496-499 on p17)

Other processes such as deposition and freezing produce the mass of solid hydrometeors and act as sources of precipitation, however, their contribution to precipitation is ~one order of magnitude smaller than that by condensation in the control run and the low-aerosol run. Hence, here, we zero in on condensation.

(LL551-554 on p19)

Sublimation and melting also enhance negative buoyancy, however, their contribution is ~one order of magnitude smaller than the contribution by cloud-liquid evaporation. Hence, here, we focus on cloud-liquid evaporation.

2 Specific comments

1. p. 4, l. 94: What is aerosol supposed to be most representative for?

   Here, we meant that aerosol is included in a group of variables which have the high-degree spatial variability or whose values vary with time and space substantially. To remove confusion, the corresponding text is revised as follows:

(LL98-99 on p4)

Aerosol is also one of those variables which have large spatial variability.

2. p. 4, l. 105-108: The authors cite two studies to suggest that increasing aerosol concentrations can intensify deep convective clouds by enhanced latent heating due to freezing. This hypothesis has been discussed controversially in recent literature (e.g., van den Heever et al., 2006; Fan et al., 2009; Lebo and Seinfeld, 2011; Lebo, 2017) and this should be mentioned in the introduction.

The following is added:

(LL113-118 on p4)

Studies (e.g., van den Heever et al., 2006; Fan et al., 2009; Lebo and Seinfeld, 2011; Lebo, 2017) have shown that aerosol-induced invigoration of convection and enhancement of precipitation depend on competition between aerosol-induced increases in buoyancy and those in hydrometeor loading, and aerosol-induced increases in condensational heating and associated invigoration in the warm sector of a cloud system.

p. 5, l. 148: Please check this reference.

Checked and replaced with the following paper:

- Khain, A., A. Pokrovsky, D. Rosenfeld, U. Blahak, and A. Ryzhkov (2011), The role of CCN in precipitation and hail in a mid-latitude storm as seen in simulations using a spectral (bin) microphysics model in a 2D dynamic frame, *Atmos. Res.*, **99**, 129–146, doi:10.1016/j.atmosres.2010.09.015.

4. p. 9, l. 246: Do you mean the aerosol in the PBL does not vary vertically?

Yes. To clarify this, text is revised:

(LL282-285 on p10)

It is assumed that in the planetary boundary layer (PBL), background aerosol concentrations do not vary with height but above the PBL, background aerosol concentrations reduce exponentially with height.

5. p. 9, l. 255: Please chose a more meaningful title for this section. It would also be good to introduce all sensitivity simulations conducted in the paper here. In particular, the simulations with homogeneous aerosol concentrations, since these are the obvious test simulations the reader is expecting for addressing the outlined scientific questions.

We believe that the title should be simple and short, and should not be long and complicated. Hence, we replaced the old title with a simple and short title which is "3.3 Additional runs".

We introduced all sensitivity simulations in this section 3.3 as follows:

(LL328-342 on p11-12)

In addition to the control run and the low-aerosol run, there are more simulations that are performed to better understand the effect of aerosol on precipitation here. To isolate the effects of aerosol concentrations on precipitation from those of aerosol spatial variability or vice versa, the control run and the low-aerosol run are repeated with homogeneous spatial distributions of aerosol. These homogeneous spatial distributions mean that there is no contrast in aerosol number concentrations between the western part of the domain and the eastern part, and aerosol number concentrations do not vary over the domain. The repeated simulations are referred to as the control-homoge run and the low-aerosol-homoge run. The analyses of model results below indicate that differences in precipitation between the control run and the low-aerosol run are closely linked to cloud-liquid evaporative cooling and to elucidate this linkage, the control run and the low-aerosol run are repeated again by turning off cooling from cloud-liquid evaporation. These repeated simulations are referred to as the control-noevp run and the low-aerosol-noevp run. While a detailed description of those repeated simulations is given in Section 4.3, a brief description is given in Table 1.

6. p. 9, l. 257: The aerosol field consist of two air masses with two different aerosol concentrations and a relatively small transition zone between the two. I would not call this is "high-degree spatial inhomogeneity". Please avoid using this term. However, I agree that the aerosol variability investigated here is larger than in most numerical studies, which do nor represent spatial aerosol variability.

The term is replaced with "large spatial variability"

7. p. 9, l. 269: It is claimed that the effects of inhomogeneity and number concentration can be investigated. However, it is not possible discriminate the impact of two changes based on just the two simulations, which have been introduced in the manuscript up to this point.

Following the comment #5 above, we introduced additional simulations for the discrimination in Section 3.3.

8. p. 10, l. 303: Please specify whether these are surface precipitation observations or derived from radar data.

Precipitation is directly measured by rain gauges that are parts of AWS. To clarify this, text is revised as follows:

(LL370-371 on p13)

Here, observed precipitation is obtained from measurement by rain gauges that are parts of the automatic weather system (AWS) at the surface.

