Response to Reviewer #1:

We appreciate the reviewer who reviewed the manuscript carefully and provided insightful follow-up comments. We have tried our best to address all concerns and revised the manuscript accordingly. The comments are in normal font. A point-by-point response is listed as below in bold italics.

1. The authors missed the point of my first major comment. My comment is about the regions with opposite precipitation response, which could be corresponding to the cold and warm sectors of the convective system, respectively. In their response, the authors chose two narrow areas (Box_N and Box_S), both of which have increased precipitation, to show the consistent features between those two boxes. Both areas are in the convergence zone based on Figure R1 and their cloud properties are of course similar. The cold section is probably northwest or northeast where decreased precipitation is seen (can be identified based on temperature field). Clouds at the cold sector would not be invigorated by aerosols so decreased precipitation can be seen as a result of suppressed conversion into rain or snow. Again, the point is that the authors need to explain the opposite precipitation response for different sections of the system, particularly for the 10X run, the decrease of precipitation is in a similar magnitude with the increase and occupies half of the simulation domain (Figure 19b). Based on Figure 19b, there is really no justification of only picking up the red box region to study.

Response: Thanks for the comments. We are sorry that we didn't make the responses clear in 1st version of the revised manuscript.

The mechanism of precipitation decrease over another region has been investigated in the discussion of main text along with Figure S11–S15, which is described as follows (P16L26–P17L8):

The mechanism of precipitation decreases over another region, in 24°–25°N, 110°–112°E, is also investigated. Figure S11 shows the distribution of time-height mass and number concentrations of different hydrometeors averaged over this region from CTL run. There are lots of ice crystals with cloud ice extending up to 16 km, indicating strong deep convection, which is consistent with low cloud top temperature in Figure S1b. However, the cloud base is higher than that over the region denoted by the red box, characterized by smaller low-level cloud water on 15 Dec when strong aerosol impact occurs. This can also

be indicated from the surface temperature field (Figure RR 1), characterized by a dipole with low in northwest and high in southeast. With aerosols, more cloud droplets nucleated on which water can condensate. Additional cloud water is subsequently formed near to 4 km (Figure S12a), accompanied by reduced supersaturation. The reduction of rain water and ice crystals (particularly in graupel) suggest that both the warm rain and cold rain are suppressed. Less latent heat is released dominated by condensation in warm cloud and deposition in cold cloud. There could be three reasons for this. The first one is that the mass of water vapor is small over this region in the northwest corner of the domain, so that not enough water supply for convective invigoration effect with aerosols. The second one is related to the very strong wind shear over this region with maximum value up to 80 m s^{-1}***. This condition is unfavored for latent heat to accumulate, which is key factor to convection strength (Fan et al., 2009). In addition, the cold cloud bases may suppress convection and precipitation due to strong evaporative cooling and less efficient ice crystals formation (Fan et al., 2016). Thus, the precipitation is suppressed over this region with aerosols. With ten times of aerosol emissions, the mass and number of rain water and ice crystals are further reduced, accompanied by weaker latent heat release (Figure S14 and S15). As a result, the precipitation is further suppressed (***_Error! Reference source not found._***b).***

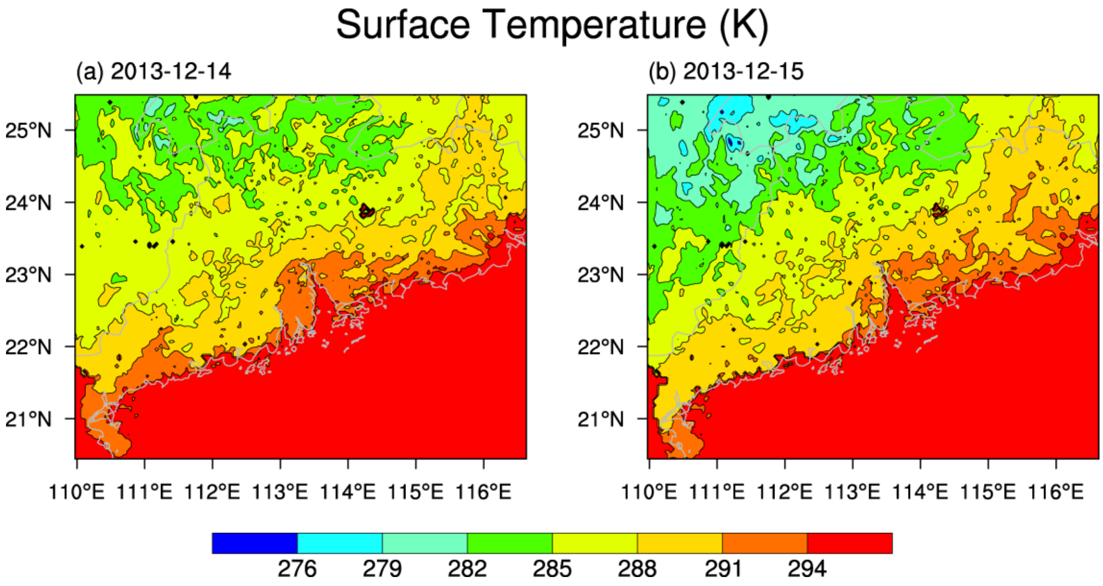


Figure RR 1. Spatial distribution of surface temperature (unit: K) on (a) December 14 and (b) December 15 in 2013 in the CTL run.

2. The authors did not do a neat job in responses. Many responses have wrong line numbers and they also did not describe what changes they made (also did not copy the revised text to the responses), which made me have a hard time to check their changes.

Response: Sorry to bring the troubles. The line numbers of responses are corrected and corresponding changes made in the manuscript are described in the responses to your comments.

3. There are quite a bit misunderstandings of cloud microphysical processes by reading the responses only (since I had a difficulty to find the changes in the manuscript due to incorrect line numbers). Here are examples, (1) a mistake in calculating cloud droplet number concentrations. They got unreasonably high ($8e^4$ cm^{-3}) cloud droplets (particularly for area mean, not a maximum value at gird-level) by using water density instead of air density to convert to number concentrations. What's surprising me is that they still argue the reasonability of it. Such a high number concentration is only possible for aerosols (not droplets) in a very polluted condition. (2) the misunderstandings of BF process, latent heat, and precipitating particles (see my comments on #14 response below). (3) the primary driver of convergence (my comments on #16 response). All these aspects that they misunderstood are the key aspects for analyzing and interpreting the model results this study.

Response: (1) Thanks for pointing this out. We should use the air density rather than water density to convert the unit of number concentration from kg^{-1} ***to*** cm^{-3}***; (2) and (3) please see the response below.***

4. For many comments on clarifications, the authors responded but did not clarify in the manuscript, such as comment #4.

Response: Per your suggestions, we clarify the responses to comments #4, # in the main text.

5. The writing is a little sloppy. There are typos and many statements are confusing. Here are a few just in a short abstract:

Response: Thanks for pointing this out. Please see the response below accordingly. We tried our best to correct other typos and misleading statements.

Abstract:

Line 28, “cloud property changes also resembled that in the control run” does not make sense. Changes means the differences between the 10× run and control run, how can the changes resemble control run?

Response: We revised the description as:

“Compared with CLEAN experiment, the precipitation and cloud property changes in 10× run also resembled that in the control run, but with much greater magnitude.”

Line 29, “The precipitation average over Guangdong province decreased by 1.0 mm but increased by 1.4 mm in the control run” does not make sense either. Looks like you are describing an increase or decrease in the control run. Then what are you comparing with? Generally, the description should be the increase or decrease by comparing with the control run.

Response: Sorry for the confusing. The comparison made here is between CTL and CLEAN run. The control run in this study is chosen as real case. The statement has been revised as:

“With aerosols, the precipitation average over Guangdong province decreased by 1.0 mm but increased by 1.4 mm in the control run by comparing with CLEAN run”

Line 30, “reinforced” should be removed. Also, downsteam of what? Urban city or aerosol source?

Last sentence in Abstract: Be specific about “the cloud invigoration effect”, which is different from convective invigoration. Cloud invigoration refers to larger and/or taller clouds. Convective invigoration refers to stronger storm intensity which usually leads to more extreme rain, more lightning, etc.

Response: Per you suggestions, reinforced is delete. Sorry for the confusing, we mean downstream of aerosol source.

Thanks for explaining the differences. We change the term to convective invigoration.

6. Detailed comments on responses

(1) #4 response: the description in the manuscript is still confusing. In the manuscript, you said BC is also scaled by a factor of 0.1 for domain 2. Since BC for domain 2 should be from domain 1 simulation, how can you scale it? About “In D2 experiment, the IC, BC, and emissions were scaled by 0.1 for domain 1. The IC and emissions were kept as same with the control run at the same time”, Isn't the second sentence contradicted with the first one? I am still confused about what you wanted to say in the second sentence.

Response: Yes, the BCs is only applied for domain 1 and this is a typo error. In D2 experiment, the IC, BC, and emissions were scaled by 0.1 for domain 1. The IC and emissions were kept as same with the control run for domain 2. Sorry for the confusion. The statement has been corrected in the main text (P5 L25–30).

(2) #8 response: Need to clarify in the manuscript (such as in the figure caption).

Response: Per your suggestions, the response to comment #8 has been clarified in both the caption and the main text (P8 L32–33).

(3) #10 response: Line number is not correct so it is difficult to identify the text you revised for this comment. But I found there is a mistake in P8 Line 24, how can the cloud top for deep convection only extends up to 1 km?

Response: Sorry for the incorrect line number. The description has been revised as (P8 L17–19):

“Distinct effects of aerosols appear during the second day when the rainfall peaked (*Error! Reference source not found.****d), although aerosols lead to more cloud droplet number concentration associated with smaller radius on the first day (Figure 5a); this suggests that the effects of aerosols on precipitation are modulated by other factors (e.g. meteorological conditions).”***

Yes, thanks for pointing this out. The mistake has been corrected. It should be 14 km.

(4) #11 response: Need to clarify in the figure caption that only cloud ice is considered.

Response: Per your suggestions, the response to comment #11 has been clarified in the caption in Figure 5.

(5) #12 response: The authors made a mistake in calculating the droplet number concentrations. They used water density (1 g cm^{-3}) instead of air density (~1e^{-3} g cm^{-3} at low levels) for the calculation. The area mean value should ~ 80 cm^{-3} as I mentioned in the previous round, not 8e4 cm-3 that is not totally reasonable.

Response: Thanks for correcting this mistake. We should use the air density rather than water density to convert the unit of number concentration from kg^{-1} to cm^{-3}.

(6) #13 response: I do not understand how more cloud droplets are lifted to freeze can be named as "interim processes". Why not directly describe the process instead of using a term that is not known?

Response: Thanks for your suggestions. As we found the source of latent heat cannot be attributed to freezing, the description has been removed in the main text.

