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Impacts of Cloud Microphysics Parameterizations on Simulated Aerosol-Cloud-Interactions for Deep Convective Clouds over Houston

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Abstract

Aerosol-cloud interactions remain largely uncertain in predicting their impacts on weather and climate. Cloud microphysics parameterization is one of the factors leading to the large uncertainty. Here we investigate the impacts of anthropogenic aerosols on the convective intensity and precipitation of a thunderstorm occurring on 19 June 2013 over Houston with the Chemistry version of Weather Research and Forecast model (WRF-Chem) using the Morrison two-moment bulk scheme and spectral-bin microphysics (SBM) scheme. We find that the SBM predicts a deep convective cloud agreeing better with observations in terms of reflectivity and precipitation compared with the Morrison bulk scheme that has been used in many weather and climate models. With the SBM scheme, we see a significant invigoration effect on convective intensity and precipitation by anthropogenic aerosols mainly through enhanced condensation latent heating (i.e., the warm-phase invigoration). Whereas such effect is absent with the Morrison two-moment bulk microphysics, mainly due to limitations of the saturation adjustment approach for droplet condensation and evaporation calculation.

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1 Introduction

Deep convective clouds (DCCs) produce copious precipitation and play important roles in the hydrological and energy cycle as well as regional and global circulation (e.g., Arakawa, 2004; Houze, 2014). DCCs and associated precipitation are determined by water vapor, vertical motion of air, and cloud microphysics that could be affected by aerosols through aerosol-radiative interactions (ARI) or aerosol-cloud interactions (ACI) or both. The cloud-mediated aerosol effects are recognized by the Intergovernmental Panel on Climate Change (IPCC) as one of the key sources of uncertainty in our knowledge of Earth's energy budget and anthropogenic climate forcing (e.g., Arakawa, 2004; Andreae et al., 2005; Haywood and Boucher, 2000; Lohmann and Feichter, 2005).

Precipitation, latent heat, and cloud radiative forcing associated with DCCs are strongly associated with cloud microphysical processes, which can be modulated by aerosols through serving as cloud condensation nuclei (CCN) and ice nuclei (IN). For aerosol-DCC interactions, a well-known theory is that increasing aerosol concentrations can suppress warm rain as a result of increased droplet number but reduced droplet size. This allows more cloud water to be lifted to a higher altitude wherein the freezing of this larger amount of cloud water induces larger latent heating associated with stronger ice microphysical processes, thereby invigorating convective updrafts (referred to as "cold-phase invigoration,"; Khain et al. 2005; Rosenfeld et al., 2008). It is significant in the situations of warm-cloud bases (> 15°C; Fan et al., 2012b; Li et al., 2011; Rosenfeld et al., 2014) and weak wind shear (Fan et al., 2009, 2012b, 2013; Li et al., 2008; Lebo et al., 2012). Another theory is that increasing aerosols enhances droplet nucleation particularly secondary nucleation after warm rain initiates, which promotes condensation because of larger integrated droplet surface area associated with a higher number of small droplets (Fan et al., 2007, 2013, 2018; Koren at al., 2014; Lebo, 2018; Sheffield et al., 2015). This so-called "warm-phase invigoration" , which is manifested in a warm, humid, and clean environment under which the addition of a large number of ultrafine aerosol particles from urban pollution leads to stronger invigoration than the "cold-phase invigoration" (Fan et al., 2018). Many factors can affect whether aerosols invigorate or suppress convective intensity through ACI, such as environmental wind shear (Fan et al., 2009; Lebo et al., 2012), relative humidity (Fan et al., 2007; Khain et al., 2008), and Convective Available Potential Energy (Lebo et al., 2012; Morrison, 2012; Storer et al., 2010). For DCCs with complicated dynamics, thermodynamics, and microphysics, aerosol impacts are extremely complex and still remain poorly known.

Modeling of ACI is quite dependent on cloud microphysics parameterization schemes (e.g., Fan et al., 2012a; Khain and Lynn, 2009; Khain et al., 2009, 2015; Lebo and Seinfeld, 2011; Lee et al., 2018; Loftus and Cotton, 2014; Wang et al., 2013). Two-moment bulk and bin schemes have been widely used in ACI studies (e.g., Chen et al., 2011; Fan et al., 2013; Khain et al., 2010). In two-moment bulk schemes, hydrometeor size distributions are diagnosed from the predicted number and mass with an assumed spectral shape (e.g., gamma function). Saturation adjustment approach is often used for calculating condensation and evaporation, meaning supersaturation and undersaturation with respect to water are removed in cloud within a timestep. In bin schemes, the size distributions of hydrometeors are discretized by a number of size bins and predicted, which represents some aerosol-cloud interaction processes more physically compared with bulk schemes (Fan et al., 2016; Khain et al., 2015).

Many studies have shown that bulk schemes are limited in representing certain important microphysical processes such as aerosol activation, condensation, deposition, sedimentation, and rain evaporation (Ekman et al., 2011; Khain et al., 2009; Lee et al. 2018; Li et al., 2009; Milbrandt and Yau, 2005; Morrison, 2012; Wang et al., 2013). Though bin cloud microphysics can provide a more rigorous numerical solution and a more robust cloud microphysics representation than typical bulk microphysics, it is often applied in simulations for process understanding but rarely in operational applications due to the expensive computation cost. For not introducing further computation cost, bins schemes are also often run with a prescribed aerosol spectrum assuming a fixed composition and a simple aerosol budget treatment without coupling with chemistry/aerosol calculations. As a result, many aerosol life cycle processes such as aerosol nucleation, growth, aqueous chemistry, aerosol resuspension, and below-cloud wet removal are missing or crudely parameterized. Therefore, it is difficult to simulate spatial and temporal variabilities of aerosol chemical composition and size distribution. In Gao et al. (2016), we have coupled a spectral-bin microphysics scheme (SBM; Fan et al., 2012a; Khain et al., 2004) with the Chemistry version of Weather Research and Forecast model (WRF-Chem; Grell et al., 2005; Skamarock et al., 2008), called WRF-Chem-SBM, to address above-mentioned limitations. In this new model, the SBM was coupled with the Model for Simulating Aerosol Interactions and Chemistry (MOSAIC; Fast et al., 2006; Zaveri et al., 2008). The newly coupled system was initially evaluated for warm marine stratocumulus clouds and showed much improved simulation of cloud droplet number concentration and liquid water content compared with the default Morrison two-moment bulk scheme (Gao et al., 2016).

The Houston area in summer, where isolated convective clouds with very warm cloud-bases often occurred in the afternoon (Yuan et al., 2008), offers (a) a combination of polluted aerosols from the urban and industrial area of Houston with significantly low background aerosol concentrations surrounding Houston, (b) aerosol sources that are not correlated with meteorology, and (c) weak synoptic forcing along with strong local triggering in the form of land-sea contrasts

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and sea breeze fronts. This combination allows the manifestation of potentially large aerosol effects. In this study, we choose a sea-breezed induced DCC case occurring 19-20 June 2013 near Houston to (1) evaluate the performances of WRF-Chem-SBM in simulating deep convective clouds and (2) gain a better understanding of the differences in aerosol effects predicted by SBM and the Morrison two-moment bulk scheme as well as the major factors/processes responsible for the differences. Considering that the convective clouds over the Houston area are mainly impacted by the aerosols produced from anthropogenic activities, we focus on the anthropogenic aerosol effect in this study. The simulated storm case is the same as the case for the Aerosol-Cloud-Precipitation-Cloud (ACPC) Model Intercomparison Project (Rosenfeld et al., 2014; www.acpcinitiative.org).

2 Case Description and Observational Data

A local convective event near Houston, Texas on 19-20 June 2013 is selected for the study owing to the most favorable conditions for simulating isolated convective cells. As above-mentioned, the case is also selected for the ACPC Model Intercomparison Project (www.acpcinitiative.org). The isolated relatively weak convective clouds started from the late morning because of a trailing front. With increased solar radiation in early afternoon and strengthening of a sea breeze circulation that transports warm and humid air from the Gulf of Mexico to Houston urban area, deep convective cells over Houston and Galveston bay areas developed (Fig. 1). The strong convective cell observed near the Houston city was initiated around 2145 UTC (local time 16:45), and developed to its peak precipitation at 2217 UTC based on radar observation (Fig. 1). The maximum reflectivity was more than 55 dBZ. This storm cell lasted for about 1.5 hours.

We used the following observation data for model evaluation. Particulate matter (PM) 2.5 data provided by Texas Commission for Environmental Quality (TCEQ) at https://www.tceq.texas.gov/agency/data/pm25.html are used to evaluate the simulated aerosols near the surface. The data for evaluating cloud base heights and CCN number concentration at cloud base are obtained from the Visible Infrared Imaging Radiometer Suite (VIIRS) retrievals based on the method of Rosenfeld et al., (2016). The 2-m temperature and 10-m winds are from the North American Land Data Assimilation System (NLDAS) with 0.125-deg resolution at https://climatedataguide.ucar.edu/climate-data/nldas-north-american-land-data-assimilation-system. The observed radar reflectivity is used to evaluate the simulated convective system. The radar reflectivity is obtained from Next-Generation Weather Radar (NEXRAD) network at https://www.ncdc.noaa.gov/data-access/radar-data/nexrad-products, with a temporal frequency of every ~ 5 minutes and 1 km horizontal spatial resolution.

3. Model description and experiments

We conducted model simulations using the version of WRF-Chem based on Gao et al. (2016) coupling with the Morrison two-moment scheme (Morrison et al., 2005; Morrison et al., 2009; Morrison and Milbrandt, 2011) and SBM (Khain et al., 2004; Fan et al., 2012). The version of SBM employed in this study is a fast version of the Hebrew University Cloud Model (HUCM) described by Khain et al. (2004) with improvements from Fan et al. (2012a) and (2017). The considered hydrometer size distributions are droplets/raindrops, cloud ice/snow and graupel. The graupel version is used because it is more appropriate for simulating the convective storm over the Houston area than the hail version. SBM is currently coupled with the four-sector version of MOSAIC (0.039-0.156, 0.156-0.624, 0.624-2.5 and 2.5-10.0 μm). As detailed in Gao et al. (2016), the aerosol processes including aerosol activation, resuspension, and in-cloud wet-removal are also improved. Theoretically, both aerosol and cloud processes can be more realistically simulated particularly under the conditions of complicated aerosol compositions and aerosol spatial heterogeneity compared with original WRF-Chem. The dynamic core of WRF-Chem-SBM is the Advanced Research WRF model that is fully compressible and nonhydrostatic with a terrain-following hydrostatic pressure vertical coordinate (Skamarock et al., 2008). The grid staggering is the Arakawa C-grid. The model uses the Runge-Kutta 3rd order time integration schemes, and the 3rd and 5th order advection schemes are selected for the vertical and horizontal directions, respectively. The positive definite option is employed for advection of moist and scalar variables.

Two nested domains with horizontal grid spacings of 2 and 0.5 km and horizontal grid points of 450 × 350 and 500 × 400 for Domain 1 and Domain 2, respectively, are used (Fig. 2a), with 51 vertical levels up to 50 hPa. The chemical and aerosol lateral boundary and initial conditions for Domain 1 simulations were from a quasi-global WRF-Chem simulations at 1-degree grid spacing, and meteorological lateral boundary and initial conditions were created from MERRA-2 (Gelaro et al., 2017). Two simulations were run over Domain 1 with anthropogenic emissions turned on and off, respectively, to provide two different aerosol scenarios for the initial and boundary chemical and aerosol conditions for Domain 2 simulations: (1) a polluted aerosol scenario with anthropogenic aerosols accounted which is for the real situation; (2) an assumptive clean scenario without anthropogenic aerosols. Domain 2 is run with initial and lateral boundary chemical and aerosols fields from Domain 1 outputs and initial and lateral boundary meteorological conditions from MERRA-2. Note that we use the meteorology from MERRA-2 as the initial and lateral boundary conditions for Domain 2 instead of Domain 1 outputs, because we want to keep the initial and lateral boundary meteorological conditions the same for all the sensitivity tests with

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different microphysics and aerosol setups (meteorology is different between the two simulations over Domain 1).