9. p. 11, l. 313: Have you interpolated the 3km observational data to the 500m model data. The linear interpolation does not represent the correct frequency distribution at higher resolution. A less problematic approach would be to coarse-grain the model data to the resolution of the observational data.

Based on this comment, we checked the validity of the interpolation of observational data to model data by performing the suggested interpolation of model data to observation points. However, this suggested interpolation gives us the same conclusion as the previous interpolation which is described in Section 4.1.2. Hence, we let the previous interpolation stay in the manuscript.

10. e.g. p. 15, l. 427/428: The authors refer at various points to an "extension" or "movement" of the convergence field. I think they refer to changes in the spatial extend or location of regions with high convergence. The formulation should be altered accordingly.

Following comments by the other reviewer, Section 4.2.1 is simplified and during this process of simplification, text including extension and movement of the convergence field is removed.

11. p. 18, l. 520: Is the different location of the convergence line in the two simulations taken into account for the calculation of the mean values? And its eastward propagation?

For Figures 12a and 12b, the average is performed over the period between 17 and 19 LST. The strong convergence field and associated heavy precipitation, in the area surrounded by the green rectangle, start to appear up when time reaches around 19 LST in both of the runs. However, during most of the period between 17 and 19 LST, the strong convergence field and heavy precipitation are absent and thus, the area which can be marked by the green rectangle is not identified. In other words, during most of the period between 17 and 19 LST, the green rectangle is not identified and when time reaches around 19 LST, the rectangle starts to be identified. We are simply interested in differences in evaporation between areas to the east of the rectangle and those to the west before 19 LST, more specifically, between 17 LST and 19 LST without needing to consider the eastward propagation of the green rectangle due to its absence between 17 LST and 19 LST; here, we just want to say that although the rectangle is absent between 17 LST and 19 LST, we can apply the locations of the rectangle at 19 LST to the period before 19 LST as a process of identifying those areas to the east and those areas to the west before 19 LST. This interest is caused by the fact that those differences in evaporation before 19 LST affect differences in downdrafts and its outflow (between areas to the east of the rectangle and those to the west) that are essential for the formation of the strong convergence line in the green rectangle around 19 LST.

To indicate that the green rectangle starts to form around 19:00 LST, the following is added:

(LL429-430 on p15)

Since heavy precipitation starts to form around 19:00 LST, the green rectangle starts to be identified around 19:00 LST.

Yes, it is true that the location of the convergence line or the green rectangle is slightly different between the runs at 19 LST as shown in Figures 8, 10, and 11 and this was reflected for the calculation of differences in evaporation between areas to the east of the rectangle and those to the west for the period between 17 LST and 19 LST. However, in the old manuscript, the reflection was not indicated. To correct this, the following is added:

(LL526-538 on p18)

For the calculation of the averaged values in Figure 12, the area to the west (east) of the strong convergence field is set to include all parts of the north-south direction, which is the y-direction, and the vertical domains but a portion of the east-west direction domain, which is the x-direction domain that extends from the western boundary of Domain 3 to 90 km where the western boundary of the green rectangle at 19:00 LST is located (from 110 km where the eastern boundary of the green rectangle at 19:00 LST is located to the eastern boundary of Domain 3) in Domain 3 for the control run. For the low-aerosol run, the area to the west (east) of the strong convergence field is identical to that in the control run except for the fact that the area includes a portion of the x-direction domain that extends from the western boundary of Domain 3 to 70 km where the western boundary of the green rectangle at 19:00 LST is located (from 90 km where the eastern boundary of the green rectangle at 19:00 LST is located to the eastern boundary of Domain 3) in Domain 3.

12. p. 20, l. 586: What is the motivation for not switching of latent cooling from rain evaporation? This is usually considered the most important for cold-pool formation and the interaction of deep convective systems with boundary-layer dynamics.

It is known that downdrafts are generally initiated by the loading of raindrops that drags down air parcels (Houze, 1993). However, once downdrafts are initiated or once air parcels (having both cloud liquid (or droplets) and rain (or raindrops)) start to move downward, the speed of air parcels moving down or the speed of downdrafts is strongly controlled by the negative buoyancy and the negative buoyancy is mostly provided by evaporation of liquid particles in those air parcels (Houze, 1993 and Bluestein, 1993). The terminal velocity of droplets is negligible as compared to that of rain drops and thus it can be assumed that droplets within air parcels move together with air parcels and thus droplets within air parcels remain in those parcels as those parcels move downward as downdraft entities or move upward as updraft entities; in general, in microphysics parameterizations, cloud liquid or droplets are assumed to have no or negligible terminal velocity and thus to move with air parcels or wind. In this study, rain evaporation and associated cooling (as a source of negative buoyancy) are smaller over the west part of the domain than over the east part of the domain as seen in Figure 12a, while cloud-liquid evaporation and associated cooling (as another source of negative buoyancy) are greater over the west part than over the east part in air parcels. Hence, the greater negative buoyancy and the associated greater speed of air parcels moving downward or the greater speed of downdrafts over the west part than over the east part are induced by the greater cloud-liquid evaporation but not by the smaller rain evaporation in those air parcels over the west part than over the east part.