(7) #14 response: there are a few fundamental misunderstandings about cloud microphysical processes: (a) BF process. This process only occurs in the limited regime where $Sw<0$ but $Si>0$. In deep convection, most of updrafts are strong enough to make $Sw>0$. In that situation, both droplet and ice crystal will grow. In addition, this process only increases ice crystal mass, not ice crystals as authors claimed. (b) latent heat. The statements “the magnitude of snow and graupel mass is ten times of that of rain water. The latent heat release due to deposition in cold cloud is stronger than that due to condensation in warm cloud even though the latter is also important” have problems. It is conceptually wrong to discuss latent heat magnitude based on the mass for different phase of hygrometers. snow and graupel are not mainly formed from deposition. Riming is the process for graupel forming which converts a lot of liquid mass to solid phase. The latent heat release from riming may be small only because the latent heat release for converting per unit liquid to ice is only about 1/8 of that converting per unit of water vapor to liquid. I'd want to know in detail how you calculate latent heat for each process in the model. Currently it is just said “diagnosed”. If it is diagnosed from the mass like described here. Then it is not correct. (c) It is also not correct to say “most of the ice crystals fall as

precipitation”. Ice crystals would not fall as precipitation. Snow and graupel are the precipitating particles. (d) The figure R10 is confusing. How can warm cloud have deposition and freezing? How do you define warm clouds? Also, why not show the values below 3 Kd-1, which is significant in differences? Please clarify "anomalies that exceed 90% significance level". First, there is no observations so please define anomaly here. Second, how the significance test is done since data between two simulations cannot be compared in pairs in grid level because very different clouds could form. If the test is conducted based on mean values, are there enough data for such a test?

Response: (a) Yes, agree. In Figure R9, the mass of cloud water and cloud ice increases, indicating the saturated situation for both water and ice. Moreover, the number of ice crystals also increases, suggesting inappropriate to attribute to BF processes. The response to comment 14 has been revised as:

“Figure R9 shows the changes in the mass and number concentration of the different hydrometers. The aerosols are activated to form more cloud droplets on which water condenses and produces more cloud water (Figure R9a). This process releases additional latent heat at 3–5 km due to condensation (Figure R10a) and lower supersaturation, which is also discussed in Fan et. al (2018). The smaller radius of cloud droplet shown in Figure 5a is not favorable to fast droplet coalescence and suppress warm rain. The precipitation decreases from 15Z to 20Z on 14 December (Figure S4). With aerosols, the precipitation is increased between 03Z on December 15 to 10Z on December 16. However, the changes in the hydrometers, particular for rain water, and sources of latent heat release are quite different between before and after 15Z on December 15. These differences indicate that the processes and their related mechanisms may differ from each other. In the first stage, before 15Z on December 15, there are abundant ice crystals (i.e. snow and graupel) above the 0°C isotherm around 5 km (Figure S8). With aerosols, the snow and graupel grows at the expenses of ice crystals and rain water via aggregation and rimming, respectively (Figure R9c–e). The former refers to the collision and coalescence of ice crystals to form snow while the latter represents the accretion of cloud drops and rain drops by snow and graupel to form larger graupels. These are the main processes of converting liquid mass to solid phase, contributing to additional precipitating particles. However, the latent heat due to rimming is relatively small (Figure R10f) because the latent heat release per unit for freezing (334 kJ kg^{-1}) is only 1/8 of that for deposition (2256 kJ kg^{-1}). The latent heat release due to deposition

in cold cloud is stronger than that due to condensation in warm cloud even though the latter is also important (Figure R9a and f). In deep convection, the strong updraft usually makes the atmospheric condition saturated for water which is supersaturated with respect to ice. With the presence of ice crystals (Figure S8), the formation of ice crystals is enhanced accompanied by additional latent heat release due to deposition (Figure R9 and 10). After 15Z on December 15, most of the snow and graupel sedimentate. Compared with depositional heating, the condensational heating plays a dominant role in intensifying convective strength. The rain water increases through accretion of added cloud droplets, leading to precipitation increases."

The descriptions have been integrated in the main text (P9L14–P10L27).

(b) Thanks for pointing this out. Yes, agree, rimming and aggregation are the main processes for the growth of snow and graupel. Please the revision accordingly in the responses to (a) above.

The output latent heat release due to phase change (i.e., condensation, deposition and freezing) are derived by adding additional diagnostic in the Morrison microphysical scheme. Each term is calculated based on the equation as follows:

For warm clouds,

$$\mathrm{T3D\_Wcon}(\mathrm{K}) = (\mathrm{PRE}(\mathrm{K}) + \mathrm{PCC}(\mathrm{K})) * \mathrm{XXLV}(\mathrm{K})/\mathrm{CPM}(\mathrm{K}) \quad (1)$$

$$\mathrm{T3D\_Wdep}(\mathrm{K}) = (\mathrm{EVPMS}(\mathrm{K}) + \mathrm{EVPMG}(\mathrm{K}) * \mathrm{XXLS}(\mathrm{K}))/\mathrm{CPM}(\mathrm{K}) \quad (2)$$

$$\mathrm{T3D\_Wfrz}(\mathrm{K}) = (\mathrm{PSMLT}(\mathrm{K}) + \mathrm{PGMLT}(\mathrm{K}) - \mathrm{PRACS}(\mathrm{K}) - \mathrm{PRACG}(\mathrm{K})) * \mathrm{XLF}(\mathrm{K})/\mathrm{CPM}(\mathrm{K}) \quad (3)$$

Where the left terms refer to latent heat release due to condensation, sublimation, and melting in Equation (1), (2), and (3), respectively. K is the layer in vertical for loop. The first term in the bracket on the right side represent different microphysical processes contributing the latent heat release. Based on Mao et al., (2018), more information on the warm-cloud transfer processes between different hydrometers for each process is described in Table 1. The terms of XXLV, XXLS, and XLF denote the latent heat release per unit of condensation, deposition, and freezing, respectively. CPM is specific heat at constant pressure for moist air.

Similarly, for cold clouds,

$$\mathrm{T3D\_Ccon}(\mathrm{K}) = (\mathrm{PRE}(\mathrm{K}) + \mathrm{PCC}(\mathrm{K})) * \mathrm{XXLV}(\mathrm{K})/\mathrm{CPM}(\mathrm{K}) \quad (4)$$

$$\begin{aligned}\mathrm{T3D\_Cdep}(\mathrm{K}) = {} & (\mathrm{PRD}(\mathrm{K}) + \mathrm{PRDS}(\mathrm{K}) + \mathrm{MNUCCD}(\mathrm{K}) + \mathrm{EPRD}(\mathrm{K}) + \mathrm{EPRDS}(\mathrm{K}) + \mathrm{PRDG}(\mathrm{K}) + \mathrm{EPRDG}(\mathrm{K})) \\ & * \mathrm{XXLS}(\mathrm{K})/\mathrm{CPM}(\mathrm{K}) \quad (5)\end{aligned}$$

$$\begin{aligned}\mathrm{T3D\_Cfrz}(\mathrm{K}) = {} & (\mathrm{PSACWS}(\mathrm{K}) + \mathrm{PSACWI}(\mathrm{K}) + \mathrm{MNUCCC}(\mathrm{K}) + \mathrm{MNUCCR}(\mathrm{K}) + \mathrm{QMULTS}(\mathrm{K}) + \mathrm{QMULTG}(\mathrm{K}) \\ & + \mathrm{QMULTR}(\mathrm{K}) + \mathrm{QMULTRG}(\mathrm{K}) + \mathrm{PRACS}(\mathrm{K}) + \mathrm{PSACWG}(\mathrm{K}) + \mathrm{PRACG}(\mathrm{K}) + \mathrm{PGSACW}(\mathrm{K}) \\ & + \mathrm{PGRACS}(\mathrm{K}) + \mathrm{PIACR}(\mathrm{K}) + \mathrm{PIACRS}(\mathrm{K})) * \mathrm{XLF}(\mathrm{K})/\mathrm{CPM}(\mathrm{K}) \quad (6)\end{aligned}$$

The information on the cold-cloud transfer processes between different hydrometers for each process is described in Table 2.

Table 1. Description of warm-cloud processes contributing to latent heat release. Red, green, and blue indicate condensation, deposition, and freezing related processes, respectively. If the term is negative, it refers to the opposite transfer process from sink to source. For example, negative of PRE represent the evaporation of Q_r.

Abbreviation	Warm-cloud processes	Source	Sink
PRE	Condensation of Q_v	Q_v	Q_r
PCC	Condensation of Q_v	Q_v	Q_c
EVPMS	Sublimation of Q_s	Q_s	Q_v
EVPMG	Sublimation of Q_g	Q_g	Q_v
PSMLT	Melting of Q_s	Q_s	Q_r
PGMLT	Melting of Q_g	Q_g	Q_r
PRACS	Collection of Q_r by Q_s	Q_r	Q_s
PRACG	Collection of Q_r by Q_g	Q_r	Q_g

Table 2. Same as Table 1 but for cold cloud.

Abbreviation	Cold-cloud processes	Source	Sink
PRE	Condensation of Q_v	Q_v	Q_r
PCC	Condensation of Q_v	Q_v	Q_c
PRD	Deposition of Q_v	Q_v	Q_s
PRDS	Deposition of Q_v	Q_v	Q_g
MNUCCD	Ice nucleation	Q_v	Q_i
EPRD	Sublimation of Q_i	Q_i	Q_v
EPRDS	Sublimation of Q_s	Q_s	Q_i
PRDG	Deposition of Q_v	Q_v	Q_g
EPRDG	Sublimation of Q_g	Q_g	Q_v
PSACWS	Accretion of Q_c by Q_s	Q_c	Q_s
PSACWI	Accretion of Q_c by Q_i	Q_c	Q_i
MNUCCC	Contacting freezing of Q_c	Q_c	Q_i
MNUCCR	Contacting freezing of Q_r	Q_r	Q_g
QMULTS	Multiplication due to collision Q_c by Q_s	Q_c	Q_i
QMULTG	Multiplication due to collision Q_c by Q_g	Q_c	Q_i
QMULTR	Multiplication due to collision Q_r by Q_s	Q_r	Q_i
QMULTRG	Multiplication due to collision Q_r by Q_g	Q_r	Q_i
PRACS	Collection of Q_r by Q_s	Q_r	Q_s

PSACWG	Collection of Q_c by Q_g	Q_c	Q_g
PRACG	Collection of Q_r by Q_g	Q_r	Q_g
PGSACW	Collection of Q_c by Q_s, conversion to Q_g	Q_c	Q_g
PGRACS	Collection of Q_r by Q_s, conversion to Q_g	Q_r	Q_g
PIACR	Collection of Q_r by Q_i, conversion to Q_g	Q_r	Q_g
PIACRS	Collection of Q_r by Q_i conversion to Q_s	Q_r	Q_s

These contents has been integrated in the main text as Appendix A.

