

1 Dear Editor,

2 Thanks for giving us an opportunity to revise our manuscript (acp-2019-1045). We appreciate your positive and con-
3 structive comments. We have checked the technical errors carefully and make revisions on the manuscript. These
4 comments and the corresponding replies are listed below.

5 The **comments** are highlighted by **gray**. The symbol ">>" quotes the original texts in the manuscript. Followed by the
6 comments are our responses and revisions in the manuscript. Some important revisions are colored by **red**. The tracked
7 change is attached at the end of this file.

8 With regards,

9 Shuqi Yan, Bin Zhu*, and all co-authors.

10

11

12 **1. Line 44. remove "do".**

13 >>Line 44: The urban surface has a lower albedo than **do** rural surface.

14 Thank you for this valuable suggestion. We have corrected it.

15 **Revision in Line 44 (Introduction)**

16 The urban surface has a lower albedo than ~~do~~ rural surface.

17

18

19 **2. Line 81. change "change" to "changes".**

20 >>Line 81: urbanization mainly refers to UHI and UDI induced by anthropogenic heating and land use change with the
21 corresponding **surface property change** (e.g., surface albedo, surface roughness, surface flux).

22 Thank you for this valuable suggestion. We have corrected it.

23 **Revision in Line 81 (Introduction)**

24 urbanization mainly refers to UHI and UDI induced by anthropogenic heating and land use change with the corre-
25 sponding surface property ~~change changes~~ (e.g., surface albedo, surface roughness, surface flux).

26

27 Other revisions

28 **Line 71 (Introduction): error in tense**

29 This anomaly results in more vapor transported inland and ~~strengthened enhances~~ advection-radiation fog.

30

31 **Line 85 (Introduction): error in year**

32 (e.g., Yang et al., ~~2018~~2019)

33

34 **Line 230 (Section 3.4): missing a citation**

35 In North China Plain where air pollution is thought to be more serious, a case study by WRF-Chem also indicates
36 that fog properties (e.g., LWC, Nd and LWP) increase monotonically when emission intensity varies from 0.05-
37 fold to 1-fold ([Jia et al., 2018](#)).

38

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43 a sea fog event over the Yellow Sea, Atmos. Res., 215, 253–267, <https://doi.org/10.1016/j.atmosres.2018.09.004>, 2019.

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To what extents do urbanization and air pollution affect fog?

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Abstract. The remarkable development of China has resulted in rapid urbanization (urban heat island and dry island) and severe air pollution (aerosol pollution). Previous studies demonstrate that these two factors have either suppressing or promoting effects on fog, but what are the extents of their individual and combined effects? In this study, a dense radiation fog event in East China in January 2017 was reproduced by the Weather Research and Forecasting with Chemistry (WRF-Chem) model, and the individual and combined effects of urbanization and aerosols on fog (indicated by liquid water content (LWC)) are quantitatively revealed. Results show that urbanization inhibits low-level fog, delays its formation and advances its dissipation due to higher temperatures and lower saturations. In contrast, upper-level fog could be enhanced because of the updraft-induced vapour convergence. Aerosols promote fog by increasing LWC, increasing droplet concentration and decreasing droplet effective radius. Further experiments show that the current pollution level in China could be still below the critical aerosol concentration that suppresses fog. Urbanization influences fog to a larger extent than do aerosols. When urbanization and aerosol pollution are combined, the much weaker aerosol promoting effect is counteracted by the stronger urbanization suppressing effect on fog. Budget analysis of LWC reveals that urban development (urbanization and aerosols) alters LWC profile and fog structure mainly by modulating condensation/evaporation process. Our results infer that urban fog will be further reduced if urbanization keeps developing and air quality keeps deteriorating in the future.

31 1 Introduction

32 During the past five decades, China has achieved remarkable developments, accompanied by strong anthropogenic activities
33 (rapid urbanization and severe air pollution). Urbanization and air pollution have significantly affected climate change,
34 monsoons, air quality, fog, clouds and precipitation (e.g., Li et al., 2016; Li et al., 2017). Previous studies have linked the
35 changes in clouds and precipitation to urbanization and aerosols. Urbanization destabilizes the boundary layer, which trig-
36 gers strong updrafts and invigorates convection (e.g., Rozoff et al., 2003; Shepherd, 2005). Aerosols modify the macroscopic,
37 microphysics, thermodynamics and radiative properties of clouds through complicated pathways, which are called as aero-
38 sol-radiation and aerosol-cloud interactions and have been systematically reviewed by Fan et al. (2016), Rosenfeld et al.
39 (2014), Tao et al. (2012), etc. Fog can be viewed as a cloud (Leng et al., 2014) that occurs near the surface. Land use features
40 and aerosol properties may instantly affect fog, so fog is more sensitive to anthropogenic activities than other types of clouds
41 are (Zhu and Guo, 2016). Previous studies have analysed the effects of urbanization and aerosols on fog, mostly in segregat-
42 ed manners.

43 Urbanization is featured with urban heat island (UHI) and dry island (UDI) effects. The urban surface has a lower albedo
44 than ~~de~~ rural surface, which reduces the reflected solar radiation and enhances heat storage. Urban expansion decreases the
45 coverage of cropland, water bodies and forestland, which reduces the sources of water vapour. As a result, urban areas com-
46 monly experience higher temperatures and lower vapour contents. These conditions induce a lower relative humidity that is
47 unfavourable for fog formation (Gu et al., 2019). In the long-term scale, urban fog days are reported to decrease significantly
48 (e.g., Guo et al., 2016; LaDochy, 2005; Sachweh and Koepke, 1995; Shi et al., 2008; Yan et al., 2019). Although UHI and
49 UDI inhibit near-surface fog, the upward motions can promote upper-level fog (Li et al., 2011; Niu et al., 2010b). Surface
50 roughness and thermal circulation cause strong updrafts (Rozoff et al., 2003), which transfer water vapour aloft and cause
51 wet island phenomenon in the upper-level (Kang et al., 2014). The fog at that altitude may be subsequently enhanced.

52 Aerosols exert sophisticated impacts on fog through direct (radiation) effects and indirect (microphysical) effects (Khain and
53 Pinsky, 2018). Aerosols attenuate shortwave radiation, influencing PBL structure and the vertical profile of moisture and
54 aerosols (Tie et al., 2017, 2019), which can alter the formation and dissipation condition of fog. Scattering aerosols block
55 downwelling solar radiation in the daytime, thus delaying the dissipation and elongating the duration of fog (Shi et al., 2008;
56 Maalick et al., 2016). Although they increase downwelling longwave radiation at night, scattering aerosols have negligible
57 effects on the fog formation time (Stolaki et al., 2015; Maalick et al., 2016). The role of absorbing aerosols like black carbon
58 (BC) on fog depends on its residence height. If BC resides above the fog layer, BC causes a dome effect (Ding et al., 2016)
59 which blocks solar radiation and prevents the dissipation of fog (Bott, 1991). If BC resides within the fog layer, BC heats fog
60 droplets and accelerates the dissipation of fog (Maalick et al., 2016). The aerosol indirect effect on cloud is addressed as one

61 of the most uncertain factors in the IPCC report (IPCC, 2013). This effect on fog is also complex and two-fold, which is de-
62 termined by aerosol concentration. Under saturation conditions, increasing aerosols commonly result in more CCNs. It pro-
63 motes activation and condensation, yielding more but smaller droplets and increasing cloud water content (Fan et al., 2018;
64 Rosenfeld et al., 2008). These changes have two kinds of positive feedback on fog (Maalick et al., 2016): more droplets
65 cause stronger radiative cooling at fog top and enhance condensation (Jia et al., 2018); smaller droplet size inhibits sedimen-
66 tation and the depletion of cloud water (Zhang et al., 2014). However, if aerosol concentration exceeds a certain threshold,
67 this promoting effect disappears (Quan et al., 2011) or even turns into a suppressing effect due to the strong vapour competi-
68 tion (Guo et al., 2017; Koren et al., 2008; Liu et al., 2019; Rangognio, 2009; Wang et al., 2015). Additionally, large-scale
69 aerosol pollution can change weather patterns and affect large-scale fog formation conditions (Niu et al., 2010a). Ding et al.
70 (2019) found that the dome effects of BC induce a land-sea thermal contrast and generate a cyclonic anomaly over coastal
71 areas. This anomaly results in more vapor transported inland and ~~strengthened~~ enhances advection-radiation fog.

