

Response Letter

Dear Editors and Reviewers:

We sincerely thank you for facilitating the review process and providing valuable feedback. The comments received have been instrumental in enhancing our manuscript's quality and clarity.

Additionally, in response to the editorial support team's feedback, we have revised the color schemes in our maps and charts to ensure accessibility for readers with color vision deficiencies. We utilized colorblind-safe palettes from Color Brewer and implemented color schemes recommended by Crameri et al. (2020), which are specifically designed for individuals with color vision deficiencies. We also verified our figures using the Color Blindness Simulator to ensure the updated color schemes remain interpretable across various types of color blindness. We appreciate your attention to this important accessibility concern and have made these adjustments to enhance the inclusivity of our visualizations.

We have carefully considered all the comments and have made comprehensive revisions to address each point raised. Our detailed responses to the reviewers' comments are provided below.

Yours sincerely,
Zining Yang and co-authors

Reference:

Crameri, F., Shephard, G. E., and Heron, P. J.: The misuse of colour in science communication, *Nature Communications*, 11, <https://doi.org/10.1038/s41467-020-19160-7>, 2020.

Reviewer #2

General comments:

- *The research conducted by Yang et al. investigated the impact of different grid resolutions on meteorology, especially turbulent mixing, as well as its subsequent influence on air pollution transport and dispersion. Although the topic is of interest, some flaws in model validation and interpretation would undermine the scientific validity and clarity of this work and should be properly addressed before its consideration in ACP.*

Response: Thank you for your thorough evaluation of our manuscript and for identifying areas needing improvement. We fully agree that model validation and interpretation are critical to ensuring the scientific rigor and clarity of our work. Your constructive feedback has provided valuable direction for our revisions. We are committed to addressing the clarifications you have highlighted and have made the necessary revisions to enhance both the clarity and quality of the paper. Below, we outline our responses to each of your points to ensure that the manuscript meets the standards for publication in ACP.

Specific comments:

- *1. My major concern about this work is the validation for the model. The current validation is limited to comparisons between simulations and meteorology/BC concentration data from a single surface station. To enhance the robustness of the validation, additional stations with meteorological or air quality data should be incorporated.*

Response: We sincerely appreciate your constructive feedback regarding the validation of our model. We fully agree that expanding validation beyond a single surface station is critical for ensuring the robustness of the simulation results. In response to this concern, we have significantly enhanced the validation framework by incorporating multi-site meteorological observations and multi-pollutant air quality data from additional monitoring stations. Below we provide a detailed summary of the revisions made to address this critical issue.

1. Enhanced Meteorological Data Validation

As you rightly pointed out, validation using data from a single station is insufficient to establish the model's robustness. To address this, we have integrated data from four additional Automatic Weather Stations (AWS) located in the Hefei region (marked by purple solid dots in Figure S5), thereby broadening the scope of the meteorological validation. These AWS stations provide high-quality, hourly data for several key meteorological variables, including 2 m temperature and 10 m wind speed. The data undergoes strict quality control (QC) by local meteorological bureaus, following World Meteorological Organization guidelines (Estevez et al., 2011), ensuring their reliability for comparison with model simulations. We have updated Section 2.2.1 of the manuscript to include this new data source: “**Additionally, we employed meteorological data from automatic weather stations (AWSs), which were established based on the operational standards issued by the China Meteorological**

Administration (CMA, 2018). The hourly data underwent quality control (QC) by local meteorological bureaus of Anhui, following World Meteorological Organization guidelines (Estevez et al., 2011). The QC included checks of consistency, such as internal, temporal-spatial, and climatic range validations. These QC data were used to determine daily mean, minimum, and maximum meteorological variables. The AWSs recorded various parameters, including air temperature (T , $^{\circ}\text{C}$), wind speed (U , m/s), air pressure (P , Pa), and wind direction. In this study, we focus on the 3-hourly 2 m temperature and 10 m wind speed obtained from four AWS stations located in the study region. The four AWS sites are marked by purple solid dots in Figure S5.”

We carefully analyzed the simulation results for these new meteorological data from AWS and found that the model performs consistently across different resolutions, as shown in Figure S6. Specifically, the comparison between simulated and observed 10-m wind speeds and 2-m temperatures from these stations generally showed good agreement, although there were occasional discrepancies in some time periods. For example, the wind speed was sometimes overestimated or underestimated, but the overall trends, including diurnal variations, were well captured by the model. This expanded validation offers a more comprehensive evaluation of the model’s performance across a range of meteorological variables and geographical locations, addressing the concern about the limited validation in the initial manuscript. Section 3.1 has been updated to include a detailed comparison between the simulated and observed meteorological variables across the four AWS stations: “Additionally, Figure S6 displays the time series of observed and simulated meteorological variables averaged across four AWS stations in the study region. Figure S6a presents a comparison of 10-m wind speed simulated at three different resolutions, revealing generally consistent results with observations. The overall pattern is similar to that observed at the single USTC station, characterized by a clear diurnal variation with higher wind speeds during daytime and lower speeds at night. However, simulations at all three resolutions occasionally deviate from observations. For example, on March 11, the 5 km and 1 km resolution models overestimate wind speed at approximately 7 m/s compared to the observed 4 m/s. Conversely, on March 14 during the daytime, all three resolutions underestimate wind speed, simulating around 2 m/s against an observed value of 4 m/s. Figure S6b compares the simulated 2-m temperatures across three resolutions with observational data. The simulated temperatures are remarkably similar across all resolutions and show strong correlation with observations throughout most of the study period. Only a few outliers were noted, which minimally impact the overall pattern. For example, all resolution models overestimate temperature at noon on March 20, simulating approximately 28°C while the observed temperature is only about 20°C .”

