Dear editors and reviewers:

Thank you for your comments concerning our manuscript entitled “The interaction between urbanization and aerosols during the typical haze event”. The comments are all valuable for improving the manuscript and also have great guiding significance for our research. We have studied the comments carefully and made corrections that we hope will be met with your approval. One version of the revised manuscript is highlighted with Track Changes. In the following we quoted each review question and added our response after each paragraph.

Reviewer #1:

General comments:

1. *A general description of physical processes between aerosols or $PM_{2.5}$ and warming and cooling are missing in the abstract. A more general discussion of the atmospheric physics which is studied here is required to understand what the authors want to tell us.*

Thank you for your suggestion. We added a general description of warming and cooling processes by aerosols or $PM_{2.5}$ in the Abstract to improve the expression of physical mechanisms in the revised manuscript.

The new part was added in Lines 27-29 in the revised manuscript:

Aerosols cause cooling at the surface by reducing shortwave radiation, while urbanization causes warming by altering the surface albedo and releasing anthropogenic heat. The combined effect of the two phenomena needs to be studied in depth.

2. *This topic is much better handled in the chapter Introduction. But the last sentence of the Introduction is producing questions so that this statement should be deleted here but discussed in the chapter Conclusions.*

We deleted the last sentence of the Introduction and added it to the Discussion section in the revised manuscript.

3. *The description of methods is missing an overall statement which data are required and why. There it is necessary also to show what is available and which data are missing. It should be explained why the data basis is complete for this study. Then the algorithms and models should be discussed by the same view: why you do what and why this way can provide the expected results or answers to the hypothesis.*

The description of results is very detailed so that more information for understanding is required as mentioned above.

Thank you for your suggestion. We added more information and reorganized the Methods section to explain the data basis.

The revised Methods section is as follows (the added parts are shown in red):

2 Methods

2.1 Observational data

To investigate the interaction between urbanization and aerosols, observation data on basic meteorological elements, air quality, radiation and surface heat flux and the mixing layer height (MLH) are very important to reveal the impact of urbanization and aerosols during haze events.

The basic meteorological elements were obtained from 309 national basic weather stations in the BTH region and were provided by the China Meteorological Administration (http://data.cma.cn/). The locations of the national basic weather stations are shown in Fig 1 (red dots). The mass concentrations of fine particulate matter ($PM_{2.5}$) were recorded by 251 environmental monitor stations managed by the Ministry of Ecology and Environment of the People's Republic of China (http://hbk.cei.cn/aspx/default.aspx) (Fig 1, black dots). We also used radiation and surface heat flux data to analyze the urban surface energy budget obtained from the Beijing meteorological tower (39.97°N, 116.37°E). The tower is 325 m high and is operated by the Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (CAS). The heat flux data were measured by a fast response eddy covariance sensor system that was sampled at 10 Hz using CR500 (Campbell Scientific Inc., USA). The radiation data were provided by Kipp & Zonen (Netherlands) four-component unventilated CNR1 radiometers. Radiation and surface flux data from 140 m of the tower were used in this study. In addition, the MLH is an important factor affecting pollutant diffusion and is also affected by both urbanization and aerosols. Because the MLH is not a routine observation, we obtained the data from only one site. The MLH and backscattering coefficient were measured by enhanced single-lens ceilometers (Vaisala, CL51, Finland) deployed by the IAP (Tang et al., 2016). Backscattering coefficient profiles were calculated by referencing the attenuation strobe laser LiDAR technique (910 nm), which is cited in Tang et al. (2015).

2.2 Model description and experimental design

To investigate the respective effects of urbanization and aerosols and further determine the interaction between urbanization and aerosols, a high-resolution regional model with satisfactory performance is necessary for sensitivity tests.

…

4. *The chapter Conclusions are a summary, a discussion and some conclusions. The discussion is missing the relation of the study results to the overall knowledge. What is new? What are the conclusions for the overall knowledge and the study area?*

Thank you for your suggestion. We added a Discussion section to show the innovations and the relation of the study results to the overall knowledge.

The Discussion section is as follows:

5 Discussion

In this study, it was easier to distinguish the impacts of aerosols and urbanization by using RMAPS-ST with AOD hourly inputs than with RMAPS-Chem. One reason for this difference is that the model performance of RMAPS-ST is much better than that of RMAPS-Chem in meteorological fields. Although real-time feedback in modeling is not provided, RMAPS-ST is more efficient and more suitable for short-term operational forecasting.

This study not only qualified the impacts of aerosols and urbanization on haze events but also analyzed the interaction between aerosols and urbanization during haze events. This research will help to improve air quality under the continuous urbanization and sustainable development of large cities.

The government has taken a series of emission reduction measures, including limiting industrial emissions and vehicle plate number traffic restriction measures, to improve the air quality in the BTH region. The policies have been effective in reducing aerosols. At the same time, urbanization continues mainly in the areas around Beijing (such as the Xiongan New Area). The results of this study show that the combined impact of urbanization and decreasing aerosols will increase the downward shortwave radiation and further increase the surface temperature and ozone concentration in the boundary layer. Previous studies indicated that ozone generally increases with temperature and decreases with humidity (Camalier et al., 2007; Cardelino et al., 1990). It is well known that ozone is not only a pollutant but also a greenhouse gas. Therefore, ozone will form a positive feedback mechanism to induce warming and ozone pollution in the boundary layer. This feedback will pose a new challenge regarding how to reduce ozone pollution in urban areas. Some studies have suggested that urban greening can effectively reduce ozone pollution (Nowak et al., 2000; Benjamin and Winer, 1998). More attempts should be made to add the interaction between urbanization and ozone in regional models.

Reference

Camalier, L., Cox, W., and Dolwick, P.: The effects of meteorology on ozone in urban areas and their use in assessing ozone trends, Atmospheric Environment, 41(33), 7127-7137, 2007.

Cardelino, C. A., and Chameides, W. L.: Natural hydrocarbons, urbanization, and urban ozone, Journal of Geophysical Research, 95(D9), 13971, 1990.

Nowak, D. J., Civerolo, K. L., Rao, S. T., Sistla, G., Luley, C. J., and Crane, D. E.: A modeling study of the impact of urban trees on ozone, Atmospheric Environment, 34(10), 1601-1613., 2000.

Benjamin, M. T., Winer, A. M.: Estimating the ozone-forming potential of urban trees and shrubs, Atmospheric Environment, 32(1), 53-68, 1998.

5. *The figure captions should be improved so that these are understandable without the overall manuscript: terms must be explained, description of parameters (Fig. 2c).*

Thank you for your suggestion. The revised Fig 2 is as follows:

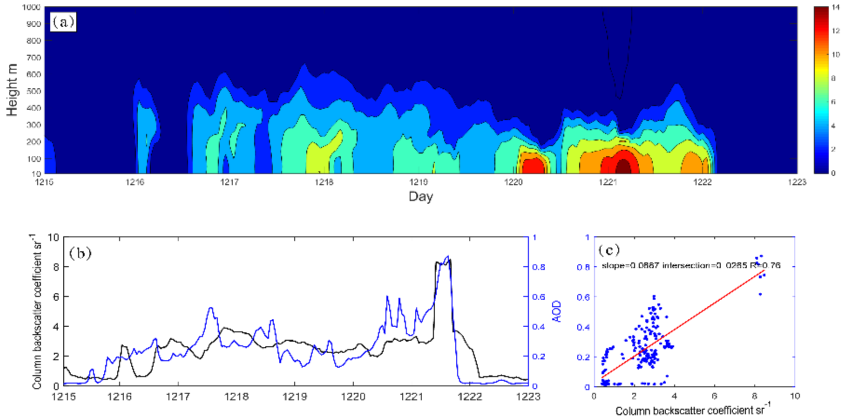

Figure 2 (a) Hourly backscattering coefficient (shading; Mm·sr^{-1}) observed by single-lens ceilometers (39.97°N, 116.37°E) from the 15th to 23rd of December; (b) hourly column backscatter coefficient (black line; sr^{-1}) and AOD used in modeling for Beijing (blue line) and (c) scatter diagram of hourly column backscatter coefficient and AOD (blue dots) and their correlations (red line).

6. Please follow the guidelines to write the references: the authors of papers are incomplete, after the title you set a”.” or a “,”, some paper references include the doi number and other not. Technical corrections Line 76 Crutzen instead of Cruten.

Thank you for your suggestion. We unified the format and added information to improve the References section.

Reviewer #2:

The authors investigate the interaction between aerosols and urbanization during a severe haze event via *the RMAPS-ST model. Results indicate that a 100% increase in PM2.5 (200 to 400 _g/m3) reduced daytime urban-related warming by 20% (from 30-50%). However, urban-related warming increased approximately 28% in response to aerosols- important for haze formation. With regards to urbanization, the aerosol-related cooling effect was reduced by approximately 54%, changing little with aerosol increases. The study also found that aerosols reduced the urban-impact on the mixing layer, sensible heat flux, and latent heat flux by 148%, 156%, and 48.8%, respectively. This reviewer's main concern is related to whether or not the authors address aerosol typology in the model. If so aerosol chemistry was considered, then how?*

Thank you for your suggestion. The aerosol typology has been considered in this study. The AOD was extracted from the output of RMAPS-Chem (Zhao et al., 2019; Zhang et al., 2018), which included the aerosol typology in the model. Then, we added the hourly distribution of AOD in the RRTMG radiation scheme in RMAPS-Urban. The particle size distribution and typology of aerosols also calculated in the RRTMG radiation scheme is according to Ruiz et al. (2014). Therefore, the particle size distribution and typology of aerosols are included in both the input hourly AOD fields and the RRTMG radiation scheme. We added the sentence "The particle size distribution and typology of aerosols used in this study is according to Ruiz et al. (2014)" in Lines 153-154 to clarify this information.

The work could be greatly improved with better section transitions, and by addressing several items described below.

1. Abstract:

a) Which haze event? The authors should specify.

We added information on the haze event in Line 30.

Line 30: The interaction between aerosols and urbanization during the haze event that occurred from the 15^{th} to 22^{nd} of December 2016 in Beijing was investigated using the rapid-refresh multiscale analysis and prediction system-short term (RMAPS-ST).

b) Lines 30-33: Rephrase for better flow.

Aerosols reduced urban-related warming during the daytime. The urban-related warming decreased by 30 to 50% as the concentration of PM2.5 increased from 200 to 400 $\mu g \cdot m^{-3}$. Conversely, aerosols also enhanced urban-related warming at dawn, and the increment was approximately 28%, which contributed to haze formation.

c) Lines 37-38: Unclear.

Furthermore, aerosols decreased the latent heat flux; however, this reduction decreased by 48.8% due to urbanization.

2. *Introduction-The authors thoroughly cite references to support statements and do a good job of showing the importance of aerosol-urban impacts. They also state that quantitative evaluation of urban impacts on aerosols and vice-versa has not been conducted simultaneously in metropolitan areas. There are several sentences that need to be rephrased- some of which are listed below.*

We revised the Introduction section according to your suggestions.

a) Lines 43-46: Rephrase to improve the flow.

In recent years, heavy haze pollution events have increasingly occurred in densely populated urban areas, such as the Beijing-Tianjin-Hebei region (BTH region) and Yangtze River Delta region of China (Zhang et al., 2019). These events have caused increasingly severe adverse effects on transportation, the ecological environment and human health (Zhao et al., 2012; Wu et al., 2010; Liu et al., 2012).

b) Lines 49-54: These lines can be connected better connected.

The revised version: The conditions for the formation of heavy haze in the BTH region are very complex (Miao et al., 2017; Wei et al., 2018; Ren et al., 2019). Although emissions, meteorological conditions, terrain, and high-density human activities in urban areas are all important conditions for the evolution of heavy haze (Huang et al., 2008a; Zhu et al., 2018), meteorological conditions are critical for the evolution of heavy haze pollution weather under the background of constant emissions (Wang et al., 2020; Pei et al., 2020).

c) Lines 74-75: Rephrase.

The revised version: However, in contrast to the effects of urbanization, aerosols cause cooling at the surface by reducing shortwave radiation to enhance static stability (Grimmond, 2007; Cruten, 2004, Huang et al., 2007).

d) Lines 87-88: Which "conclusions" specifically?

Xu et al. (2019) indicated that the impact of irrigation on regional climate may vary depending on the scale. We cited Xu et al. (2019) to explain that the different conclusions obtained by Cao et al. (2016) and Yang et al. (2020) may be due to the focus on different scales.

e) Line 103: Add the word "model" after (RMAPS-ST)

The suggested change has been made.

f) Line 104: Remove "the mechanism of"

The suggested change has been made.

3. Methods:

a) The authors immediately describe four observational data types used for the study and provide a map of the locations (in Figure 1, is the shaded region topography? What units?).

We improved the caption of Figure 1 to clarify this information.

The revised capture: Figure 1 Domain configuration of RMAPS-ST and the location of the study area, indicated by the solid white line. The black dots indicate the locations of the 251 environmental monitoring stations, and the red dots represent the 309 meteorological stations in the BTH region, where the gray loop lines show the locations of the second to sixth ring roads. The shading is the terrain height (unit: m).

b) This reviewer was expecting a mention of the high RMSE values for longwave and shortwave (Table 1). What is this attributed to?