(c) Agree. The text has been revised as:

"most of the snow and graupel sedimentate".

(d) Yes, agree. The deposition and freezing in warm cloud refer to sublimation and melting, respectively. The figures have been revised accordingly. The warm cloud in this study is defined as the cloud at the vertical layer above 0°C. Sorry for the confusing, the values below 3 K d^{-1} are not shown because zero-value lines are omitted, and the contour interval is 3 K d^{-1}. To avoid confusion, we remove the description "Note the blank represent the values are within 3 K d^{-1}". The anomaly is the deviation of experiment relative to CLEAN run. The significance test in this study is analogous to that conducted in climate. For example, given the climatology differences between two 30-year datasets, the sample is 30 for each experiment to conduct significance test. In this work, if we look at the significance of the differences in precipitation average on 15 December, the sample is 120 which is derived as the product of hours per day (24 hours precipitation performing average) and number of ensemble members for each experiment. This means we conduct significance test at grid level. We removed them if this is inappropriate. Thanks for pointing this out.

(8) #16 response: The convergence should be primarily because the dry cold air meet with warm humid air as a result of large-scale dynamics. Microphysics might enhance the convergence, but it is not the cause of the convergence over the large region. In addition, moisture is increased in the red box domain, which need to discuss where the source is.

Response: Agree. We revised the text to "The convergence is enhanced via microphysical processes". As discussed in the main text, the column-integrated water vapor changes are small compared with precipitation changes (Figure RR 2). The precipitation increase is mainly through the enhanced moisture flux convergence via microphysical-dynamical

feedback (Figure 8). The changes in moisture flux convergence is driven by convergence in a dynamical way. The source of moisture is mainly from the ocean transported by the southerly flow (Figure 20d). A clear gradient of moisture is seen from the ocean to the land.

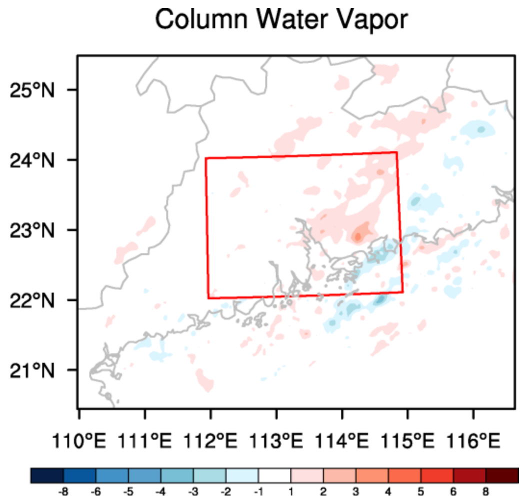


Figure RR 2. Spatial distribution of column-integrated water vapor changes (unit: mm) on 15 December between CTL and CLEAN.

(9) #18 response: (a) I do not understand "the persistent convective system makes the impact last for longer time". (b) The authors missed the point about my question "how the changes in domain 1 impact the results over domain 2". When emissions and aerosols are changed in Domain 1, the methodological field including temperature and moisture would be changed too. Those changes would impact domain 2 simulation since BC is from domain 1.

Response: (a) Sorry for the confusion. We removed the description in the main text.

(b) Agree and thanks for pointing this out. We integrate the following contents into our discussion (P17 L9–L25):

"One may wonder whether the precipitation differences over domain 2 in D1 experiment is driven by meteorological fields changes or by transport of aerosols because the scaling of emissions in domain 1 also modify the local atmospheric conditions. The changes in meteorology in turn may affect the precipitation in domain 2. Figure RR 3 shows the aerosol effects on 2-m temperature and column water vapor in domain 1. With aerosols, the moisture change is small over the whole China. The surface temperature decreases up to about 1 K is seen over northeastern China, Sichuan, and northeastern Indo-China Peninsula through

absorbing and scattering solar radiation as well as serving cloud condensation nuclei. The temperature over Guangdong province show marginal changes as the aerosol concentration is concentrated to the north of Guangdong and incident solar radiation is weak in rainy days. The relatively small changes in meteorological fields over domain 2 may indicate a dominant role of transboundary aerosols. Figure RR 4 shows the precipitation differences over domain 2 on 15 December based on domain 1 output. The pattern of precipitation changes is very different from that calculated based on domain 2 output, suggesting that the atmospheric condition changes in domain 1 cannot account for the precipitation differences in Figure 3d. Moreover, the importance of aerosol-cloud interactions discussed above works for both D1 and D2 experiment which may further confirm the precipitation changes in Guangdong is driven by transboundary aerosols rather than changes in meteorology in domain 1. Note the cumulus scheme is used in domain 1 but not in domain 2 which may result in different response of precipitation to atmospheric changes in domain 1. To completely disentangle the meteorology impact from that of transboundary aerosols, the possible solution could be application of nudging to constrain the meteorology as same as CTL and scale the emissions in domain 1. This could be in future sensitivity studies.”

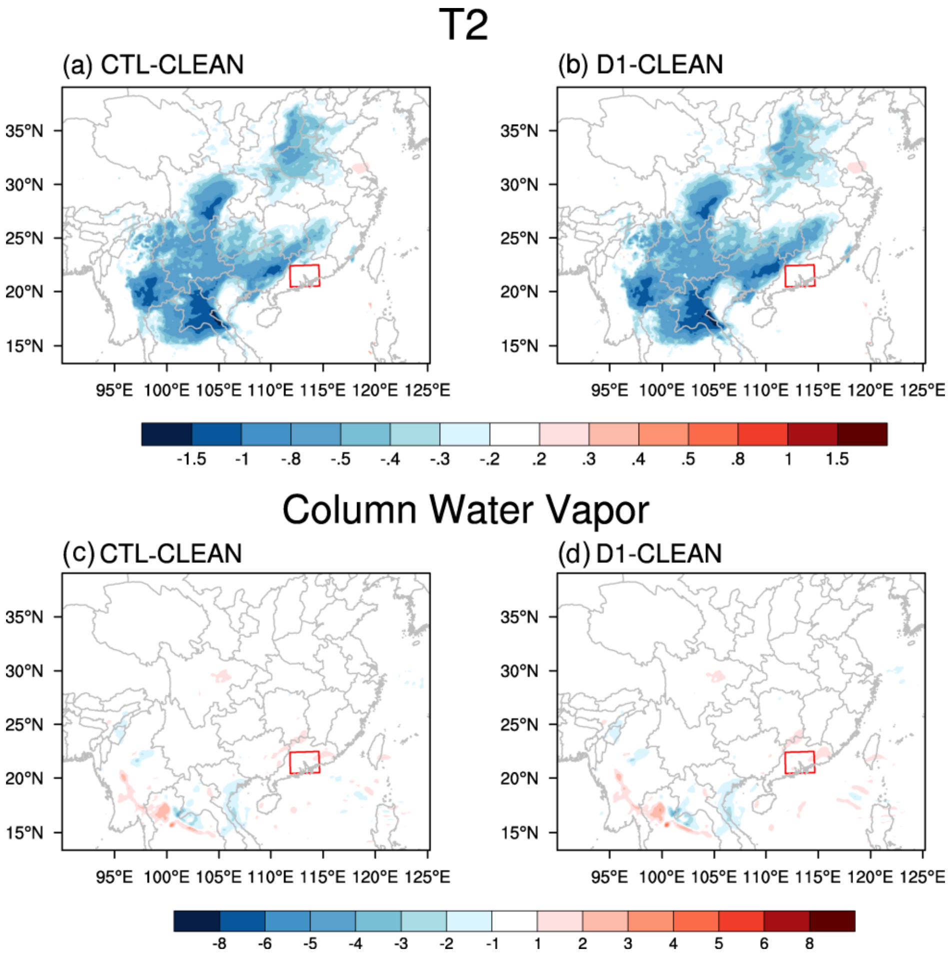


Figure RR 3. Differences in 2-m temperature (unit: K) between (a) CTL and CLEAN (i.e. CTL minus CLEAN) and (b) D1 and CLEAN (i.e. D1 minus CLEAN) on December 15. (c, d) Same as (a, b) but for column water vapor (unit: mm). Red boxes (22°–24°N, 112°–115°E) denote the analysis region.

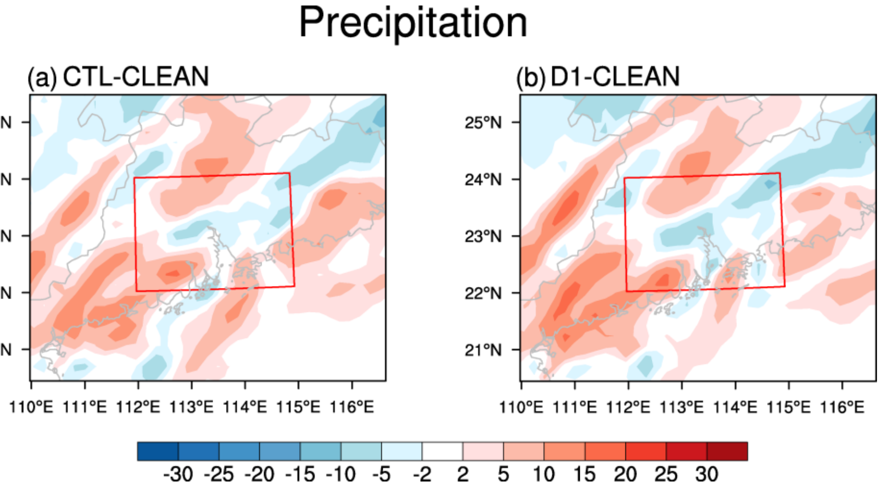


Figure RR 4. Differences in precipitation (unit: mm) between (a) CTL and CLEAN (i.e. CTL minus CLEAN) and (b) D1 and CLEAN (i.e. D1 minus CLEAN) on December 15 based on domain 1 output.

Reference:

Fan, J., Wang, Y., Rosenfeld, D. and Liu, X.: Review of Aerosol–Cloud Interactions: Mechanisms, Significance, and Challenges, J. Atmos. Sci., 73(11), 4221–4252, doi:10.1175/JAS-D-16-0037.1, 2016.

Mao, J., Ping, F., Yin, L. and Qiu, X.: A Study of Cloud Microphysical Processes Associated With Torrential Rainfall Event Over Beijing, J. Geophys. Res. Atmos., doi:10.1029/2018JD028490, 2018.