The simulations in Domain 1 were initiated at 0000 UTC on 14 Jun and ended at 1200 UTC 20 June with about 5 days for the chemistry spin-up. The meteorological field was reinitialized every 36 hours to prevent the model drifting. The dynamic time step was 6 s for Domain 1 and 3 s for Domain 2. The anthropogenic emission was from NEI-2011 emissions. The biogenic emission came from the Model of Emissions of Gases and Aerosols from Nature (MEGAN) product (Guenther et al., 2006). The biomass burning emission was from the Fire Inventory from NCAR (FINN) model (Wiedinmyer et al., 2011). We used the Carbon Bond Mechanism Z (CBMZ) gas-phase chemistry (Zaveri and Peters, 1999) and MOSAIC aerosol model with four bins (Zaveri et al., 2008). The physics schemes other than microphysics applied in the simulation are the Unified Noah land surface scheme (Chen and Dudhia, 2001), Mellor-Yamada-Janjic planetary boundary layer scheme (Janjic et al., 1994), Multi-layer, Building Environment Parameterization (BEP) urban physics scheme (Salamanca and Martilli, 2010), the RRTMG longwave and shortwave radiation schemes (Iacono et al., 2008).

The main purpose of the simulations in Domain 1 is to provide initial and boundary chemical and aerosol conditions for the simulations in Domain 2. To save computational cost, WRF-Chem coupled with Morrison two-moment bulk microphysics scheme (Morrison et al., 2005) is used for the simulations in Domain 1. Two simulations run for Domain 1 are referred to as D1_MOR_anth in which the anthropogenic emissions are turned on and D1_MOR_noanth where the anthropogenic emissions are turned off. Then four major experiments are carried out to simulate the convective event near the Houston over Domain 2 with two cloud microphysics schemes and two aerosol scenarios, respectively. We refer to the simulation in which SBM is used and the

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anthropogenic emissions are included using the initial and boundary chemicals and aerosols from D1_MOR_anth, as our baseline simulation (referred to as "SBM_anth"). SBM_noanth is based on SBM_anth but uses initial and boundary chemicals and aerosols from D1_MOR_noanth and turns off the anthropogenic emissions, meaning that anthropogenic aerosols are not taken into account. MOR_anth and MOR_noanth are the two corresponding simulations to SBM_anth and SBM_noanth, respectively, using the Morrison two-moment bulk microphysics scheme. To examine the contribution of the saturation adjustment approach for condensation and evaporation to the simulated aerosol effects with the Morrison scheme, we further conducted two sensitivity tests, based on MOR_anth and MOR_noanth, by replacing the saturation adjustment approach in the Morrison scheme with the condensation and evaporation calculation based on an explicit representation of supersaturation over a time step as described in Lebo et al. (2012). Note in both SBM and this modified Morrison schemes, the supersaturation for condensation and evaporation are calculated after the advection. These two simulations are referred to as MOR_SS_anth and MOR_SS_noanth, respectively. To present more robust results, we carry out a small number of ensembles (three) for each case over Domain 2 (we do not have computer time to do more ensemble runs). The three ensemble runs are only different in the initialization time: 0000 UTC, 0600 UTC, and 1200 UTC on 19 June. All the simulations end at 1200 UTC 20 June. All analysis results for Domain 2 simulations in this study are the mean values of three ensemble runs.

We evaluate the aerosol and CCN properties simulated by D1_MOR_anth to ensure realistic aerosol fields, which are used for the Domain 2 simulations with anthropogenic aerosols considered. These evaluations are included in the section 4.1.

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From D1_MOR_anth simulation, we see a very large spatial variability of aerosol number concentrations (Fig. 2b). There are three regions with significantly different aerosol loadings over the domain as shown by the black boxes in Fig. 2b: (a) the Houston urban area, (b) the rural area about 100 km northeast to Houston, and (c) Gulf of Mexico. Aerosols over the Houston urban area are mainly contributed by organic aerosols, which are highly related with industrial and ship channel emissions. The rural area aerosols are mainly from sulfate and sea salt aerosol is the major contributor over the Gulf of Mexico. This suggests that aerosol properties are extremely heterogenous in this region. The aerosols over Houston urban area are generally about 5 and 10 times higher than the rural and Gulf area, respectively (Fig. 2c). The size distributions show a three-mode distribution with the largest differences from the Aitken mode (peaks at 50 nm; Fig. 2c). These ultrafine aerosol particles are mainly contributed by anthropogenic activities (Fig. 2b, d). With the anthropogenic emissions turned off, the simulated aerosols are much lower and have much less spatial variability (Fig. 2d).

4 Result

4.1 Model Evaluation

We first show the evaluation of the aerosol and CCN properties simulated by D1_MOR_anth, which runs over Domain 1, much larger than Domain 2. As described in Table 1, there are eight PM monitoring sites from TCEQ around the Houston area. Surface PM2.5 shows high concentrations at Houston and its downwind regions (Fig. 3). The values from D1_MOR_anth show a very good agreement with the observations in terms of the surface PM2.5 averaged over 24 hours (the day before the convection near Houston). The hourly variations of ground-level PM2.5 concentrations from both observation and D1_MOR_anth for these sites in

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the day before the convective initiation is depicted in Fig. 4. Generally, the simulated hourly pattern agrees with the observation for eight stations. D1_MOR_anth reproduces the diurnal variations, especially the increasing trend from 1200 UTC to 1800 UTC 19 Jun prior to the initiation of deep convective cells over Houston and Galveston bay areas.

The evaluation of the cloud base heights and CCN at cloud bases at the warm cloud stage before transitioning to deep clouds (2000 UTC) are shown in Fig.5. Over the Houston and its surrounding area (black box in Fig. 5), the simulated cloud base heights are about 1.5-2 km, in an agreement with the retrieved values from VIIRS satellite, which are around 1.2-1.8 km (Fig. 5a-b). The retrieved CCN concentrations at cloud bases vary significantly over the domain and this spatial variability is generally captured by the model (Fig. 5c-d). For example, D1_MOR_anth simulates some high CCN concentrations (400-800 cm^{-3} with some above 1000 cm^{-3}) over the Houston and around the Bay area, relatively low CCN values at the rural areas (about 200-600 cm^{-3}) and very low values over the Gulf of Mexico (less than 200 cm^{-3}), as shown in Fig. 5d. This is consistent with the spatial variability from the retrievals (Fig. 5c). The evaluation of aerosol properties before the initiation of Houston convective cells and CCN at the warm cloud stage before transitioning to deep clouds provides us confidence in using the chemical and aerosol fields from Domain 1 outputs to feed Domain 2 simulations.

Now we are evaluating near-surface temperature and winds, reflectivity and precipitation simulated by SBM_anth and MOR_anth. Fig. 6 shows the comparisons in 2-m temperature and 10-m winds at 1800 UTC (before the convective initiation). Both SBM_anth and MOR_anth capture the general temperature pattern with a little overestimation at the northeast part of the domain (mainly rural area). SBM_anth predicts a slightly higher temperature than MOR_anth in the northern part of the Houston region (purple box in Fig. 6), which agrees with NLDAS better.

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SBM_anth gets the similar southerly winds from Gulf of Mexico to Houston as shown in NLDAS, while the southerly winds from Gulf of Mexico become very weak or disappear prior to reaching Houston in MOR_anth.

For the Houston convective cell that we focused (red box in Fig. 7a), SBM_anth simulates it well in both location and high reflectivity value (greater than 50 dBZ) in comparison with the NEXRAD observation (Fig. 7a-b). The simulated composite reflectivities (i.e., the column maximum) are up to 55-60 dBZ, consistent with NEXRAD. With the Morrison scheme, MOR_anth simulates several small convective cells near Houston with maximum reflectivity of 55 dBZ or less (Fig. 7c). The contoured frequency by altitude diagram (CFAD) plots for the entire storm period show that SBM_anth is in a better agreement with observation compared with MOR_anth, especially for vertical structure of the high reflectivity range (greater than 48 dBZ, black dashed lines in Fig. 8) and echo top heights, which can reach up to 14-15 km (Fig. 8a-b). MOR_anth overestimates the occurrence frequencies of the 35-45 dBZ range and underestimates those of the low and high reflectivity ranges (less than 15 dBZ or larger than 50 dBZ) as well as the echo top heights (1-2 km lower than SBM_anth; Fig. 8c).

For the precipitation rates averaged over the study area (red box in Fig. 7), the observation shows two peaks, which are captured by both SBM_anth and MOR_anth (Fig. 9a). However, the timing for the first peak is about 30 and 60 min earlier in SBM_anth and MOR_anth than the observation, respectively. Also, SBM_anth predicts the rain rate intensities at the two peak times more consistent with the observations whereas MOR_anth underestimates the rain rate intensity at the second peak time (Fig. 9a). The large precipitation rates (greater than 15 mm h^{-1}) in SBM_anth has a ~1.5 times larger occurrence probability than those in MOR_anth, showing a better agreement with the observation (Fig. 9b). Overall, the performance of SBM_anth is superior to

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MOR_anth in simulating the location and intensity of the convective storm and associated precipitation.

4.2 Simulated Aerosol Effects on Cloud and Precipitation

Now we look at the effects of anthropogenic aerosols on the deep convective storm simulated with SBM and Morrison microphysics schemes. Fig. 9a shows that with the SBM scheme, anthropogenic aerosols remarkably increase the mean surface rain rates (by ~30%; from SBM_noanth to SBM_anth), mainly because of the increased occurrence frequency (nearly doubled) for relatively large rain rates (i.e., 10-15 mm h^{-1} and >15 mm h^{-1}) in Fig. 9b . With the Morrison scheme, the changes in mean precipitation and the PDF from MOR_noanth to MOR_anth are relatively small, showing a very limited aerosol effect on precipitation. With the SBM scheme, the increase in the updraft speeds by the anthropogenic aerosols is even more notable than the precipitation (Fig. 10a-b). Above 5-km altitude, the occurrence frequencies of updraft speeds greater than 0.4% extend to a much larger values, with 36 m s^{-1} at the upper levels in SBM_anth while only ~ 20 m s^{-1} in SBM_noanth. With the Morrison scheme, the changes are not significant by the anthropogenic aerosols (MOR_noanth vs MOR_anth in Fig. 10c-d). From MOR_noanth to MOR_anth, there is a slight increase in updraft speed at around 9-11 km altitudes but a slight decrease at 6-8 km altitudes. The significant invigoration of convective intensity by anthropogenic aerosols with the SBM scheme explains the much larger occurrences of relatively large rain rates and overall more surface precipitation due to the anthropogenic aerosol effect (Fig. 9).

Now the question is why the anthropogenic aerosols enhance convective intensity of the storm with the SBM scheme while the effect is very small with the Morrison scheme. Fig. 11 shows the vertical profiles of mean updraft velocity, thermal buoyancy, and total latent heating

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rate of the top 25th percentile updrafts with value greater than 2 m s^{-1} during the deep convective cloud stage. With the SBM microphysics scheme, the increased convective intensity due to anthropogenic aerosol effect corresponds to the increased thermal buoyancy which is particularly notable at upper levels (~ 20%) from SBM_noanth to SBM_anth (Fig. 11a, c). The increased thermal buoyancy can be explained by the increased total latent heating (Fig. 11e), which is mainly from the larger condensation latent heating (Fig. 12a). From SBM_noanth to SBM_anth, the latent heating from ice-related microphysical processes (including deposition, drop freezing, and riming) has a relatively smaller increase than that from condensation (about half of the increase in condensation latent heating as shown in Fig. 12a). As shown in Fan et al., (2018), the increase in lower-level condensation latent heating has a much larger effect on intensifying updraft intensity compared with the same amount of increase in high-level latent heating from ice-related microphysical processes. This suggests that the convective invigoration by the anthropogenic aerosols with the SBM scheme should be mainly through the "warm-phase invigoration" mechanism. Compared with the Morrison scheme, the increase of total latent heating by the anthropogenic aerosols is almost doubled with the SBM scheme, explaining more remarkable enhancement of thermal buoyancy and thus the convective intensity (red lines vs blue lines in Fig. 11). From MOR_noanth to MOR_anth, there is a small increase in both the condensation latent heating and high-level latent heating associated with ice-related processes (blue lines in Fig. 12b). The major difference in the increase of latent heating by the anthropogenic aerosols between SBM and Morrison microphysics schemes comes from the condensation latent heating, with a ~20% increase with SBM but only ~ 8% with Morrison (Fig. 12). The lack of significant increase in condensation latent heating limits the "warm-phase invigoration", mainly responsible for the

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limited aerosol impacts on convective intensity and associated precipitation with the Morrison scheme.