To clarify the role of cloud-liquid evaporation against that of rain evaporation, we added rain evaporation in Figure 12a and associated text. Also, the following is added to give a more explanation of the effect of cloud-liquid evaporation on downdrafts:

(LL557-564 on p19)

Previous studies have shown that aerosol-induced increases in cloud-liquid evaporation are closely linked to the enhancement of the intensity of downdrafts (Lee et al., 2008a, b; Lee et al., 2013; Lee, 2017). Cloud liquid or droplets in downdrafts move together with downdrafts, thus, when downdrafts descend, cloud liquid descends while being included in downdrafts. Cloud liquid in the descending downdrafts evaporates. More evaporation of cloud liquid provides greater negative buoyancy to downdrafts so that they accelerate more (Byers and Braham, 1949; Grenci and Nese, 2001).

References:

Byers, H. R., and Braham, R. R., The thunderstorm, U. S. Weather Bur., Washington, D. C., 287 pp, 1949.

Grenci, L. M., and Nese, J. M., A world of weather: fundamentals of meteorology: a text/ laboratory manual, Kendall/Hunt Publishing Company, 2001

13. Figure 1: Can you include the topography in this plot. This would be interesting for readers not very familiar with the geographic context.

Done.

14. Figure 5 and 6: Can you include all the results from all sensitivity experiments in these plots?

Done.

15. Figure 7: I find the contour plots extremely hard to read, especially the different contours for the precipitation rate. Would it be possible to use filled contours to show the precipitation rates?

Filled contours are now used for precipitation and shown in Figures 8, 10, and 11.

16. Figure 11: It would be interesting to show the evolution of the low-level wind field in these simulations and for earlier times as well.

Done.

3 Technical corrections

There are numerous places in the manuscript, where the language is quite awkward and reformulation of the sentences should be considered. In particular, please check the use of articles. A none exhaustive list is provided:

• The authors use phrases like ”frequency or occurrence” in many places (e.g. page 3, line 59; page 9, line 264/265; etc). These ”or”-statements should be removed and just one term be used.

Done.

• p. 4, l. 101: “Collision and collection are”

Done.

• p. 5, l. 123: “A further increase in aerosol loading in the district ...”

Done.

• p. 5, l. 125: “... create a greater inhomogeneity ...”

Done.

• p. 5, l. 131: “ ... select a MCS over ...”

Done.

• p. 7, l. 183: “ ... the large-scale environment ...”

Done.

• p. 7, l. 186: “... assumes horizontally homogeneous aerosol properties ... ”’

Done.

• p. 7, l. 191: “... assumption of homogeneity and ... spatio-temporal inhomogeneity ...”

Done.

• p. 7, l. 193: “... able to represent the inhomogeneity ...”

Done.

• p. 7, l. 197: “... with about 1 km distance ...”

Done.

• p. 7, l. 200: “ ... size distributions at those sites ...”

Done.

• p. 7, l. 210: "... follow a tri-modal ..."

Done.

• p. 8, l. 218: "... and aerosol particles are assumed to be internally mixed."

Done.

• p. 8, l. 230: "... above, precipitation is ..."

Done.

• p. 10, l. 279: "... has "low" inhomogeneity ..."

Done.

• p. 10, l. 302: "... simulations perform reasonably ..."

Done.

• p. 11, l. 316: "... the observed frequency distribution is consistent with the ..."

Done.

• p. 12, l. 340: "... initial stages of the precipitating system ..."

Done.

• p. 12, l. 354f: Please explicitly state the meaning of these lines again.

Done.

• p. 12, l. 360: "By 20:00 LTS the maximum ..."

Done.

• p. 13, l. 375: " ... Figure 7e for easier comparison. This ..."

Done.

• p. 13, l. 378: "The system propagates eastwards after 20:00 LST ..."

Done.

• p. 15, l. 444: "... the associated larger intensification ..."

The paragraph including this sentence is removed by following a comment by a reviewer.

• p. 15, l. 456: Can you please rephrase this sentence, its meaning is unclear to me in its current form.

The paragraph including this sentence is removed by following a comment by a reviewer.

• p. 17, l. 512f: "... there is a larger horizontal wind-speed than in ..."

Done.

• p. 21, l. 624: "... vice versa. For this purpose, ..."

Done.