Contribution of local and remote anthropogenic aerosols to ~~intensification of~~ a record-breaking torrential rainfall event in Guangdong Province, China

Z. Liu[1,2,3], Y. Ming[5], C. Zhao[6], N.C. Lau[1,2,4], J.P. Guo[7], M. Bollasina[3], Steve H.L. Yim[1,4,2]

[1]Institute of Space and Earth Information Science, The Chinese University of Hong Kong, Hong Kong, China
[2]Institute of Environment, Energy and Sustainability, The Chinese University of Hong Kong, Sha Tin, N.T., Hong Kong
[3]School of Geosciences, University of Edinburgh, UK
[4]Department of Geography and Resource Management, The Chinese University of Hong Kong, Sha Tin, N.T., Hong Kong
[5]Geophysical Fluid Dynamics Laboratory/NOAA, Princeton, New Jersey, USA
[6]School of Earth and Space Sciences, University of Science and Technology of China, Hefei, Anhui, China
[7]State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing 100081, China

Correspondence to: Steve H.L. Yim (steveyim@cuhk.edu.hk)

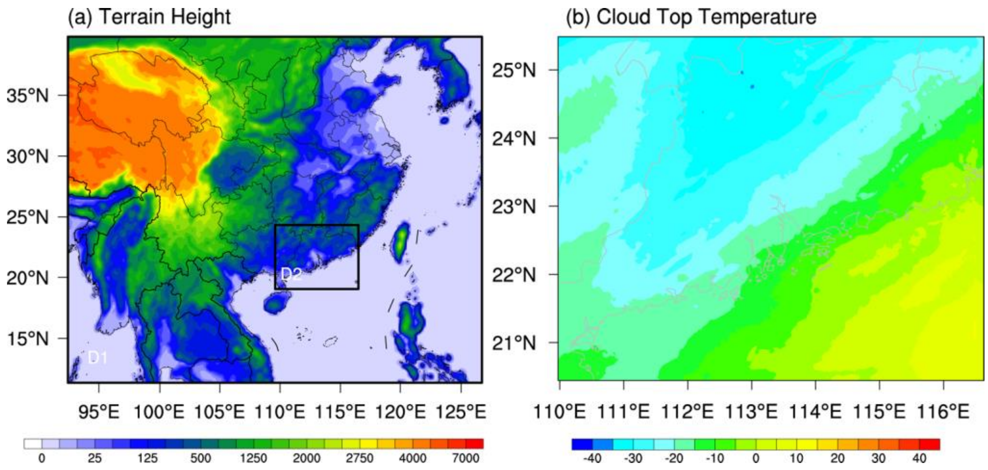


Figure S1. (a) WRF-Chem model two-nested domains with resolutions of 20 km and 4 km for domain 1 (D1) and domain 2 (D2), respectively. Shading represents terrain height (unit: m). (b) Spatial distribution of 3-day averaged cloud top temperature (shading; unit: °C) during December 14–16, 2013 over domain 2 in control run.

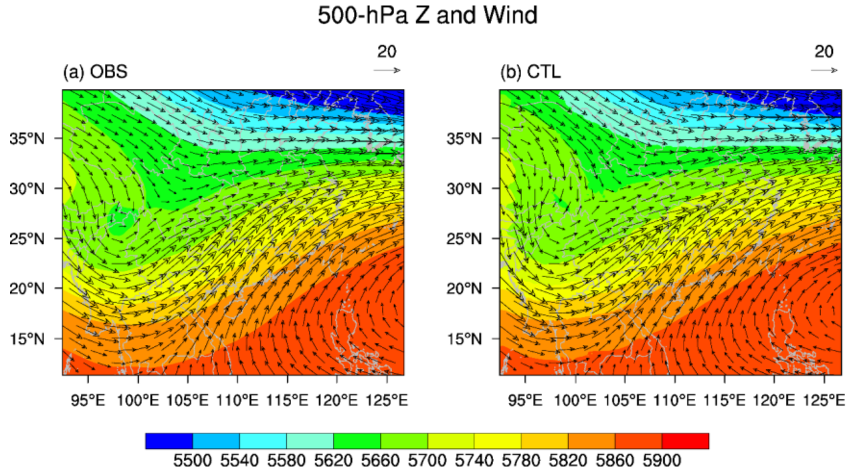


Figure S2. Spatial distribution of 3-day averaged 500-hPa wind (vector; unit: m s^{-1}) and height (shading; unit: m) during December 14–16, 2013 for (a) OBS from ERA-interim and (b) CTL from control simulation.

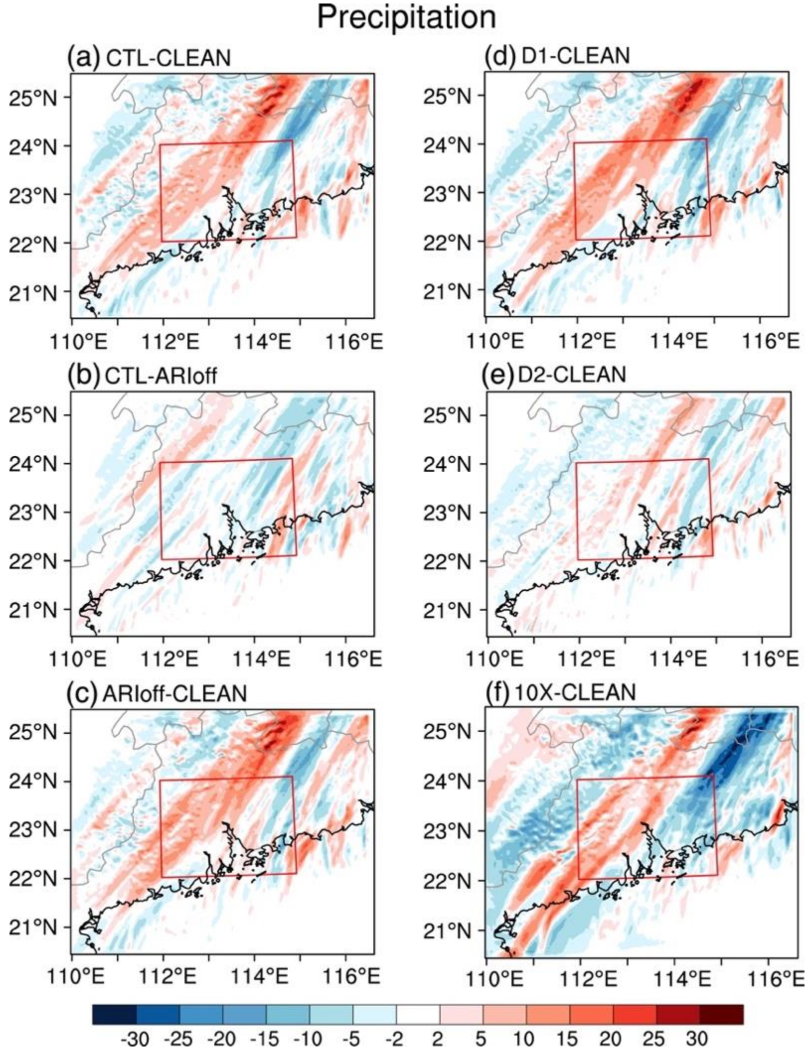


Figure S3. Differences in accumulated precipitation (unit: mm) on December 16 between (a) CTL and CLEAN (i.e., CTL minus CLEAN), (b) CTL and ARIoff (i.e., CTL minus ARIoff), (c) ARIoff and CLEAN (i.e., ARIoff minus CLEAN), (d) D1 and CLEAN (i.e., D1 minus CLEAN), (e) D2 and CLEAN (D2 minus CLEAN), and (f) 10X and CLEAN (10X minus CLEAN). Red boxes (22°–24° N, 112°–115° E) denote the analysis region. ARIoff run refers to simulation with aerosol-radiation interactions off.

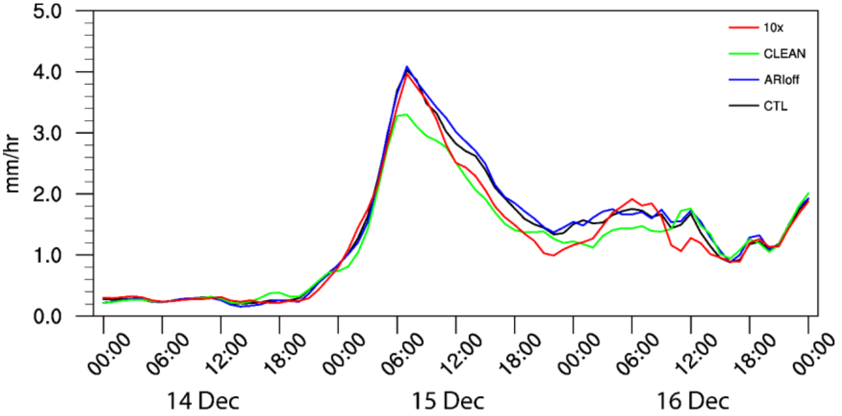


Figure S4. Time series of station average rain rate (unit: mm h^{-1}) over 22°–24° N, 112°–115° E (a) for OBS (red), CMORPH (black), CTL (blue), ARIoff (green), and CLEAN (purple).

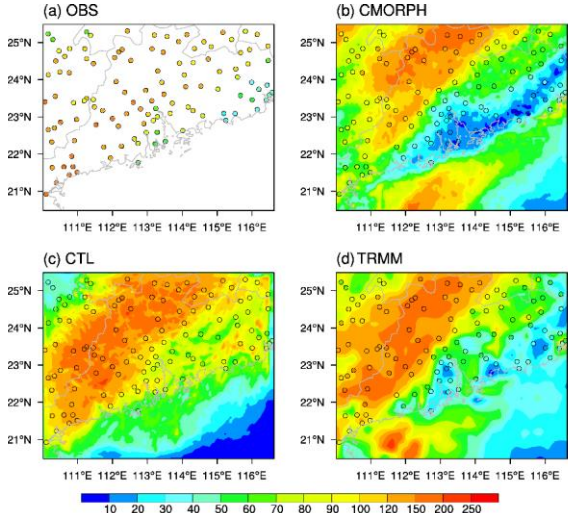


Figure S5. Spatial distribution of accumulated precipitation (unit: mm) from 00Z on December 14, 2013, to 00Z on December 17, 2013 from (a) station observations (OBS), (b) CMORPH, (c) control simulation (CTL), and (d) TRMM. Circles denote locations of in situ observations.

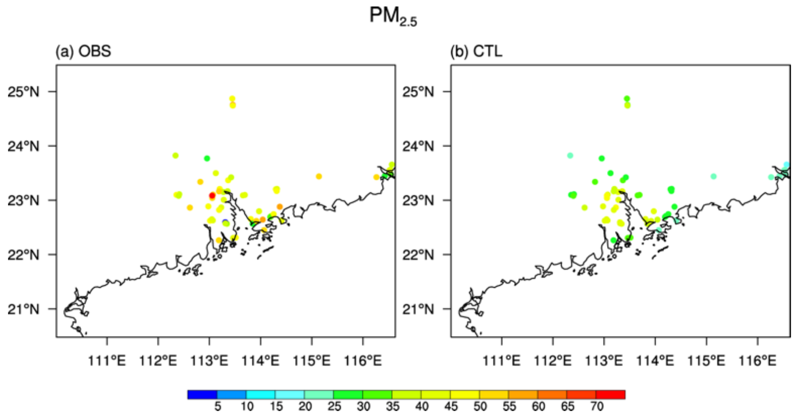


Figure S6. PM$_{2.5}$ concentration (unit: µg m^{-3}) average during December 14–16, 2013 for (a) observation and (b) control simulation. Colored circles denote in situ station locations.