To understand why the responses of condensation to the anthropogenic aerosols are different between the SBM and Morrison schemes, we look into the process rates of drop nucleation and condensation (Fig. 13). The calculations of aerosol activation and condensation/evaporation in the SBM scheme are based on the Köhler theory and diffusional growth equations in light of particle size and supersaturation, receptively. Whereas in the Morrison scheme, the Abdul-Razzak and Ghan (2002) parameterization is used for aerosol activation and the saturation adjustment method is applied for condensation and evaporation calculation. With the SBM scheme, the anthropogenic aerosols increase the drop nucleation rates by a few times over the profile (red lines in Fig. 13a), and the condensation rates are also drastically increased (doubled between 4-6 km altitudes as shown in Fig. 13c). The enhanced condensation rate by the anthropogenic aerosols is because much more aerosols are activated to form a larger number of small droplets, increasing the integrated droplet surface area for condensation, as documented in Fan et al., (2018). As a result, supersaturation is drastically lower in SBM_anth than SBM_noanth (green lines in Fig. 13a). With the Morrison scheme, we still see a large increase in droplet nucleation rate (Fig. 13b). However, the condensation rates are barely increased (blue solid vs. dashed lines in Fig. 13d). We hypothesize that the lack of response of condensation to the increased aerosol activation with the Morrison scheme is mainly because of the saturation adjustment calculation of the condensation and evaporation process. The approach does not allow supersaturation in cloud and the calculation does not depend on supersaturation, thus removes the sensitivity to the anthropogenic aerosols.

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To verify our hypothesis and examine how much the saturation adjustment method is responsible for the weak responses of condensation latent heating and convection to the added anthropogenic aerosols, we conducted two additional sensitivity tests by replacing the saturation adjustment approach in Morrison scheme with the condensation and evaporation calculation based on an explicit representation of supersaturation over a time step, as described in Section 3. The result shows the Morrison scheme with the simple calculation of supersaturation for condensational growth significantly changes the condensation rate (orange vs. blue lines in Fig. 13d) and a similarly large enhancement (from MOR_SS_noanth to MOR_SS_anth in Fig. 13d) is seen as the SBM scheme (Fig. 13c). This leads to a larger increase in condensation latent heating (orange lines in Figure 12b) compared with the original Morrison scheme, resulting a similarly large increase in thermal buoyancy by the anthropogenic aerosols as with the SBM scheme(orange lines in Fig. 11d), thus a similarly large increase in the convective intensity (orange lines in Fig. 11b). The increase of precipitation from MOR_SS_noanth to MOR_SS_anth is also similar to that with the SBM scheme (not shown). These results verify that the saturation adjustment approach for parameterizing condensation and evaporation is the major reason responsible for limited aerosol effects on convective intensity and precipitation with the Morrison scheme. Past studies also showed the limitations of the saturation adjustment approach in simulating aerosol impacts on deep convective clouds (e.g., Fan et al., 2016; Lebo et al., 2012; Lee et al., 2018; Wang et al., 2013).

Fig. 14 shows the responses of hydrometeor mass to anthropogenic aerosol effects. With the SBM scheme, the increases of cloud mass, rain mass, and total ice mass (ice, snow, and graupel) by the anthropogenic aerosols are very significant (Fig. 14, left), corresponding to convective invigoration. The increase of the total ice mass is particularly significant (from 3.5 to 5.5 g kg^{-1}

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around 10-km altitude), suggesting a large effect of enhanced convective intensity on ice hydrometeors. However, with the Morrison scheme, little change is seen (Fig. 14, right, blue lines). By replacing the saturation adjustment with a simple calculation based on supersaturation for condensation and evaporation in the Morrison scheme, the increases in those hydrometeor masses become as evident as those with the SBM scheme (Fig. 14, right, orange lines).

5 Conclusions and Discussion

We have conducted model simulations of a deep convective cloud case occurring on 19 June 2013 over the Houston area with WRF-Chem coupled with the SBM and Morrison microphysics schemes to (1) evaluate the performance of WRF-Chem-SBM in simulating the deep convective clouds, and (2) explore the differences in aerosol effects on the deep convective clouds produced by the SBM and Morrison schemes and the major factors responsible for the differences.

We have evaluated the simulated aerosols, CCN, cloud base heights, reflectivity, and precipitation. The model simulates the large spatial variability of aerosols and CCN from Gulf of Mexico, rural area, to Houston city. On the bulk magnitudes, the model captures the surface PM2.5, cloud base height, and CCN at cloud base near the Houston reasonably well. These realistically simulated aerosol fields were fed to higher resolution simulations (0.5 km) using the SBM and Morrison schemes. With the SBM scheme, the model simulates a deep convective cloud over the Houston in a better agreement with the observed radar reflectivity and precipitation, compared with using the Morrison scheme.

By excluding the anthropogenic aerosols in the simulations, the effects of anthropogenic aerosols on the deep convective clouds and differences in aerosol effects using the two microphysics schemes were examined. With the SBM scheme, anthropogenic aerosols notably increase convective intensity, enhance the peak precipitation rate over the Houston area (by ~ 30%),

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and double the frequencies of relatively large rain rates (> 10 mm h^{-1}). The enhanced convective intensity by anthropogenic aerosols makes the simulated storm agree better with the observed, mainly attributed to the increased condensation latent heating, indicating the "warm-phase invigoration". In contrast, with the Morrison scheme, there is no significant anthropogenic aerosol effect on the convective intensity and precipitation.

Sensitivity tests by replacing the saturation adjustment with the condensation and evaporation calculation based on an explicit representation of supersaturation over a time step show the similar aerosol effects on condensation, convective intensity, hydrometeor mass mixing ratios, and precipitation as with the SBM scheme. Therefore, the saturation adjustment method for the condensation and evaporation calculation is mainly responsible for the limited aerosol effects with the Morrison scheme. This is because the saturation adjustment method does not allow for the "warm-phase invigoration", which is different from Lebo et al. (2012) showing that the saturation adjustment artificially enhanced condensation latent heating at low levels and limited the potential for aerosols to invigorate convection through the "cold-phase invigoration" mechanism in their idealized simulations of a supercell storm with the thermal bubble initiation. In this study of the thunderstorm with WRF real-case simulations for both chemistry/aerosols and clouds, the saturation adjustment method actually leads to a smaller condensation latent heating than the explicit calculation with supersaturation (solid bold blue vs. solid bold orange line in Fig. 12b). Thus, when the computational resource is not sufficient or in other situations such as the application of SBM is not available, the Morrison scheme modified with the condensation and evaporation calculation based on a simple representation of supersaturation can be applied to study aerosol effects on convective clouds, especially for warm and humid cloud cases in which the response of condensation to aerosols is particularly important.

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Following Fan et al., (2018), which showed that the "warm-phase invigoration" mechanism was manifested by ultrafine aerosol particles in the Amazon warm and humid environment with extremely low background aerosol particles. Here we showed that in summer anthropogenic aerosols over the Houston area may also enhance the thunderstorm intensity and precipitation through the same mechanism by secondary nucleation of numerous ultrafine aerosol particles from the anthropogenic sources. But the magnitude of the effect is not as substantial as in the Amazon environment. Possible reasons include that background aerosols are much higher over the Houston area and air is not as humid as Amazon.

Acknowledgments

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https://doi.org/10.5194/acp-2020-372
Preprint. Discussion started: 6 May 2020

Reference

Abdul-Razzak, H., and Ghan, S. J.: A parameterization of aerosol activation - 3. Sectional representation, J Geophys Res-Atmos, 107, 4026, doi: 10.1029/2001jd000483, 2002.

Andreae, M. O., Jones, C. D., and Cox, P. M.: Strong present-day aerosol cooling implies a hot future, Nature, 435, 1187-1190, doi: 10.1038/nature03671, 2005.

Arakawa, A.: The cumulus parameterization problem: Past, present, and future, J Climate, 17, 2493-2525, doi: 10.1175/1520-0442(2004)017<2493:Ratcpp>2.0.Co;2, 2004.

Chen, F., and Dudhia, J.: Coupling an advanced land surface-hydrology model with the Penn State-NCAR MM5 modeling system. Part I: Model implementation and sensitivity, Mon Weather Rev, 129, 569-585, doi: 10.1175/1520-0493(2001)129<0569:Caalsh>2.0.Co;2, 2001.

Chen, Y. C., Xue, L., Lebo, Z. J., Wang, H., Rasmussen, R. M., and Seinfeld, J. H.: A comprehensive numerical study of aerosol-cloud-precipitation interactions in marine stratocumulus, Atmos Chem Phys, 11, 9749-9769, doi: 10.5194/acp-11-9749-2011, 2011.

Ekman, A. M. L., Engstrom, A., and Soderberg, A.: Impact of Two-Way Aerosol-Cloud Interaction and Changes in Aerosol Size Distribution on Simulated Aerosol-Induced Deep Convective Cloud Sensitivity, J Atmos Sci, 68, 685-698, doi: 10.1175/2010jas3651.1, 2011.

Fan, J. W., Zhang, R. Y., Li, G. H., and Tao, W. K.: Effects of aerosols and relative humidity on cumulus clouds, J Geophys Res-Atmos, 112, D14204, doi: 10.1029/2006jd008136, 2007.

Fan, J. W., Yuan, T. L., Comstock, J. M., Ghan, S., Khain, A., Leung, L. R., Li, Z. Q., Martins, V. J., and Ovchinnikov, M.: Dominant role by vertical wind shear in regulating aerosol effects

https://doi.org/10.5194/acp-2020-372
Preprint. Discussion started: 6 May 2020

on deep convective clouds, J Geophys Res-Atmos, 114, D22206, doi: 10.1029/2009jd012352, 2009.

Fan, J. W., Leung, L. R., Li, Z. Q., Morrison, H., Chen, H. B., Zhou, Y. Q., Qian, Y., and Wang, Y.: Aerosol impacts on clouds and precipitation in eastern China: Results from bin and bulk microphysics, J Geophys Res-Atmos, 117, D00k36, doi: 10.1029/2011jd016537, 2012a.

Fan, J. W., Rosenfeld, D., Ding, Y. N., Leung, L. R., and Li, Z. Q.: Potential aerosol indirect effects on atmospheric circulation and radiative forcing through deep convection, Geophys Res Lett, 39, L09806, doi: 10.1029/2012gl051851, 2012b.

Fan, J. W., Leung, L. R., Rosenfeld, D., Chen, Q., Li, Z. Q., Zhang, J. Q., and Yan, H. R.: Microphysical effects determine macrophysical response for aerosol impacts on deep convective clouds, P Natl Acad Sci USA, 110, E4581-E4590, doi: 10.1073/pnas.1316830110, 2013.

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

Fan, J. W., Han, B., Varble, A., Morrison, H., North, K., Kollias, P., Chen, B. J., Dong, X. Q., Giangrande, S. E., Khain, A., Lin, Y., Mansell, E., Milbrandt, J. A., Stenz, R., Thompson, G., and Wang, Y.: Cloud-resolving model intercomparison of an MC3E squall line case: Part I-Convective updrafts, J Geophys Res-Atmos, 122, 9351-9378, doi: 10.1002/2017jd026622, 2017.

Fan, J. W., Rosenfeld, D., Zhang, Y. W., Giangrande, S. E., Li, Z. Q., Machado, L. A. T., Martin, S. T., Yang, Y., Wang, J., Artaxo, P., Barbosa, H. M. J., Braga, R. C., Comstock, J. M.,

https://doi.org/10.5194/acp-2020-372
Preprint. Discussion started: 6 May 2020

Atmospheric Chemistry and Physics Discussions

Feng, Z., Gao, W. H., Gomes, H. B., Mei, F., Pohlker, C., Pohlker, M. L., Poschl, U., and de Souza, R. A. F.: Substantial convection and precipitation enhancements by ultrafine aerosol particles, Science, 359, 411-418, doi: 10.1126/science.aan8461, 2018.

Fast, J. D., Gustafson, W. I., Easter, R. C., Zaveri, R. A., Barnard, J. C., Chapman, E. G., Grell, G. A., and Peckham, S. E.: Evolution of ozone, particulates, and aerosol direct radiative forcing in the vicinity of Houston using a fully coupled meteorology-chemistry-aerosol model, J Geophys Res-Atmos, 111, D21305, doi: 10.1029/2005jd006721, 2006.

Gao, W. H., Fan, J. W., Easter, R. C., Yang, Q., Zhao, C., and Ghan, S. J.: Coupling spectral-bin cloud microphysics with the MOSAIC aerosol model in WRF-Chem: Methodology and results for marine stratocumulus clouds, J Adv Model Earth Sy, 8, 1289-1309, doi: 10.1002/2016ms000676, 2016.

Gelaro, R., McCarty, W., Suarez, M. J., Todling, R., Molod, A., Takacs, L., Randles, C. A., Darmenov, A., Bosilovich, M. G., Reichle, R., Wargan, K., Coy, L., Cullather, R., Draper, C., Akella, S., Buchard, V., Conaty, A., da Silva, A. M., Gu, W., Kim, G. K., Koster, R., Lucchesi, R., Merkova, D., Nielsen, J. E., Partyka, G., Pawson, S., Putman, W., Rienecker, M., Schubert, S. D., Sienkiewicz, M., and Zhao, B.: The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), J Climate, 30, 5419-5454, doi: 10.1175/Jcli-D-16-0758.1, 2017.