72 Our recent observational work (Yan et al., 2019) indicated a decreasing trend in fog days, and the inhibiting effects of urban-
73 ization outweigh the promoting effects of aerosols on fog during the mature urbanization stage. This study aims to quantita-
74 tively confirm the roles of urbanization and aerosols in a dense fog event by an online-coupled synoptic and air quality mod-
75 el, Weather Research and Forecasting with Chemistry (WRF-Chem). This event is a radiation fog event with weak synoptic
76 forcing (detailed in Sect. 3.1), so the effects of urbanization and aerosols should be obvious. Determining the quantitative
77 extents of urbanization effect, aerosol effect and their combined effect is an interesting topic, which has barely been studied
78 previously to the best of our knowledge. This work is expected to facilitate the understanding of how anthropogenic activi-
79 ties affect the natural environment, fog (cloud) physics and aerosol-cloud interactions near the surface.

80 In this study, urbanization mainly refers to UHI and UDI induced by anthropogenic heating and land use change with the
81 corresponding surface property ~~change~~ changes (e.g., surface albedo, surface roughness, surface flux), excluding the in-
82 creasing aerosol pollution caused by urban expansion. Air pollution refers to aerosols and is indicated by anthropogenic
83 emissions because aerosol concentration is highly proportional to emission intensity. Liquid water content (LWC) and
84 cloud/fog droplet number concentration (N_d) are two important parameters representing fog intensity and visibility. Follow-
85 ing previous studies (e.g., Ding et al., 2019; Gu et al., 2019; Jia et al., 2018; Maalick et al., 2016; Yang et al., ~~2018~~2019), we
86 use LWC as the indicator of fog to reveal different characteristics of fog in different experiments. This study is organized as
87 follows. The data, model and methods are described in Sect. 2. Section 3.1 overviews the fog event and provides preliminary
88 evidence of how urban development affects fog. Section 3.2 evaluates the model performance. Sections 3.3 to 3.5 analyse the
89 urbanization, aerosol and combined effects on fog. Section 3.6 discusses the rationality and reliability of the results. Section
90 4 concludes the findings of this study.

91 **2 Data, model and methods**

92 **2.1 Data**

93 The first data are the hourly automatic weather station data from the Shouxian National Climate Observatory (SX; 32.4° N,
94 116.8° E, 23 m) that are used to evaluate the model performance. SX is a rural site surrounded by vast croplands and is ap-
95 proximately 30 km away from the nearest large city, Huainan (Fig. 1b). The data include horizontal visibility, temperature,
96 relative humidity, wind direction and speed. The second data are the Himawari 8 satellite data that are used to represent fog
97 area (<https://www.eorc.jaxa.jp/ptree/index.html>). Fog area is mainly indicated by the albedo at three visible bands: red (band
98 3, 0.64 μm), green (band 2, 0.51 μm) and blue (band 1, 0.47 μm). The third data are the 3-hourly data from the Meteorologi-
99 cal Information Comprehensive Analysis and Process System (MICAPS) (Li et al., 2010) that are also used to represent the
100 fog area. The fourth data are the land use data from the Moderate Resolution Imaging Spectroradiometer Land Cover Type
101 Version 6 data (MCD12Q1; <https://lpdaac.usgs.gov/products/mcd12q1v006>) in the year of 2017, the same as the simulation
102 period. The data are resampled from 500 m to 30 arc-seconds (approximately 1 km) and used to replace the geological data
103 of the WRF model.

104 **2.2 Model configuration**

105 The model used in this study is the WRF-Chem (V3.9.1.1) model. It is an online-coupled mesoscale synoptic and air quality
106 model that considers the sophisticated interactions among various dynamic, physical and chemical processes (Chapman et al.,
107 2009; Fast et al., 2006). WRF or WRF-Chem has been successfully used in simulating fog events (Jia and Guo, 2012; Jia and
108 Guo, 2015; Jia et al., 2018) and exploring aerosol-cloud interactions (Fan et al., 2018). Two nest domains are set up (Fig. 1).
109 The d01 domain has a size of 217 \times 223 grids and a resolution of 6 km, covering the entire fog area of this event (Fig. 2a).
110 The d02 domain has a size of 115 \times 121 grids and a resolution of 2 km, covering SX and the adjacent areas. The land use data
111 are replaced by MCD12Q1 data, which represent the latest condition.

112 Fog simulation is highly sensitive to vertical grids (Gultepe et al., 2007). A fine vertical resolution with a proper lowest
113 model level can better resolve turbulences, thus yielding a reasonable fog structure (Yang et al., 2019). Here, 42 vertical lev-
114 els are established with the first five η values of 1.000, 0.999, 0.998, 0.997, 0.996. There are 25 levels below the boundary
115 layer (approximately 1500 m), and the lowest model level is approximately 8 m.

116 Fog simulation is also sensitive to physical schemes (Gu et al., 2019). Through numerous experiments, radiation, micro-
117 physics and boundary schemes are found to significantly influence the model performance, and the boundary layer scheme
118 plays a decisive role (Naira Chaouch et al., 2017). The radiation schemes are the RRTM longwave scheme and the Goddard

119 shortwave scheme. The microphysical scheme is the Morrison double-moment scheme (Morrison et al., 2005). The boundary
120 layer scheme is the YSU 1.5-order closure non-local scheme, which yields better results than do any other schemes. The
121 major schemes are listed in Tab. 1.

122 The model is driven by the highest resolution product (0.125°, approximately 13 km) of ECMWF data
123 (<https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/>). The anthropogenic emissions are derived from the
124 Multi-resolution Emission Inventory for China (MEIC) database (<http://www.meicmodel.org>). The simulation starts at
125 2017-01-01 08:00 and ends at 2017-01-03 14:00, with the first 24 hours as the spin-up period (all the times here are in local
126 time).

127 **2.3 Sensitivity experiments**

128 The study site is SX because only its visibility is observed hourly and is a multiple of 1 m, which is suitable for evaluating
129 the model performance. To investigate the effects of urbanization and aerosols on fog, we change the land use and emission
130 intensity around SX. Four experiments, i.e., u0e0, u3e0, u0e3 and u3e3 are designed. The u0e0 is the base experiment, with
131 no urbanization and weak emission at SX. The u3e0 is set as the urbanization condition. The u0e3 is set as the polluted con-
132 dition. The u3e3 is set as the urban development condition (urbanization and pollution coexist). The experiment settings are
133 listed in Tab. 2.

134 On the setting of urbanized condition, we replace the land use of SX as that of Hefei, the most urbanized city and the capital
135 of Anhui Province. The downtown of Hefei has a built area of approximately 570 km². Therefore, the 11x13 box centered on
136 SX (572 km²) is replaced by urban surface in the u3e0 and u3e3 experiments to represent the urbanization condition.

137 The downtown of Hefei has much higher emissions than SX. For example, the PM2.5 emission rate of Hefei is 40 times
138 higher than that of SX. To represent the polluted condition, the emission intensity of the aforementioned box is set to be
139 equal to that of downtown Hefei in the u0e3 and u3e3 experiments.

140 **2.4 Calculating visibility**

141 The LWC is the proxy of fog as mentioned above. Since the LWC is not observed, and visibility (VIS) is related to LWC, the
142 VIS is used to assess the model performance. VIS is not diagnosed by the model and can be parameterized by the function of
143 LWC, N_d or droplet effective radius (R_e). Equation 1 (Kunkel, 1983) and 2 (Gultepe et al, 2006) are two parameterization
144 methods.

$$\text{VIS}[\text{m}] = 27 \text{LWC}[\text{g cm}^{-3}]^{-0.88} \quad (1)$$

$$\text{VIS}[\text{m}] = 1002(\text{LWC}[\text{g cm}^{-3}] \cdot N_d[\text{cm}^{-3}])^{-0.6473} \quad (2)$$

145 Another parameterization method is based on the Mie theory (Gultepe et al., 2017). VIS is inverse proportional to atmos-
 146 pheric extinction at visible wavelength. The extinction coefficient of cloud water (β_c) is

$$\beta_c [\text{km}^{-1}] = \frac{3Q_{\text{ext}} \rho_a \text{LWC}}{4\rho_w R_e} \times 10^6 \quad (3)$$

147 where ρ_a (ρ_w) is the air (water) density in kg m^{-3} , LWC is in g kg^{-1} , R_e is in μm , and Q_{ext} is the extinction efficiency, which is
 148 assumed to be 2 for cloud droplets.