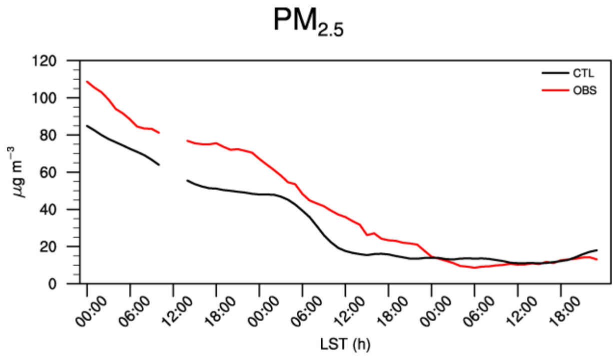


Figure S7. Time series of PM$_{2.5}$ averaged over all the stations during December 14–16, 2013 for CTL (black) and OBS (red).

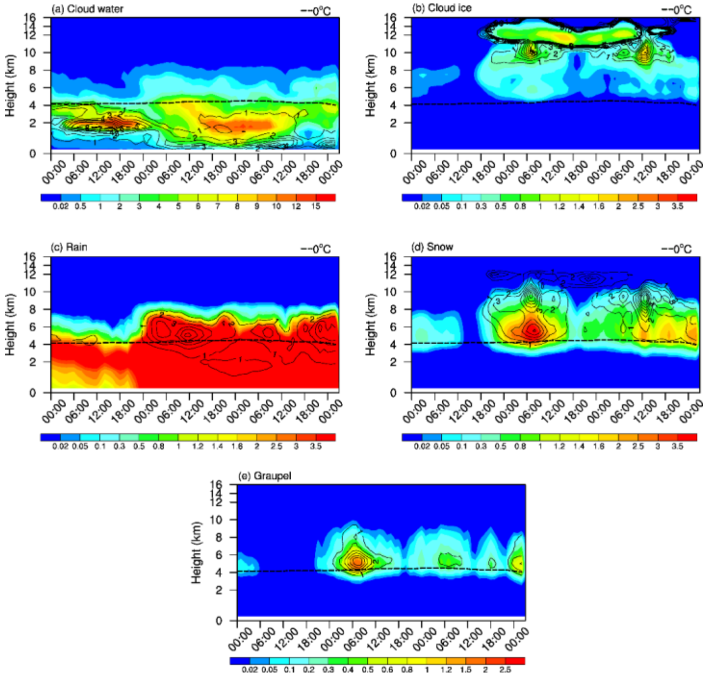
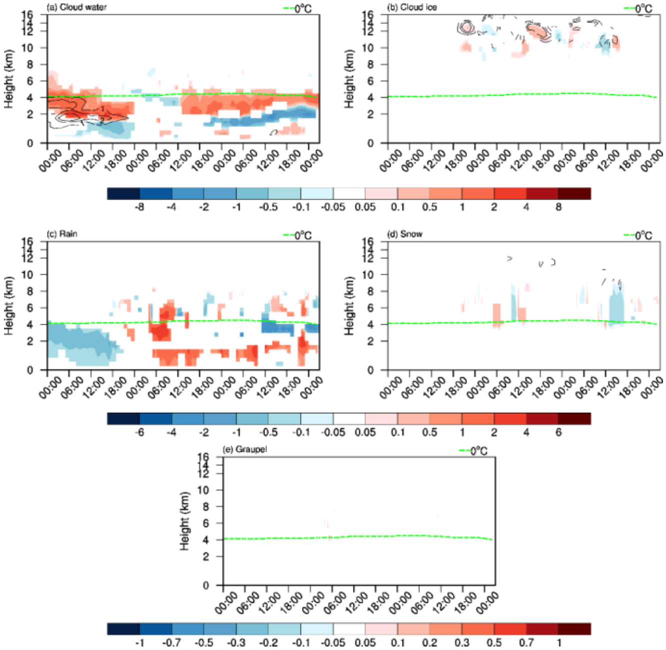


Figure S8. Distribution with time (abscissa) and height (ordinate) in (a) cloud water (shading; unit: 10^{-5} kg kg^{-1}) and CDNC (contour; unit: 10^{7} kg^{-1}), (b) cloud ice (shading; unit: 10^{-5} kg kg^{-1}) and CINC (contour; unit: 10^{4} kg^{-1}), (c) rain (shading; unit: 10^{-5} kg kg^{-1}) and rain number concentration (contour; unit: 10^{5} kg^{-1}), (d) snow (shading; unit: 10^{-4} kg kg^{-1}) and snow number concentrations (contour; unit: 10^{3} kg^{-1}), and (e) graupel (shading; unit: 10^{-4} kg kg^{-1}) and graupel number concentration (contour; unit: 10^{3} kg^{-1}) averaged over the red box in CTL run. Only anomalies that exceed 90% significance level are depicted with shading and contour.


(a) Cloud water
(b) Cloud ice
(c) Rain
(d) Snow
(e) Graupel
0°C
Height (km)
0
2
4
6
8
10
12
14
16
00:00
06:00
12:00
18:00
-8
-4
-2
-1
-0.5
-0.1
-0.05
0.05
0.1
0.5
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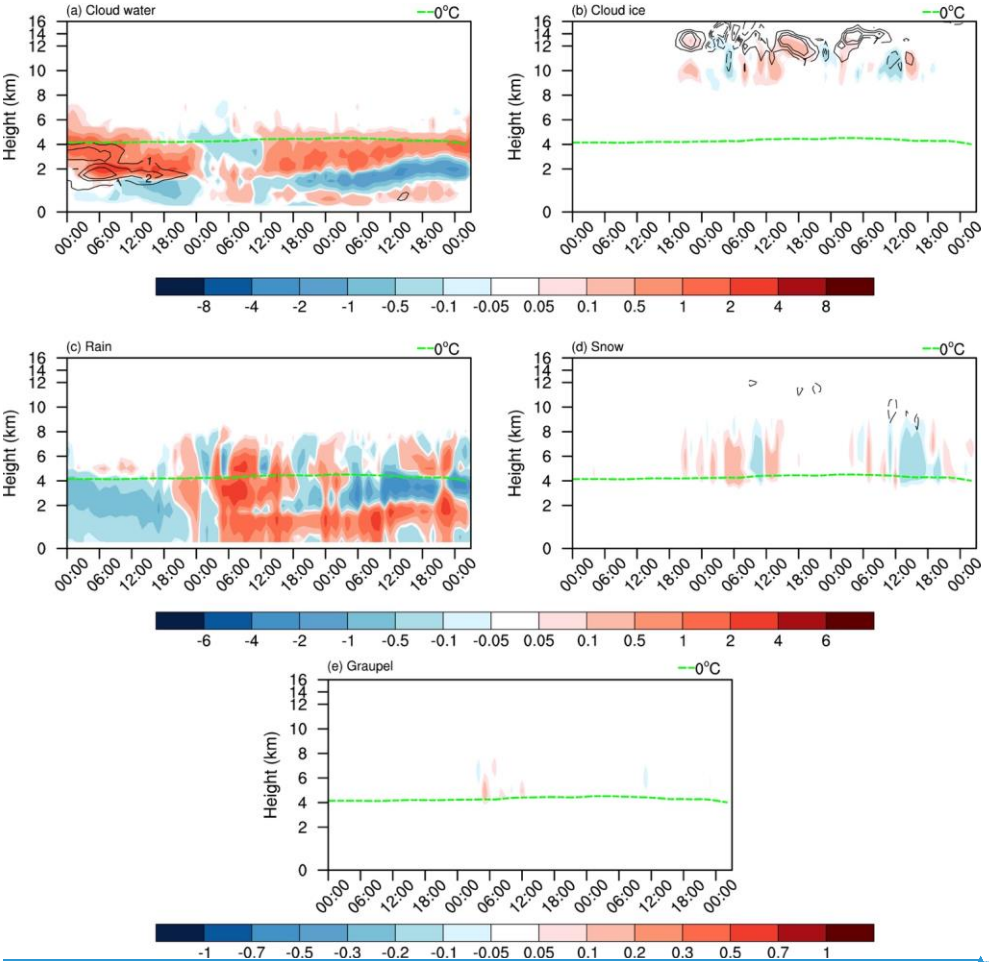
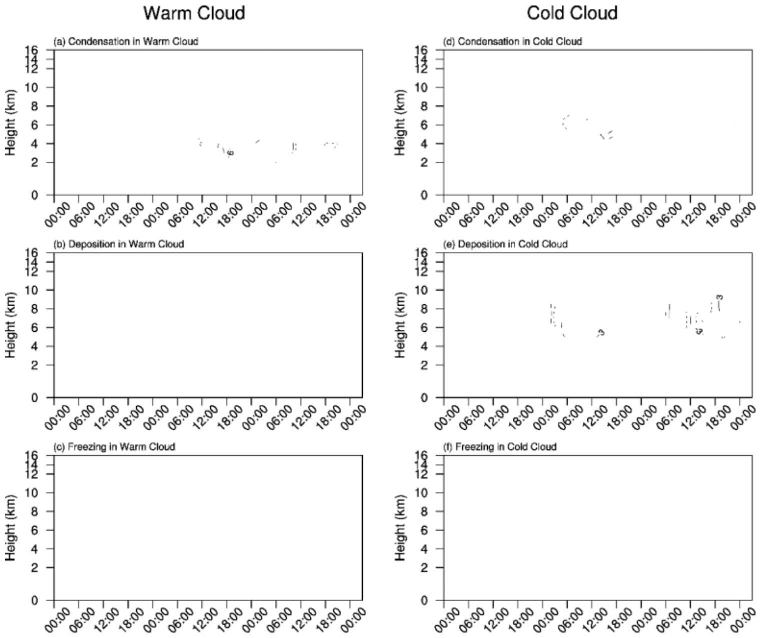


Figure S9. Differences with time (abscissa) and height (ordinate) in (a) cloud water (shading; unit: 10^{-5} kg kg^{-1}) and CDNC (contour; unit: 10^{7} kg^{-1}), (b) cloud ice (shading; unit: 10^{-5} kg kg^{-1}) and CINC (contour; unit: 10^{4} kg^{-1}), (c) rain (shading; unit: 10^{-5} kg kg^{-1}) and rain number concentration (contour; unit: 10^{5} kg^{-1}), (d) snow (shading; unit: 10^{-4} kg kg^{-1}) and snow number concentrations (contour; unit: 10^{3} kg^{-1}), and (e) graupel (shading; unit: 10^{-4} kg kg^{-1}) and graupel number concentration (contour; unit: 10^{3} kg^{-1}) between D2 and CLEAN (i.e. D2 minus CLEAN) averaged over the red box. ~~Only anomalies that exceed 90% significance level are depicted with shading and contour.~~