Grell, G. A., Peckham, S. E., Schmitz, R., McKeen, S. A., Frost, G., Skamarock, W. C., and Eder, B.: Fully coupled "online" chemistry within the WRF model, Atmos Environ, 39, 6957-6975, doi: 10.1016/j.atmosenv.2005.04.027, 2005.

Guenther, A., Karl, T., Harley, P., Wiedinmyer, C., Palmer, P. I., and Geron, C.: Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and

https://doi.org/10.5194/acp-2020-372
Preprint. Discussion started: 6 May 2020

Aerosols from Nature), Atmos Chem Phys, 6, 3181-3210, doi: 10.5194/acp-6-3181-2006, 2006.

Haywood, J., and Boucher, O.: Estimates of the direct and indirect radiative forcing due to tropospheric aerosols: A review, Rev Geophys, 38, 513-543, doi: 10.1029/1999rg000078, 2000.

Houze, R. A.: Cloud dynamics, 2. edn., Elsevier/Acad. Press, Amsterdam, 2014.

Iacono, M. J., Delamere, J. S., Mlawer, E. J., Shephard, M. W., Clough, S. A., and Collins, W. D.: Radiative forcing by long-lived greenhouse gases: Calculations with the AER radiative transfer models, J Geophys Res-Atmos, 113, D13103, doi: 10.1029/2008jd009944, 2008.

Janjic, Z. I.: The Step-Mountain Eta Coordinate Model - Further Developments of the Convection, Viscous Sublayer, and Turbulence Closure Schemes, Mon Weather Rev, 122, 927-945, doi: 10.1175/1520-0493(1994)122<0927:Tsmecm>2.0.Co;2, 1994.

Khain, A., Pokrovsky, A., Pinsky, M., Seifert, A., and Phillips, V.: Simulation of effects of atmospheric aerosols on deep turbulent convective clouds using a spectral microphysics mixed-phase cumulus cloud model. Part I: Model description and possible applications, J Atmos Sci, 61, 2963-2982, doi: 10.1175/Jas-3350.1, 2004.

Khain, A., Rosenfeld, D., and Pokrovsky, A.: Aerosol impact on the dynamics and microphysics of deep convective clouds, Q J Roy Meteor Soc, 131, 2639-2663, doi: 10.1256/qj.04.62, 2005.

Khain, A., and Lynn, B.: Simulation of a supercell storm in clean and dirty atmosphere using weather research and forecast model with spectral bin microphysics, J Geophys Res-Atmos, 114, D19209, doi: 10.1029/2009jd011827, 2009.

https://doi.org/10.5194/acp-2020-372
Preprint. Discussion started: 6 May 2020

Atmospheric Chemistry and Physics Discussions

Khain, A., Lynn, B., and Dudhia, J.: Aerosol Effects on Intensity of Landfalling Hurricanes as Seen from Simulations with the WRF Model with Spectral Bin Microphysics, J Atmos Sci, 67, 365-384, doi: 10.1175/2009jas3210.1, 2010.

Khain, A. P., BenMoshe, N., and Pokrovsky, A.: Factors determining the impact of aerosols on surface precipitation from clouds: An attempt at classification, J Atmos Sci, 65, 1721-1748, doi: 10.1175/2007jas2515.1, 2008.

Khain, A. P., Leung, L. R., Lynn, B., and Ghan, S.: Effects of aerosols on the dynamics and microphysics of squall lines simulated by spectral bin and bulk parameterization schemes, J Geophys Res-Atmos, 114, D22203, doi: 10.1029/2009jd011902, 2009.

Khain, A. P., Beheng, K. D., Heymsfield, A., Korolev, A., Krichak, S. O., Levin, Z., Pinsky, M., Phillips, V., Prabhakaran, T., Teller, A., van den Heever, S. C., and Yano, J. I.: Representation of microphysical processes in cloud-resolving models: Spectral (bin) microphysics versus bulk parameterization, Rev Geophys, 53, 247-322, doi: 10.1002/2014rg000468, 2015.

Koren, I., Dagan, G., and Altaratz, O.: From aerosol-limited to invigoration of warm convective clouds, Science, 344, 1143-1146, doi: 10.1126/science.1252595, 2014.

Lebo, Z.: 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, 75, 535-554, doi: 10.1175/Jas-D-16-0368.1, 2018.

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

https://doi.org/10.5194/acp-2020-372
Preprint. Discussion started: 6 May 2020

Lebo, Z. J., Morrison, H., and Seinfeld, J. H.: Are simulated aerosol-induced effects on deep convective clouds strongly dependent on saturation adjustment? Atmos Chem Phys, 12, 9941-9964, doi: 10.5194/acp-12-9941-2012, 2012.

Lee, S. S., Li, Z. Q., Zhang, Y. W., Yoo, H., Kim, S., Kim, B. G., Choi, Y. S., Mok, J., Um, J., Choi, K. O., and Dong, D. H.: Effects of model resolution and parameterizations on the simulations of clouds, precipitation, and their interactions with aerosols, Atmos Chem Phys, 18, 13-29, doi: 10.5194/acp-18-13-2018, 2018.

Li, G. H., Wang, Y., and Zhang, R. Y.: Implementation of a two-moment bulk microphysics scheme to the WRF model to investigate aerosol-cloud interaction, J Geophys Res-Atmos, 113, D15211, doi: 10.1029/2007jd009361, 2008.

Li, X. W., Tao, W. K., Khain, A. P., Simpson, J., and Johnson, D. E.: Sensitivity of a Cloud-Resolving Model to Bulk and Explicit Bin Microphysical Schemes. Part I: Comparisons, J Atmos Sci, 66, 3-21, doi: 10.1175/2008jas2646.1, 2009.

Li, Z. Q., Niu, F., Fan, J. W., Liu, Y. G., Rosenfeld, D., and Ding, Y. N.: Long-term impacts of aerosols on the vertical development of clouds and precipitation, Nat Geosci, 4, 888-894, doi: 10.1038/Ngeo1313, 2011.

Loftus, A. M., and Cotton, W. R.: Examination of CCN impacts on hail in a simulated supercell storm with triple-moment hail bulk microphysics, Atmos Res, 147, 183-204, doi: 10.1016/j.atmosres.2014.04.017, 2014.

Lohmann, U., and Feichter, J.: Global indirect aerosol effects: a review, Atmos Chem Phys, 5, 715-737, doi: 10.5194/acp-5-715-2005, 2005.

https://doi.org/10.5194/acp-2020-372
Preprint. Discussion started: 6 May 2020

Milbrandt, J. A., and Yau, M. K.: A multimoment bulk microphysics parameterization. Part II: A proposed three-moment closure and scheme description, J Atmos Sci, 62, 3065-3081, doi: 10.1175/Jas3535.1, 2005.

Morrison, H., Curry, J. A., and Khvorostyanov, V. I.: A new double-moment microphysics parameterization for application in cloud and climate models. Part I: Description, J Atmos Sci, 62, 1665-1677, doi: 10.1175/Jas3446.1, 2005.

Morrison, H., Thompson, G., and Tatarskii, V.: Impact of Cloud Microphysics on the Development of Trailing Stratiform Precipitation in a Simulated Squall Line: Comparison of One- and Two-Moment Schemes, Mon Weather Rev, 137, 991-1007, doi: 10.1175/2008mwr2556.1, 2009.

Morrison, H., and Milbrandt, J.: Comparison of Two-Moment Bulk Microphysics Schemes in Idealized Supercell Thunderstorm Simulations, Mon Weather Rev, 139, 1103-1130, doi: 10.1175/2010mwr3433.1, 2011.

Morrison, H.: On the robustness of aerosol effects on an idealized supercell storm simulated with a cloud system-resolving model, Atmos Chem Phys, 12, 7689-7705, doi: 10.5194/acp-12-7689-2012, 2012.

Rosenfeld, D., Lohmann, U., Raga, G. B., O'Dowd, C. D., Kulmala, M., Fuzzi, S., Reissell, A., and Andreae, M. O.: Flood or drought: How do aerosols affect precipitation?, Science, 321, 1309-1313, doi: 10.1126/science.1160606, 2008.

Rosenfeld, D., Andreae, M. O., Asmi, A., Chin, M., de Leeuw, G., Donovan, D. P., Kahn, R., Kinne, S., Kivekas, N., Kulmala, M., Lau, W., Schmidt, K. S., Suni, T., Wagner, T., Wild, M., and Quaas, J.: Global observations of aerosol-cloud-precipitation-climate interactions, Rev Geophys, 52, 750-808, doi: 10.1002/2013rg000441, 2014.

https://doi.org/10.5194/acp-2020-372
Preprint. Discussion started: 6 May 2020

Rosenfeld, D., Zheng, Y. T., Hashimshoni, E., Pohlker, M. L., Jefferson, A., Pohlker, C., Yu, X., Zhu, Y. N., Liu, G. H., Yue, Z. G., Fischman, B., Li, Z. Q., Giguzin, D., Goren, T., Artaxo, P., Barbosa, H. M. J., Poschl, U., and Andreae, M. O.: Satellite retrieval of cloud condensation nuclei concentrations by using clouds as CCN chambers, P Natl Acad Sci USA, 113, 5828-5834, doi: 10.1073/pnas.1514044113, 2016.

Salamanca, F., and Martilli, A.: A new Building Energy Model coupled with an Urban Canopy Parameterization for urban climate simulations-part II. Validation with one dimension off-line simulations, Theor Appl Climatol, 99, 345-356, doi: 10.1007/s00704-009-0143-8, 2010.

Sheffield, A. M., Saleeby, S. M., and van den Heever, S. C.: Aerosol-induced mechanisms for cumulus congestus growth, J Geophys Res-Atmos, 120, 8941-8952, doi: 10.1002/2015jd023743, 2015.

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D. M., Duda, M., Huang, X. Y., Wang, W., and Powers, J. G.: A description of the advanced research WRF version 3, NCAR, Tech. Note, Mesoscale and Microscale Meteorology Division, National Center for Atmospheric Research, Boulder, Colorado, USA, 2008.

Storer, R. L., van den Heever, S. C., and Stephens, G. L.: Modeling Aerosol Impacts on Convective Storms in Different Environments, J Atmos Sci, 67, 3904-3915, doi: 10.1175/2010jas3363.1, 2010.

Wang, Y., Fan, J. W., Zhang, R. Y., Leung, L. R., and Franklin, C.: Improving bulk microphysics parameterizations in simulations of aerosol effects, J Geophys Res-Atmos, 118, 5361-5379, doi: 10.1002/jgrd.50432, 2013.

https://doi.org/10.5194/acp-2020-372
Preprint. Discussion started: 6 May 2020

Wiedinmyer, C., Akagi, S. K., Yokelson, R. J., Emmons, L. K., Al-Saadi, J. A., Orlando, J. J., and Soja, A. J.: The Fire INventory from NCAR (FINN): a high resolution global model to estimate the emissions from open burning, Geosci Model Dev, 4, 625-641, doi: 10.5194/gmd-4-625-2011, 2011.

Yuan, T. L., Li, Z. Q., Zhang, R. Y., and Fan, J. W.: Increase of cloud droplet size with aerosol optical depth: An observation and modeling study, J Geophys Res-Atmos, 113, D04201, doi: 10.1029/2007jd008632, 2008.