References

Fan, J., T. Yuan, J. M. Comstock, S. Ghan, A. Khain, L. R. Leung, Z. Li, V. J. Martins, and M. Ovchinnikov, 2009: Dominant role by vertical wind shear in regulating aerosol effects on deep convective clouds. J. Geophys. Res. Atmos., 114, D22206, doi:10.1029/2009JD012352.

Lebo, Z., 2017: A numerical investigation of the potential effects of aerosol-induced warming and updraft width and slope on updraft intensity in deep convective clouds. J. Atmos. Sci., doi:10.1175/JAS-D-16-0368.1.

Lebo, Z. J. and J. H. Seinfeld, 2011: Theoretical basis for convective invigoration due to increased aerosol concentration. Atmos. Chem. Phys., 11, 5407–5429, doi:10.5194/acp-11-5407-2011.

van den Heever, S. C., G. G. Carrió, W. R. Cotton, P. J. DeMott, and A. J. Prenni, 2006: Impacts of nucleating aerosol on florida storms. part I: Mesoscale simulations. J. Atmos. Sci., 63, 1752–1775, doi:10.1175/JAS3713.1.

First of all, we appreciate the reviewer's comments and suggestions. In response to the reviewer's comments, we have made relevant revisions to the manuscript. Listed below are our answers and the changes made to the manuscript according to the questions and suggestions given by the reviewer. Each comment of the reviewer (in black) is listed and followed by our responses (in blue).

Review of "Aerosol as a potential factor to control the increasing torrential rain events in urban areas over the last decades" submitted to ACP for publication by Lee et al.

The authors examine the roles played by aerosol concentration and spatial distribution in torrential rain that occurred in Seoul, using cloud-system resolving model simulations. The model results show that the inhomogeneity of the spatial distribution of aerosol concentrations or loading causes the inhomogeneity of the spatial distribution of evaporative cooling and the intensity of associated outflow around the surface. This inhomogeneity generates a strong convergence field in which torrential rain forms. The effects of the increases in the inhomogeneity play a much more important role in the increases in torrential rain than the much-studied effects of the increases in aerosol loading.

The study provides new understanding about aerosol effects on convection and precipitation over large cities, which warrants a publication in ACP. However, many clarifications are needed before the paper can be accepted as shown below, particularly in the introduction, model description and the model results on the section of convergence. In addition, if aerosol radiative effects are included (it seems to be that way, but not very sure), then the results shown are not only the indirect effects. When you change aerosol concentration or inhomogeneity, aerosol radiative effects also change, and this impact could be more significant. The could impact the standpoint of your analysis in Section 4 (currently, your standpoint is purely from aerosol indirect effect).

Section 1,

1. Line 80-86, The description here mixes the cloud cell dynamics with synoptic-scale dynamics. It is true that synoptic-scale dynamics may be homogenous for MCS. However, the convective cells are affected by many small-scale dynamics such as cold pool, rear-inflow, wind shear, vortex, etc. Those small-scale cloud dynamical processes are generally inhomogeneous even with the same aerosol loading everywhere because they are complexly impacted by small-scale environment such as land-surface, microphysics, etc. Aerosol inhomogeneity could only be one of these factors. Therefore, the description here needs to be rewritten.

> We agree that the small-scale dynamics and small-scale environment, mentioned by the reviewer here, are factors which disrupt the synoptic-forcing-induced homogeneity of the MCS in urban areas (as we phrased in text). For this study, among those factors, we focus on aerosol. Text is revised to reflect these reviewer' and authors' points as follows:

(LL91-101 on p4)

The highly inhomogeneous distribution of precipitation means that there are highly inhomogeneous variables, processes and forcings which disrupt the synoptic-forcing-induced homogeneity of MCSs in urban areas. Some of those forcings are mesoscale forcings that show mesoscale variability and, for example, are related to phenomena such as sea-breeze fronts and lake breezes. In particular, in urban areas, due to strong heat fluxes at the surface, there is the urban heat island (UHI) effect as another example of those phenomena. Examples of those variables and processes are cold pool, rear inflow, wind shear, and mesoscale vorticity. Aerosol is also one of those variables which have large spatial variability. In particular, urban aerosol particles are produced by randomly distributed sources (e.g., traffic), which enables aerosol to have large variability in urban areas.

(LL136-144 on p5)

A further increase in aerosol concentration in the portion with the higher aerosol concentration will further enhance precipitation and torrential rain there and thus create a greater inhomogeneity of precipitation distributions. Motivated by the hypothesis and associated argument here, among the forcings, processes and variables which have spatial variability, this study focuses on aerosol. To examine aerosol effects on clouds and precipitation, numerical simulations are performed by using a cloud-system resolving model (CSRM) that resolves cloud-scale microphysical and dynamic processes and simulates the effect of the variability and loading of aerosol on precipitation.