There are two possible reasons for the high RMSE values for longwave and shortwave radiation:

i) Deficiency of observation sites and interpolation methods

Only observed longwave and shortwave data from the Beijing meteorological tower (39.97°N, 116.37°E) were available for evaluation. The weighted interpolation of the nine points was used to transfer the grid modeling results to the station locations. A total of 294 observation stations were used to evaluate basic meteorological elements such as temperature. The RMSE of the basic meteorological elements is the average of the 294 observation stations. Therefore, it is reasonable that the RMSE values of the radiation and heat flux values are larger than those of basic meteorological elements.

The magnitudes of longwave and shortwave radiation are larger than that of heat flux (Fig 5e and f). Although the RMSE of radiation is larger than that of heat flux, the absolute error ratio is similar.

ii) Height differences between observations and simulations

Observed shortwave and longwave radiation data from the tower were only available from 140 m. However, the surface radiation was simulated from the shortwave and longwave radiation.

We added an explanation in the revised version as follows.

Lines 171-173: The deficiency of observation sites, interpolation methods and the height differences between the observations and simulations resulted in higher root mean square error (RMSE) values for radiation and heat flux than for the other variables.

c) Line 113: Rephrase to "synoptic conditions"

We deleted this sentence in the revised manuscript.

d) Lines 143-154: What considerations were made for other important aerosol parameters such aerosol particle size distribution and typology?

Aerosol particle size distribution and typology:

Ruiz et al. (2014) elaborated on how to specify the AOD at each spectral band in the RRTMG scheme. A 2-band version of the Ångström law (Gueymard, 2001) was used as follows:

$$\tau(\lambda) = \tau 0.55(\frac{\lambda}{0.55})^{-\alpha_i}$$

where λ is the wavelength in μm and α_i is the Ångström exponent for each band, defined as $\alpha_i = \alpha_1$ for _<0.55 μm, and $\alpha_i = \alpha_2$ otherwise. The corresponding values of α_i are given in Table 2. For α_1, extinction coefficients of 0.337, 0.55 and 0.649 μm were used. The values at 0.55, 0.649, 1.06 and 1.536 μm were used for α_2.

We added an explanation of the aerosol particle size distribution and typology in the new version as follows.

Lines 153-154: The particle size distribution and typology of aerosols used in this study is according to Ruiz et al. (2014).

Reference

Ruiz-Arias, J. A., Dudhia, J., and Gueymard, C. A. (2014). A simple parameterization of the short-wave aerosol optical properties for surface direct and diffuse irradiances assessment in a numerical weather model. Geoentific Model Development, 7(3), 1159-1174.

4. Results:

a) The authors first describe the haze 15-22 December 2016 haze event, thoroughly describing the evolution of the event in three stages. The specifics of the simulation are then described, but this section *should be moved to Methodology (Section 3.2).*

Thank you for your suggestion. We first showed the weather maps and time series of meteorological elements in Section 3.1 from observations, namely, what the observations told us. However, we begin to design sensitivity tests and analyze the modeling results in Section 3.2. Therefore, we changed the chapter title to "3.1 Observation and weather condition analysis" to make it clear.

b) *Simulation results are then described. There are so many numbers in the results section that an additional table could be added.*

We added Table 3 to summarize the numbers.

Table 3 Quantitative results of the interaction between urbanization and aerosols

	Temperature °C		**Specific humidity ×10-2 g kg^{-1}**		**Longwave W·m^{-2}**		**MLH m**	**Sensible heat flux W·m^{-2}**	**Latent heat flux W·m^{-2}**
Time	16^{th}-19^{th}	20^{th}-21^{st}	16^{th}-19^{th}	20^{th}-21^{st}	16^{th}-19^{th}	20^{th}-21^{st}	16^{th}-21^{st}	16^{th}-21^{st}	16^{th}-21^{st}
UI_aero	0.42	0.19	3.66	3.08	0.10	-0.02	-1.97	-1.01	0.03
UI_noaero	0.60	0.35	4.78	4.48	0.62	0.51	4.04	1.74	0.49
AI_urban	-0.16	-0.19	-0.88		-0.24		-4.37	-1.64	-0.50
AI_nourba	-0.34	-0.43	1.36		-0.73		-10.38	-4.02	-0.96

c) *The authors could also organize the results better, as it is a bit confusing going back and forth from aerosol impact on the urban to urban impacts on the aerosol.*

Thank you for your suggestion. We unified the order of the analysis to show the impacts of aerosols on urban areas first for each variable and added Table 3 to clarify this information in the revised manuscript.

d) *Line 167: What makes a heavy haze event typical?*

Large-scale weather conditions result in poor dispersion of pollutants are the main factor of typical continuous severe heavy haze formation.

e) *Lines 194: "on" the morning of: : :*

The suggested change has been made

f) *Lines 222-226: Rephrase, and also consider replacing the word "obviously".*

The revised version: The impact of urbanization on the near-surface temperature displays diurnal variation in the Beijing area. The warming effect of urbanization was dominant at night. The urban impact on temperature was partly offset under aerosol conditions when comparing the results of UI_aero and UI_noaero, especially during the daytime (Fig 6a, red lines).

g) Figure 6: Are these results averaged over a specific grid?

The results are processed to the regional average for the Beijing area.

h) Lines 270-271: What is meant by "a few differences"?

"a few differences" means the difference was very small. We revised the sentence to "Aerosols reduce the downward shortwave radiation during the daytime, and the differences between AI_urban and AI_nourban are very small." to clarify this information.

i) Lines 308-309: I think I understand what you're saying here, but this needs to be clearer.

We revised the sentence to the following: The above results indicate that the offsetting effect of aerosols on urbanization is more important than the impact of urbanization on aerosols on local weather.

j) Line 329: wind fields "are" very important.

The suggested change has been made.

5. *Conclusion*
    a) *The authors summarize their findings and highlight the most important results. The paper ends without the authors discussing the implications of their findings their findings, and could benefit from such a discussion being added.*

We added a Discussion section in the new version as follows.

5 Discussion

In this study, it was easier to distinguish the impacts of aerosols and urbanization by using RMAPS-ST with AOD hourly inputs than with RMAPS-Chem. One reason for this difference is that the model performance of RMAPS-ST is much better than that of RMAPS-Chem in meteorological fields. Although real-time feedback in modeling is not provided, RMAPS-ST is more efficient and more suitable for short-term operational forecasting.

This study not only qualified the impacts of aerosols and urbanization on haze events but also analyzed the interaction between aerosols and urbanization during haze events. This research will help to improve air quality under the continuous urbanization and sustainable development of large cities.

The government has taken a series of emission reduction measures, including limiting industrial emissions and vehicle plate number traffic restriction measures, to improve the air quality in the BTH region. The policies have been effective in reducing aerosols. At the same time, urbanization continues mainly in the areas around Beijing (such as the Xiongan New Area). The results of this study show that the combined impact of urbanization and decreasing aerosols will increase the downward shortwave radiation and further increase the surface temperature and ozone concentration in the boundary layer. Previous studies indicated that ozone generally increases with temperature and decreases with humidity (Camalier et al., 2007; Cardelino et al., 1990). It is well known that ozone is not only a pollutant but also a greenhouse gas. Therefore, ozone will form a positive feedback mechanism to induce warming and ozone pollution in the boundary layer. This feedback will pose a new challenge regarding how to reduce ozone pollution in urban areas. Some studies have suggested that urban greening can effectively reduce ozone pollution (Nowak et al., 2000; Benjamin and Winer, 1998). More attempts should be made to add the interaction between urbanization and ozone in regional models.

Reference

Camalier, L., Cox, W., and Dolwick, P.: The effects of meteorology on ozone in urban areas and their use in assessing ozone trends, Atmospheric Environment, 41(33), 7127-7137, 2007.

Cardelino, C. A., and Chameides, W. L.: Natural hydrocarbons, urbanization, and urban ozone, Journal of Geophysical Research, 95(D9), 13971, 1990.

Nowak, D. J., Civerolo, K. L., Rao, S. T., Sistla, G., Luley, C. J., and Crane, D. E.: A modeling study of the impact of urban trees on ozone, Atmospheric Environment, 34(10), 1601-1613., 2000.

Benjamin, M. T., Winer, A. M.: Estimating the ozone-forming potential of urban trees and shrubs, Atmospheric Environment, 32(1), 53-68, 1998.

b) *Line 379: Why not just list the actual maximum concentration?*

Line 379 to Line 403: We rephrased this sentence and added the actual maximum concentration of $PM_{2.5}$. The revised sentence: The average concentration of $PM_{2.5}$ was approximately 200 $\mu g \cdot m^{-3}$, and the maximum was 695 $\mu g \cdot m^{-3}$.

6. *Figures:*

a) *Figure 3: Is difficult to see, the red dashed contours are not clear on the panels.* We improved the quality of Figure 3 to make it clear.

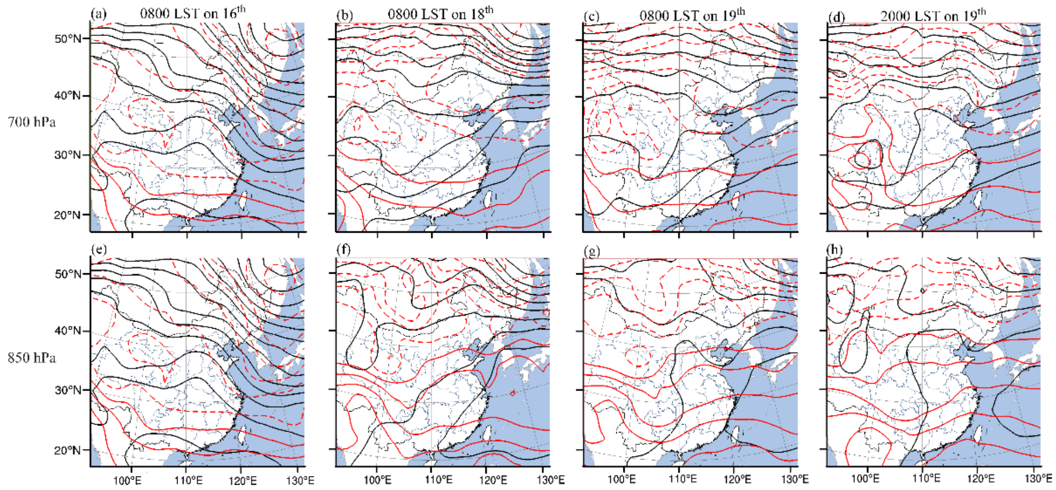

Figure 3 Weather maps. (a) 0800 LST on the 16th at 700 hPa; (b) 0800 LST on the 18th at 700 hPa; (c) 0800 LST on the 19th at 700 hPa; (d) 2000 LST on the 19th at 700 hPa; (e) 0800 LST on the 16th at 850 hPa; (f) 800 LST on the 18th at 850 hPa; (g) 0800 LST on the 19th at 850 hPa; (h) 2000 LST on the 19th at 850 hPa.

b) *Figure 4: Add units on the left axis. Also, consider using a box instead of the extra shaded regions on the 16th, 17th, and 19th.*

We added the units and replaced the shading with a box in Figure 4.

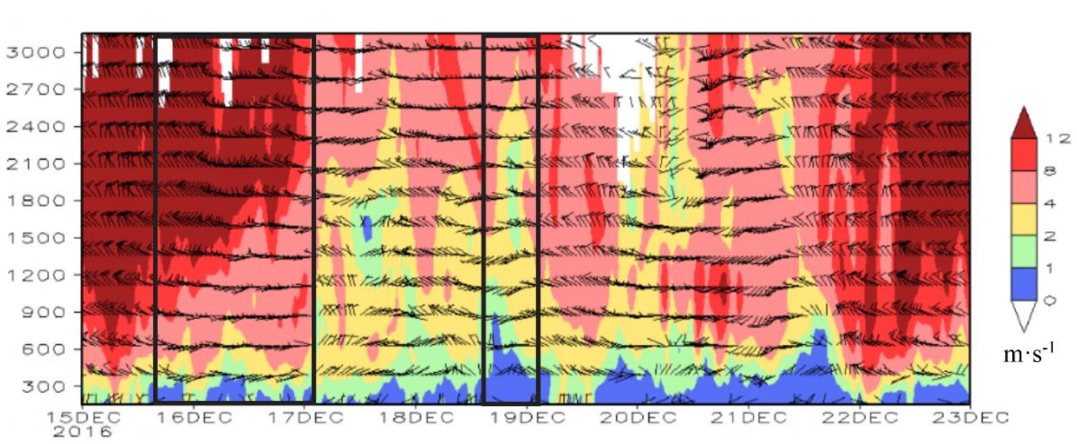

Figure 4 Hourly wind profile from the 15th to 23rd of December. Wind speed (shading; $m \cdot s^{-1}$) and horizontal wind field (vector; $m \cdot s^{-1}$). The black boxes show the two periods of south wind conveyance.