Zaveri, R. A., Easter, R. C., Fast, J. D., and Peters, L. K.: Model for Simulating Aerosol Interactions and Chemistry (MOSAIC), J Geophys Res-Atmos, 113, D13204, doi: 10.1029/2007jd008782, 2008.

https://doi.org/10.5194/acp-2020-372
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623 **Table 1** Descriptions of the PM2.5 Monitoring Sites over the Houston area from TCEQ

Abbreviation	Site Descriptions	Latitude	Longitude
HA	Houston Aldine	29.901	-95.326
HDP	Houston Deer Park 2	29.670	-95.129
SFP	Seabrook Friendship Park	29.583	-95.016
CR	Conroe Relocated	30.350	-95.425
KW	Kingwood	30.058	-95.190
CT	Clinton	29.734	-95.258
PP	Park Place	29.686	-95.294
GS	Galveston 99th Street	29.254	-94.861

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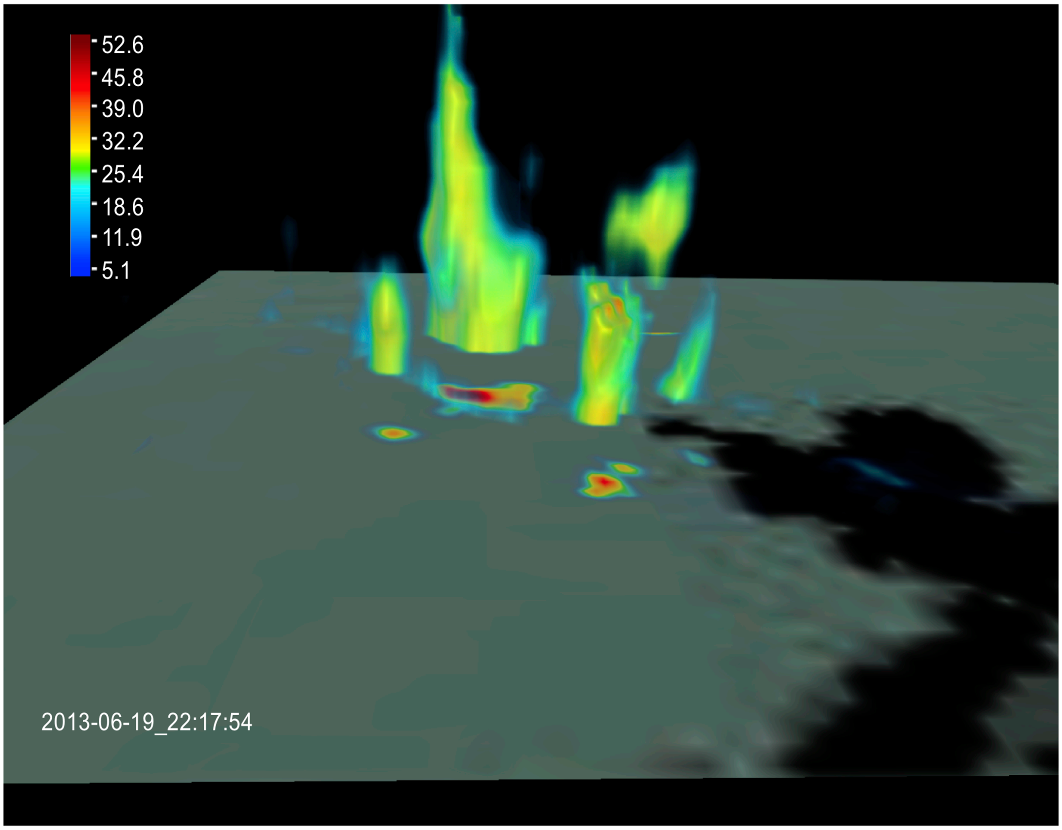

Figure 1 3D structure snapshot of radar reflectivity (unit: dBZ) from NEXRAD, overlaid with the composite reflectivity shown on the surface at the time when the maximum reflectivity is observed (2217 UTC). The dark shade shows the water body and the largest cell is in the Houston.

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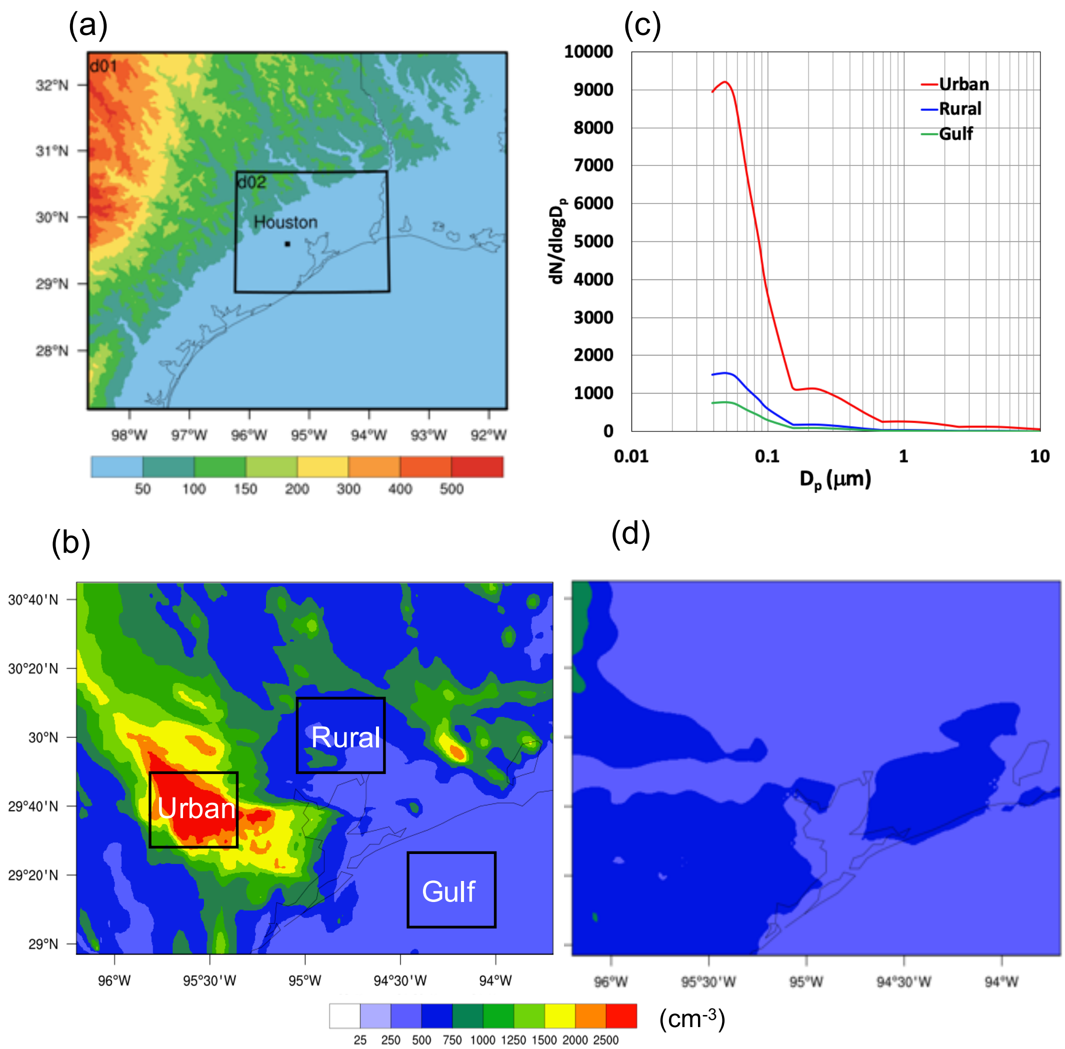

Figure 2 (a) Simulation domains with the terrain heights (unit: m), (b) aerosol number concentration (unit: cm^{-3}) from D1_MOR_anth, (c) aerosol size distributions over the urban, rural, and Gulf of Mexico as marked by three black boxes in Fig. 2b at 1200 UTC, 19 Jun 2013 (6-hr before the convection initiation), and (d) the same as Fig. 2b, but for D1_MOR_noanth in which the anthropogenic aerosols are excluded.

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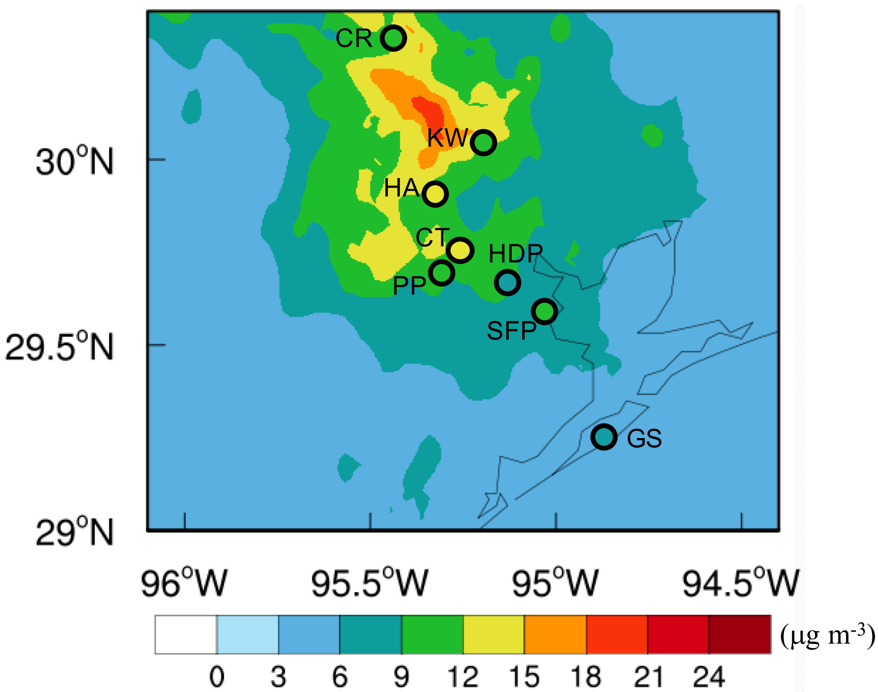

Figure 3 Comparisons of 24-hr averaged PM2.5 mass concentrations (unit: μg m^{-3}) between model simulation D1_MOR_anth (contoured) and site observation from TCEQ (colored circles) from 1800 UTC, 18 June 2013 to 1800 UTC, 19 June 2013 (1 day before the convection initiation). The site names and other information are shown in Table 1.

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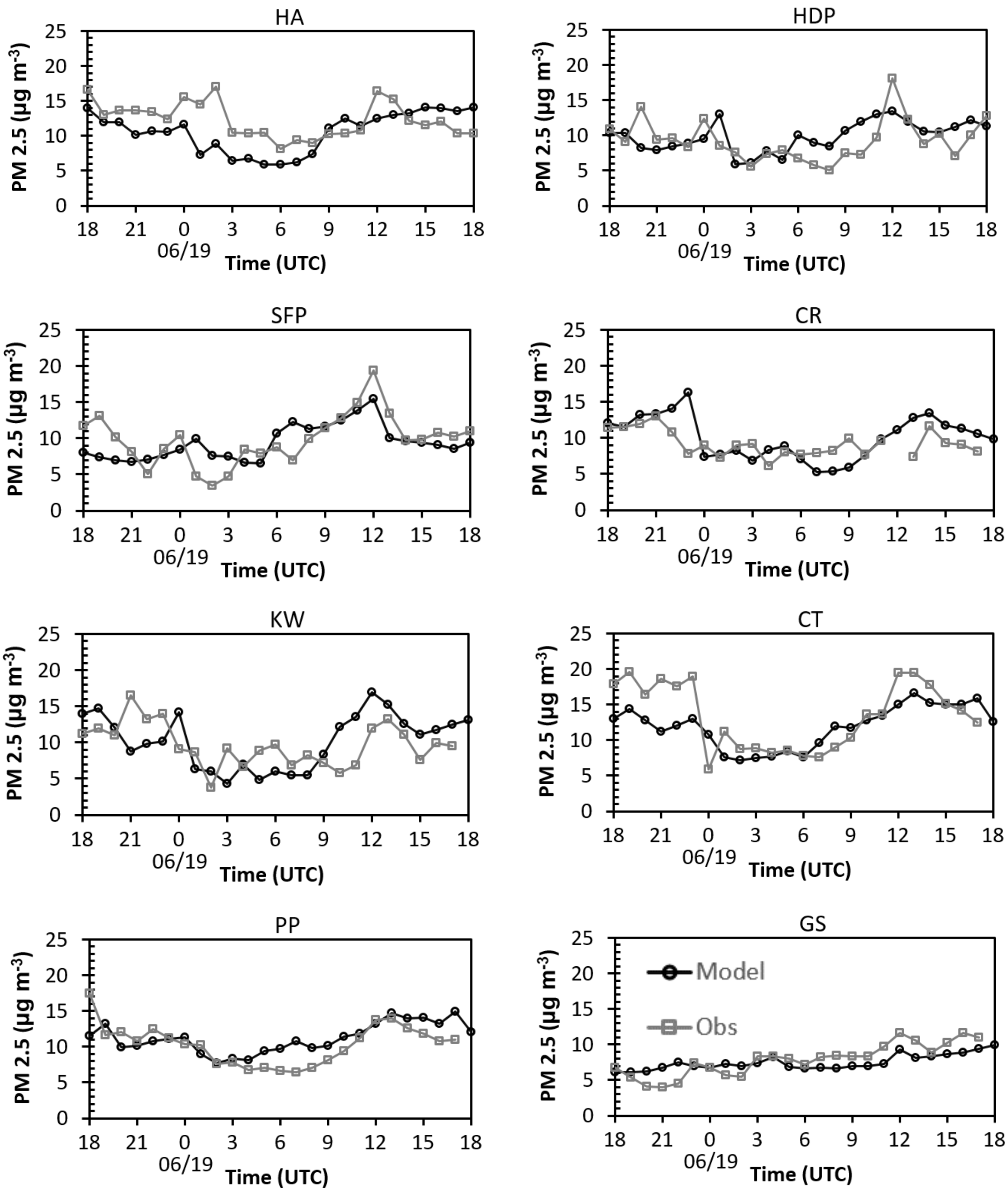

Figure 4 Site-by-site comparisons of hourly PM2.5 mass concentrations (unit: µg m^{-3}) from D1_MOR_anth and TCEQ site observation over 24 hours from 1800 UTC, 18 June 2013 to 1800 UTC, 19 June 2013 (1 day before the convection initiation).