2. Line 92-94, similar comment as above. The inhomogeneity of the convective cell and precipitation occurs everywhere, not only just over urban area. Many other factors could contribute to the inhomogeneity. For the urban area, there is effect of urban heat, which is so relevant and should be discussed in the introduction.

See our response to the comment 1. The urban heat or the urban heat island (UHI) effect is included in introduction as shown in our response to the comment 1. Also, the UHI effect is discussed in "summary and conclusion".

3. Line 106-108, Are you talking about observed studies here? If so, then need to be clear about it. If not, you should cite the symbolic papers illustrating the invigoration through enhanced latent heat induced by freezing such as Khain et al. 2005 and Rosenfeld et al. 2008.

Those symbolic papers are now included.

4. The description about literature studies in aerosol indirect effects on convective clouds are

one-sided. Many studies showed that the enhanced or suppressed precipitation by aerosols could be very dependent on RH, wind shear, CAPE, etc., which should be clearly delivered to readers.

The following is added:

(LL118-121 on p4-5)

Other studies (e.g., Khain et al., 2008; Lee et al., 2008b; Fan et al., 2009) have shown that the invigoration-related enhancement of precipitation also depends on environmental conditions that are represented by wind shear, relative humidity, and instability.

Section 3,

1. Section 3.1, first paragraph, what are the domain sizes? Where is Seoul in Domain 3?

The Seoul boundary is marked in Figure 2. Seoul city itself occupies a portion of Domain 3, however, in this study, the Seoul area means the conurbation area or the metropolitan area that is composed of Seoul and highly populated cities around Seoul in Domain 3. To clarify this, the following is added:

(LL201-205 on p7)

The Seoul area is a conurbation area that centers in Seoul and includes Seoul and surrounding highly populated cities. Hence, the Seoul area is composed of multiple cities whose total population is ~twenty five millions. The boundary of Seoul, which has the largest population among those cities, is marked by a dotted line in Figure 2.

The following is added to indicate the domain sizes:

(LL198-201 on p7)

The length of Domain 3 in the east-west direction is 220 km, while the length in the north-south direction is 180 km. The lengths of Domain 2 and Domain 3 in the east-west direction are 390 and 990 km, respectively, and those in the north-south direction are 350 and 1100 km, respectively.

2. Line 165, Domain 1 is 4.5 km. Does the cumulus parameterization work for this resolution?

   We used Kain and Fritsch's cumulus parameterization scheme. According to Gilliland and Rowe (2007), the use of this scheme at a resolution similar to 4.5 km does not affect the quality of the simulation of convective cells and instead, this use improves the quality of the simulation of some features of those cells. Hence, we believe that the use works reasonably well.

The following is added:

(LL211-213 on p7-8)

Here, we use a cumulus parameterization scheme that was developed by Kain and Fritsch (1990 and 1993). This scheme is shown to work reasonably well for resolutions that are similar to what is used for Domain 1 (Gilliland and Rowe, 2007).

3. About the RRTMG scheme you used, did you use the effective radius calculated from microphysics in the radiation calculation?

The following is added:

(LL180-183 on p6-7)

The effective sizes of hydrometeors are calculated in a microphysics scheme that is adopted by this study and the calculated sizes are transferred to the RRTMG. Then, the effects of the effective sizes of hydrometeors on radiation are calculated in the RRTMG.

4. Line 192: need some details about the aerosol module you developed. What was included in the module and is there any reference? Is aerosol formation excluded? If so, how are aerosol properties (SD, composition, vertical distribution) specified? How are the aerosol optical properties calculated? Is aerosol module similar to the idea used in Fan J. et al. 2008, JGR? If so, providing references would help readers understand better about what the aerosol module is.

The aerosol module simply interpolates the observed background aerosol properties such as $PM_{10}$ at observation sites to model grid points and time steps. There are no other functions of the aerosol module other than this. The interpolated $PM_{10}$ is used to calculate aerosol number concentration at each grid point and at each time step as explained in Section 3.2 by following assumptions on aerosol size distribution and composition as elaborated in Section 3.2.

To better describe aerosol module, the following is added:

(LL226-228 on p8)

This aerosol module interpolates observed background aerosol properties such as aerosol mass (e.g., $PM_{10}$) at observation sites to model grid points and time steps. This aerosol module is now implemented to the ARW model.

The assumptions on aerosol size distribution and composition or specified aerosol size distribution and composition are described in Section 3.2. The assumed vertical distribution of aerosol is also described in Section 3.2. In this study, aerosol radiative properties, which are associated with aerosol optical properties, are not considered. To clarify this, the following is added:

(LL249-252 on p9)

Since the mixture includes chemical components that absorb solar radiation insignificantly as compared to strong radiation absorbers such as black carbon, we assume that the mixture does not absorb solar radiation and thus do not simulate the solar absorption of aerosol and attendant effects on stability.