149 The atmospheric extinction (β) is also largely contributed by aerosols (β_a) and other types of hydrometeors. The model diag-
 150 noses β_a at 550 nm. No other types of hydrometeors occur in this fog case, so we assume $\beta = \beta_a + \beta_c$. Then VIS is determined
 151 by the Koschmieder rule (Koschmieder, 1924): $\text{VIS}[\text{m}] = 3.912/\beta[\text{km}^{-1}] \times 1000$.

152 During fog period (Fig. 4 shaded zone), the three methods nearly yield the same results (Fig. S1), so the last method is used
 153 to calculate the simulated VIS.

154 **3 Results and discussions**

155 **3.1 Overview of the fog event**

156 **3.1.1 Formation condition and lifetime**

157 From 01 to 06 January 2017, East China is dominated by zonal circulation, with weak trough, ridge, pressure gradient and
 158 atmospheric diffusion (Zhang and Ma, 2017). Under this stable weather pattern, the accumulation of pollutants and water
 159 vapour promotes the occurrence of fog-haze events. From the evening of 02 January to the noon of 03 January, a dense fog
 160 event occurs in wide regions of East China. The fog reaches its peak at 08:00 03 January, covering south Hebei, east Henan,
 161 west Shandong, Anhui, Jiangsu and Shanghai (Fig. 2a). Figure 4a shows the temporal variation of visibility at SX. The fog
 162 forms at 18:00 02 January and dissipates at 12:40 03 January. This is a radiation fog which is promoted by strong radiative
 163 cooling at night and weak easterly water vapour transport from northwest Pacific (Zhu et al., 2019).

164 **3.1.2 Preliminary evidence of urban development affecting fog**

165 Lee (1987) and Sachweh and Koepke (1995) observed "fog holes" over urban areas on satellite images. Here, fog hole means

166 the low liquid water path (LWP) region within the fog region, which is visualized as pixels with weak fog (high visibility) or
167 clear sky surrounded by dense fog. These holes demonstrate that urban development (urbanization and aerosols) has a clear-
168 ing effect on fog. In this fog event, fog holes are also present over urban areas on the Himawari 8 image at 11:00 03 January
169 (Fig. 3). We hypothesize that urbanization could have profound effects on fog by reducing the LWP or advancing the dissipa-
170 tion of fog, and the role of aerosols on fog is weaker than that of urbanization.

171 **3.2 Model evaluation and simulations**

172 The model performance is evaluated by comparing the fog spatial coverage. Satellite cloud image and modelled LWP ($>2 \text{ g}$
173 m^{-2}) can represent the observed and simulated fog zone, respectively (Jia et al., 2018). Figure 2 shows the Himawari 8 visible
174 cloud image and the simulated LWP distribution at 08:00. The light white pixels and light red dots indicate the observed fog
175 area. The model well captures the fog in south Hebei, east Henan, west Shandong, Anhui, Jiangsu and Shanghai.

176 The model performance is also evaluated by comparing the visibility and other basic parameters at the SX site (Fig. 4). Seen
177 from the visibility, the simulated fog forms at 19:30, 1.5 h later than the observation, and dissipates at 12:20, 30 min earlier
178 than the observation. During the fog period, the simulated visibility agrees well with the observation. The other parameters
179 such as temperature, wind speed and relative humidity are also effectively reproduced by the model, with relative small
180 RMSEs of 0.8 K, 0.7 m/s and 5.9 %, respectively. Overall, the model well captures the spatial feature and temporal evolution
181 of the fog.

182 **3.3 Urbanization effects**

183 From different sensitivity experiments (u3e0, u0e3 and u3e3), we can deduce the extents of the separate or combined effects
184 of urbanization and aerosols on fog. Figure 5 compares the LWC between u0e0 and u3e0. The general results are: (1) Before
185 02:00, urbanization leads to a decreasing LWC in all layers. Fog forms on the surface at 22:30 in u3e0, 3 h later than in u0e0.
186 (2) After 02:00, the LWC decreases in the low-level while it increases in the upper-level. Fog dissipates at 10:50 in u3e0, 1.5
187 h earlier than in u0e0. To better explain the LWC difference, its profiles are shown in Fig. 6. At 23:00, although fog has
188 formed in u3e0, the fog is rather weak compared with u0e0, which is caused by the higher temperature (Fig. 6f) and lower
189 saturation associated with UHI and UDI. At 02:00, fog develops in u3e0, but its intensity (the value of LWC) cannot reach
190 the same level as that in u0e0.

191 An interesting phenomenon is the opposite change of LWC in the low-level and upper-level after 02:00. This phenomenon
192 can be explained by the role of updrafts. The increasing roughness length and extra warming in urban conditions could trig-
193 ger horizontal wind convergence (Fig. S2) and the enhanced updrafts (Fig. 5c). The stronger updrafts in u3e0 affect conden-

194 sation via two possible pathways: (1) the vertical transport of vapour ($-w\frac{\partial q}{\partial z}$) and vertical convergence/divergence ($-q\frac{\partial w}{\partial z}$) re-
195 distribute water vapour and affect condensation; (2) the adiabatic cooling promotes condensation. The role of the first path-
196 way is measured by vertical vapour flux divergence ($\frac{1}{g}\frac{\partial(qw)}{\partial z}$). At 05:00, u3e0 shows a stronger vapour convergence above 110
197 m (Fig. 6h), and the LWC increases above 130 m (Fig. 6c). At 08:00, u3e0 shows a stronger vapour convergence above 130
198 m (Fig. 6i), and the LWC increases above 170 m (Fig. 6d). Therefore, it is possible that the adiabatic cooling and up-
199 draft-induced vapour flux convergence increase the vapour content and promote condensation in the upper-level, while the
200 fog in the low-level is suppressed by the divergence of vapour flux. At 11:00, fog disappears at the ground in u3e0 likely due
201 to the higher temperature (Fig. 6j). In summary, the UHI, UDI and updrafts alter the profile of LWC and reduce the LWP
202 most of the time (Fig. 5c), and the decreasing LWP in the daytime can explain why fog holes occur above urban areas (Fig.
203 3).

204 3.4 Aerosol effects

205 Figure 7 compares the LWC between u0e0 and u0e3. The formation time, dissipation time of fog and fog top show almost no
206 changes. The LWC increases at almost all layers in the polluted condition. Accordingly, the LWP also increases (Fig. 7c). It
207 is probable that the current pollution level of China always promotes fog occurrence. To testify whether the u0e3 is below
208 the transition point that suppresses fog, eight additional experiments (D10, D7.5, D5, D2.5, M2.5, M5, M7.5 and M10) are
209 performed. These experiments are the same as u0e3, except that the emissions around SX (the black box in Fig. 1b) are mul-
210 tiplied (the "M" prefix) or divided (the "D" prefix). For example, the name M2.5 means multiplying by 2.5; the name D10
211 means dividing by 10.

212 Figure 8 compares the LWC, N_d , R_e and LWP among the nine emission-variant experiments. The variation shape of the four
213 parameters demonstrates that the model is able to simulate the dual effects of aerosols. Below u0e3, the four parameters
214 monotonically vary with emission level or CCN concentration, indicating that aerosol pollution could always promote fog.
215 This phenomenon is because stronger emissions produce more aerosols and CCN. Under saturation conditions, the larger
216 amount of CCN boost activation and yield a higher N_d . The higher N_d reduces R_e and inhibits autoconversion and sedimen-
217 tation (Twomey, 1977); thus, this situation decreases the depletion of fog water and increases the LWC. This promoting effect
218 has been confirmed by previous model studies (e.g., Maalick et al., 2016; Stolaki et al., 2015) and observations (e.g., Chen et
219 al., 2012; Goren and Rosenfeld, 2012). The $CCN_{0.1}$ concentration of u0e3 (570 cm^{-3}) is lower than that of the turning point
220 (experiment M2.5) (1349 cm^{-3}), possibly indicating that the current pollution level in China (u0e3) is still located in the
221 promoting regime rather than the suppressing regime of fog occurrence.