Warm Cloud
Cold Cloud
(a) Condensation in Warm Cloud
(b) Deposition in Warm Cloud
(c) Freezing in Warm Cloud
(d) Condensation in Cold Cloud
(e) Deposition in Cold Cloud
(f) Freezing in Cold Cloud
Height (km)
0
2
4
6
8
10
12
14
16
00:00
06:00
12:00
18:00

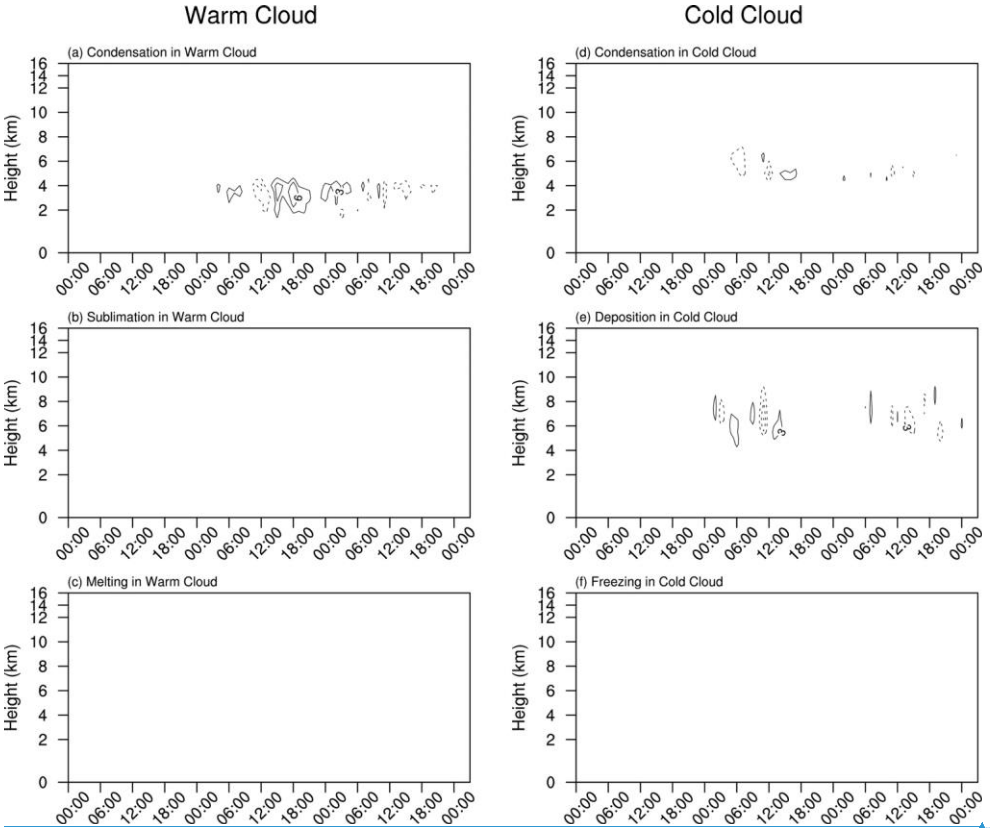


Figure S10. Differences with time (abscissa) and height (ordinate) in latent heat release (unit: K d^{-1}) from (a) condensation, (b) deposition, and (c) freezing processes between D2 and CLEAN (i.e. D2 minus CLEAN) averaged over the red box for the warm cloud. (d–f) Same as (a–c) but from cold cloud. ~~Only anomalies that exceed 90% significance level are depicted with and contour.~~ Zero-value contour lines are omitted, and negative values are dashed. The contour interval is 3 K d^{-1}. ~~Note the blank represent the values are within 3 K d^{-1}.~~

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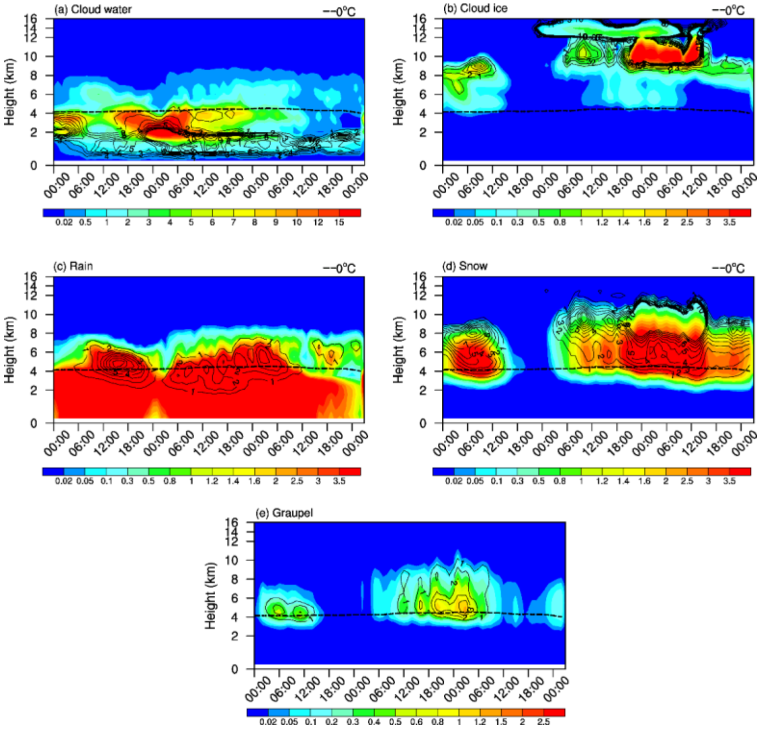
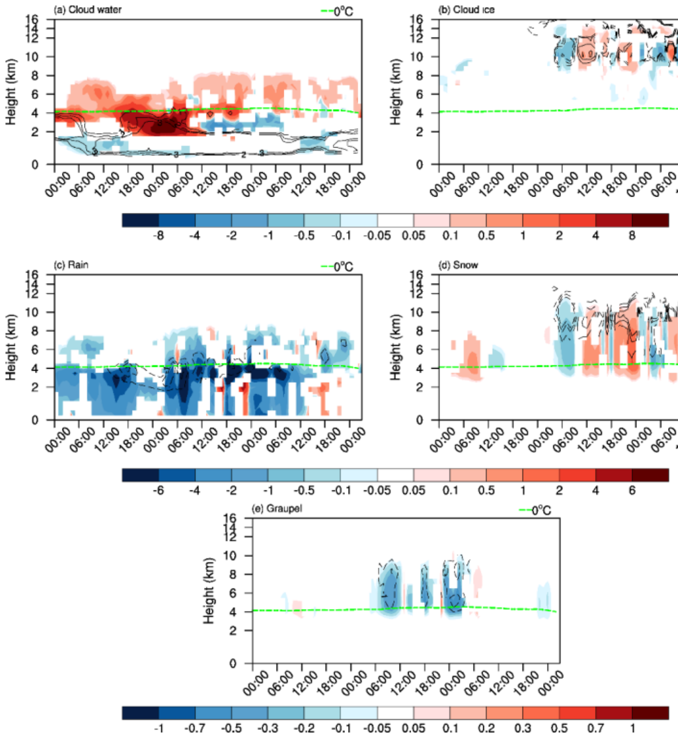


Figure S11. Distribution with time (abscissa) and height (ordinate) in (a) cloud water (shading; unit: 10^{-5} kg kg^{-1}) and CDNC (contour; unit: 10^{7} kg^{-1}), (b) cloud ice (shading; unit: 10^{-5} kg kg^{-1}) and CINC (contour; unit: 10^{4} kg^{-1}), (c) rain (shading; unit: 10^{-5} kg kg^{-1}) and rain number concentration (contour; unit: 10^{5} kg^{-1}), (d) snow (shading; unit: 10^{-4} kg kg^{-1}) and snow number concentrations (contour; unit: 10^{3} kg^{-1}), and (e) graupel (shading; unit: 10^{-4} kg kg^{-1}) and graupel number concentration (contour; unit: 10^{3} kg^{-1}) averaged over the region in 24°–25°N, 110°–112°E from CTL run. ~~Only anomalies that exceed 90% significance level are depicted with shading and contour.~~


(a) Cloud water
(b) Cloud ice
(c) Rain
(d) Snow
(e) Graupel
0°C
Height (km)
0
2
4
6
8
10
12
14
16
00:00
06:00
12:00
18:00
-8 -4 -2 -1 -0.5 -0.1 -0.05 0.05 0.1 0.5 1 2 4 8
-6 -4 -2 -1 -0.5 -0.1 -0.05 0.05 0.1 0.5 1 2 4 6
-1 -0.7 -0.5 -0.3 -0.2 -0.1 -0.05 0.05 0.1 0.2 0.3 0.5 0.7 1