5. Line 222-223, how did you convert PM10 to aerosol number concentration? Theoretically you can not do this since PM10 is only contributed by the very large aerosol particles. Do you have any reference for what you did here?

We calculate aerosol mass for each size bin of the size distribution up to 10 micron in Figure 3 based on assumptions of aerosol chemical composition and associated aerosol particle density; we just want to remind that the assumed size distribution and aerosol chemical composition are obtained based on the analysis of the AERONET observation.

In the size distribution in Figure 3, which is obtained by the AERONET observation, we know the aerosol number for each size bin and this aerosol number is multiplied by the particle density, which is calculated based on the assumed aerosol chemical composition, to obtain the aerosol mass for each size bin. Then, we sum up the aerosol mass for each size bin over all bins up to 10 micron in the size distribution to obtain PM10 which is referred to as PM10_standard. At each grid point and at each time step in the model domain and over the simulation period, we have an observed PM10 varying from one grid point to the other and with time, referred to as PM10_grid. We calculate the ratio which is "PM10_grid/PM10_standard". To obtain the size distribution at each grid point and at each time step, based on the assumption that the size distribution of background aerosol at all grid points and time steps has the size distribution parameters or the shape of distribution that is identical to that in Figure 3, the aerosol number for each size bin of the size distribution of aerosol number in Figure 3 is multiplied by this ratio. After this multiplication, the new aerosol number, which is the aerosol number multiplied by the ratio, in each bin is summed up over size bins up to 10 micron to obtain total aerosol number concentration at each grid point and at each time step. Note that after this multiplication, if we sum up aerosol mass (corresponding to the new aerosol number) over size bins up to 10 micron, the sum is equal to PM10_grid at each grid point and at each time step.

As shown in Figure 6.3 in Rogers and Yau (1989; the third edition), it is true that large particles make the large contribution to total aerosol mass. However, it does not prevent the conversion between mass (or PM10) and number as described in Tittarelli et al. (2008). In addition, Tittarelli et al. (2008) showed that small particles smaller than 1 micron contribute to the total aerosol mass or PM10 as much as those particles greater than 1 micron for their selected cases. The observed size distribution of aerosol particle mass by AERONET for the case here shows the large contribution of large particles to total aerosol mass or PM10. However, when the size distribution of aerosol particle mass is converted to that of aerosol number, most of contributions to total aerosol number are made by small aerosol particles whose size is smaller than 1 micron as exemplified by Figure 3. This point can be seen in comparisons between the first panel and the third panel in Figure 6.3 in Rogers and Yau (1989; the third edition).

To clarify assumption used to convert PM10 to aerosol number concentration, the following is added:

(LL254-257 on p9)

Stated differently, it is assumed that the size distribution of background aerosol at all grid points and time steps has size distribution parameters or the shape of distribution that is identical to that in Figure 3.

Reference:

Rogers, R. R., and M. K. Yau, A short course in cloud physics, Pergamon Press, 293 pp, 1989.

Tittarelli, A., Borgini A., Bertoldi, M., et al., Estimation of particle mass concentration in ambient air using a particle counter, Atmos. env., 42, 8543-8548, 2008.

6. Line 237-238, the aerosol generation is not included in the SBM released in WRF. The reference Fan et al. 2009 shown here indeed had it for that study, but it was not included in the WRF releases. Did you make your own code to do this or you assumed this process was included in the released version?

We checked the code and found that the aerosol generation has not been included yet. Text is revised accordingly.

7. Description of model simulations and Table 1 are confusing currently. Need clear description about how the aerosol concentration and inhomogeneity are changed, respectively, from one to other simulations. For example, in Line 279-280, “The repeated simulation has the “low” inhomogeneity and concentrations of “aerosol” as compared to the control run and thus is referred to as the low-aerosol run”, if both aerosol number and inhomogeneity are changed as described here, then how do you distinguish the effect by changing aerosol number from changing aerosol inhomogeneity? What are the other simulations you ran to help you distinguish? As I read along, I found much of the description is at the different result parts. So, the description should be moved to here to help people clearly understand the purpose of the simulations and how the simulations were set up.

To clarify additional simulations for the distinguishment between the effect of aerosol number and that of inhomogeneity, and those additional simulations with evaporative cooling off, the following is added in Section 3.3:

(LL329-342 on p11-12)

To isolate the effects of aerosol concentrations on precipitation from those of aerosol spatial variability or vice versa, the control run and the low-aerosol run are repeated with homogeneous spatial distributions of aerosol. These homogeneous spatial distributions mean that there is no contrast in aerosol number concentrations between the western part of the domain and the eastern part, and aerosol number concentrations do not vary over the domain. The repeated simulations are referred to as the control-homoge run and the low-aerosol-homoge run. The analyses of model results below indicate that differences in precipitation between the control run and the low-aerosol run are closely linked to cloud-liquid evaporative cooling and to elucidate this linkage, the control run and the low-aerosol run are repeated again by turning off cooling from cloud-liquid evaporation. These repeated simulations are referred to as the control-noevp run and the low-aerosol-noevp run. While a detailed description of those repeated simulations is given in Section 4.3, a brief description is given in Table 1.