222 Rosenfeld et al. (2008) revealed that the turning point in convective clouds is $CCN_{0.4} = 1200 \text{ cm}^{-3}$. The $CCN_{0.4}$ of u0e3 is

223 6023 cm^{-3} , which seems to suppress fog. Aerosols affect convective clouds through two competing mechanisms: 1) invigorating convection by promoting vapour condensation. 2) suppressing convection by blocking solar radiation and reducing surface heat flux. Under polluted conditions ($\text{AOD} > 0.3$ or $\text{CCN}_{0.4} > 1200 \text{ cm}^{-3}$), the suppressing effect outweighs the invigoration effect, so the turning point occurs (Koren et al., 2008; Rosenfeld et al., 2008). This suppressing effect does not exist in fog because fog commonly formed at night. Therefore, the turning point in fog might occur later than that in convective clouds. In North China Plain where air pollution is thought to be more serious, a case study by WRF-Chem also indicates that fog properties (e.g., LWC, N_d and LWP) increase monotonically when emission intensity varies from 0.05-fold to 1-fold (Jia et al., 2018).

231 3.5 Combined effects of urbanization and aerosols

232 Figure 9 compares the LWC between u0e0 and u3e3. The u3e3-induced change is quite similar to but not the same as the u3e0-induced change. The time-height average of absolute change of LWC induced by u3e0, u0e3 and u3e3 are 0.120, 0.019, 0.124 g kg^{-1} , respectively. This result indicates that urbanization affects fog to a larger extent than do aerosols; when urbanization and aerosols are combined, the effect of aerosols is indiscernible. The LWP is also significantly suppressed in the daytime, and the promoting effect of aerosols in Fig. 7c is indiscernible in Fig. 9c. To further explain the changes in LWC, we perform budget analysis of the LWC to determine which physical processes are the dominant contributors.

238 In WRF, the budget of LWC is composed of the following items,

$$239 \frac{\partial q_c}{\partial t} = - \underbrace{\left(u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + w \frac{\partial}{\partial z} \right) q_c}_{\text{adv}} + \left(\frac{\partial q_c}{\partial t} \right)_{\text{PBL}} + \left(\frac{\partial q_c}{\partial t} \right)_{\text{micro}} + \left(\frac{\partial q_c}{\partial t} \right)_{\text{cumu}} \quad (4)$$

240 where q_c is LWC, and the subscripts denote advection, boundary layer, microphysical and cumulus processes, respectively.

241 The microphysical tendency is further decomposed into the following items,

$$242 \left(\frac{\partial q_c}{\partial t} \right)_{\text{micro}} = \left(\frac{\partial q_c}{\partial t} \right)_{\text{cold}} + \left(\frac{\partial q_c}{\partial t} \right)_{\text{auto}} + \left(\frac{\partial q_c}{\partial t} \right)_{\text{accr}} + \left(\frac{\partial q_c}{\partial t} \right)_{\text{sedi}} + \left(\frac{\partial q_c}{\partial t} \right)_{\text{cond/evap}} \quad (5)$$

243 where the subscripts denote cold phase processes, autoconversion, accretion, sedimentation and condensation/evaporation, respectively.

244 All the processes regarding precipitation and cold phase (the cumu, cold, auto and accr subscripts) are not analysed because no precipitation occurs, and the temperature is above 0°C in the simulated fog (figure not shown). Summing the integral of

245 microphysical (condensation/evaporation and sedimentation), boundary layer and advection tendencies with respect to time
246 is equal to LWC, so the contributions of other physical processes can be safely ignored.

247 We can also infer that to what extents the various physical processes affect fog through the sensitivity experiments (u3e0,
248 u0e3 and u3e3). Additional aerosols weakly influence these processes (Fig. S3 right column) and subsequently result in weak
249 LWC change (Fig. 7c). Compared with aerosols, urbanization effect is much more considerable (Fig. S4 right column); it
250 dominantly accounts for the variation in physical tendencies from u0e0 to u3e3 (Fig. 10 right column). In u3e3 condition,
251 urban development (urbanization and aerosols) induces different magnitude of changes in different physical tendencies. The
252 relative magnitudes are 52.1, 38.3 and 9.6 % for the microphysical, boundary layer and advection processes, respectively,
253 indicating that microphysics is most susceptible to urban development and contributes most to the LWC change. Among
254 various microphysical processes, condensation/evaporation contributes most (72.7 %) to the change in microphysical ten-
255 dency (Fig. 11 right column). The above results indicate that urban development affects the LWC mainly by modulating the
256 condensation/evaporation process. Since u3e3 condition still witnesses higher temperatures and stronger updrafts (figure not
257 shown), the notable variation in condensation/evaporation tendency induced by u3e3 can also be attributed to the predomi-
258 nant role of UHI, UDI and updrafts. The mechanism has been analysed in Sect. 3.3.

259 **3.6 Discussions**

260 As mentioned above, urbanization influences fog to a larger extent than do aerosols; the LWC in fog does not vary substan-
261 tially with pollution level. This section discusses the rationality and reliability of our results through mechanism analysis and
262 observational evidence.

263 The sensitivity of cloud properties to aerosols depends on aerosol concentration and saturation environment. In convective
264 clouds with intense upward motions and high saturations, the response of cloud properties to additional aerosols is signifi-
265 cant ("aerosol-limited regime") (Fan et al., 2018). However, in fog with much weaker updrafts and lower saturations, this
266 response could be more sensitive to vapour content rather than aerosol concentration ("vapour-limited regime"). It possibly
267 implies that the LWC in fog varies slightly with pollution level but considerably with saturation condition that related to ur-
268 banization. Our results reveal that the time-height average LWC varies within the extent of 0.07g kg^{-1} when emission inten-
269 sity varies within two orders of magnitude (Fig. 8). This relative weak response of the LWC to pollution level is also report-
270 ed by Jia et al. (2018).

271 In terms of observational evidence, Yan et al. (2019) revealed that fog days in polluted regions of East China have decreased
272 since the 1990s. Through quantitative analysis, the promoting effects of aerosols are weakening, while the suppressing ef-
273 fects of urbanization are enhancing and dominantly cause this decrease. Sachweh and Koepke (1995) also claimed that the

274 hindering effects of urbanization outweigh the promoting effects of aerosols on fog in southern Germany. Additionally, satel-
275 lite images present discernible fog holes above urban areas (Fig. 3) (Lee, 1987; Sachweh and Koepke, 1995). Therefore,
276 these observational evidence support the model results that the promoting effect of aerosols is counteracted by the hindering
277 effect of urbanization. We believe that the results can also be applied to other large cities in China because these cities com-
278 monly witness strong UHI, UDI and severe air pollution.

279 **4 Conclusions**

280 A dense radiation fog event occurred in East China from 02 to 03 January 2017. Satellite images show that fog holes occur
281 over urban areas, demonstrating the remarkable effects of urbanization and air pollution on fog. Hence, the mechanism is
282 investigated by the WRF-Chem model. The model well captures the spatial coverage and temporal evolution of the fog. Fur-
283 thermore, the separate and combined effects of urbanization (refers to UHI and UDI) and air pollution (refers to aerosols) on
284 fog (indicated by the LWC) are revealed, and the extents of these effects are quantitatively determined. Results show that:

285 Urbanization redistributes the LWC profile by the UHI, UDI effect and updrafts. The updrafts may be caused by surface
286 roughness and extra warming. The UHI and UDI suppress low-level fog, delay its formation by 3 h, and advance its dissipa-
287 tion by 1.5 h. However, the upper-level fog could be enhanced due to the updraft-induced adiabatic cooling and vapour flux
288 convergence. Urbanization reduces the LWP most of the time, and this reduction in the daytime can explain why fog holes
289 are present above urban areas on satellite images.

290 Aerosols promote fog mainly by changing microphysical properties. The increasing emissions (aerosol concentration) pro-
291 duce more CCN and fog droplets, which decreases R_c and inhibits sedimentation, thus leading to a higher LWC. Further sen-
292 sitivity experiments show that the current pollution level in China could be still below the critical aerosol concentration that
293 suppresses fog. The macroscopic properties such as fog top and lifetime remain nearly unchanged.

294 The role of urbanization far outweighs that of aerosols. Therefore, when they act together, the urbanization effect is domi-
295 nant, and the aerosol effect is indiscernible. Budget analysis of LWC shows that increasing aerosols influence various physi-
296 cal processes to a lesser extent, while urbanization influences these processes to a larger extent, eventually leading to a sub-
297 stantial LWC change in urban development condition (urbanization and aerosols). In this condition, the comparisons among
298 various physical processes reveal that microphysics dominates the change in LWC, and condensation/evaporation dominates
299 the change in microphysical tendency. This result highlights the importance of condensation/evaporation process in modu-
300 lating the LWC profile and fog structure.