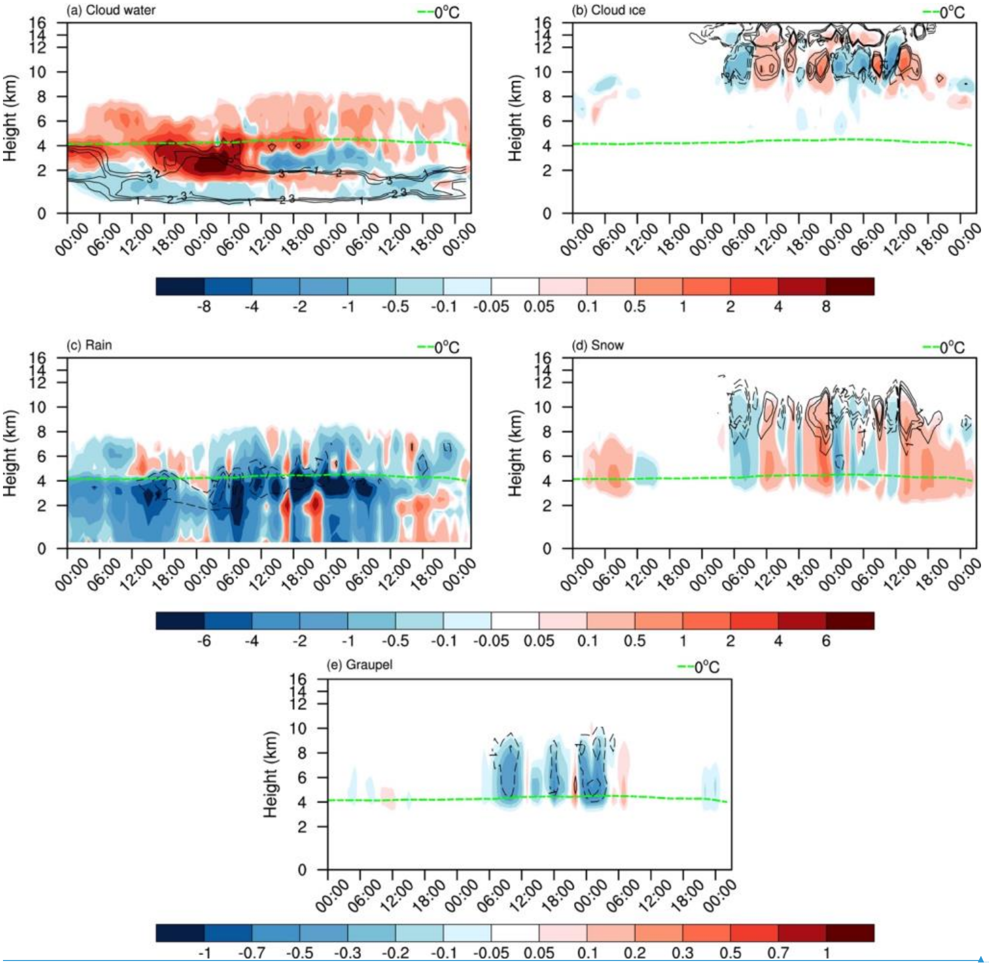


Figure S12. Differences with time (abscissa) and height (ordinate) in (a) cloud water (shading; unit: 10^{-5} kg kg^{-1}) and CDNC (contour; unit: 10^{7} kg^{-1}), (b) cloud ice (shading; unit: 10^{-5} kg kg^{-1}) and CINC (contour; unit: 10^{4} kg^{-1}), (c) rain (shading; unit: 10^{-5} kg kg^{-1}) and rain number concentration (contour; unit: 10^{5} kg^{-1}), (d) snow (shading; unit: 10^{-4} kg kg^{-1}) and snow number concentrations (contour; unit: 10^{3} kg^{-1}), and (e) graupel (shading; unit: 10^{-4} kg kg^{-1}) and graupel number concentration (contour; unit: 10^{3} kg^{-1}) between CTL and CLEAN (i.e. CTL minus CLEAN) averaged over the region in 24°–25°N, 110°–112°E. ~~Only anomalies that exceed 90% significance level are depicted with shading and contour.~~

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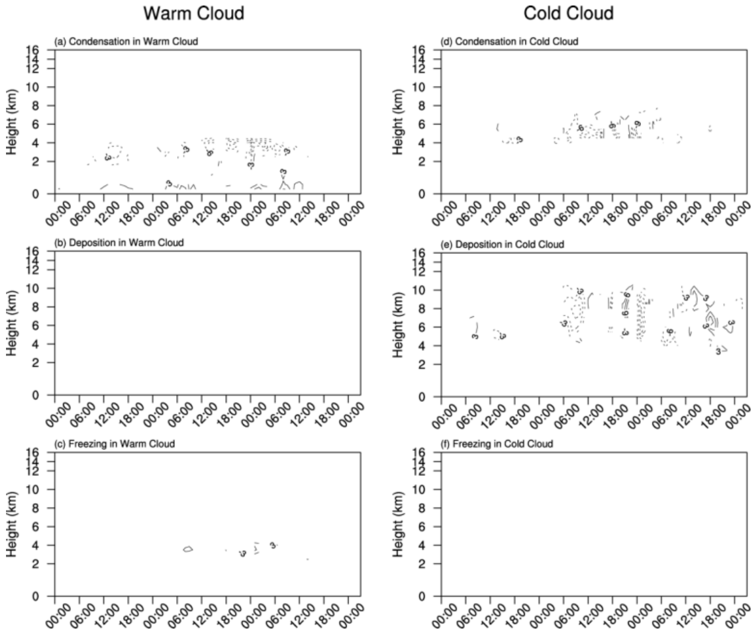
Warm Cloud
Cold Cloud
(a) Condensation in Warm Cloud
(b) Deposition in Warm Cloud
(c) Freezing in Warm Cloud
(d) Condensation in Cold Cloud
(e) Deposition in Cold Cloud
(f) Freezing in Cold Cloud
Height (km)
0
2
4
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8
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12
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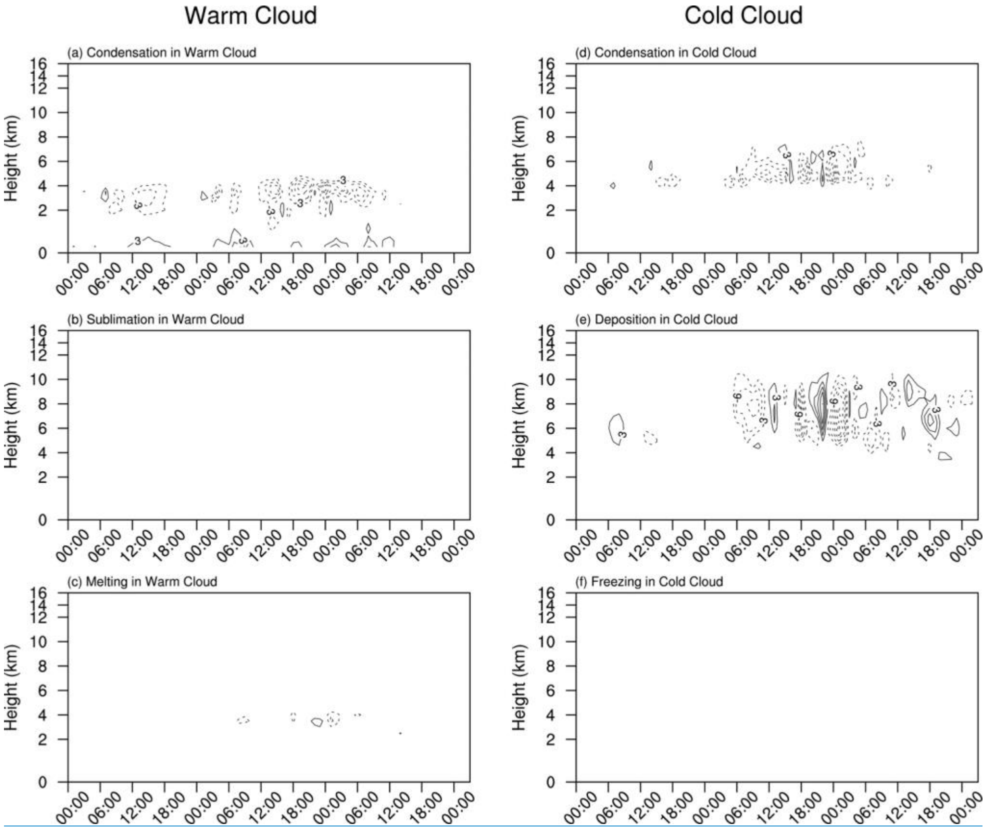
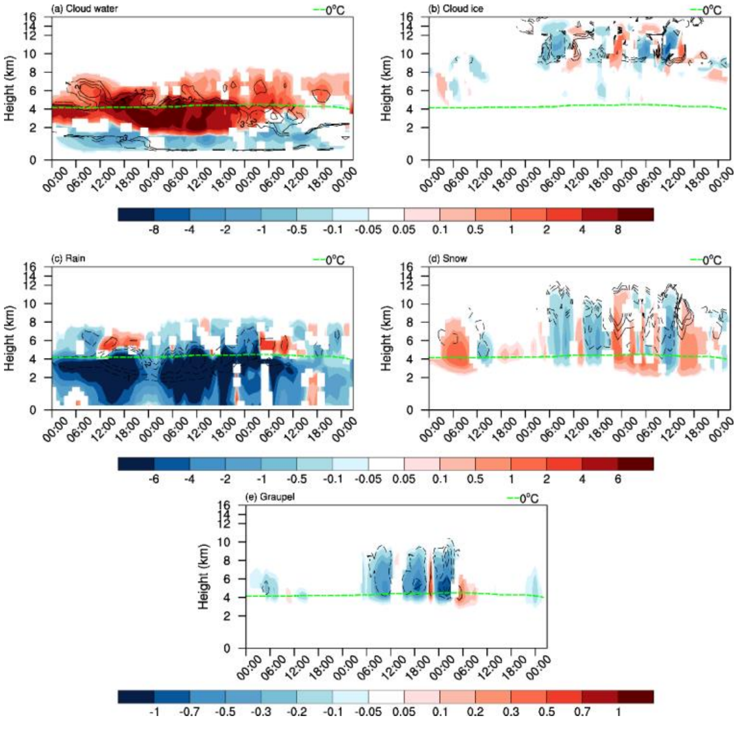


Figure S13. Differences with time (abscissa) and height (ordinate) in latent heat release (unit: K d^{-1}) from (a) condensation, (b) deposition, and (c) freezing processes between CTL and CLEAN (i.e. CTL minus CLEAN) averaged over the region in 24°–25°N, 110°–112°E for the warm cloud. (d–f) Same as (a–c) but from cold cloud. ~~Only anomalies that exceed 90% significance level are depicted with and contour.~~ Zero-value contour lines are omitted, and negative values are dashed. The contour interval is 3 K d^{-1}. ~~Note the blank represent the values are within 3 K d^{-1}.~~


(a) Cloud water
(b) Cloud ice
(c) Rain
(d) Snow
(e) Graupel
0°C
Height (km)
0
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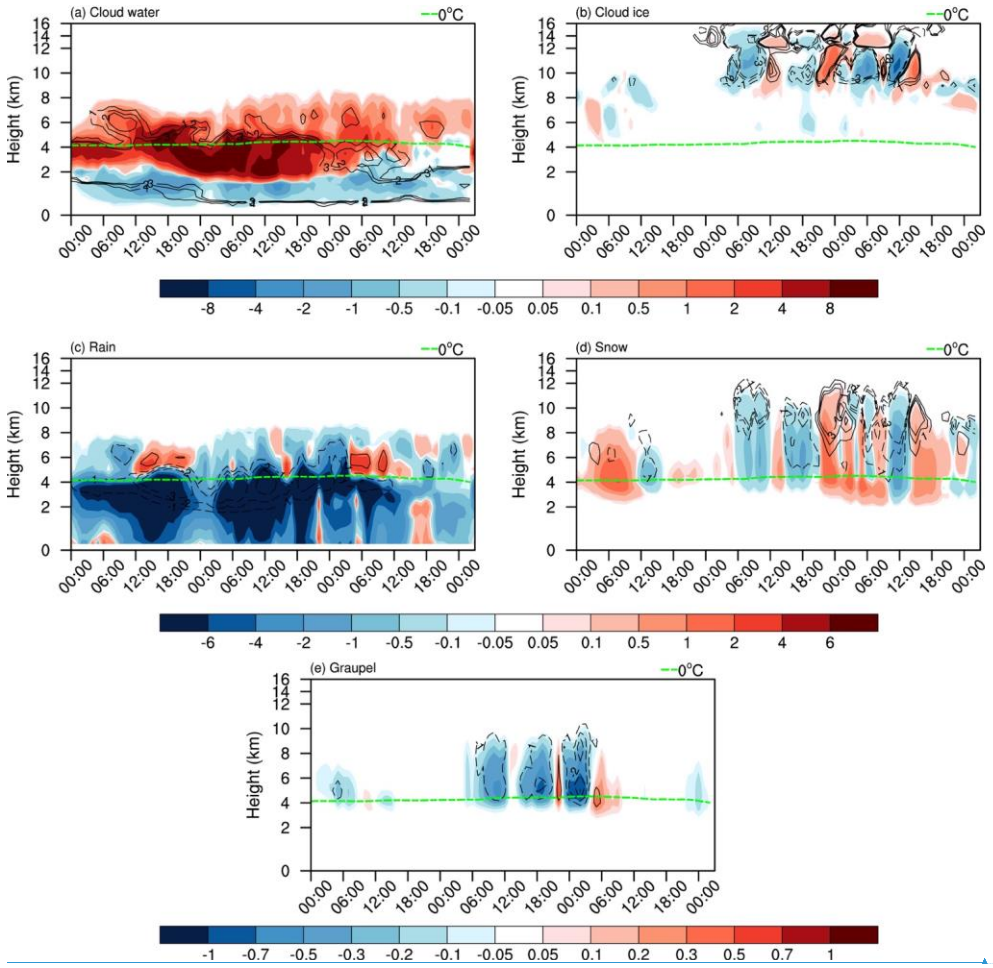