The interaction between urbanization and aerosols during the haze event

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Abstract

Aerosols cause cooling at the surface by reducing shortwave radiation, while urbanization causes warming by altering the surface albedo and releasing anthropogenic heat. The combined effect of the two phenomena needs to be studied in depth. The interaction between aerosols and urbanization during the haze event occurred from the 15th to 22nd of December 2016 in Beijing was investigated using the Rapid-Refresh Multiscale Analysis and Prediction System-Short Term (RMAPS-ST). The mechanisms of the impacts of aerosols and urbanization were also analyzed and quantified. Aerosols reduce urban-related warming during the daytime. The urban-related warming decreased by, and the warming decreased by 30 to 50% as the concentration of $PM_{2.5}$ increased from 200 to 400 μg·m^{-3}. Conversely, aerosols Aerosols also enhance the urban-related warming at dawn and the increment is , with an increase of approximately 28%, which contributed to haze formation., which is important for haze formation. Urbanization reduced the aerosol-related cooling effect by approximately 54% during the haze event, and the strength of the impact changed little with increasing aerosol content. The impact of aerosols on urban-related warming is more significant than the impact of urbanization on aerosol-related cooling. Aerosols decreased the urban-impact on the mixing layer height by 148% and on the sensible heat flux by 156%. Furthermore, the aerosols decreased the latent heat flux; however, this reduction decreased by 48.8% due to urbanization., and the impact was reduced by 48.8% by urbanization. The impact of urbanization on the transport of pollutants is more important than that of aerosols. The interaction between urbanization and aerosols may enhance the accumulation of pollution and weigh against diffusion.

1 Introduction

In recent years, heavy haze pollution events have increasingly occurred heavy haze pollution events have occurred more frequently in densely populated urban areas, such as the Beijing-Tianjin-Hebei region (BTH region) and Yangtze River Delta region of China, (Zhang et al., 2019). These events which has caused increasingly serious adverse effects on transportation, the ecological environment and human health (Zhao et al., 2012; Wu et al., 2010; Liu et al., 2012). A statistical analysis of the variation in haze days in Beijing over the past 10 years shows that the number of haze days has significantly increased (Chen and Wang, 2015; Zhai et al., 2019). The average annual number of haze days was 162 in 1981-1990, 167 in 1991-2000, and 188 in 2001-2010. The conditions for the formation of heavy haze weather in the BTH region are very complex (Miao et al., 2017; Wei et al., 2018; Ren et al., 2019). Although Atmospheric pollutant emissions, meteorological conditions, terrain, and urban high-density human activities are all important conditions for the evolution~~formation~~ of heavy haze ~~weather~~ (Huang et al., 2008a; Zhu et al., 2018~~).~~), the ~~However,~~ meteorological conditions are ~~becoming the most~~ critical ~~conditions~~ for the evolution~~development~~ of heavy haze pollution weather under the background of constant emissions~~when there is little change in atmospheric pollutant emissions~~ (Wang et al., 2020; Pei et al., 2020).

The characteristics of the atmospheric boundary layer structure determine the horizontal fluidity, vertical diffusion ability, stability and capacity (mixed layer thickness) of the atmosphere, which are the main factors affecting the formation, intensity and duration of haze and atmospheric pollution (Guo et al., 2016). Coulter R L. (1979) indicated that the height of the mixing layer would affect the concentration and diffusion of pollutants, which has been one of the most important physical parameters in atmospheric numerical models and atmospheric environment evaluations, and urbanization and aerosols have been proven to influence the boundary layer height (Tao et al., 2015).

Urbanization, as the most drastic means by which human activities transform the environment, has had an important impact on regional climate and weather processes (Miao et al., 2011; Yu and Liu, 2015; Yu et al., 2017). Existing research suggests that there are three main ways by which urbanization influences the climate (Oke, 1982 and 1995). The change with land use from natural surfaces to impervious underlying surfaces in association with urbanization alters the surface albedo and roughness, which results in the formation of urban heat islands (UHIs) (Taha, 1997; Folberth et al., 2014). This leads to a change in the surface energy balance and the form of the thermal difference between urban and rural areas and further changes the boundary layer structure (Grimmond, 2007; Li and Bou-Zeid, 2013). Second, thermal differences further lead to heat island circulation, which can influence the local circulation of synoptics and the transport of pollutants (Crutzen, 2004). Anthropogenic aerosols and heat from the development of transportation and industry are also important parts of urban impacts on climate (Huang et al. 2008b). However, in contrast to the effects of urbanization, aerosols ~~can reduce the decrease in shortwave radiation and~~ cause cooling at the surface by reducing the shortwave radiation to ~~and~~ enhance static stability~~, which is opposite to the effects of urbanization~~ (Grimmond, 2007; Cruten, 2004, Huang et al., 2007). Furthermore, aerosols may increase longwave radiation in urban areas because they are likely to absorb and emit more energy than water vapor or greenhouse gases under certain conditions (Jacobson,1998; Rudich et al., 2007). There have been few studies on the mechanism of the interaction between urbanization and aerosols, although many studies focus on their respective effects.

Accordingly, the interaction between urbanization and aerosols is important for studying regional climate.

Researchers are increasingly aware of the importance of the interaction between urbanization and aerosols. A very important study by Cao et al. 2016 was the first attempt to determine the effects of aerosols on urbanization and indicated that aerosols can increase the nighttime UHI effect using a climate model. Yang et al. 2020 obtained different results when using observational data to perform similar research in the BTH region.

More detailed research needs to be performed by combining observational data and modeling because the conclusions may vary depending on the scale (Xu et al., 2019). Other illuminating work with regional models showed that the combined effect of UHIs and aerosols on precipitation depends on synoptic conditions (Zhong et al., 2015). However, for winter haze, Zhong et al. (2017) evaluated the urban impact on air quality and indicated that urbanization can increase ventilation in daytime and increase aerosol emissions, which outweighs the UHI effect.

However, very few studies have quantified the individual effects of urbanization-induced UHIs and aerosols with elevated emissions on the formation and development of haze in metropolitan areas. A difficulty is that the radiative forcing of aerosols is not a prognostic variable in most climate models (Cao et al. 2016). Some regional models such as WRF-Chem can overcome this problem by parameterizing aerosols to aerosol optical depth (AOD) in some specific radiation schemes. Tao et al. 2015 and Zhong et al. 2018 have made some progress in this area, and their results also indicate that the regional model can be used as an effective way to study the interaction between urbanization and aerosols. However, a quantitative evaluation of urban impacts on aerosols and aerosol impacts on urban-impact at the same time in metropolitan areas has not been attempted.

In this study, the Rapid-Refresh Multiscale Analysis and Prediction System-Short Term (RMAPS-ST) was used to investigate the mechanism of the influence of the above two factors in a typical winter haze event. The objective of this study is 1) to quantify impact of urban on aerosols and impact of aerosols on urbanization respectively and 2) to obtain a better understanding of the interaction between urbanization and aerosols and its influence mechanism on the boundary layer structure and haze transmission during the typical winter haze events in the BTH region. ~~This research will help to improve air quality under the continuous urbanization and sustainable development of large cities.~~

2 Methods

2.1 Observational data

To investigate the interaction between urbanization and aerosols, observation data on basic meteorological elements, air quality, radiation and surface heat flux and the mixing layer height (MLH) are very important to reveal the impact of urbanization and aerosols during haze events.

~~Four kinds of observational data were used in this study to reveal the synoptic situation of haze events and perform model evaluation.~~ The basic meteorological elements were obtained from ~~Meteorological data from~~ 309 national basic weather stations in the BTH region were provided by the China Meteorological Administration (http://data.cma.cn/). The locations of the national basic weather stations are shown in Fig 1 (red dots). The mass concentrations of fine particulate matter ($PM_{2.5}$) were recorded by 251 environmental monitor stations managed by the Ministry of Ecology and Environment of the People's Republic of China (http://hbk.cei.cn/aspx/default.aspx) (Fig 1, black dots). We also used radiation and surface heat flux data to analysis the urban surface energy budget which obtained~~Radiation and surface heat flux data were obtained~~ from the Beijing meteorological tower (39.97°N, 116.37°E~~),~~). The tower~~which~~ is 325 m high and operated by the Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (CAS). The heat flux data were measured by a fast response eddy covariance sensor system that was sampled at 10 Hz using CR500 (Campbell Scientific Inc., USA). The radiation data were provided by Kipp & Zonen (Netherlands) four-component unventilated CNR1 radiometers. Radiation and surface flux data from 140 m of the tower were used in this study. In addition, the MLH is an important factor affecting pollutant diffusion and is also affected by both urbanization and aerosols. Because the MLH is not a routine observation, we obtained the data from only one site. The ~~mixing layer height (~~MLH~~)~~ and backscattering coefficient were measured by enhanced single-lens ceilometers (Vaisala, CL51, Finland) deployed by the IAP. Backscattering coefficient profiles were calculated by reference to the attenuation strobe laser LiDAR technique (910 nm), which is cited in Tang et al. (2015).

2.2 Model description and experimental design

To investigate the respective effects of urbanization and aerosols and further determine the interaction between urbanization and aerosols, a high-resolution regional model with satisfactory performance is necessary for sensitivity tests.

The model used in this study is the latest available version of RMAPS-ST, developed by the Institute of Urban Meteorology, China Meteorological Administration. RMAPS-ST is based on the Weather Research and Forecasting (WRF v3.8.1) model (Skamarock et al., 2008) and its data assimilation system (WRFDA v3.8).

The simulation domain was centered at 37.0 °N, 105.0 °E and implemented with two nested grids with resolutions of 9 and 3 km for two domains (D1 and D2, respectively) (Fig 1a). The model performance was verified and RMAPS-ST runs operationally (Fan et al., 2018). The assimilation began every three hours, and the assimilated data included automatic meteorological station data, sounding data and radar data when available. The model settings are shown in Table 1. The simulation started at 0000 LST and ran from 15 to 23 December 2016 with hourly output.

The urban impact was represented by a high-resolution (30 m) land use map interpreted from Landsat Thematic Mapper satellite data for 2015 in Beijing. The urban canopy parameters were optimized according to Miao and Chen (2014). The impact of aerosols was represented by adding the hourly distribution of AOD in the RRTMG radiation scheme. The AOD was extracted from the output of RMAPS-Chem (Zhao et al., 2019; Zhang et al., 2018) for the BTH region, which is shown in Fig 1b. Anthropogenic emission data were obtained according to the Multiresolution Emission Inventory for China (2012) (http://www.meicmodel.org/) with a resolution of 0.1°×0.1°. The particle size distribution and typology of aerosols used in this study is according to Ruiz et al. (2014).– The simulated distribution of AOD in Beijing has been verified to be satisfactory when compared to the observed vertical profile of the backscattering coefficient (Fig 2a and b). The correlation of AOD and the column backscatter coefficient is 0.76 (Fig 2c). Four tests were designed to investigate the impacts of aerosols and urbanization on typical haze events. Test 1: Both urban and aerosol impacts were considered in the simulation. We updated the grid AOD distribution hourly as the input field for the RRTMG radiation scheme in Domain 2. Test 2: Only aerosol impact was considered in the simulation, and we replaced the urban grid with cropland to shield the impact of urbanization. Test 3: Only urban impact was considered, and the direct radiative forcing of aerosols was not considered in the simulation. Test 4: Both urban and aerosol impacts were not considered in the simulation.

The model evaluation results for the four tests are shown in Table 2. As the service operational system, the RMAPS-ST model assessment report indicated that the model performance was satisfactory (Fan et al. 2018). We evaluated not only the conventional meteorological variables (including temperature, humidity and wind speed) but also unconventional but important variables for this study (including radiation and surface heat flux). A total of 309 meteorological station data points were used to evaluate the conventional variables. The unconventional variables were evaluated according to the observational data from 140 m of the Beijing meteorological tower. Test 1 was found to be the best simulation and considers both the urban and aerosol impacts. The deficiency of observation sites, interpolation methods and the height differences between the observations and simulations resulted in higher root mean square error (RMSE) values for radiation and heat flux than for the other variables.

3 Results

3.1 Observation and weather condition analysisWeather analysis

A typical continuous severe heavy haze occurred from the 15th to 22nd of December 2016 in the BTH region. Three stages dominated by three different synoptic patterns controlled the formation of this haze. In the first stage, northwest airflow in front of a ridge of high pressure was observed in the BTH region at a height of 700 to 500 hPa and in eastern China at a height of 850 hPa on the 15th to 16th of December, which induced a sharp warming pattern (Fig 3a and b). At the surface, Beijing was located under the front of the high pressure system to under the southwest airflow in front of the low pressure system (Fig 4), which favored pollutant transport from Hebei Province to Beijing. From the 17th to the night of the 18th, the control system turned to the latitude circulation at 700 to 500 hPa over the BTH region (there was a trough line south of 40°N at 2000 LST on the 17th and 18th) (Fig 3c). There was a northwest wind located north of 40°N and a southwest wind located south of 40°N at 850 hPa (Fig 3d). The near surface was controlled by the northeast airflow located in the inverted trough of the low pressure. The weak convergence of the high trough cooperates with the low pressure at the surface, leading to continuous pollution accumulation near the surface. Under this weather situation, the near-surface temperature began to continuously increase from the 16th to 18th, and the specific humidity also correspondingly increased (Fig 5a). The near-surface wind speed and pressure decreased during this period (Fig 5b). The concentration of $PM_{2.5}$ gradually increased from the 16th, and the average concentration of $PM_{2.5}$ reached 200 $\mu g \cdot m^{-3}$ on the 18th. The density of ozone obviously decreased from the 16th (Fig 5c).