301 Mechanism analysis and the observational evidence support our key finding that urbanization influences fog to a much larger

302 extent than do aerosol pollution. Therefore, we believe our results are reasonable and robust in radiation fog events without
303 strong synoptic forcings, and the results can also be applied to other large cities in China due to the similar urban develop-
304 ment patterns. This study is expected to facilitate a better understanding of how anthropogenic activities affect the natural
305 environment, fog (cloud) physics and aerosol-cloud interactions near the surface. We can also infer the future change of fog
306 occurrence. Under the traditional urban development pattern, i.e., urbanization keeps developing and air quality keeps dete-
307 riorating, urban fog occurrence will be further reduced.

308

309 *Code and data availability.* Some of the data repositories have been listed in Sect. 2. The other data, model outputs and
310 codes can be accessed by contacting Bin Zhu via binzhu@nuist.edu.cn.

311

312 *Author contributions.* SY performed the model simulation, data analysis and manuscript writing. BZ proposed the idea, su-
313 pervised this work and revised the manuscript. YH provided the observation data at the SX site. JZ processed the observation
314 data. HK offered helps to the model simulation. CL and TZ also contributed to the manuscript revision.

315

316 *Competing interests.* The authors declare that they have no conflict of interest.

317

318 *Acknowledgments.* We are grateful to the High Performance Computing Center of Nanjing University of Information Science
319 and Technology for doing the numerical calculations in this work on its blade cluster system. We thank American Journal
320 Experts (AJE) for the English language editing.

321

322 *Financial support.* This work is supported by the National Key Research and Development Program (2016YFA0602003)
323 and the National Natural Science Foundation of China (91544229, 41575148, 41605091).

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457 Table 1. Summary of major parameterization schemes.

Scheme	Option
Boundary layer	YSU
Longwave radiation	RRTM
Shortwave radiation	New Goddard
Microphysics	Morrison
Surface layer	MM5 similarity
Land surface	Noah
Urban surface	Urban canopy model
Gas phase chemistry	CBMZ
Aerosol chemistry	MOSAIC (4-bin)
Aerosol-cloud and aerosol-radiation interactions	All turned on
Aerosol activation	Abdul-Razzak and Ghan (2002)

458

459

460 Table 2. Settings of sensitive experiments. "N" represents no changes.

Case name	Description	Underlying surface	Anthropogenic emission
u0e0	base condition	N	N
u3e0	urbanization condition	the 11x13 grid centered on SX is replaced by urban surface	N
u0e3	polluted condition	N	the 11x13 grid centered on SX is replaced by the emission of Hefei downtown
u3e3	urbanization and polluted condition	same as u3e0	same as u0e3

Effect	Description
u3e0-u0e0	urbanization effect
u0e3-u0e0	aerosol effect
u3e3-u0e0	urbanization and aerosol effect

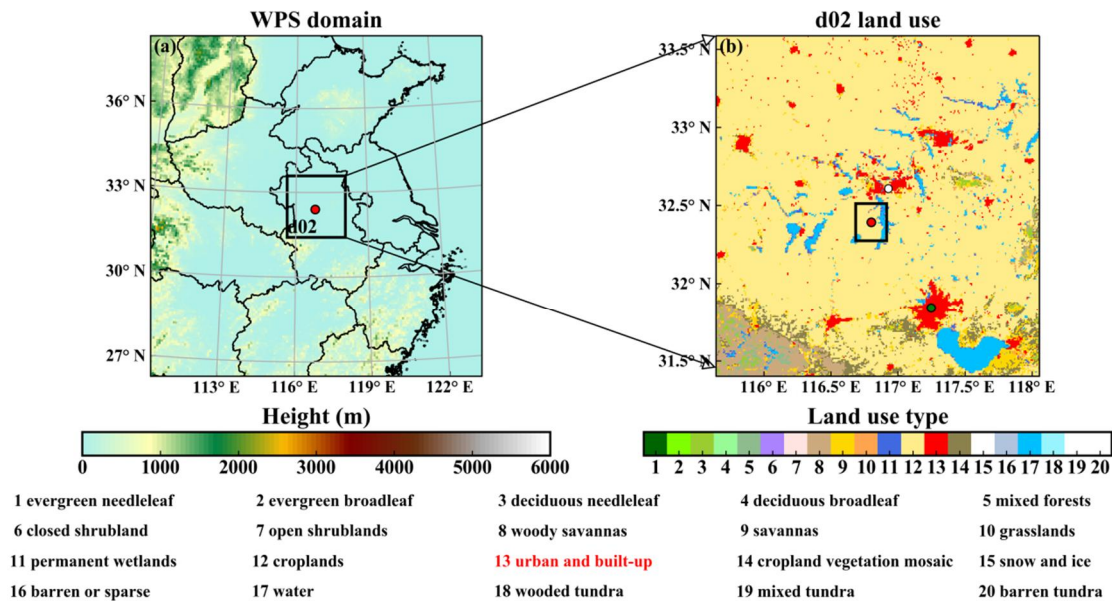
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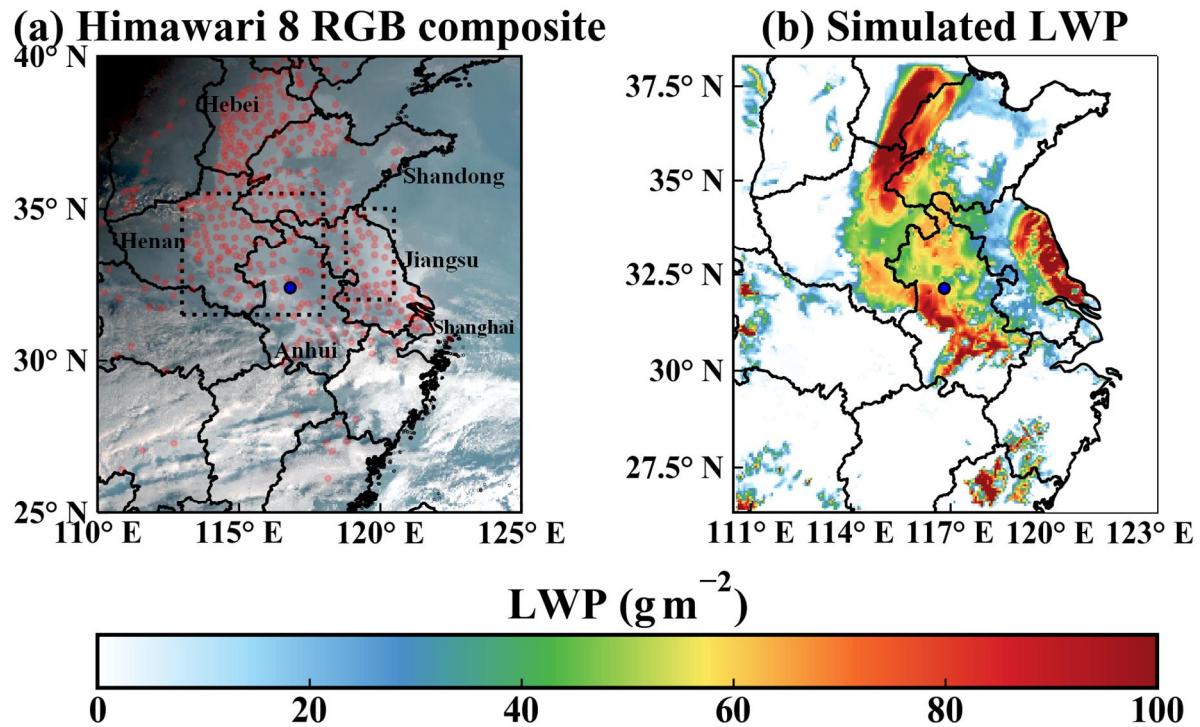
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468 Figure 1. (a) The WRF domain overlaid with terrain height. (b) The land use distribution of domain d02. The green dot is Hefei, the capital of Anhui Province. The white dot is Huainan. The two red dots are the SX site. The land use and
 469 emissions of the 22 km \times 26 km black box in the center of (b) will be altered in the sensitivity experiments.