We just give a brief overview of the repeated simulations in Section 3.3 as above and their more detailed description is given in Section 4.3. Since Section 4.3, which contains results from those repeated simulations, appears up much later than Section 3.3 and thus, when readers reach Section 4.3 to read results from the repeated simulations, readers may not recognize the nature of those repeated runs at first sight without their description in Section 4.3. This can disable readers from understanding the results well. Hence, we believe that giving the description of the runs and their results together in Section 4.3 will enable readers to understand the results with efficiency. With this thought, we put the description in Section 4.3 as well as Section 3.3. In addition, the detailed simulation setup for the repeated runs is based on the analyses of results from the standard runs (i.e., the control run and the low-aerosol run) which are described in Sections 4.1 and 4.2. Hence, we believe that giving the detailed description of the setup in Section 4.3 after explaining those analyses in Sections 4.1 and 4.2 makes the description make more sense.

In addition, Table 1, the two columns “Contrast in aerosol spatial distribution” (Column 2) and “The homogeneous aerosol distribution” (Column 4) mean the similar thing to me. The content in Column 2 “reduced by a factor of 2”, does not make sense if it is for “Contrast in aerosol spatial distribution”. Did you mean “Contrast in aerosol number concentration”?

Yes, in column 2, we agree that “contrast in aerosol number concentration” is a better expression than “contrast in aerosol spatial distribution”. Table 1 is revised accordingly. Also, to reflect the other points raised by the reviewer here, Table 1 is further revised. See Table 1 for details.

8. It is not clear if you excluded aerosol radiative effect or not? If so, please be very clear about it. If not, then the effects we see are not only the indirect effects. When you change aerosol concentration or inhomogeneity, aerosol radiative effects also change, and this impact could be more significant. The could impact your analysis in Section 4.

Aerosol radiative effect is excluded. To clarify this, the following is added:

(LL249-252 on p9)

Since the mixture includes chemical components that absorb solar radiation insignificantly as compared to strong radiation absorbers such as black carbon, we assume that the mixture does not absorb solar radiation and thus do not simulate the solar absorption of aerosol and attendant effects on stability.

Section 4,

1. Sections 4.1.1 and 4.1.2, the comparison of precipitation with observations does not seem to be fair since there is a significant fraction of the domain over ocean where no measurements are available. In addition, how about the evaluation of meteorological fields with observations? There should be a lot sounding measurements over Seoul.

We just want to confirm that for the comparison of precipitation between observation and the simulation over Domain 3, we extrapolated the land observation to ocean.

Only ~20% of Domain 3 is occupied by ocean and thus, we believe that ocean does not occupy a significant portion of Domain 3. Hence, we think that ocean does not affect the conclusions from the comparison between observation and the simulation significantly. When we performed the comparison between observation and the simulation only over land area (without the extrapolation of land observation to ocean), this comparison gives us the same conclusions that are already given in the old manuscript. Hence, due to the small portion of ocean area, inclusion of ocean through the extrapolation in the comparison does not affect the qualitative nature of conclusions from it.

There is a good consistency between simulated meteorological fields and observed counterparts as shown in Figure5.

The following is added:

(LL354-364 on p12)

Figure 5 shows the observed and simulated vertical profiles of potential temperature, water-vapor mass density, u-wind speed, and v-wind speed which represent meteorological fields. Radiosonde data as observation data are averaged over observation sites in the domain and the simulation period, while simulated meteorological fields are averaged over the domain and the simulation period to obtain the profiles. Positive (negative) u-wind speed represents eastward (westward) wind speed, while positive (negative) v-wind speed represents northward (southward) wind speed. Comparisons between the observed profiles and the simulated counterparts show that overall differences between them are within ~ 10% of observed values. Hence, with confidence, it can be considered that the simulation of meteorological fields is performed reasonably well.

2. It seems that there is an inconsistency between Figure 5 and Figure 6a for the differences between low aerosol and control runs. Figure 5 does not show that the precipitation in low-aerosol case has significantly smaller precipitation. However, Figure 6a suggest the rain should be much lower in that case because the total precipitation is mainly determined by the moderate and heavy rain rates.

We checked the program code calculating the precipitation frequency and found no errors in it.