The MLH significantly declined from the 16th, and the diurnal circle almost disappeared during this period, accompanied by a visibility reduction but diurnal variation (Fig 5d). The downward shortwave radiation and the net radiation gradually decreased from the 16th to the 18th, which directly influenced the variation trend of ozone (the maximum density of ozone was less than 110 $mg \cdot m^{-3}$), while there was little change detected in longwave radiation (Fig 5e). The observed sensible heat flux also decreased from the 16th to the 19th although the temperature increased, which means that the heat exchange became weaker in the vertical direction, while the latent heat flux changed little (Fig 5f). Southwest airflow was again captured by a wind profiler on the night of the 18th and the transport layer occurred from 300 to 1500 m, which differs from the previous surface transport pattern (Fig 4).

In the second stage, the important change occurred in on the morning of the 19th of December, when the control system turned to the northwest airflow on the front of the trough over the BJH region at 500 to 850 hPa (Fig 3e and f). After 2000 LST on the 19th, obvious warming occurred again at 850 hPa in eastern China (Fig 3h). However, the near-surface maximum temperature and diurnal range in Beijing significantly decreased but with high specific humidity during the 20th to the 21st (Fig 5a). According to the surface weather map, the control system turned to the southwest at 1400 LST on the 19th, and a large-scale southeast wind appeared in eastern Beijing after 2000 LST, which induced wide advection fog formation during the night (Fig 3g). Due to the influence of the southwest airflow on the tough at 500 hPa, the inverted trough moved east, and Beijing was located in the southeast wind zone. The near-surface pressure increased slightly, and the wind speed remained low at approximately 1 $m\cdot s^{-1}$ (Fig 5b). The synoptic system caused the $PM_{2.5}$ concentration to peak (approximately 400 $\mu g\cdot m^{-3}$ on average and above 500 $\mu g\cdot m^{-3}$ observed at some stations) and was maintained from the 20th to the 21st in the BTH region. The visibility was less than 400 meters, and the diurnal circle disappeared (Fig 5d). The decrease in the downward shortwave and net radiation was more pronounced than that in the previous three days (Fig 5e). The sensible heat flux also decreased, and the diurnal circle almost disappeared from the 19th to the 20th (Fig 5e).

It was not until the strong cold air moved southward in the early morning of the 22nd when the whole atmosphere converted to the northwest stream. The air pollutants were completely removed in the third stage.

3.2 Interaction between the impacts of urbanization and aerosols on haze events

Four impacts were analyzed as following. Urban impact under the aero scenario (UI_aero) was represented by the results of Test 1 minus those of Test 2; urban impact under the no-aero scenario (UI_noaero) was represented by the results of Test 3 minus those of Test 4; The impact of the urbanization scenario was represented by the results of Test 1 minus those of Test 3 (AI_urban); the impact without urbanization was represented by the results of Test 2 minus those of Test 4 (AI_nourban). The interaction between urbanization and aerosols on local meteorological and regional transportation was discussed.

3.2.1 The impact on the local area

The quantitative results of the interaction between urbanization and aerosols are shown in Table 3.

Temperature is one of the most sensitive variables affected by urbanization and aerosols and is also the most concerning variable. ~~The impact of urbanization on the near-surface temperature in the Beijing area displays diurnal variation features. The warming induced by urbanization was dominant at night. The urban impact was obviously decreased under the aerosol scenario by comparing the results of UI_aero and UI_noaero, especially in the daytime (Fig 6a, red lines).~~ The impact of urbanization on the near-surface temperature displays diurnal variation in the Beijing area. The warming effect of urbanization was dominant at night. The urban impact on temperature was partly offset under aerosol conditions when comparing the results of UI_aero and UI_noaero, especially during the daytime (Fig 6a, red lines). The urban impact always showed a positive contribution to the temperature during the whole day under the no-aerosol scenario, while the urban impact became slightly negative with the aerosol scenario in the daytime. The maximum difference between UI_aero and UI_noaero occurred on the 20th and 21st, when the AOD value reached its maximum, and the difference almost disappeared on the 15th and 22nd, with a small AOD (Fig 2b). The results indicate that the impact of urbanization on temperature is reduced by aerosols, which is consistent with the findings of Yang et al. 2020. The average urban impact on temperature in Beijing during the 16th to 19th with a $PM_{2.5}$ concentration of approximately 200 mg·m^{-3} was a reduction of 0.42°C according to UI_aero and of 0.60°C according to UI_noaero. This means that aerosols reduce the urban impact on temperature by 30%. When the concentration of $PM_{2.5}$ reached 500 mg·m^{-3} from the 20th to the 21st, the aerosols reduced urbanization-related warming by 54~~3.5~~%.

The impact of aerosols on temperature is negative and without a diurnal circle under the urbanization scenario for the whole day (Fig 6a, blue lines). However, the impact of aerosols captured by AI_nourban is more significant and displays a diurnal circle. Another important observation is that the impact of aerosols on temperature under the no-urban scenario is not always negative. There is a slight warming period at dawn in the AI_nourban scenario, which maybe because the longwave radiation is increased (Jacobson,1998; Rudich et al., 2007). The average impact of aerosols on temperature in Beijing was -0.16°C with urbanization and -0.34°C without urbanization from the 16th to the 19th. The impact of aerosols was -0.19°C with urbanization and -0.43°C from the 20th to the 21st. Urbanization decreased the impact of aerosols by 53% under moderate pollution and by up to 56% under heavy pollution. Two different impacts of aerosols on urban-related warming were observed. There was a reducing effect in the daytime with a strength of approximately 30 to 50% of the concentration and an increasing effect occurred at dawn with a strength of approximately 28%. Urbanization reduced the aerosol-related cooling effect by approximately 54%.

The observed specific humidity continued to increase as the aerosol concentration increased (Fig 5b) and is closely related to the UHI effect and aerosol composition (Zhang et al. 2010; Sun et al., 2013; Wang et al., 2020). The specific humidity also increased with urbanization throughout the day (Fig 6b, red lines). Similar to temperature, urbanization had a more pronounced impact on specific humidity at night. The average urban impact on specific humidity was ~~0.0~~3.66×10^{-2}~~-~~g·kg^{-1} according to UI_aero and ~~0.0~~4.78×10^{-2} g·kg^{-1} according to UI_noaero during the 16th to 19th and ~~0.0~~3.08×10^{-2} and ~~0.0~~4.48×10^{-2}~~-~~g·kg^{-1} during the 20th to 21st. Aerosols not only reduced the urban impact on the average daily specific humidity by 23.43% but also reduced the diurnal range of specific humidity.

In contrast to urbanization, aerosols were found to reduce the specific humidity (Fig 6b, blue lines). The impact of aerosols under the urbanization scenario was small and without a diurnal pattern. However, their impact under the no-urban scenario was more distinct and with a diurnal circle. The average impact of aerosols on specific humidity was -~~0.0~~0.88 g·kg^{-1} according to AI_urban and -~~0.0~~1.36 g·kg^{-1} according to AI_nourban during the whole study period. Urbanization reduced the impact of aerosols on specific humidity by 35.3%. The impacts of urbanization and aerosols on humidity were slightly greater than those of aerosols on urban impacts.

There was no effect of urbanization on downward shortwave radiation according to both UI_aero and UI_noaero (Fig 6c, red lines), although the value is not absolutely related to aerosols because of model uncertainty. Aerosols reduce the downward shortwave radiation during the daytime, and the differences between AI_urban and AI_nourban are very small.~~ Aerosols reduce the downward shortwave radiation in the daytime, and there are few differences between AI_urban and AI_nourban~~.

The average decrease in shortwave radiation caused by aerosols was approximately 7% of the total downward shortwave radiation during the 16th to the 20th and up to 17% when the $PM_{2.5}$ was greater than 400 μg·m^{-3}. The urban impact increased the longwave radiation in the nighttime according to UI_aero, while the impact of urbanization was always positive for longwave radiation during the study period according to UI_noaero (Fig 6d, red lines). Because it is closely related to temperature, the urban impact on long wave radiation was also reduced by aerosols, with reductions of 83~~.3~~% from the 16th to the 19th and of 97~~6.6~~% from the 20th to the 21st. The impact of aerosols on longwave radiation is smaller than that of shortwave radiation, and there was a slight decrease captured by AI_urban with an increase from noon on the 20th to nighttime on the 21st. The impact of aerosols decreased the longwave radiation captured by AI_nourban during the 16th to the 20th and increased it on the night of 21st (Fig 6d, blue lines). Urbanization reduced the impact of aerosols on longwave radiation by 66.97% while aerosols reduced the urban impact on longwave radiation by 89.2%. The impacts of urbanization and aerosols on longwave radiation are unimportant because they are both smaller than 2 W·m^{-2}.

The change in radiation further alters the MLH. Previous studies suggest that MLH is important for the diffusion of pollutants and haze formation (Sun et al. 2013; Quan et al. 2014). Previous studies on urbanization indicated that urban-induced warming will increase the MLH during the daytime (Wang et al., 2007; Miao et al. 2012), and the results of UI_noaero show the same pattern. However, when we introduced aerosols into the simulation, urbanization was found to decrease the MLH in the daytime according to UI_aero. The impact of aerosols decreased the average urbanization by 148% during the haze event (Fig 6e, red lines). Aerosols significantly decreased the MLH in daytime according to both AI_urban and AI_nourban (Fig 6e, blue lines). Urbanization decreased the impact of aerosols on MLH by 57.848% during the haze event.

Urban land use change directly alters the surface heat flux. Urbanization increased the sensible heat flux according to UI_noaero but decreased the sensible heat flux according to UI_aero (Fig 6f, red lines). The impact of aerosols in reducing the urban impact on sensible heat flux was 156% during the haze event. Aerosols reduced the sensible heat flux according to both AI_urban and AI_nourban (Fig 6f, blue lines). The maximum impact of aerosols was on the 21st, with the maximum AOD. The impact of urbanization reduced the impact of aerosols on sensible heat flux by 59.3%.

There was little effect of urbanization on latent heat flux because the observed latent heat flux in urban areas was small (Fig 6g, red lines, and Fig 5e). Aerosols decreased the latent heat flux, and the impact increased with increasing AOD (Fig 6g, blue lines). The impact of urbanization reduced the impact of aerosols on the latent heat flux by 48.8%.

The above results indicate that the offsetting effect of aerosols on urbanization is more important than the impact of urbanization on aerosols on local weather.

In general, the impact of aerosols on urban impacts is more important than the impact of urban impacts on aerosol impacts in terms of local effects.

3.2.2 Effects on regional circulation

There are few valuable findings from the diurnal average wind speed analysis because the average wind speed was low during the haze event. Wind speed is likely to become more meaningful in the spatial analysis of wind vectors. There are two main transmission processes of pollution from Hebei Province to Beijing in this haze process according to the weather map and wind profile analysis (Fig 4). Accordingly, the diurnal pattern of $PM_{2.5}$ in Beijing (Fig 5c) also displays two increasing processes on the 16^{th} and 19^{th} (from 1800 to 2400 LST). The observed near-surface wind vector displays these two pollutant transport processes (Fig 7). In the first processes, obvious aerosol transport began on the night of the 15^{th} and continued to the night of the 16^{th} (Fig 6). The southwest wind dominated most of the southern part of Hebei Province. The transmission flux was strong in the daytime on the 16^{th}, leading to the concentration of $PM_{2.5}$ continuing to increase in Beijing and in its transmission path. The wind speed remained low from the 17^{th} to the 18^{th} in most of the plain area, and the concentration of $PM_{2.5}$ continued to increase in the southwest and northeast of Hebei Province. The second processes began at 1400 LST on the 19^{th} and the south wind dominated the south of Beijing and turned to the southwest in Beijing at 1400 to 1800 LST. The dominant wind direction turned to the southwest at 2200 LST in the southern part of Hebei Province with a rapid increase in the concentration of $PM_{2.5}$.

Most industrial aerosols in Beijing are transported from the southwest and northeast of Hebei Province due to the control of pollutant discharge in the Beijing area during haze events. Therefore, the impact of urban areas and aerosols on transport, namely wind fields is are very important for air quality in Beijing. The modeling results show that urbanization not only increased the temperature in urban areas (Fig 8a and b) but also increased the average south-wind transport flux in the two main transmission processes of pollution in the southwest area of Beijing (Fig 8a and b). The transmission flux captured by UI_noaero is stronger than that captured by UI_aero. The local cyclonic circulation induced by urbanization further induces upward movement, which is beneficial to diffusion conditions. Although aerosols decrease the transmission flux induced by urbanization, the strength of local cyclonic circulation is also reduced by aerosols. Furthermore, the aerosols reduced the temperature in most of the plain area in Hebei Province (Fig 8c and d). Urbanization decreases the impact of aerosols on temperature. There was no local or systemic effect on the wind field captured by either AI_urban or AI_nourban.