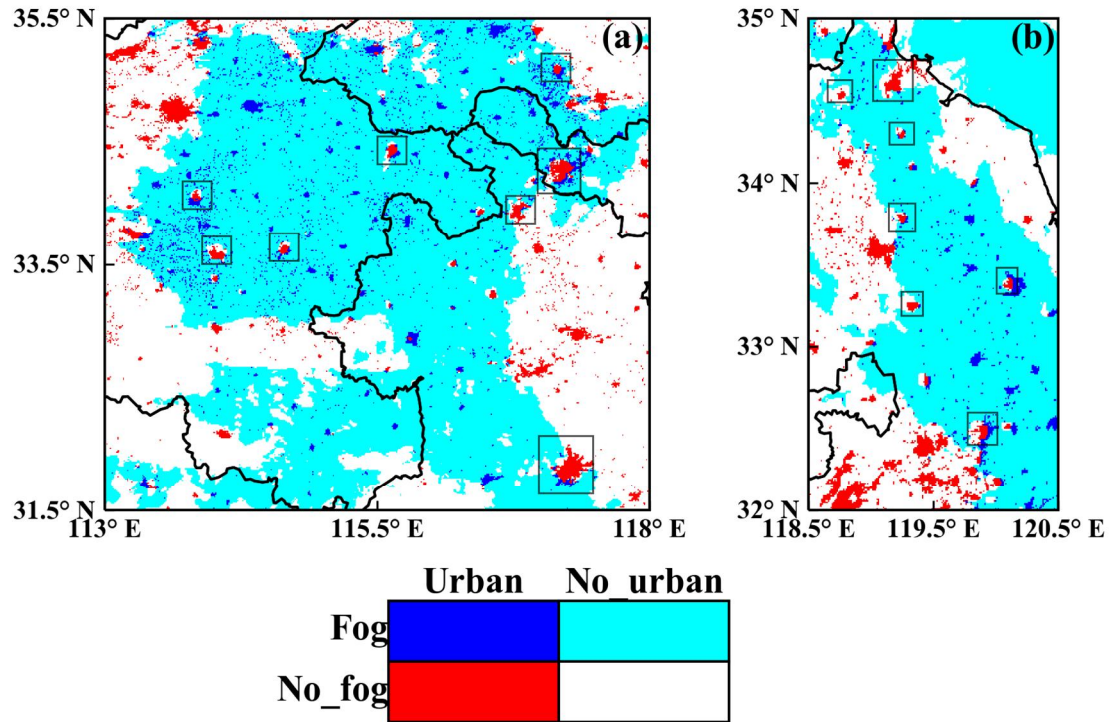
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474 Figure 2. The performance of the simulated fog zone at 08:00 03 January 2017. (a) Himawari 8 RGB composite cloud
 475 image overlaid with the MICAPS observation sites (light red dots) at which fog was observed (relative humidity > 90 %
 476 and VIS < 1 km). (b) Simulated LWP distribution. Only LWC below 1500 m are integrated. The blue dots are the SX
 477 site. The two dashed rectangles in (a) are the subregions of interest in Fig. 3.

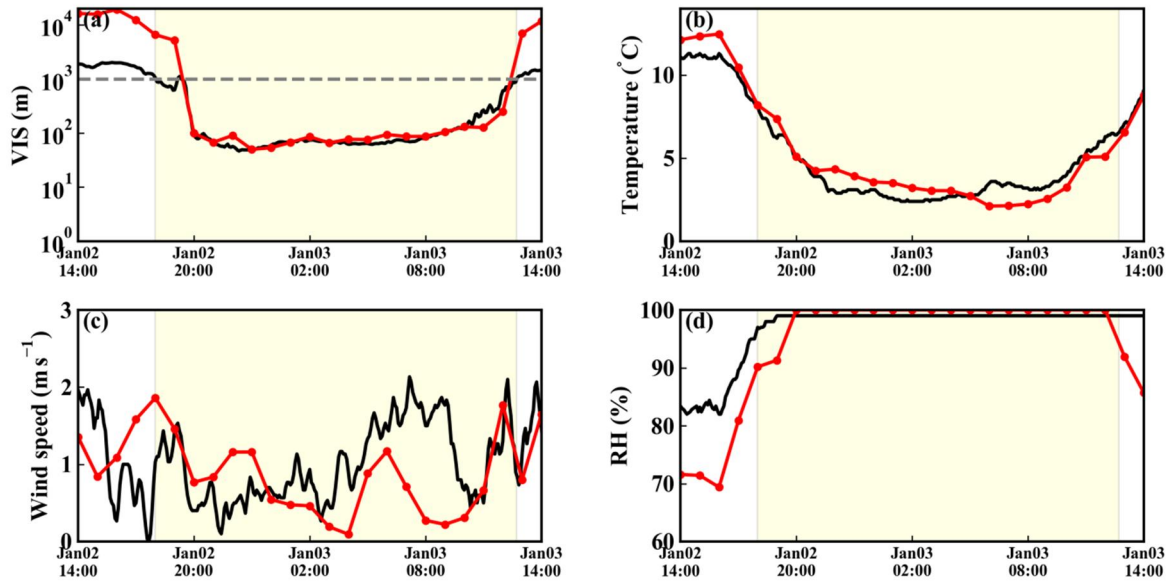
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480

481 Figure 3. Two sub-regions (a and b) with obvious fog holes on the Himawari 8 image at 11:00 03 January 2017. The
 482 fog zone, which is represented by albedo > 0.45 (at 0.64 μm) and brightness temperature > 266 K (at 12.4 μm) (Di
 483 Vittorio et al., 2002), is marked with cold colours (blue or cyan). The urban areas are marked with blue or red. The red
 484 and white pixels surrounded or semi-surrounded by cold colours are fog holes, and among these pixels, the red pixels
 485 indicate the fog holes over urban areas. Some of the cities with fog holes are marked by rectangles.

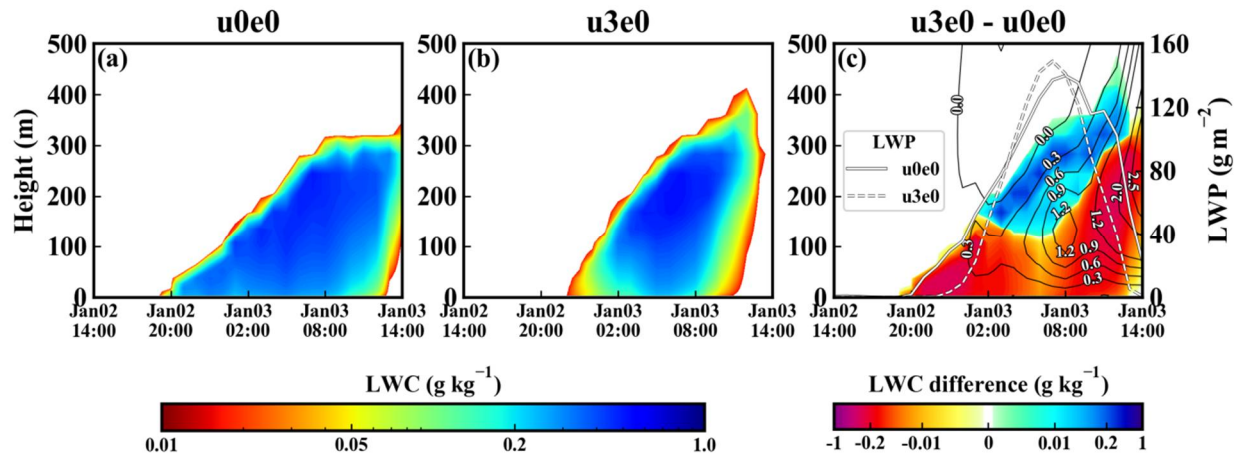
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488

489 Figure 4. The performance of the simulated meteorological parameters at the SX site. (a) VIS. (b) air temperature. (c)
 490 10-minute average wind speed. (d) Relative humidity (RH). The red dotted lines represent the model results, and the
 491 black lines are the observations. The fog period (VIS < 1 km and RH > 90 %) is shaded with light yellow.

