Tracking the Impact of Urban Air Masses on Convective Precipitation: A Multi-Member Modeling Study

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Reviewer Comments

Summary

In this study, the impact of urban aerosols on deep convection is investigated using the coupled atmosphere-chemistry model (COSMO-MUSCAT) with an improved urban parameterization, microphysics scheme, and a novel methodology. Two convective cases on the evening of 13th and 20th July 2019 are simulated with and without urban aerosol emissions (BASE vs NONURBAN) from Leipzig, Germany, using an ensemble of simulations. The results show that < 3% of total aerosols are from urban sources, and the rest are background. In both case studies, the differences in the impact of urban aerosols on the volume-averaged total condensate and the mean areal precipitation rate lie within the ensemble spread. However, vertical profiles shows varying impacts depending on the storm mode. For the July 13th case with moderate instability and a small convective systems, the urban aerosol effects are limited to the periphery, with increased precipitation on the northwest flank, closer to Leipzig, and decreased precipitation on the southeast flank during the mature stage. For the July 20th case with high instability and organized convection to the northeast of Leipzig, urban aerosol effects produced intense precipitation at the center of the system. In both cases, the increased aerosols from urban emissions showed signatures of increased cloud droplet activation and ice-phase processes leading to higher precipitation rates. In the July 20th case study, urban aerosols produced a higher precipitation rate, leading to a stronger downdraft and early system decay with lower total rainfall than simulations without urban aerosols.

This study is timely and relevant to understanding the effects of urban aerosol emission on deep convection. The introduction strongly motivates this. The aerosol-cloud interactions have large uncertainty not only in climate projections but also in its effects on deep convection dynamics and microphysics. The methodology and results from this study will benefit our scientific community but require a major change involving significance test and clear description and interpretation of the novel methodology. I recommend to the editor that the manuscript be published after major revisions listed below.

Things I liked about the manuscript

- This study uses a novel methodology. Past studies focused on a single convective system and apply aerosol forcing uniformly throughout the domain. Here, the authors use all convective systems (precipitation areas) that intersect with the analysis box centered on the urban plume trajectory.
- The model experiments are well designed to answer the intended research questions with an improved microphysics scheme, a coupled atmosphere-chemistry model, and urban parameterization
- The manuscript is well written and easy to follow, except for the methodology. Though the model experiments are complex, they are clearly explained. The readers unfamiliar with COSMOS-MUSCAT models can still understand it.

Major comments

1. **Moving box analysis method: Use of terminologies such as "system", "early stage", and "late stage" are inappropriate**

After re-reading multiple times- the methodology sections, figures 6 through 11, and the appendix, I now better understand the analysis method used in this study. I don't want other readers to go through the same.

Past studies typically analyze aerosol-cloud interactions of a single convective system or the entire domain if there are multiple systems in the domain. In this article, only columns within the analysis box centered on the plume trajectory points are analyzed. This implies that the **analysis includes only portions/chunks of multiple convective systems within the analysis box**. The choice of words throughout the manuscript created a lot of confusion. For example, singular nouns such as "the convective system" or "a precipitation system", cause confusion, because the analysis box may have multiple systems within it. Also, the use of the terminologies "early stage of a system" or "late stage of the system" is difficult to interpret. If there are multiple systems or cells inside the box, they are likely to be in different lifecycle stages- initiating, growing, dissipating, merging, or splitting.

Please provide a more detailed explanation of the moving box analysis method, describing how it differs from the traditional method and explicitly stating that only chunks or portions of convective systems within the analysis box are examined. Throughout the manuscript, please use the language that reflects this. The term "convective event or convection clusters" may be used to describe all convective systems and cells that initiated on a case study day. This is done at some places in the manuscript (e.g., lines 90,95, and other lines); please do the same throughout the manuscript. Also, instead of using "early stage or late

stage of a convective system", I recommend using "initial hours of the convective event or final hours of the event".

Results are described from a system's perspective, which bothers me because there are multiple convective systems or cells in the box, and they may be in different stages. The microphysical process varies with the lifecycle stage of a convective system. So, as a reader, it begs the question "within the analysis box, is it the same part of the same system that had a high cloud droplet concentration developed ice at high altitude in the later time?"

If all the systems in the analysis box are growing or decaying at the same time, please explicitly mention that case by case; or, if a single system contributes to the major percentage of columns examined within the analysis box, then explicitly mention that and then use the system's perspective. Similarly, downdrafts produced a cold pool that affects convection in the area, not just a single system. This may help interpret the results from a convection event perspective, not just a system perspective.