Taylor diagrams were used to analyze the relative contributions of urbanization and aerosols over time (Fig 9). The daily mean difference in these four types of impact (UI_aero, UI_noaero, AI_urban, and AI_nourban) over the eight days in the Beijing area is shown by Taylor diagrams. UI_noaero shows that temperature continues increasing from Day 1 to Day 5 and reaches a maximum on Day 7. The variation in temperature according to UI_urban is smaller. This means that the effect of urbanization on temperature is decreased by aerosols. Temperature increases from Day 1 to Day 7 according to AI_urban, while AI_nourban shows an increase from Day 3 to Day 7. The reduction of the urban impact on temperature by aerosols was more important than the reduction of aerosol impact on temperature by urbanization (Fig 9a). The effect of aerosols on urban impacts on temperature was more important than urban impacts on the effects of aerosols on temperature (Fig 9a). Specific humidity continued increasing from Day 1 to Day 5 according to UI_noaero, while the variation in specific humidity was small according to UI_aero (Fig 9b). Similar to what was observed for temperature, reducing the urban impact on specific humidity by aerosols is more important than reducing aerosol impacts by urban areas. The ventilation coefficient (VC) in UI_aero showed little change over these eight days, and this coefficient showed increases on Days 2, 3, 5, and 6 and decreases on Days 4, 7, and 8 according to UI_noaero. The reduction of the urban impact on the VC by aerosols is more important than the reduction of the impact of aerosols by urbanization. The analysis of shortwave radiation also provided the same conclusion that the reduction in the urban impact on the daily mean by aerosols was more important than the reduction of the impact of aerosols by urbanization (Fig 9d).

3.2.3 Impacts on the vertical distribution

In the period from 0000 LST to 0800 LST on the 16^{th} to 20^{th}, there was an interesting phenomenon that temperature was a slightly larger in UI_aero than in UI_noaero, and the urban impact reached a maximum at the same time. Such an outcome is easy to overlook if the analysis only focuses on the daily average. Therefore, a detailed vertical temperature and wind field analysis of the four addressed scenarios (UI_aero, UI_noaero, AI_urban, and AI_nourban) was used to determine the mechanism behind this finding (Fig 10).

The impact on warming by urbanization reached 350 m in UI_aero and 450 m in UI_noaero (Fig 10a and b). Aerosols not only increased the warming impact induced by urbanization but also reduced the warming height. Aerosols increase the near-surface warming effect induced by urbanization because of the absorption of longwave radiation. Although absorption by aerosols was always observed during the study period, the impact increased with the increase in longwave radiation induced by urbanization. Therefore, the warming effect of aerosols may dominate at night in the near-surface layer. This further induces the urban-related warming to increase and compress this effect to a lower height with a lower MLH in UI_aero than in UI_noaero (Fig 10a). The aerosols reduced the temperature below 450 m in the urban area of Beijing (Fig 10c and d) and the cooling effect was reduced by urbanization below 450 m. Urbanization also reduces the near-surface west wind induced by aerosols in urban areas because of the drag caused by buildings.

4 Conclusion

A typical persistent haze process occurred on the 15th to 22nd of December 2016 in the BTH region. The average concentration of $PM_{2.5}$ was approximately 200 μg·m^{-3}, and the maximum was 695 μg·m^{-3} ~~and the maximum was greater than 400 μg·m^{-3}~~. The interaction between aerosols and urbanization on haze events were investigated in this study. Four tests were designed using RMAPS-ST to study the mechanism of the impacts of aerosols and urbanization respectively.

Two different impacts of aerosols on urban-related warming were found. A reducing effect occurred during the daytime, and the strength was approximately 30 to 50% of the concentration. An increasing effect occurred at dawn, and the strength was approximately 28%, which is important for haze formation. The combined effect was a reducing effect on the daily mean of urban-related warming. Urbanization reduced the aerosol-related cooling effect by approximately 54% during the haze event, and the strength of the impact changed little with increasing aerosol content. The impact of urbanization on the effect of aerosols on humidity is slightly larger than the impact of aerosols on urban impact. Aerosols reduce the average downward shortwave radiation from 7% to 17% with concentrations of $PM_{2.5}$ of 200 to 400 μg·m^{-3}. There is no urban impact on downward shortwave radiation or the impact of aerosols on shortwave radiation. The impacts of urban areas and aerosols on longwave radiation are both smaller than 2 W·m^{-2}. A more significant impact of aerosols is on the MLH and sensible heat flux. The decrease in urban impact caused by aerosols reaches 148% for MLH and 156% for sensible heat flux. These values are much larger than those for urbanization, which reduces the impact of aerosols on the MLH and sensible heat flux. There is little urban impact on latent heat flux. However, aerosols decreased the latent heat flux, and the impact was reduced by 48.8% by urbanization. In general, the impact of aerosols on urban impact is more important than the impact of urbanization on aerosol impacts in terms of regional averages.

Urbanization increased the wind speed southwest of the Beijing area and the local cyclonic circulation in the urban area of Beijing during the two main transmission processes. Although aerosols reduced the urban-related southwest transmission, they made the diffusion conditions worse in urban areas. The impact of urbanization on wind fields, namely, the transport of pollutants, is more important than that of aerosols. However, the interaction between urbanization and aerosols may enhance the accumulation of pollution and weigh against diffusion.

The impact of aerosols on urban-related warming is more significant than the impact of urbanization on aerosol-related cooling according to spatial statistical analysis. Similar results were found for absolute humidity, the VC and shortwave radiation. Aerosol-related warming is dominant at dawn in the near-surface layer. Aerosols increase urban-related warming and reduce the impact height of urban-related warming. This further enhances stability and reduces the MLH.

5 Discussion

In this study, it was easier to distinguish the impacts of aerosols and urbanization by using the RMAPS-ST with AOD hourly input than with RMAPS-Chem to investigate the impact of aerosols. One reason for this is that the model performance of RMAPS-ST is much better than that of RMAPS-Chem in meteorological fields. Although real-time feedback in modeling is not provided, RMAPS-ST is more efficient and more suitable for short-term operational forecasting.

This study not only qualified the impacts of aerosols and urbanization on haze events but also analyzed the interaction between aerosols and urbanization during haze events. This research will help to improve air quality under the continuous urbanization and sustainable development of large cities.

The government has taken a series of emission reduction measures, including limiting industrial emissions and vehicle plate number traffic restriction measures, to improve the air quality in the BTH region. The policies have been effective in reducing aerosols. At the same time, urbanization continues mainly in the areas around Beijing (such as the Xiongan New Area). The results of this study show that the combined impact of urbanization and decreasing aerosols will increase the downward shortwave radiation and further increase the surface temperature and ozone concentration in the boundary layer. Previous studies indicated that ozone generally increases with temperature and decreases with humidity (Camalier et al., 2007; Cardelino et al., 1990). It is well known that ozone is not only a pollutant but also a greenhouse gas. Therefore, ozone will form a positive feedback mechanism to induce warming and ozone pollution in the boundary layer. This feedback will pose a new challenge regarding how to reduce ozone pollution in urban areas. Some studies have suggested that urban greening can effectively reduce ozone pollution (Nowak et al., 2000; Benjamin and Winer, 1998). More attempts should be made to add the interaction between urbanization and ozone in regional models.

Data availability

The data in this study are available from the corresponding author upon request (tgq@dq.cern.ac.cn).

Author contribution

Miao Yu designed the research and wrote the paper. Guiqian Tang conducted the measurements and reviewed the paper. Yang Yang conducted modelling tests. Qingchun Li and Yonghong Wang performed~~Qingchun Li did~~ synoptic analysis. Shiguang Miao, Yizhou Zhang and Yusi Wang~~Shiguang Miao and Yizhou Zhang~~ reviewed and commented on the paper.

Competing interests

The authors declare that they have no conflicts of interest to disclose.

Table 1 RMAPS-ST model settings.

WRF v3.8.1	D01	D02
Horizontal grid	649×400	550×424
Grid horizontal spacing (km)	9	3
Vertical layers	49	
PBL	YSU (Hong et al., 2006)	
Microphysics	Thompson (Thompson et al., 2008)	
Cumulus	Kain-Fritsch (Kain, 2004)	None
LW Radiation	RRTMG	
SW Radiation	RRTMG	
LSM	Noah LSM+SLUCM	
Urban parameter values	Modified according to Miao and Chen (2014)	

Table 2 Model evaluation (RMSE and BIAS) for the four tests.

	Test 1		**Test 2**		**Test 3**		**Test 4**	
	RMSE	BIAS	RMSE	BIAS	RMSE	BIAS	RMSE	BIAS
Temperature	**1.27**	**0.35**	1.45	-0.73	2.12	1.04	1.78	-0.45
Specific humidity	**0.26**	**-0.015**	0.31	0.019	0.34	-0.05	0.29	0.03
Wind speed	**1.62**	**0.97**	2.08	1.68	1.85	1.04	1.96	1.67
Shortwave	**40.91**	**11.85**	40.95	11.89	47.35	17.45	46.26	16.45
Longwave	**51.39**	**-43.65**	51.32	-44.45	51.24	**-43.53**	52.76	44.97
Sensible heat flux	**8.09**	**-1.19**	9.13	-3.92	9.34	-3.43	12.3	-6.17
Latent heat flux	**14.09**	**-5.75**	14.52	-5.95	14.85	-5.87	16.76	-6.23

Table 3 Quantitative results of interaction between urbanization and aerosols

	Temperature °C		**Specific humidity ×10-2 g·kg^{-1}**		**Longwave W·m^{-2}**		**MLH m**	**Sensible heat flux W·m^{-2}**	**Latent heat flux W·m^{-2}**
Time	16^{th}-19^{th}	20^{th}-21^{st}	16^{th}-19^{th}	20^{th}-21^{st}	16^{th}-19^{th}	20^{th}-21^{st}	16^{th}-21^{st}	16^{th}-21^{st}	16^{th}-21^{st}
UI_aero	0.42	0.19	3.66	3.08	0.10	-0.02	-1.97	-1.01	0.03
UI_noaero	0.60	0.35	4.78	4.48	0.62	0.51	4.04	1.74	0.49
AI_urban	-0.16	-0.19	-0.88		-0.24		-4.37	-1.64	-0.50
AI_nourba	-0.34	-0.43	1.36		-0.73		-10.38	-4.02	-0.96

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Figure

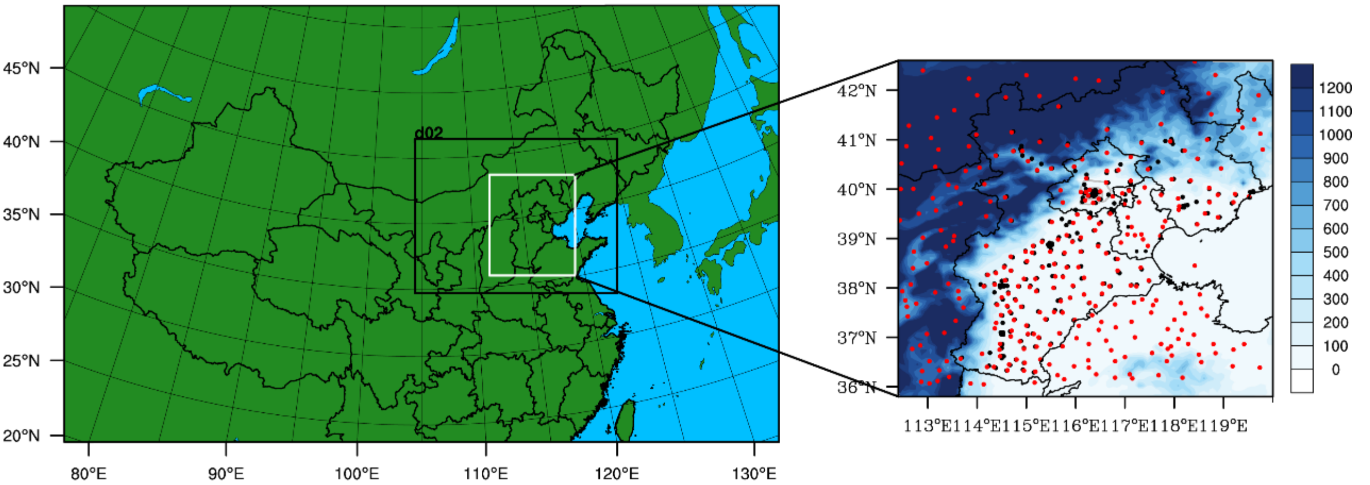
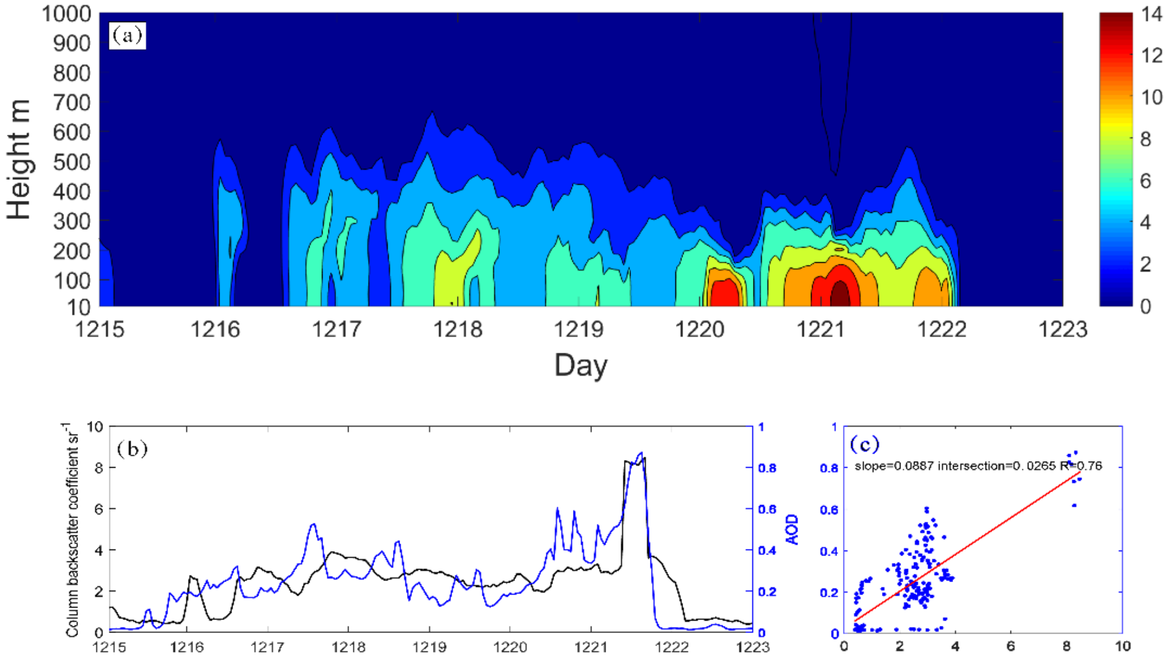