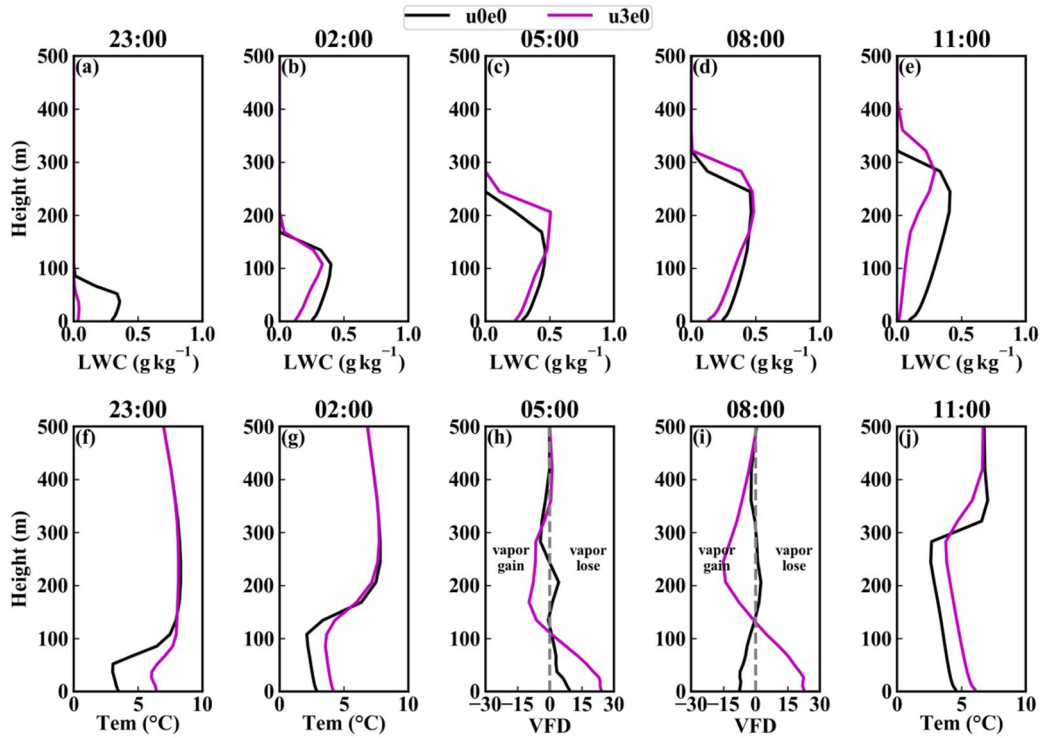
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495 Figure 5. Time-height distribution of the LWC (g kg^{-1}) in (a) $u0e0$ and (b) $u3e0$, and (c) is the urbanization effect ($u3e0$
 496 minus $u0e0$) on LWC. The two white curves in (c) are the LWP. The black contour lines in (c) are the difference of
 497 vertical velocity (cm s^{-1}) ($u3e0$ minus $u0e0$). Only the lines after 00:00 are shown for clarity.

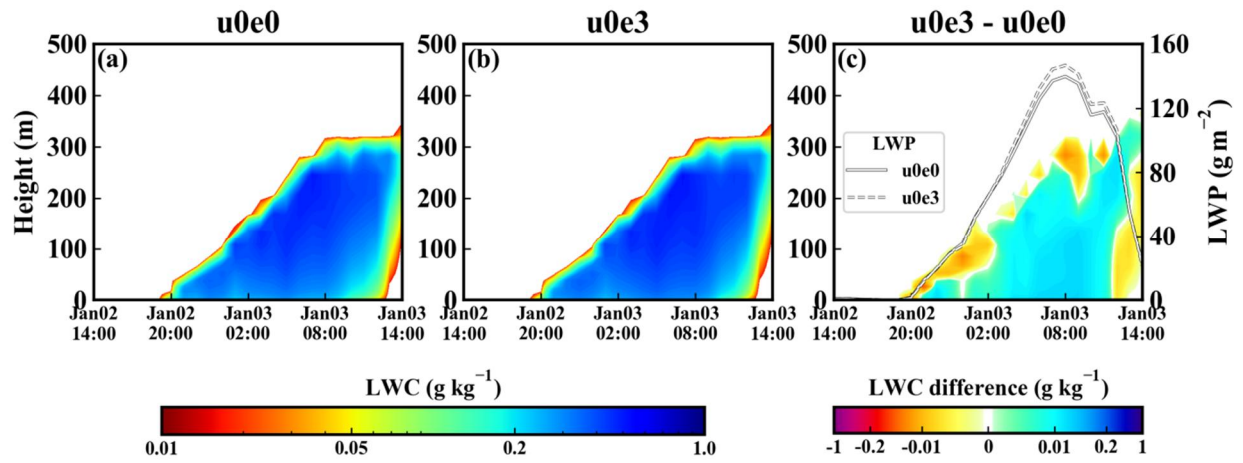
498



500

501 Figure 6. Profiles of the LWC (first row), temperature (Tem) (f, g, j) and vertical vapour flux divergence (VFD) (h, i)
 502 ($\text{g h}^{-1} \text{m}^{-2} \cdot \text{hpa}^{-1}$) in u0e0 and u3e0 at different times.

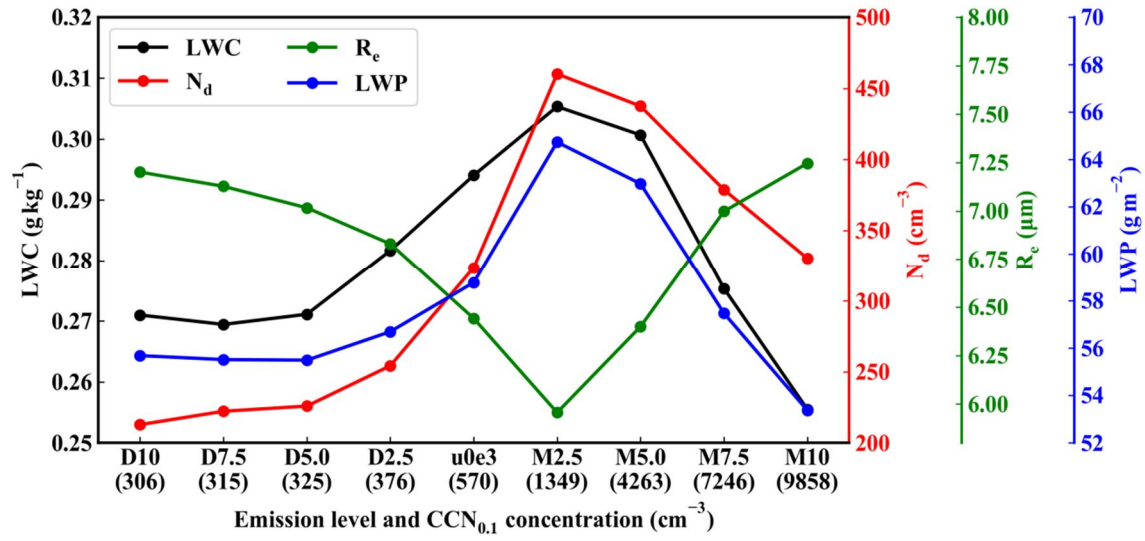
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505

506 Figure 7. Similar to Fig. 5, but for the aerosol effect ($u0e3$ minus $u0e0$).

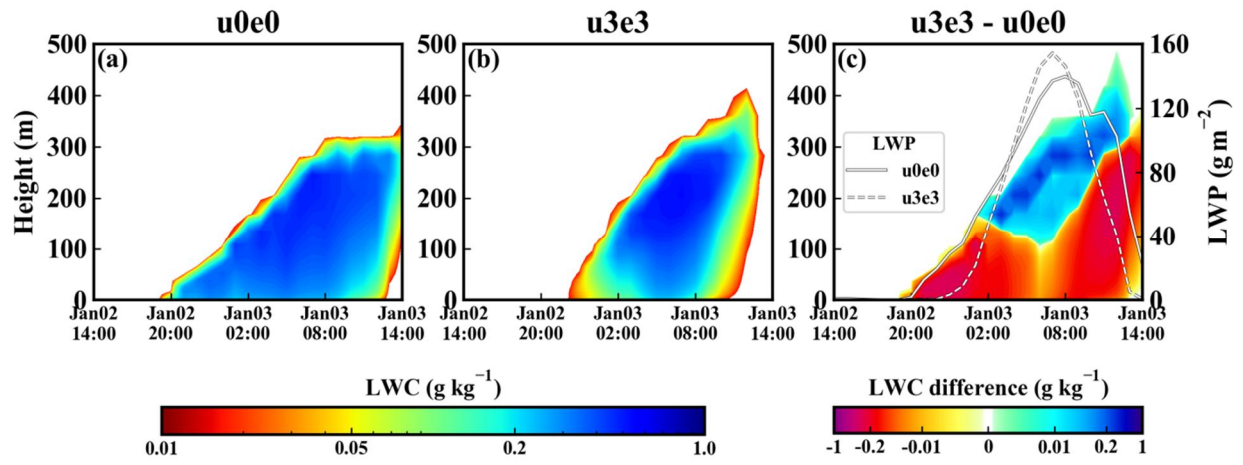
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509

510 Figure 8. Relationships of the microphysical parameters (LWC, N_d , R_e and LWP) with emission level and $CCN_{0.1}$ con-
 511 centrations. These parameters are the time-height averages (time average for the LWP) in fog.