An example of using singular nouns:
Line# 241 (precipitation system), and line#265 (convective system)

An example of text with system perspective and lifecycle stage:
Line# 298 (early stage of the system), and line#311 (later stage of the convective system)

These are just examples. Please look for the words "system" and "stage" through the manuscript and modify them appropriately as mentioned above.

2. Significance test

The study uses the Student's t-test to determine whether differences between BASE and NONURBAN simulations are significant for surface precipitation rate, condensate mixing ratio/density, and vertical velocity. However, these variables, along with many other meteorological variables, don't follow a normal distribution. They are typically modeled as gamma, exponential, or log-normal distributions. Observations sometimes show that these variables don't fit any of the above parametric distributions. The Student's t-test assumes that a variable follows a normal distribution; hence, this test cannot be applied. **I recommend using the bootstrapping method or another non-parametric significance test that doesn't assume a parametric distribution for the variable.**

The author notes that the sample size is small and that additional simulations cannot be run due to high computational demands. I agree that it's not practical to run so many

simulations. With small sample size, many tests are not reliable and defeat the purpose of having the significance test. I recommend a couple of options below.

1. **Non-Parametric significance test:** use a different but non-parametric significance testing method (Mann-Whitney U test or others). Even with different testing method, the sample size is a big problem. Without sufficient samples, the significance test is not reliable and can be misleading. So use the sampling method below on any of the non-parametric significance test.

2. **Bootstrapping method with more samples:** The sample size can be increased without running more simulations. For figures 7, 8, 9, 10, and supplemental figures, I recommended using all the values on the horizontal plane at the specified elevation and time step from all ensemble members for the significance test of the averaged values. For example, when comparing the horizontally averaged cloud droplet concentration, QNC, in Fig 7b (a single x in the figure)**, I recommend using all QNC values on a horizontal plane at a specified elevation and time. Step in the analysis box from five ensemble members** (for each of BASE and NONURBAN) **for the significance test to see if horizontally averaged QNC values from two groups are significantly different.** All the horizontal data will provide the variability in QNC and help determine whether the averages from two emission scenarios are significantly different.

Similarly, for figures 4 and 5, to test the significance of the ensemble mean rain rate between experiments, please use the rain rate from neighboring pixels limited by an arbitrary distance centered on a pixel, (say 10 x 10 km^2) from all ensemble members. For an example, 100 pixels centered on a pixel per member x 5 ensemble member = 500 pixels of rain rate values for each experiment.

As authors are aware, the significance tests are used to determine if the observed difference is due to internal variability or not. Rather than using only mean values from five ensemble members, actual values from them can be used to increase the sample size and represent the internal variability. **I recommend using bootstrapping method with more samples to test the significance of difference between experiments.**

Please clarify in the text (section 2.4.2) how averages are computed. Is it a conditional or unconditional average. A conditional average is based on conditions such as 1) grid cells with non-zero values, 2) above a threshold value, or 3) cloudy grid cells. Unconditional average uses all the grid cells and include zero values when computing mean.

Minor edits

Lines 36 to 41 - These lines lack clarity; please rewrite. They convey that both scenarios lead to invigoration from additional condensation and latent heat release. Both have more condensation and latent heat release compared to which aerosol scenario?

Line 50 - Replace "warm-based storm" with "storms with warm cloud base"

Line 67 - Please provide specific aerosol effects on deep convection rather than a general statement that aerosols significantly affected the convection and precipitation patterns.

Line 75 – replace “The study” with “It also”; because it creates confusion whether it’s referring to the current study or Van Den Heever and Cotton (2007)

Line 90- replace "highly resolved" with "high resolution"

Line 112 – replace “Aerosol dynamics” with “Aerosol processes”

Line 156 – replace "maximum" with "final" or “resulting”

Line 158 – replace “in-cloud conditions” with “in-cloud activations”

Line 166 – replace “westerly inflow” with “westerly flow”

Line 168 – please rewrite "3-step one-way nesting strategy. The outer domain covers" as "3-step one-way nested domains – D0, D1, D2. The outer domain, D0, covers" for clarity

Lines 205 & 206 – these lines about the creation of the ensemble based on spin-up time are not clear. Please explain more. On line 184, the manuscript states that the simulation for domain D1 is started 24 hours before each case study day using input from COSMO-D2 reanalysis. Are the ensemble member simulations started at 24h, 21h, 18h, 15h, 12h before 00 hours of the case day, with corresponding initial conditions from COSMO-D2; hence leading to different spin-up times of 24h, 21h, 18h, 15h, 12h?