Figure 1 Domain configuration of RMAPS-ST and the location of the study area, indicated by the solid white line. The black dots indicate the locations of the 251 environmental monitoring stations, and the red dots represent the 309 meteorological stations in the BTH region, where the gray loop lines show the locations of the second to sixth ring roads. The shading is the terrain height (unit: m).~~Domain configuration of RMAPS-ST and the location of the study area, indicated by the white solid line. The black dots indicate the locations of the 251 environmental monitoring stations, and the red dots represent the 309 meteorological stations in the Beijing-Tianjin-Hebei region, where the gray loop lines show the locations of the second to sixth ring roads.~~



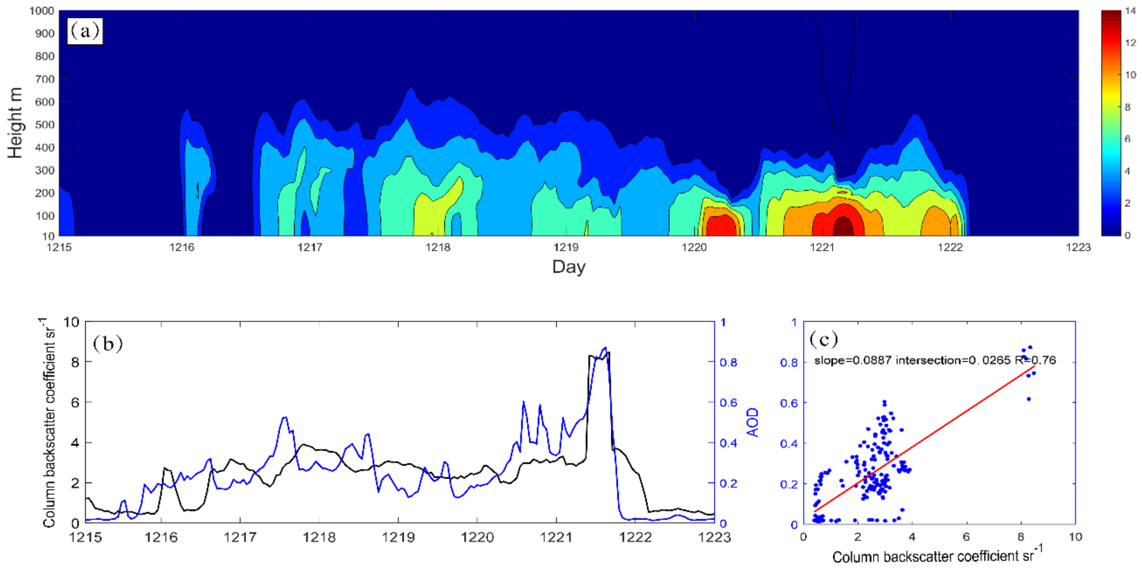
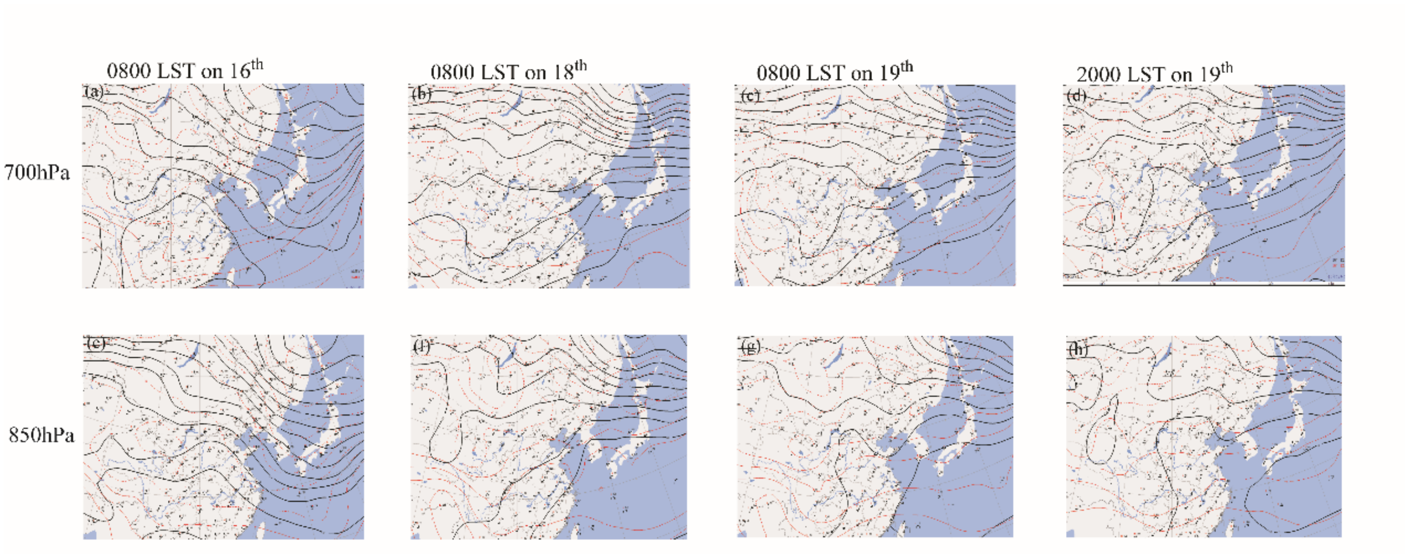


Figure 2 (a) Hourly backscattering coefficient (shading; Mm·sr^{-1}) observed by single-lens ceilometers (39.97°N, 116.37°E) from the 15th to 23rd of December; (b) hourly column backscatter coefficient (black line; sr^{-1}) and AOD used in modeling for Beijing (blue line) and (c) scatter diagram of hourly column backscatter coefficient and AOD (blue dots) and their correlations (red line).

~~(a) Hourly backscattering coefficient (shading; mm·sr^{-1}) observed by single-lens ceilometers (39.97°N, 116.37°E) from the 15th to 23rd of December; (b) hourly column backscatter coefficient (black line; sr^{-1}) and AOD used in modeling for Beijing (blue line) and (c) their correlations.~~



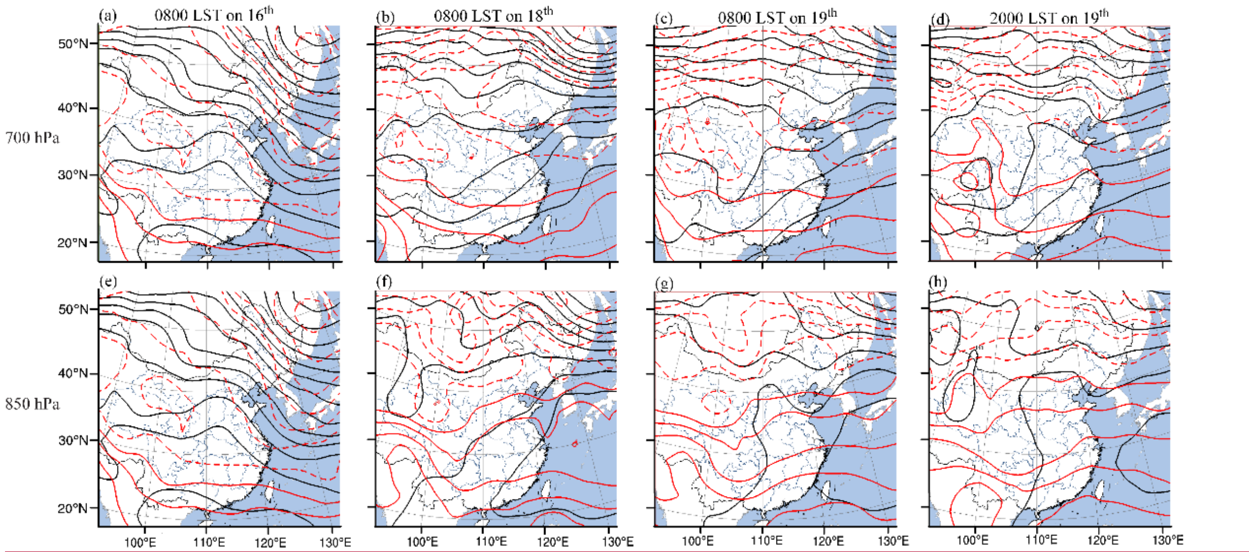
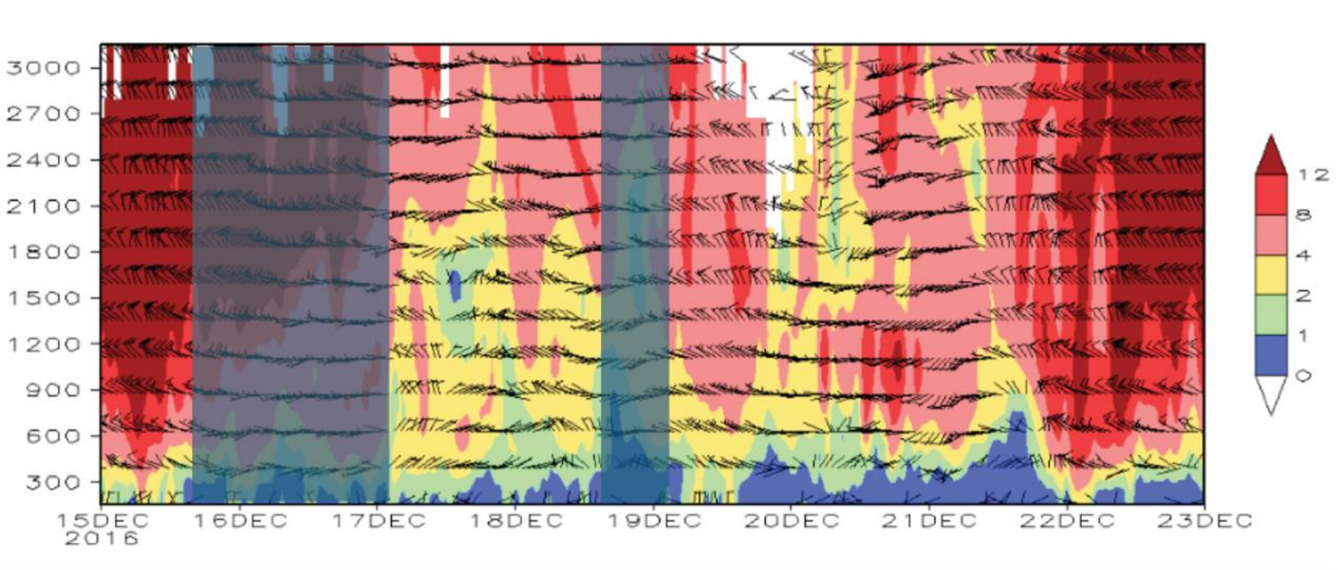


Figure 3 Weather maps. (a) 0800 LST on the 16th at 700 hPa; (b) 0800 LST on the 18th at 700 hPa; (c) 0800 LST on the 19th at 700 hPa; (d) 2000 LST on the 19th at 700 hPa; (e) 0800 LST on the 16th at 850 hPa; (f) 800 LST on the 18th at 850 hPa; (g) 0800 LST on the 19th at 850 hPa; (h) 2000 LST on the 19th at 850 hPa.



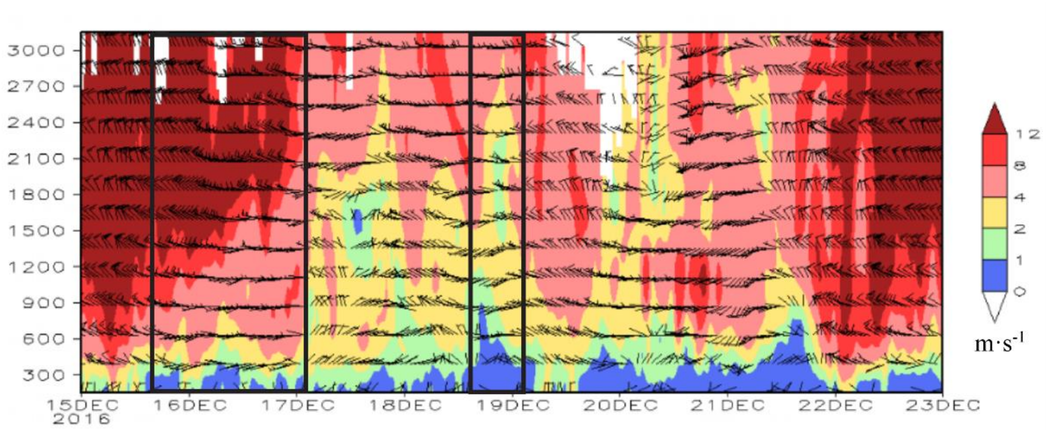


Figure 4 Hourly wind profile from the 15th to 23rd of December. Wind speed (shading; m·s^{-1}) and horizontal wind field (vector; m·s^{-1}). The black boxes ~~shaded parts~~ show the two periods of south wind conveyance.