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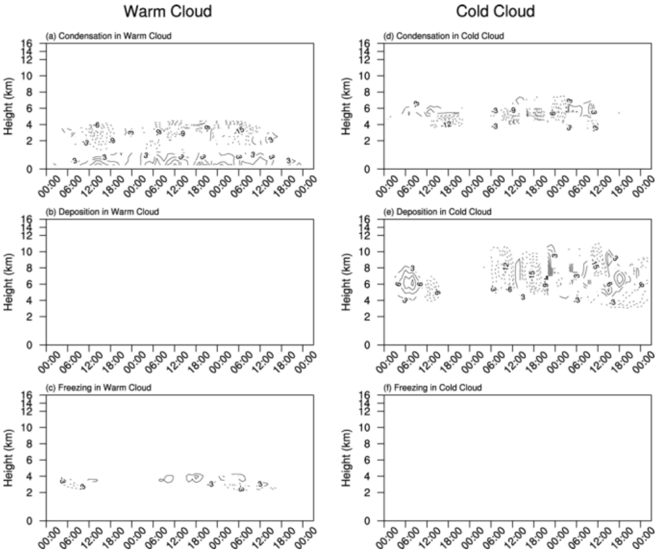
Figure S14. Differences with time (abscissa) and height (ordinate) in (a) cloud water (shading; unit: 10^{-5} kg kg^{-1}) and CDNC (contour; unit: 10^{7} kg^{-1}), (b) cloud ice (shading; unit: 10^{-5} kg kg^{-1}) and CINC (contour; unit: 10^{4} kg^{-1}), (c) rain (shading; unit: 10^{-5} kg kg^{-1}) and rain number concentration (contour; unit: 10^{5} kg^{-1}), (d) snow (shading; unit: 10^{-4} kg kg^{-1}) and snow number concentrations (contour; unit: 10^{3} kg^{-1}), and (e) graupel (shading; unit: 10^{-4} kg kg^{-1}) and graupel number concentration (contour; unit: 10^{3} kg^{-1}) between 10× and CLEAN (i.e. 10× minus CLEAN) averaged over the region in 24°–25°N, 110°–112°E. ~~Only anomalies that exceed 90% significance level are depicted with shading and contour.~~


Warm Cloud
Cold Cloud
(a) Condensation in Warm Cloud
(b) Deposition in Warm Cloud
(c) Freezing in Warm Cloud
(d) Condensation in Cold Cloud
(e) Deposition in Cold Cloud
(f) Freezing in Cold Cloud
Height (km)
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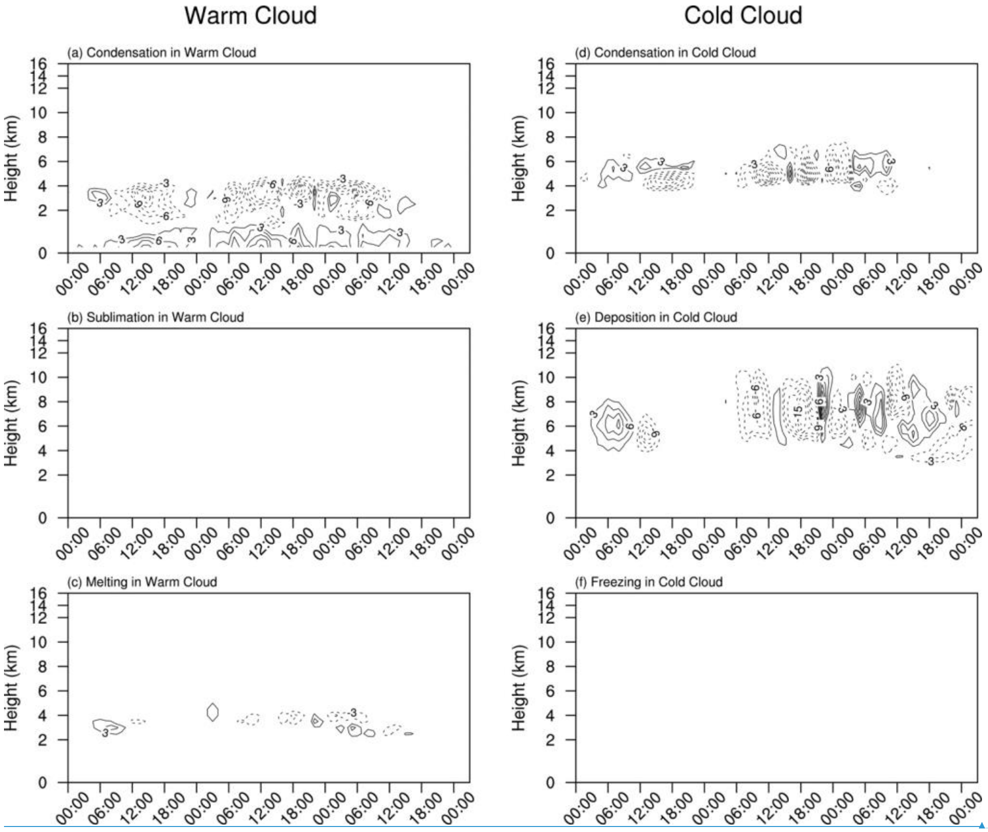

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Figure S15~~1515~~. Differences with time (abscissa) and height (ordinate) in latent heat release (unit: K d^{-1}) from (a) condensation, (b) deposition, and (c) freezing processes between 10× and CLEAN (i.e. 10× minus CLEAN) averaged over the region in 24°–25°N, 110°–112°E for the warm cloud. (d–f) Same as (a–c) but from cold cloud. Only anomalies that exceed 90% significance level are depicted with and contour. Zero-value contour lines are omitted, and negative values are dashed. The contour interval is 3 K d^{-1}. ~~Note the blank represent the values are within 3 K d^{-1}.~~

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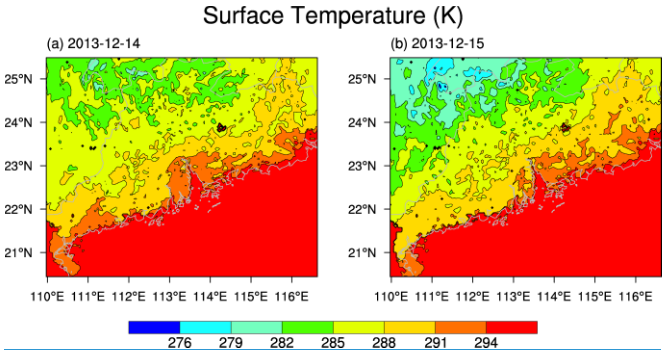

Figure S16. Spatial distribution of surface temperature (unit: K) on (a) December 14 and (b) December 15 in 2013 in the CTL run.

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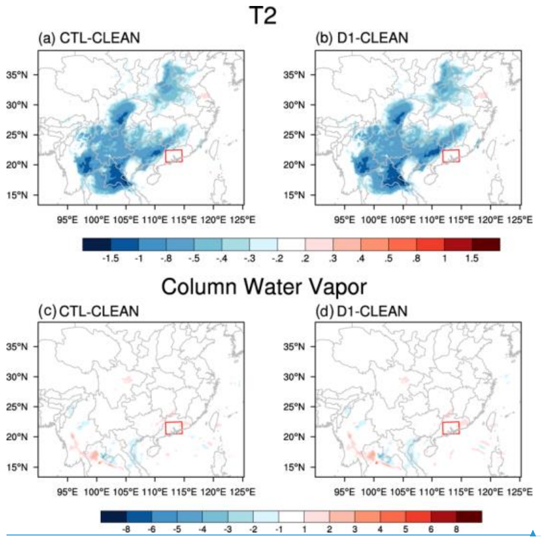

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Figure S17. Differences in 2-m temperature (unit: K) between (a) CTL and CLEAN (i.e. CTL minus CLEAN) and (b) D1 and CLEAN (i.e. D2 minus CLEAN) on December 15. (c, d) Same as (a, b) but for column water vapor (unit: mm). Red boxes (22°–24°N, 112°–115°E) denote the analysis region.

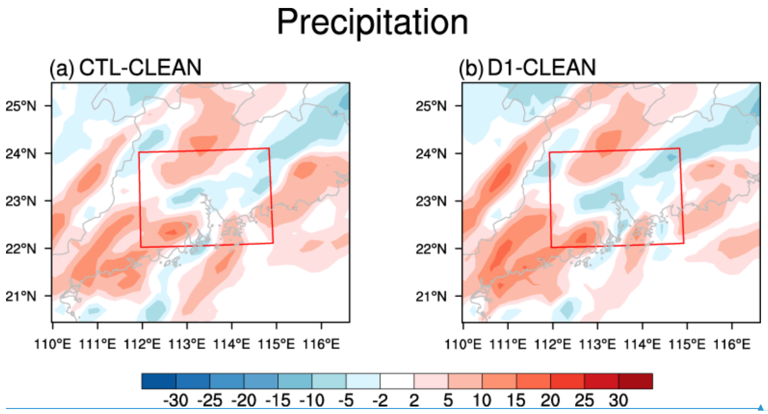

Figure S18. Differences in precipitation (unit: mm) between (a) CTL and CLEAN (i.e. CTL minus CLEAN) and (b) D1 and CLEAN (i.e. D1 minus CLEAN) on December 15 based on domain 1 output.

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