Line 219 – replace “chapter” with “the Section”

Line 223: rewrite “region of highest precipitation” as “region centered on pixel with highest precipitation”. **Also, it is not clear what "initial time" means.** Please rewrite

Line 225 – rewrite “The horizontal start box cover” as “The starting region of trajectories horizontally covers”

Line 228 – is it km^2?

Figures 3, 4, and 5 - Please increase the font size. They are difficult to read. Also, please have two or three latitude and longitude grid lines to give some idea of the scale

Figure 3 – Caption missing information about the grey regions in the plot. Please add at the end of the caption - "City boundaries of Leipzig marked with a grey and of Chemnitz with light grey outlines."

Line 236: replace “meteorological conditions” with “cloud dynamics and microphysics”; I don’t see any meteorological variables (T, Qv, P, U) analyzed in the manuscript.

Line 237 – delete “atmospheric”

Line 238, 245 – replace “trajectory point” with “mean trajectory point”

Line 249 to 251 – the term “air mass” is loosely used throughout the text and in the title. I would suggest using “air parcels” instead of “air mass” if referring to grid cells or single trajectory. Please use the term “urban air mass” or “urban aerosol plume” if referring to the entire plume.

Line 249 to 250 – please rewrite as “While the analysis box along the mean filtered trajectories show the effects of urban aerosols on cloud dynamics and microphysics, the analysis box along the mean of all trajectories (shown in appendix) represent total convective cloud properties from grid cells irrespective of its interaction with urban aerosols”.

Line 250 – replace “air masses” with “air parcels”

Lines 283 to 290 and lines 314 to 320 – Please include reference to synoptic charts in supplement material

Line 303 – delete “pattern” from “the difference pattern”

Lines 310 – please reference the figure, subpanel, and cardinal direction of the edges of the noted aerosol effects

Line 315-317 – If there is warm air over cold air, it implies increased stability not instability. Please rewrite.

Line 329 – rewrite " a clear negative precipitation anomaly appeared in the NONURBAN experiment (Fig. 5f)," as "a negative precipitation difference between experiments is seen in Fig. 5f,"

Figures 6 and 9 captions list hail as part of total condensate, but the microphysics scheme described in the methods section (2.1.1) has only five hydrometer species (cloud water, ice, snow, graupel, and rain). Can you please clarify how hail category data is obtained? Or delete hail!

Figure captions and in the manuscript: please replace "spatially" with "horizontally"; replace “box spatially’ with “horizontally”; replace “box averaged" with “horizontally averaged”; because box may refer to 2D or 3D box and spatial averaged may be horizontal, vertical, or both. So, it is confusing

Line 379 – replace "pristine" with "background aerosol"

Line 401 – for inference on increase in precipitation due to urban aerosols; please reference the supplemental figure or Figure 7D

Line 409 – replace “The subsequent slower decay” with “The subsequent loss of cloud droplets at a faster rate”

Figure 9 – delete “shows box-averaged”; because all the variables are box averaged which is mentioned at the start of the caption

Line 434 – up to 5% in “NONURBAN”?

Lines 446 to 449 – For the July 20th case, how much of the convective event duration is reduced due to strong downdrafts causing the early decay of systems in the BASE emission scenario? I don’t see a difference in duration in Figure 9. Can you please clarify in the text?

Line 456- rewrite "passing through” as "interacting with. Since the simulated convective system on July 13th didn't directly pass through Leipzig, it interacted with the plume southeast of Leipzig.

Line 464 – Related to major comment, if the parts of multiple convective systems within the analysis box are examined; how can the downdraft be tied to a single system?

Discussion and conclusions section – Contribution of urban emissions to total aerosol is < 3% in both cases. I think this is an intriguing result. Is the small contribution significant to see microphysical effects? Can you please add this result and provide some discussion?

Discussion and conclusions section – Also, the difference in contribution of urban aerosols to the timeseries of volume-averaged total condensate or mean areal rainfall lies within the ensemble spread. I think this is also an important result to include in the conclusion and the abstract. Though there are differences in vertical profiles, the net effect on surface precipitation is not significant.