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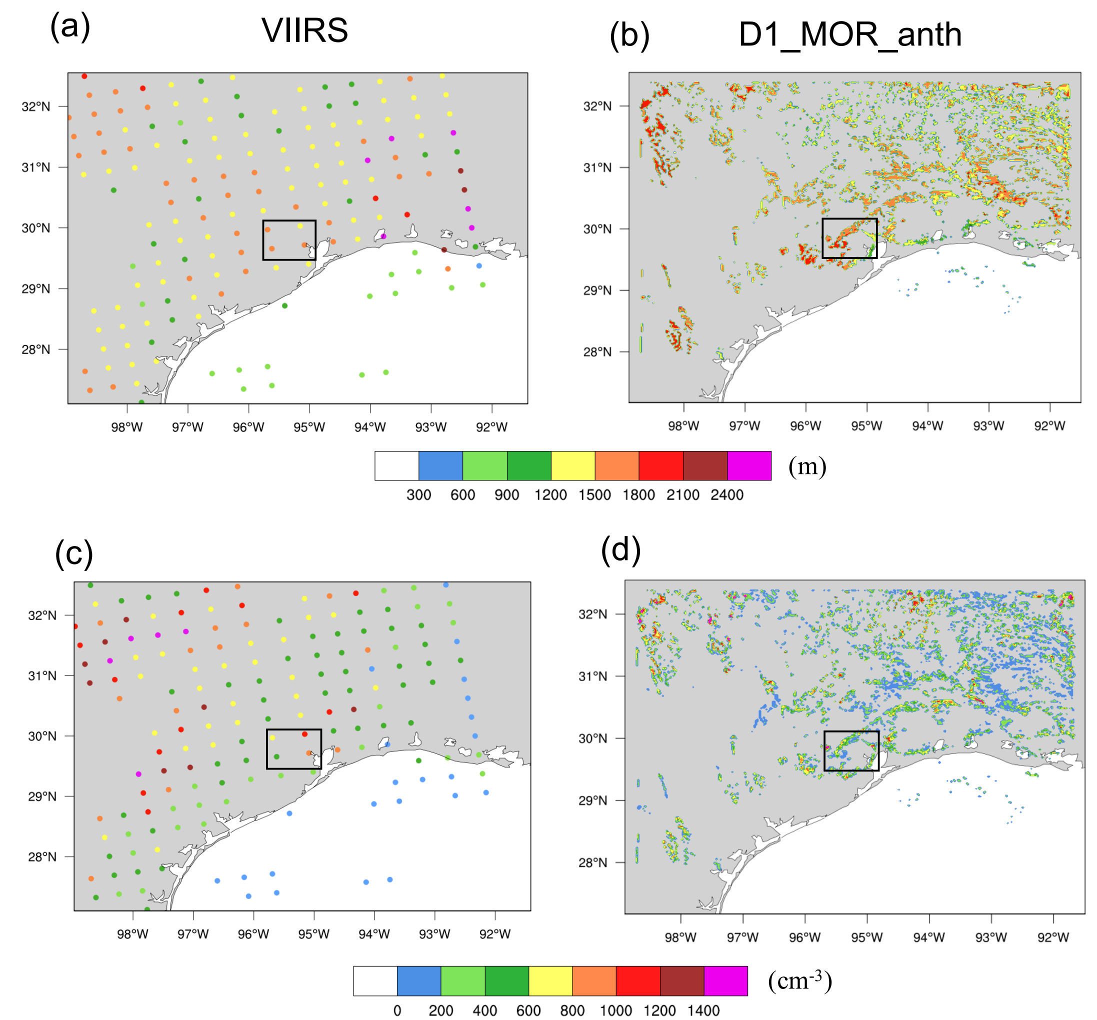

Figure 5 Evaluation of (a,b) cloud base heights (unit: m) and (c,d) CCN number concentration at cloud base (unit: cm^{-3}) from VIIRS satellite (left) retrieved at 1943 UTC (Rosenfeld et al. 2016) and model simulation D1_MOR_anth (right) at 2000 UTC, 19 June 2013. The Houston area is marked as the black box. Satellite-retrieved cloud base height was calculated from the difference between reanalysis surface air temperature (from reanalysis data) and VIIRS-measured cloud base temperature (warmest cloudy pixel) divided by the dry adiabatic lapse rate, while modeled cloud base height was determined by the lowest cloud layer with cloud mass mixing ratio greater than 10^{-5} kg kg^{-1}.

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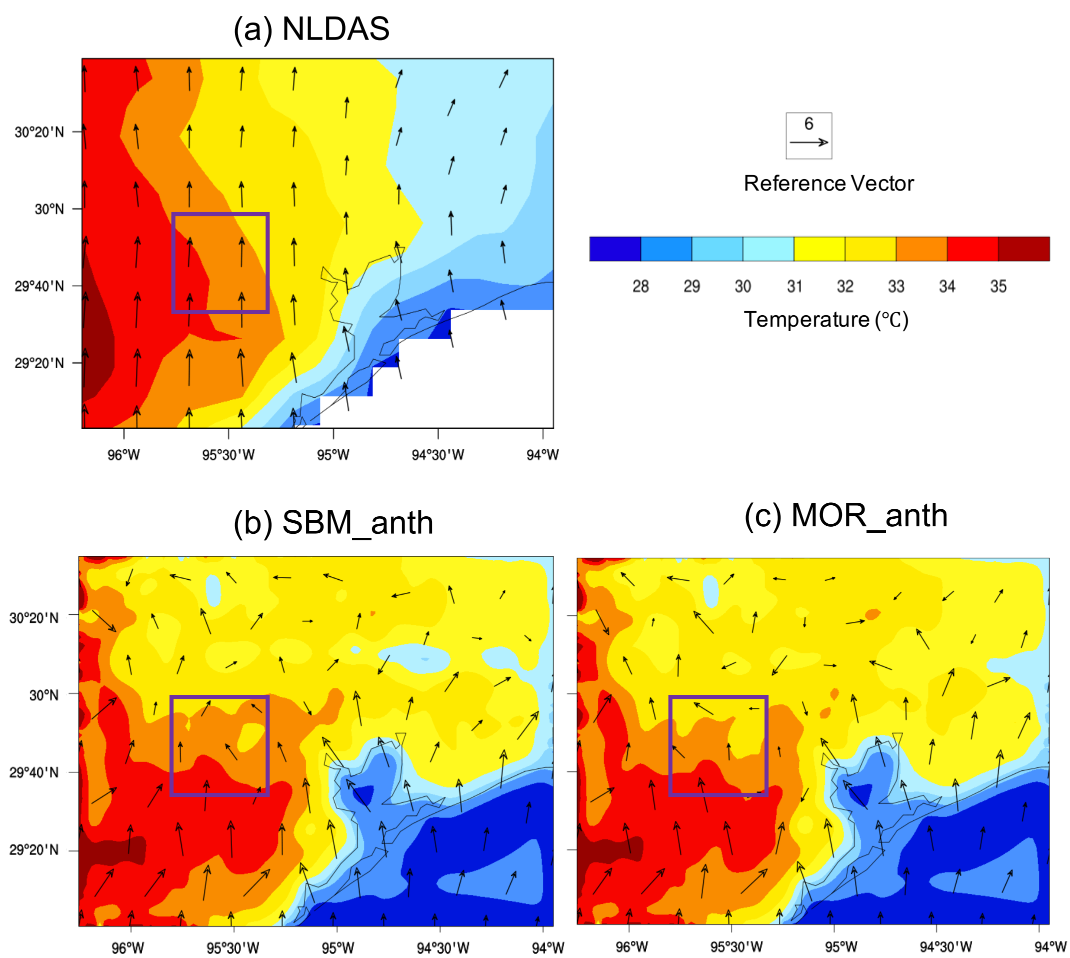

Figure 6 2-m Temperature (shaded; unit: °C) and 10-m winds (vectors; unit: m s^{-1}) from (a) NLDAS, (b) SBM_anth and (c) MOR_anth at 1800 UTC, 19 Jun 2013. The purple box denotes the Houston area.

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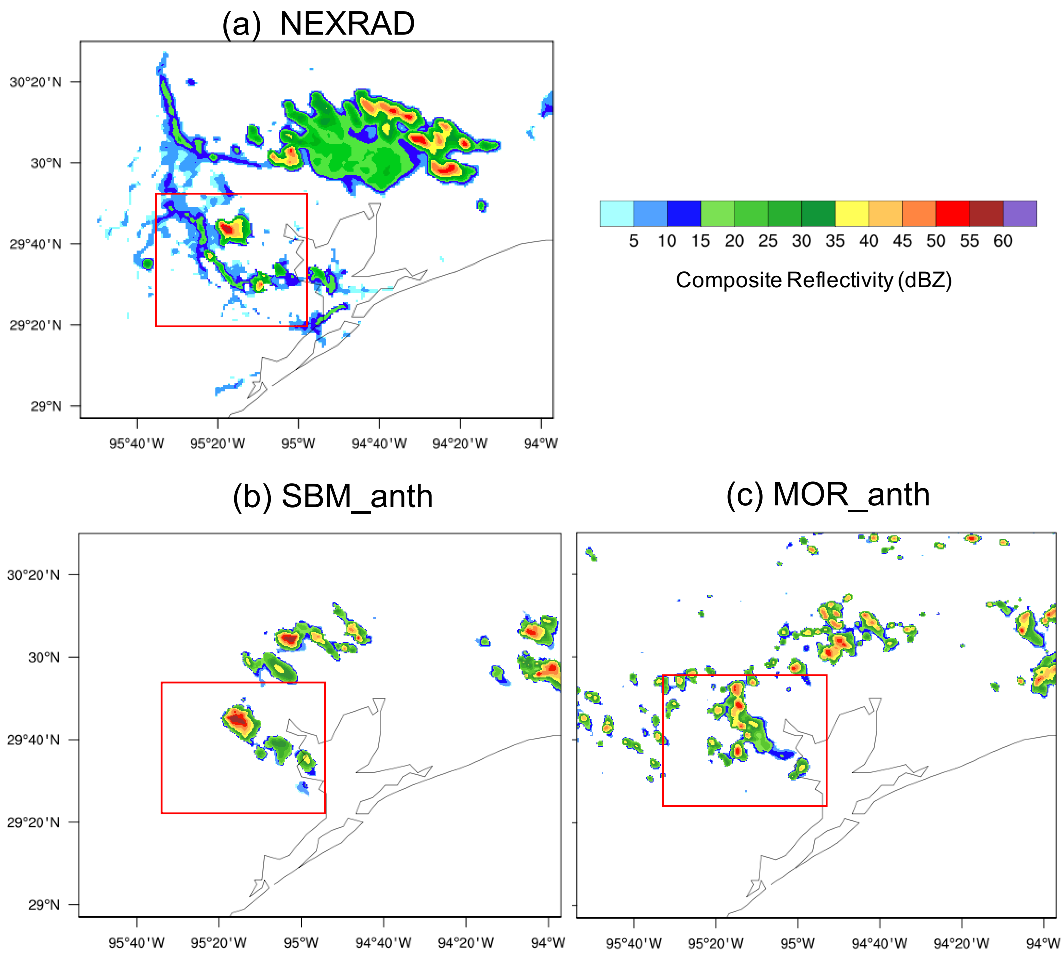

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665 **Figure 7** Composite reflectivity (unit: dBZ) from (a) NEXRAD (2217 UTC), (b) SBM_anth
666 (2140 UTC) and (c) MOR_anth (2125 UTC) when maximum reflectivity in Houston is observed
667 on 19 June 2013. The red box is the study area for convection cells near Houston.