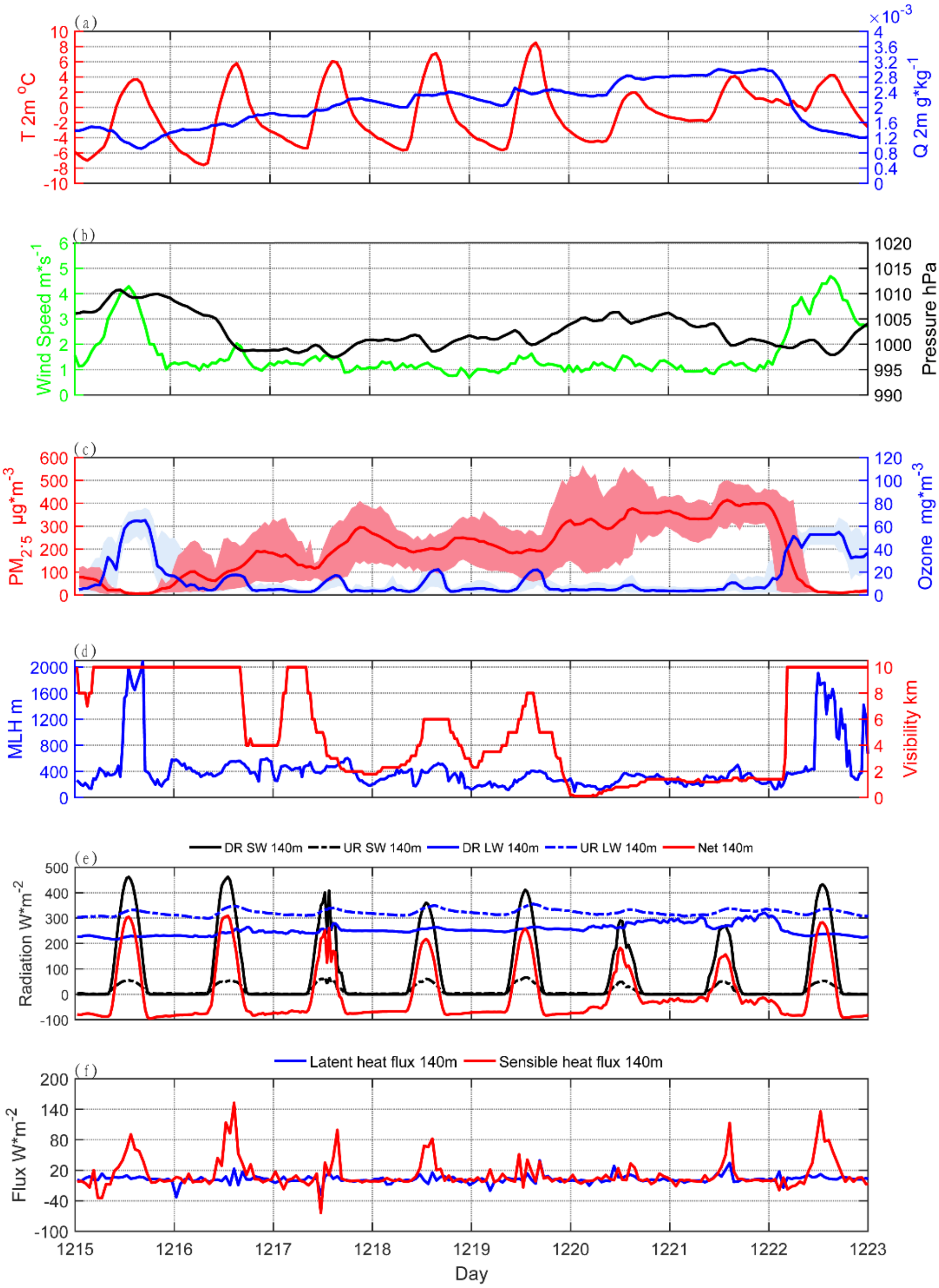


Figure 5 Diurnal pattern of observed variables from the 15th to 23rd of December in Beijing. (a) Temperature (red line; ℃) and absolute humidity (blue line; g kg^{-1}) at 2 m; (b) wind speed at 10 m (green line; m s^{-1}) and pressure (black line; hPa); (c) average $PM_{2.5}$ concentration (red line is the average and the shading indicates the standard deviation; ug m^{-3}) and ozone concentration (blue lines and the shading indicate the standard deviation; mg m^{-3}) of 35 environmental monitoring stations in Beijing; (d) mixing layer height (blue line; m) and visibility (red line; km); (e) radiation from the observation tower at 140 m, downward shortwave radiation (solid black line; W m^{-2}), upward shortwave radiation (dashed black line; W m^{-2}), downward longwave radiation (solid blue line; W m^{-2}), upward longwave radiation (dashed blue line; W m^{-2}), net radiation (red line; W m^{-2}); and (f) sensible heat flux (red line; W m^{-2}) and latent flux (red line; W m^{-2}).

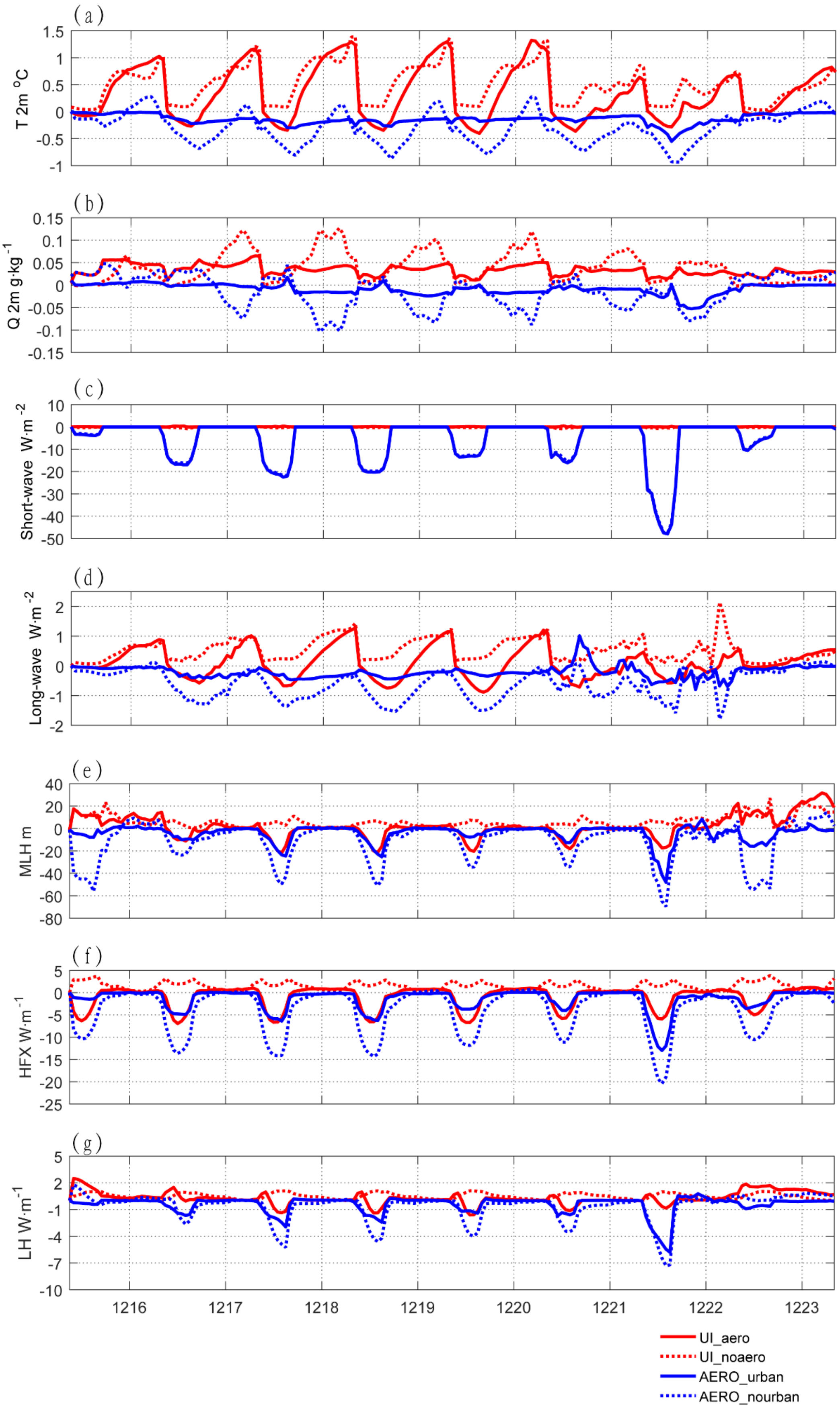


Figure 6 Diurnal pattern of the simulated variable from the 15th to 23rd of December. (a) Temperature at 2 m (℃); (b) specific humidity (g kg^{-1}) at 2 m; (c) shortwave radiation (W m^{-2}); (d) longwave radiation (W m^{-2}); (e) MLH (m); (f) sensible heat flux (W m^{-2}); and (g) latent heat flux (W m^{-2}).

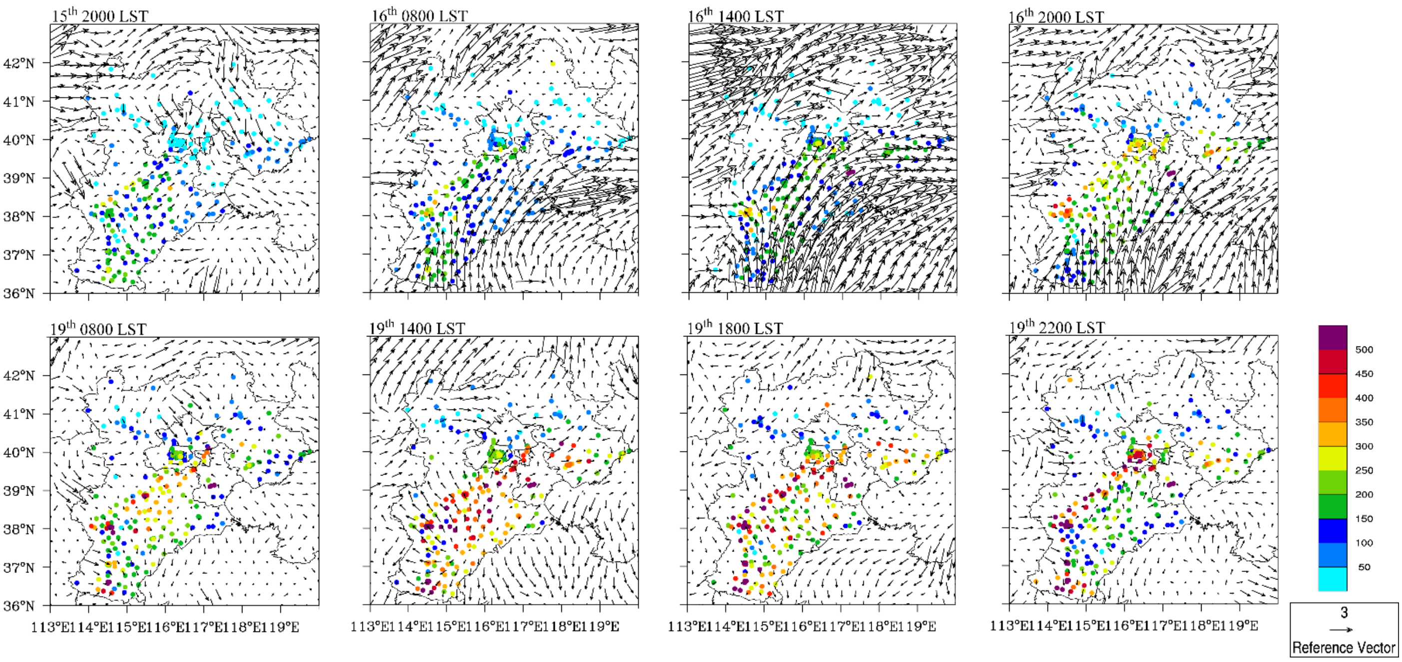


Figure 7 Spatial distribution of the observed concentration of $PM_{2.5}$ (dots; ug m^{-3}) and wind field (vector; m s^{-1}) for two increasing processes of the concentration of $PM_{2.5}$.

