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 28th and then they decay after 00 LST on July 28th 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).