For the moderate rain between ~10 and 60 mm $hr^{-1}$, the frequency is higher in the low-aerosol than in the control run. For the weak rain below 10 mm $hr^{-1}$, the frequency is also slightly higher in the low-aerosol run. Note that the frequency range is ~$10^3$ to ~$10^5$ for the moderate and weak precipitation and the range is ~1 to ~$10^3$ for the heavy precipitation. Hence, overall, the frequency range is ~two orders of magnitude greater for the moderate and weak precipitation than for the heavy precipitation. Due to the use of the log scale, it appears that there are the largest differences for the heavy precipitation and they govern the overall differences between the runs. However, although it appears that the differences for the weak and moderate precipitation are relatively much smaller (due to the use of the log scale), due to the frequency range which is much greater for the weak and moderate precipitation than for the heavy precipitation, the seemingly smaller differences for the weak and moderate precipitation can offset the seemingly larger differences for the heavy precipitation, leading to the similar total precipitation amount between the runs.

3. Line 338-341, Figure 7, the figure caption is very long and confusing. The light blue contours represent precipitation rates, but they are hard to see and the values for contour line are not clearly shown or described. Also, there could be timing shift between the convective developments in two simulations so comparison between the two simulations at a particular time may not be meaningful.

Precipitation rates are shown in new figures which are Figures 8, 10, and 11, and precipitation rates are represented by filled contours. Accordingly, the figure caption is simplified.

Yes, it is true that there can be timing shift in the convective development between the runs. However, as implied in Figure 6 that shows the similar precipitation temporal evolution between the runs, overall convection temporal evolution is similar between the runs. Convection and associated precipitation start to develop and reach their peak at a similar time before 00 LST on July 28$^{th}$ and then they decay after 00 LST on July 28$^{th}$ in both of the runs. Hence, we believe that it is not that unreasonable to say that the convection temporal development is similar between the runs. This similar development between the runs can be explained by the fact that identical synoptic-scale environment and its evolution are applied to both of the runs, and this synoptic environment and its evolution control the overall evolution of the system and associated convection.

4. Figure 8, I guess the plots are for the control run? I did not find such information in the figure caption or text. I had a trouble to understand what was plotted. Compared with Figure 7c and e, Figure 8a and 8b correspondingly have the same spatial domain for the same time, but I do not understand why the blue line and the green boxes are totally different.

We want to emphasize that the blue line is NOT from the control run BUT from observation as stated in the figure caption. We just wanted to compare the location of the green rectangle with the location of the observed heavy precipitation.

Yes, Figure 8 in the old manuscript or Figure 9 in the new manuscript is for the control run and this is now indicated in the figure caption. We double-compared the locations of the green rectangles at 19 and 20 LST in Figure 9 to those in Figure 8 (in the new manuscript) and found that the locations in Figure 9 are identical to those in Figure 8. Due to differences in the number of figure panels between different pages of the manuscript, panels are scaled differently between those pages and this makes the locations appear different between pages.

5. Please mark the city boundary or the boundary between the high/low boundaries in Figures 7-9.

The high/low boundaries are marked.

6. Section 4.2.1, the long text of the first 4 paragraphs can be simplified with just a few sentences since most of the description here is just the basic text book knowledge about the relationship of convergence, condensation, and precipitation. What's interesting here should be just the differences between the control and low-aerosol runs. Then the text that follows it should be explaining the reasons for the differences in convergence, condensation, and precipitation. The long text in this section makes readers very hard to get what the main points are.

The first 4 paragraphs are simplified into 1 paragraph. See text for more details.

7. Line 670-675, very long sentence and the meaning does not make sense based on the results shown. For example, "the absence of the strong convergence field in the control-homoge run results in the situation where the increase in the frequency of heavy precipitation in the control-homoge run" is opposite to the results shown above

As explained in text before, the strong convergence field, which is distinguishable from any other lines as shown in the green rectangles, in the control run plays an important role in much more heavy precipitation events in the control run than in the low-aerosol run. However, in the control-homoge run, there is no such strong convergence field, due to homogeneous aerosol spatial distributions, and so, there are insignificant differences in the frequency of heavy precipitation between the control-homoge run and the low-aerosol-homoge run, although there is a larger frequency of heavy precipitation in the control-homoge run than in the low-aerosol-homoge run. To clarify this and make the sentence clear, the corresponding text is revised as follows:

(LL715-725 on p24)

There is the larger frequency of heavy precipitation in the control-homoge run than in the low-aerosol-homoge run (Figure 7c). However, as mentioned above, there is no strong convergence field which is distinguishable from any other lines in the control-homoge run as seen in Figure 13c. Associated with this, differences in the frequency of heavy precipitation between the control-homoge run and the low-aerosol-homoge run are much smaller than those between the control run and the low-aerosol run particularly during the period between 19:00 LST and 23:00 LST, as seen in Figures 7i and 7l. This results in a situation where differences in the frequency of heavy precipitation between the control-homoge run and the low-aerosol-homoge run are, on average, just ~15 % of those between the control run and the low-aerosol run for the whole simulation period (Figure 7c).