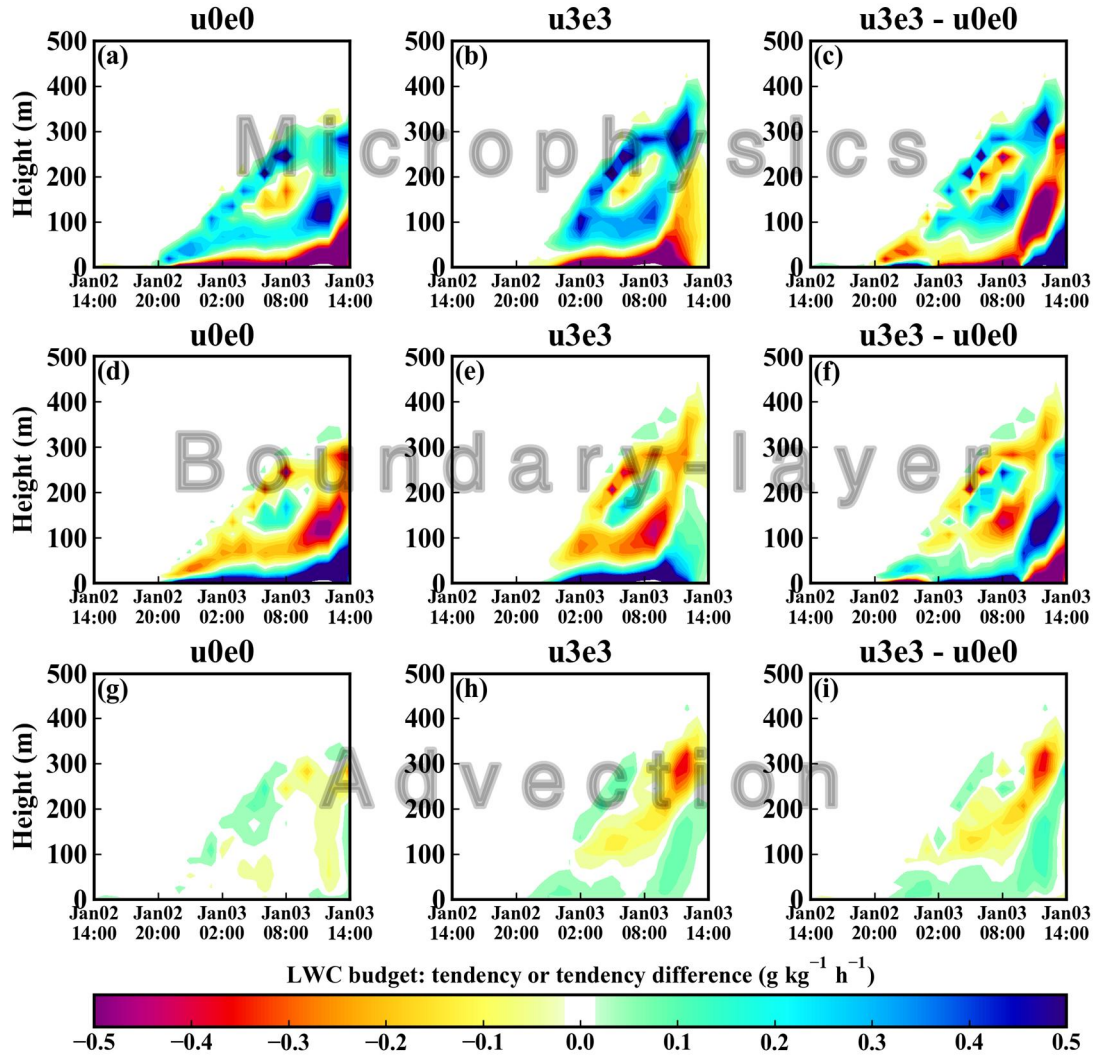
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514

515 Figure 9. Similar to Fig. 5, but for the combined effect of urbanization and aerosols ($u3e3$ minus $u0e0$).

516

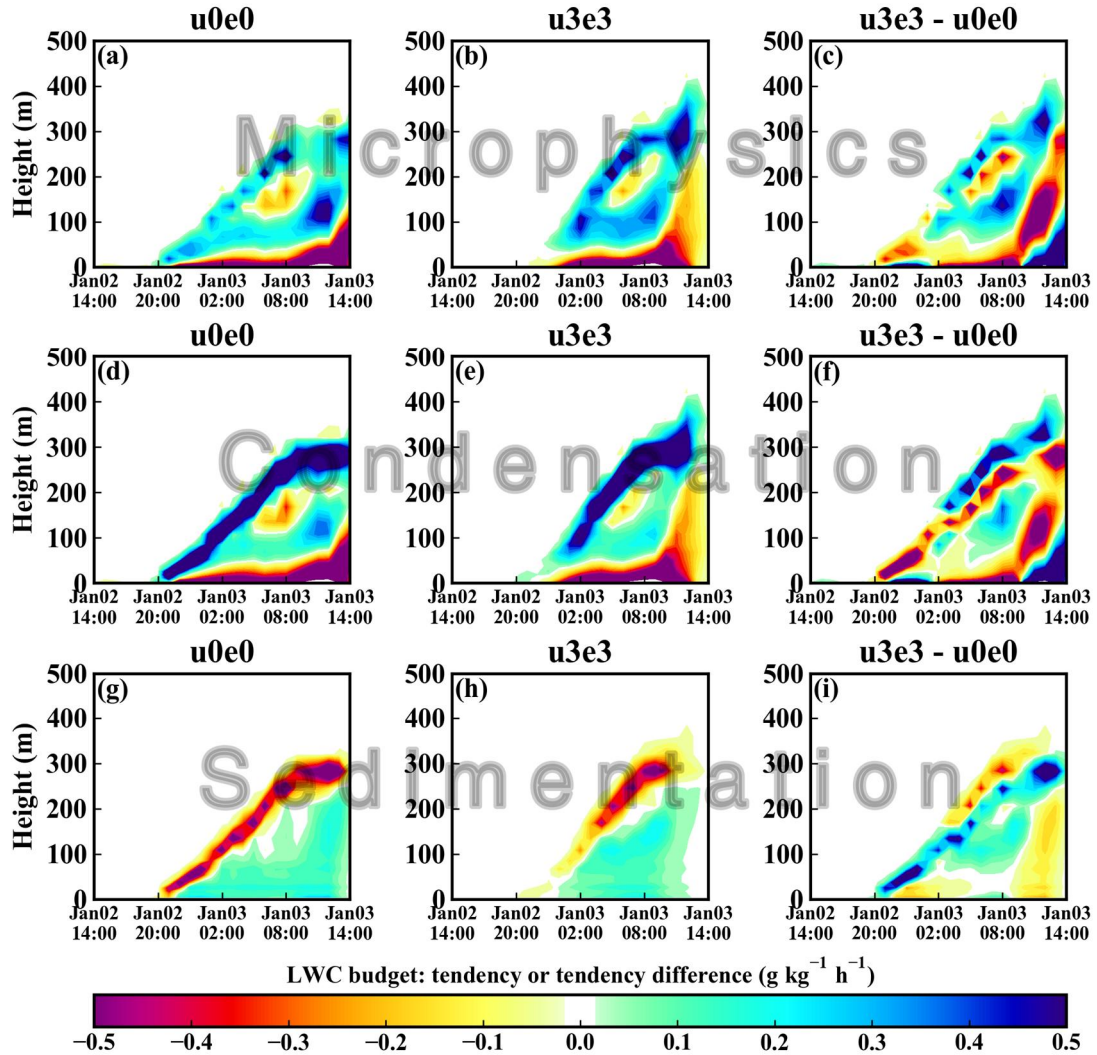


518

519 Figure 10. The combined effect of urbanization and aerosols (u3e3 minus u0e0) on various items of the LWC budget.

520 The three rows are the tendencies ($\text{g kg}^{-1} \text{h}^{-1}$) of the microphysical, boundary layer, and advection processes.

521



523

524 Figure 11. The combined effect of urbanization and aerosols (u3e3 minus u0e0) on various items of the microphysical
 525 tendency. The three rows are the tendencies ($\text{g kg}^{-1} \text{h}^{-1}$) of the microphysical, condensation/evaporation, and sedimen-
 526 tation processes.

527