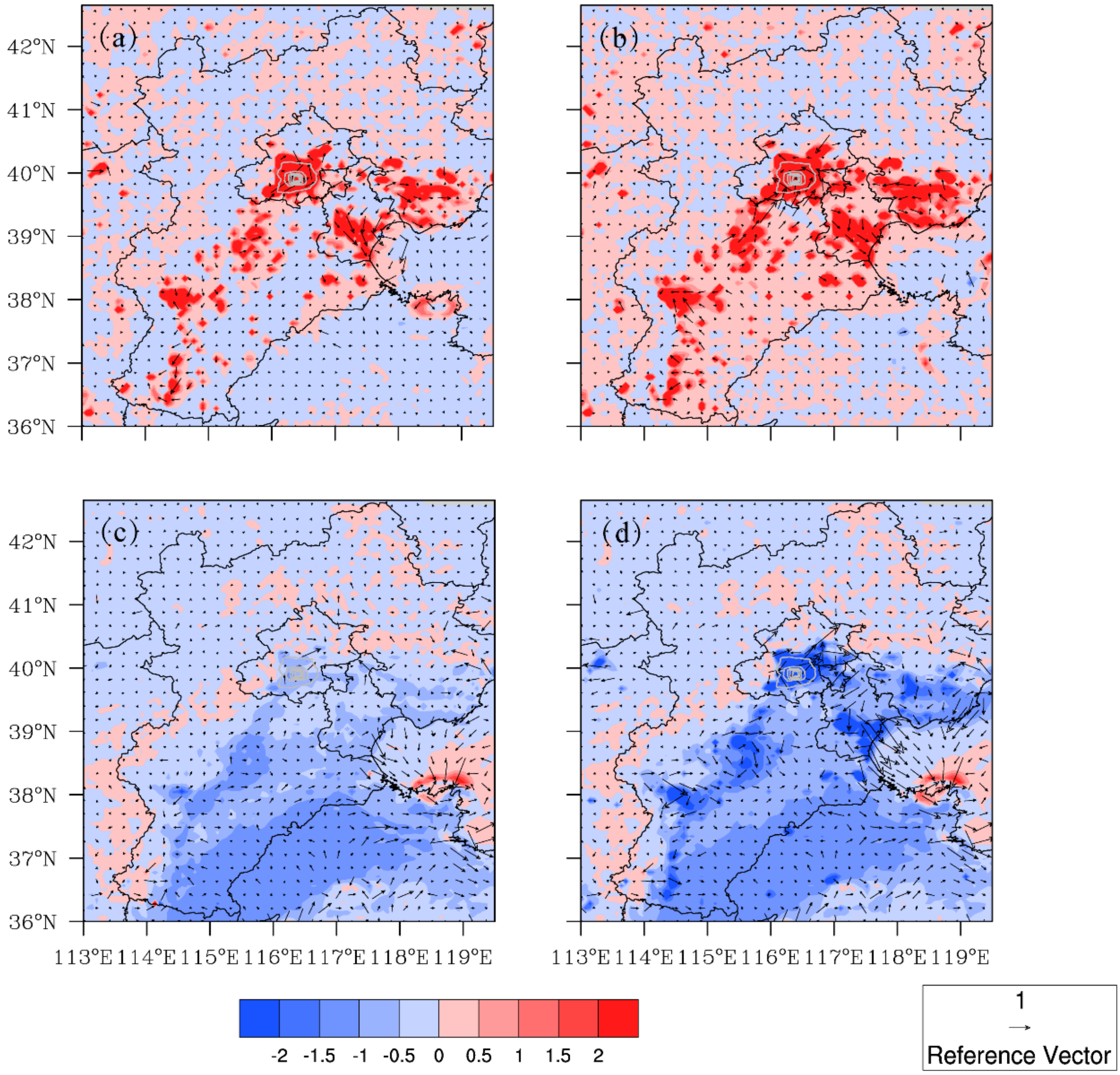
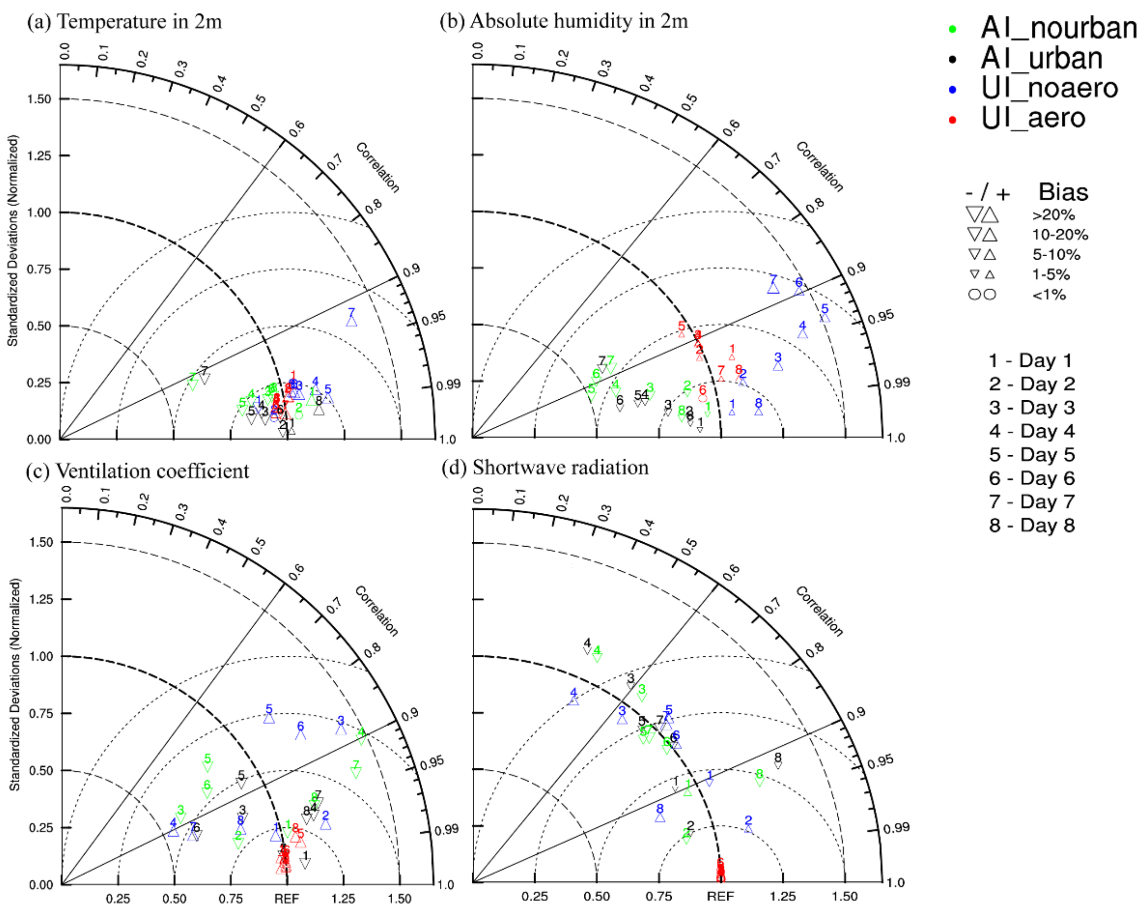


Figure 8 Spatial distribution of simulated temperature (shading; °C) and wind field (vector; m s^{-1}). (a) UI_aero; (b) UI_noaero; (c) AI_urban; (d) AI_nourban.



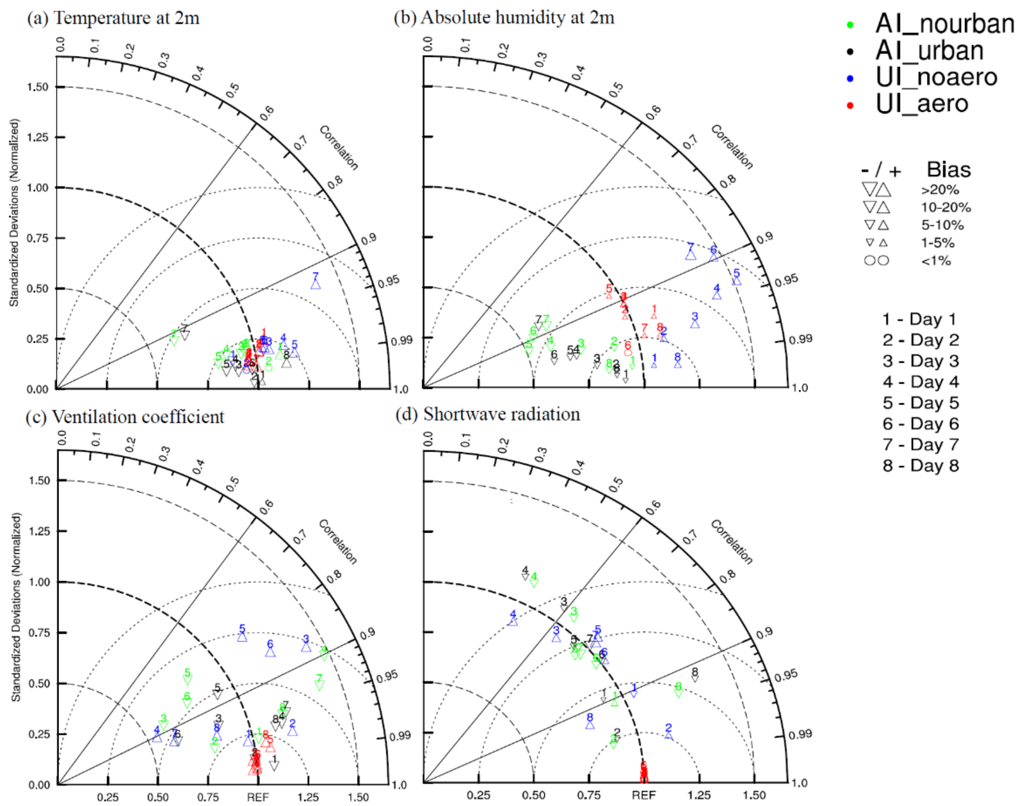


Figure 9 Daily means of the four types of impacts (UI_aero, UI_noaero, AI_urban, AI_nourban) in the eight days are shown in Taylor diagrams in the Beijing area. (a) Temperature at 2 m (°C); (b) absolute humidity (g kg^{-1}); (c) ventilation coefficient (m^2 s^{-1}); (d) shortwave radiation (W m^{-2}).

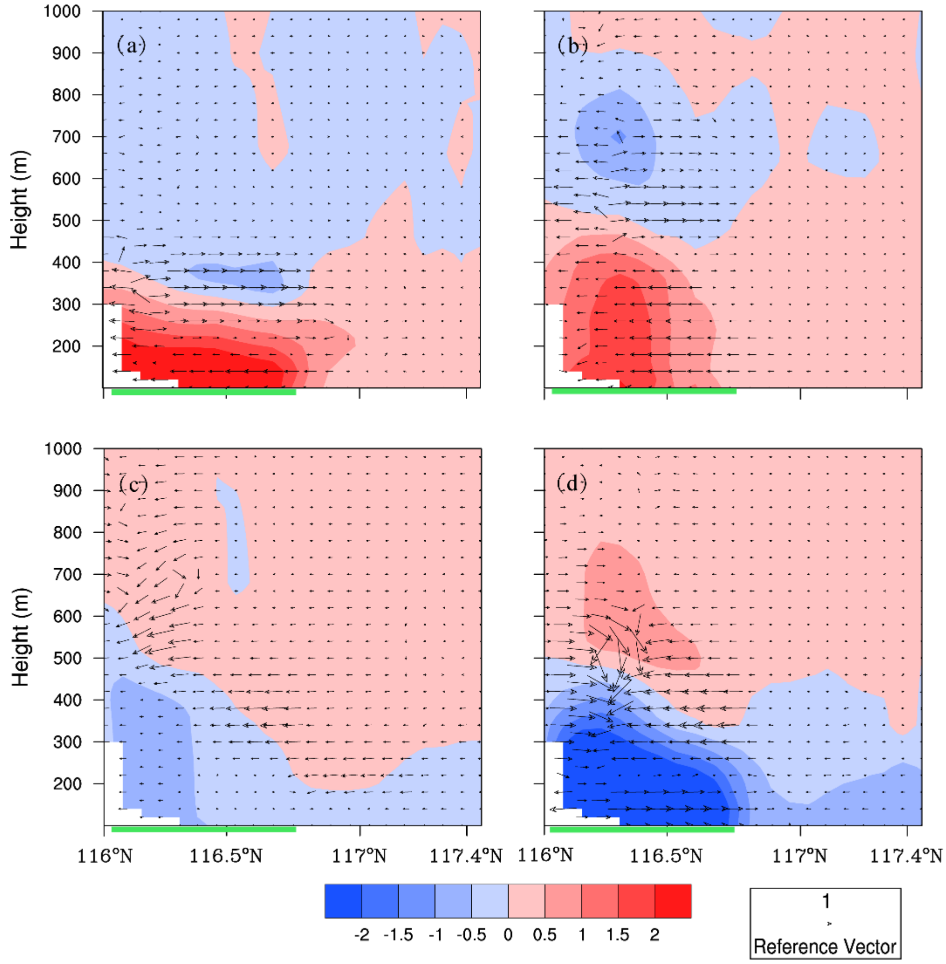


Figure 10 Cross section at 39.9 °N of average temperature (shading; °C) and wind field (vector; m s^{-1}) from 0000 LST to 0800 LST on the 16th to 20th. (a) UI_aero; (b) UI_noaero; (c) AI_urban; (d) AI_nourban.