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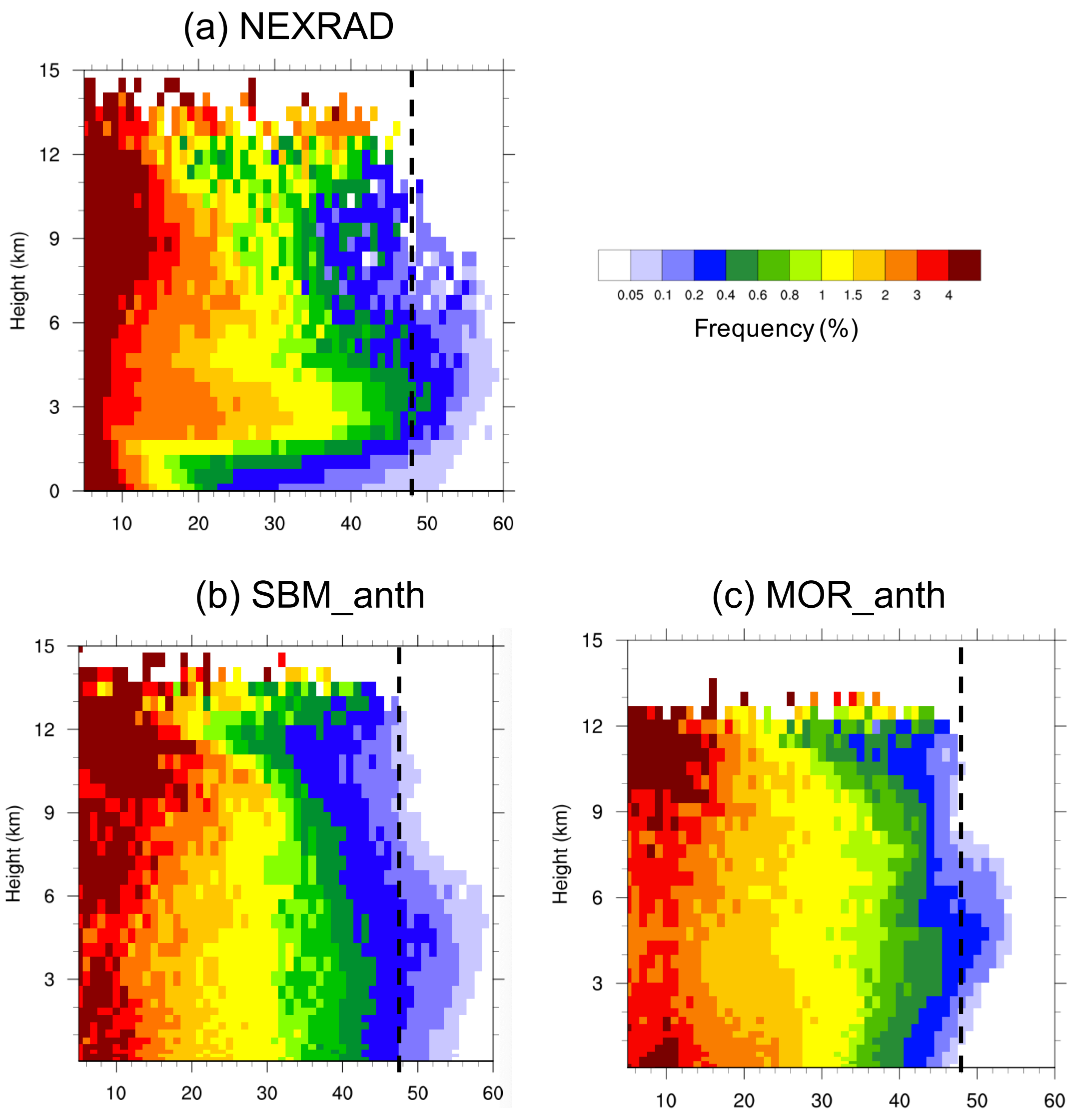
669 

670 **Figure 8** The CFAD of reflectivity (unit: dBZ) for the values larger than 0 dBZ from (a) NEXRAD,
671 (b) SBM_anth and (c) MOR_anth over the study area (red box in Fig. 7) from 1800 UTC, 19 Jun
672 to 0000 UTC, 20 Jun 2013. The black solid lines denote the reflectivity with the value of 48 dBZ.
673

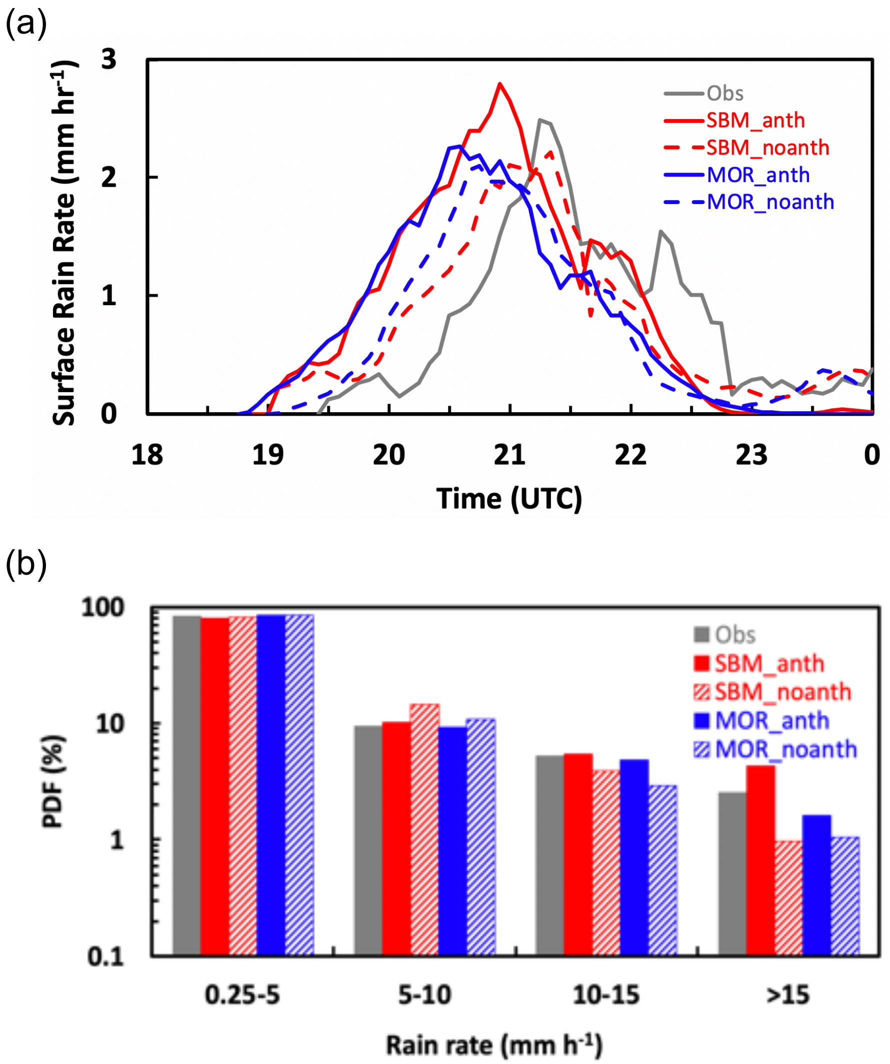


Figure 9 (a) Time series of averaged surface rain rate (unit: mm h^{-1}) and (b) PDFs of rain rate for the values larger than 0.25 mm h^{-1} over the study area (red box in Fig. 7) from observation (grey), SBM_anth and SBM_noanth (red), MOR_anth and MOR_noanth (blue) from 1800UTC, 19 Jun 2013 to 0000 UTC, 20 Jun 2013. The observed precipitation rate is obtained by NEXRAD retrieved rain rate. Both observation and model data are in every 5-min frequency.

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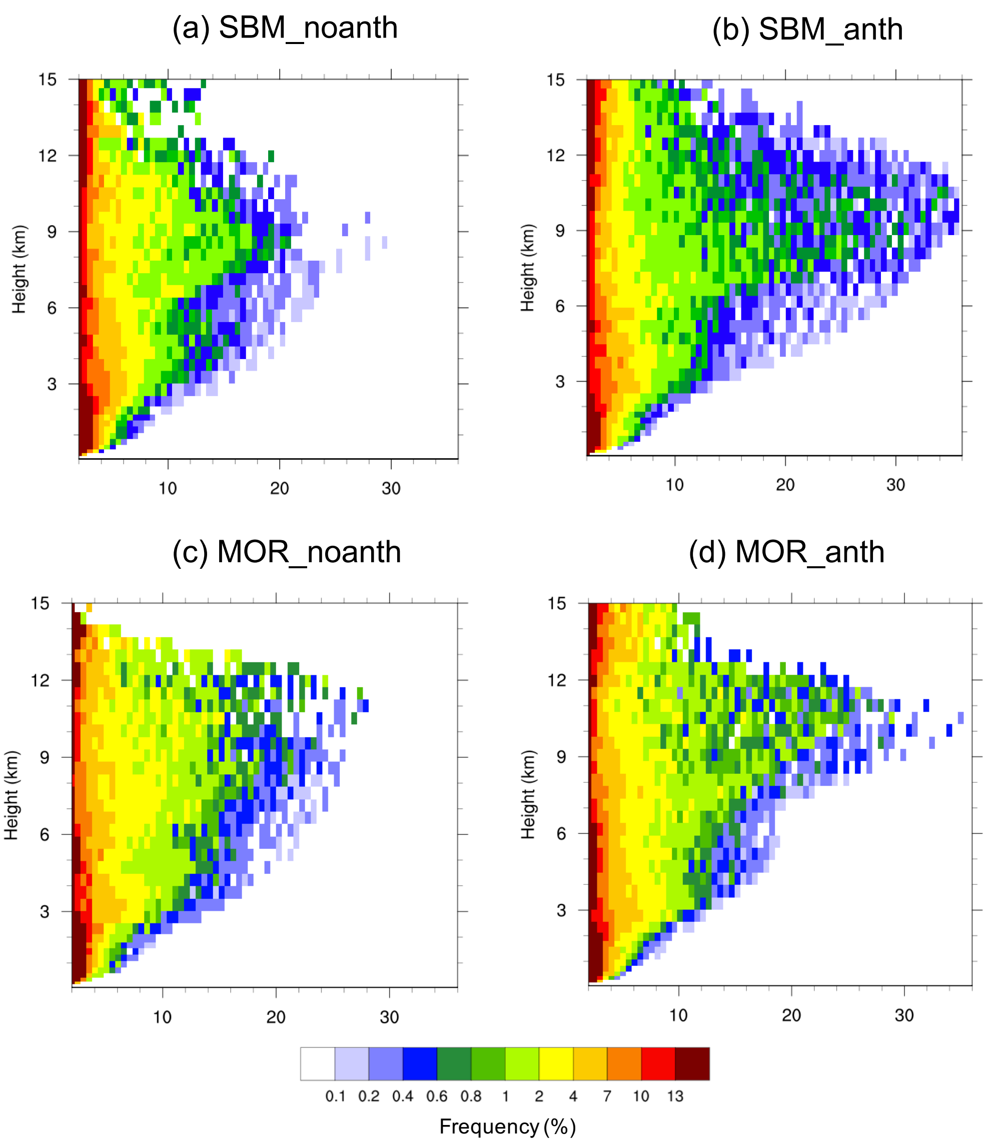

Figure 10 CFADs of updraft velocity (unit: m s^{-1}) for values larger than 2 m s^{-1} from (a) SBM_noanth, (b) SBM_anth, (c) MOR_noanth, and (d) MOR_anth over the study area (red box in Fig. 7) during the strong convection period (2000 – 2300 UTC, 19 Jun 2013).

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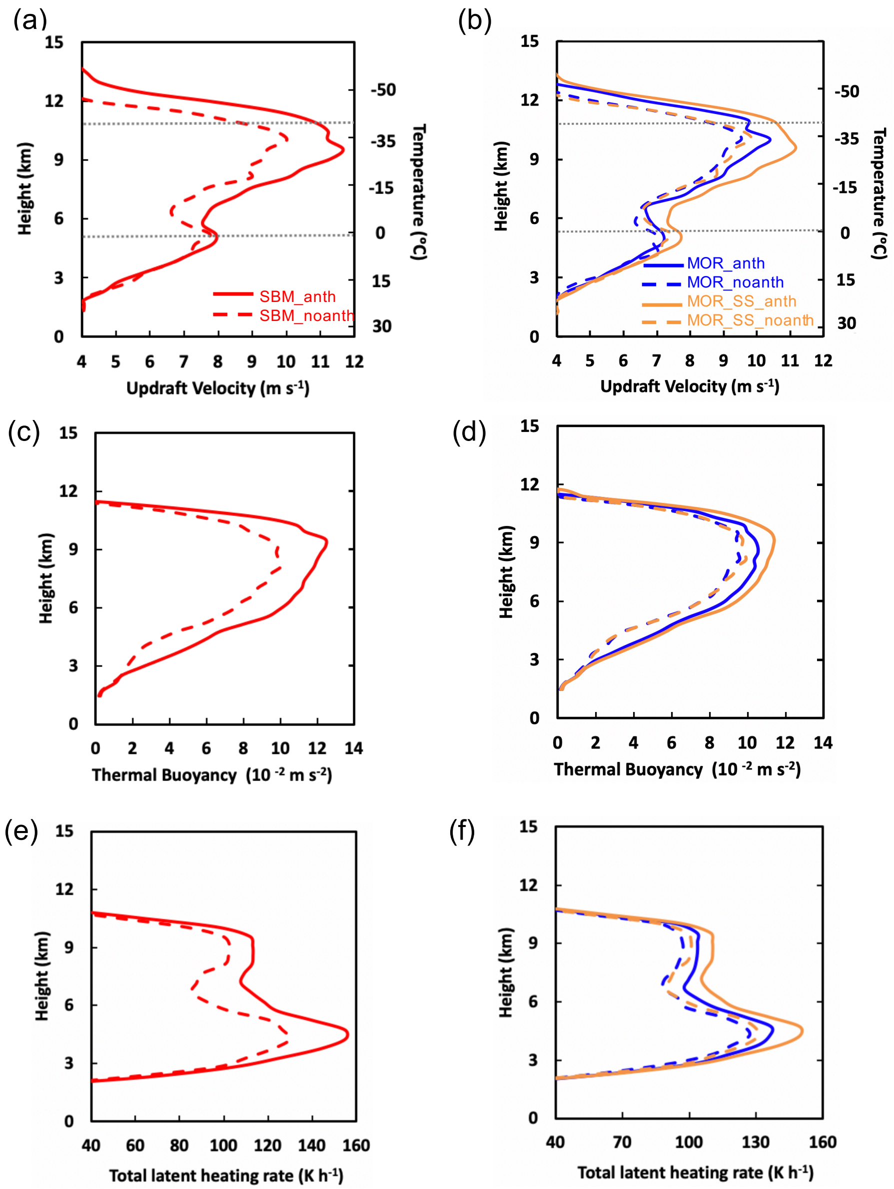

Figure 11 Vertical profiles of (a,b) updraft velocity (unit: m s^{-1}) , (c,d) thermal buoyancy (unit: m s^{-2}) and (e,f) total latent heating rate (unit: K h^{-1}) averaged over the top 25 percentiles (i.e., from 75th to 100th) of the updrafts with velocity greater than 2 m s^{-1} from the simulations SBM_anth and SBM_noanth (red), MOR_anth and MOR_noanth (blue), and MOR_SS_anth and MOR_SS_noanth (orange) over the study area (red box in Fig. 7) during the strong

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convection period (2000 – 2300 UTC, 19 Jun 2013). The dotted lines in (a) and (b) denote the freezing level (0 ^{o}C) and homogeneous freezing level (-40 ^{o}C).

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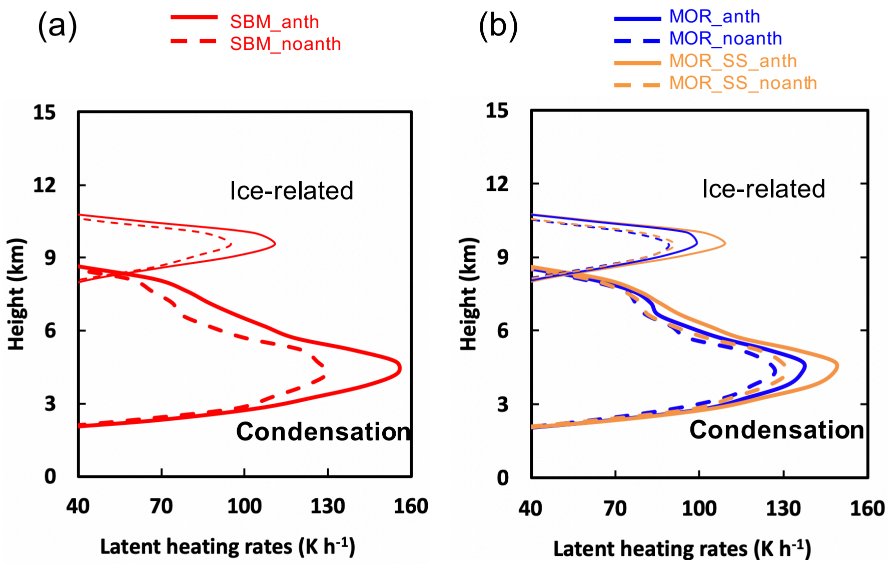

Figure 12 Vertical profiles of condensation heating rate (thick lines below 9 km; unit: K h^{-1}) and ice-related latent heating rate (thin lines above 9 km; unit: K h^{-1}) averaged over the top 25 percentiles (i.e., 75th to 100th) of the updrafts with velocity greater than 2 m s^{-1} from the simulations (a) SBM_anth and SBM_noanth (red), and (b) MOR_anth and MOR_noanth (blue), and MOR_SS_anth and MOR_SS_noanth (orange) over the study area (red box in Fig. 7) during the strong convection period (2000 – 2300 UTC, 19 Jun 2013).

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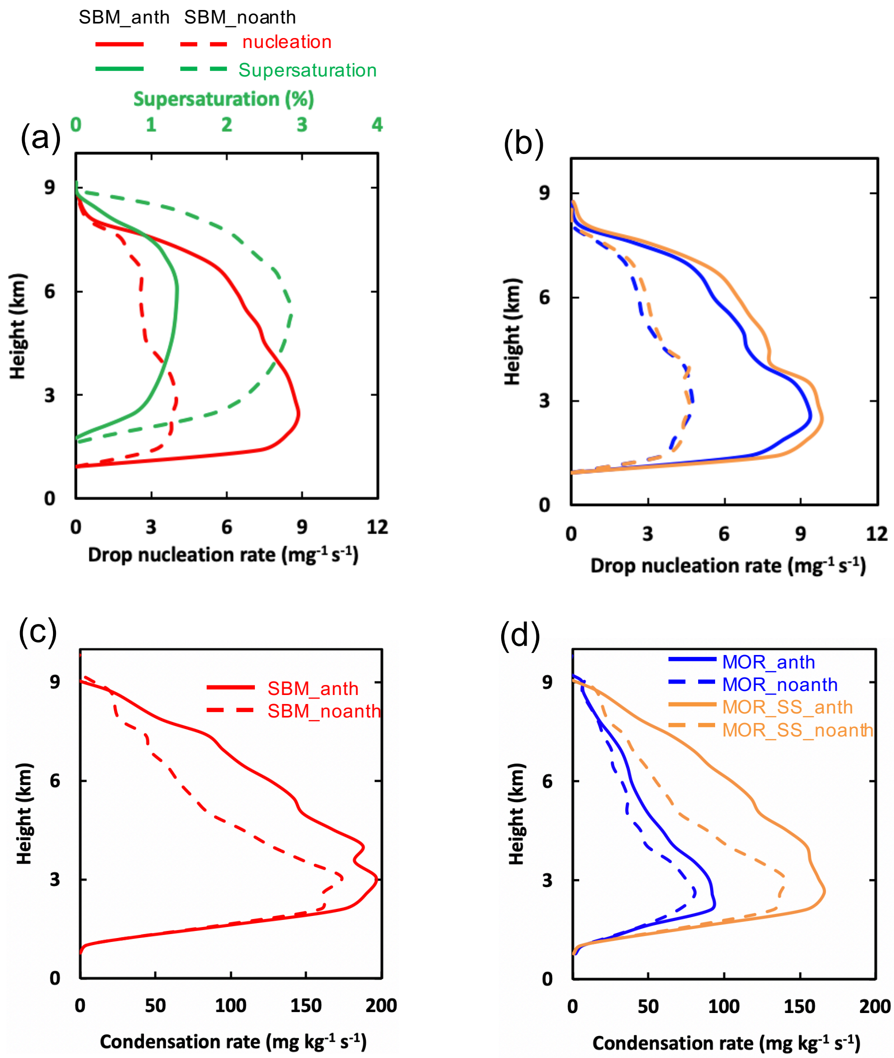

Figure 13 Vertical profiles of (a) drop nucleation rate (red; unit: mg^{-1} s^{-1}) and supersaturation with respect to water (green; unit: %) from SBM_anth and SBM_noanth, (b) drop nucleation rate (unit: mg^{-1} s^{-1}) from MOR_anth and MOR_noanth (blue), and MOR_SS_anth and MOR_SS_noanth (orange), (c) condensation rate (unit: mg kg^{-1} s^{-1}) from SBM_anth and SBM_noanth (red), and (d) the same as (c) but from MOR_anth and MOR_noanth (blue), and MOR_SS_anth and MOR_SS_noanth (orange), averaged over the top 25 percentiles (i.e., from 75^{th} to 100^{th}) of the updrafts with velocity greater than 2 m s^{-1} over the study area (red box in Fig. 7) during the strong convection period (2000 – 2300 UTC, 19 Jun 2013).

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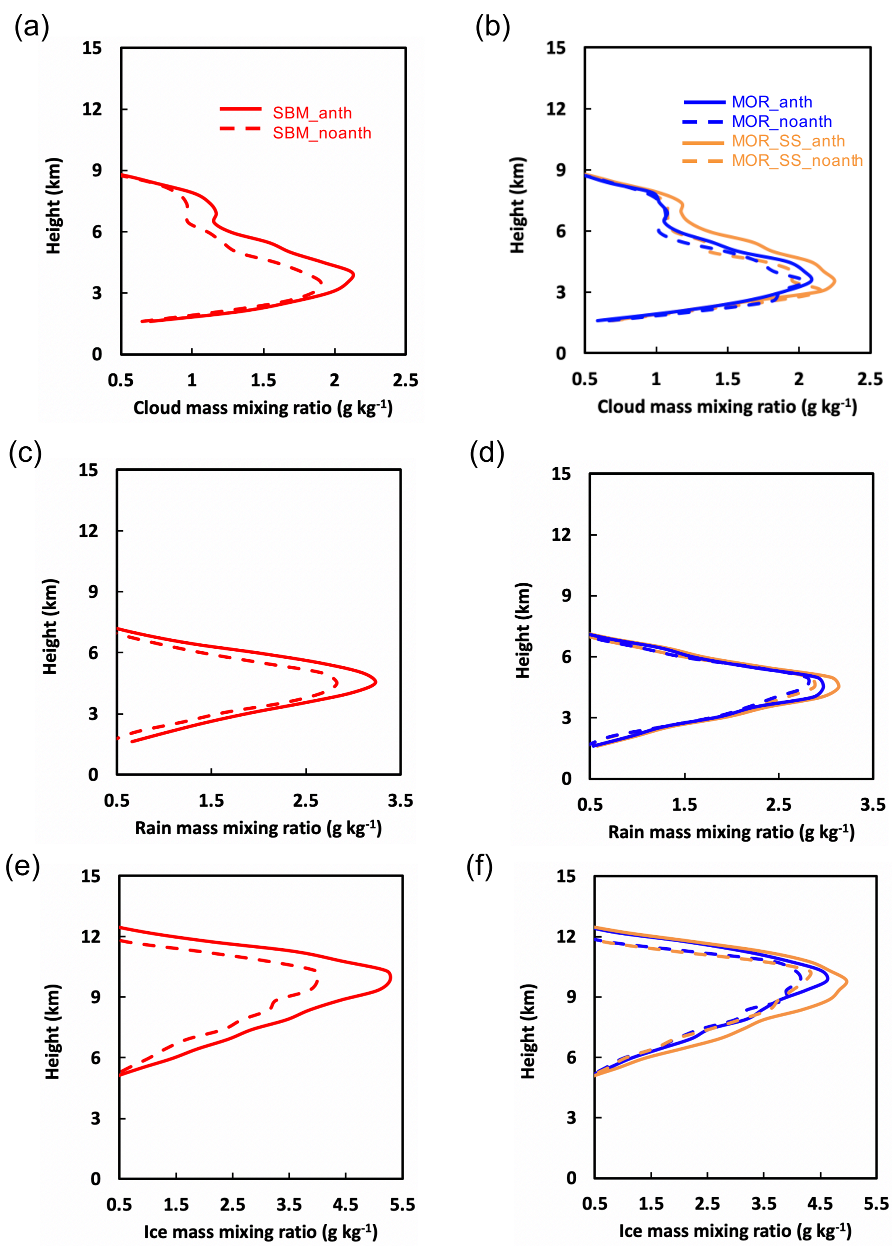

Figure 14 Vertical profiles of (a, b) cloud droplet, (c, d) rain drop and (e, f) ice particle (including ice, snow, and graupel) mass mixing ratios (unit: g kg^{-1}) averaged over the top 25 percentiles (i.e., 75th to 100th) of the updrafts with value greater than 2 m s^{-1} from the simulations SBM_anth and SBM_noanth (red), MOR_anth and MOR_noanth (blue), and MOR_SS_anth and

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MOR_SS_noanth (orange) over the study area (red box in Fig. 7) during the strong convection period (2000 – 2300 UTC, 19 Jun 2013).