2. Expanded Air Quality Data Validation

Regarding the validation of air pollutants, we agree with your suggestion to include additional observational data. In response, we incorporated data from 10 monitoring stations within the Hefei region, obtained from the website of the Ministry of Environmental Protection of China (MEP of China). These stations, marked as black triangles in Figure S5, provide hourly surface concentration data for common pollutants. However, the boundary layer mixing coefficient for gases in the WRF-Chem model is implicitly influenced by emission resolution rather than directly controlled by model resolution. As another

reviewer noted, the associated mixing coefficients are not only obtained via a parametrized PBL scheme, but further manipulated in the mixing routine. The mixing coefficients are clipped to empirically chosen thresholds of 1 m²/s over rural regions and 2 m²/s over urban regions. The distinction between rural and urban regions is made based on the local CO emission strength. The corresponding source code comments indicate that this clipping is indeed intended to prevent unrealistically low mixing coefficients. This treatment caused gas mixing coefficients across different horizontal resolutions to converge in our study, preventing us from effectively revealing the true impact of varying horizontal resolutions on gas turbulent mixing. Therefore, the existing adjustment process for gas mixing coefficients is unsuitable for our research objectives of studying resolution impacts on turbulent mixing. Thus, in this study, we limited our additional validation to PM_{2.5} (fine particulate matter with aerodynamic diameters less than 2.5 μm), whose mixing processes are governed by the same resolution-dependent mechanisms as BC.

By comparing model simulations with PM_{2.5} surface concentrations, we can ensure that our model accounts for a broader range of air quality parameters and offers a more thorough evaluation of its performance, despite the primary focus on black carbon (BC) simulation. We have updated Section 2.2.2 to introduce this new observational pollutant data: “Although this study primarily focuses on the simulation of BC, we conducted a comprehensive validation of other air pollutants to ensure the reliability of the simulation results. However, after being initially obtained via a parameterized PBL scheme, the mixing coefficients for gases are then clipped to empirically chosen thresholds of 1 m²/s over rural regions and 2 m²/s over urban regions, with the distinction between rural and urban regions made based on the local CO emission strength. Thus, the boundary layer mixing coefficient for gases in the WRF-Chem model is implicitly influenced by emission resolution rather than directly controlled by model resolution. Consequently, the existing adjustment process for gas mixing coefficients, which relies on CO emission strength, is unsuitable for studying the impact of model resolution on the turbulent mixing of gaseous pollutants. In contrast, the mixing coefficient of particulate matter is directly calculated through boundary layer parameterization without subsequent modifications. Thus, in this study, we limited our additional validation to PM_{2.5} (fine particulate matter with aerodynamic diameters less than 2.5 μm), whose mixing processes are governed by the same resolution-dependent mechanisms as BC. Ground observations of hourly PM_{2.5} surface concentrations during March 2019 were obtained from the website of the Ministry of Environmental Protection of China (MEP of China). As our study concentrates on the Hefei region, we selected 10 monitoring stations within this area for detailed analysis. These stations are marked as black triangles in Figure S5.”

We compared the simulated diurnal variation of PM_{2.5} surface concentrations across three horizontal resolutions with observations from the 10 monitoring stations, as shown in Figure S10. Our results indicate that the model generally captures the diurnal variations of PM_{2.5} surface concentrations, with some discrepancies. Specifically, the model tends to slightly underestimate PM_{2.5} during the daytime and overestimate it during the nighttime across three resolutions. However, higher spatial resolutions (5 km and 1 km) notably improved nocturnal simulations, demonstrating the benefit of fine grid resolutions in capturing localized pollution events. We further analyzed the diurnal variation of surface concentrations of four PM_{2.5}

components (sulfate (SO_4^{2-}), nitrate (NO_3^-), other inorganics (OIN), and organic carbon (OC)) averaged over 10 MEP sites in Hefei, as shown in Figure S11. In Section 3.2.1 of the revised manuscript, we have added a detailed comparison of the simulated and observed $\text{PM}_{2.5}$ surface concentrations at these 10 MEP stations:

“To verify the accuracy and comprehensiveness of the simulation results, we further analyzed the diurnal variation of $\text{PM}_{2.5}$ surface concentrations. Figure S10 illustrates the diurnal variation of simulated $\text{PM}_{2.5}$ surface concentrations across multi-resolutions compared with observations. The diurnal pattern of $\text{PM}_{2.5}$ closely resembles that of BC, characterized by higher concentrations at night and lower concentrations during daytime. Across all resolutions, the model slightly underestimates daytime $\text{PM}_{2.5}$ surface observations while overestimating nighttime values. Notably, increased horizontal resolution substantially improves nocturnal simulations. The 25 km resolution simulation generates an anomalous midnight peak ($105 \mu\text{g}/\text{m}^3$), resulting in a +61% bias, whereas the 5 km and 1 km resolutions substantially mitigate these deviations to approximately 30%. To further examine the contribution of each $\text{PM}_{2.5}$ component to the diurnal variation across multi-resolutions, Figure S11 shows the diurnal variations of four $\text{PM}_{2.5}$ constituents (sulfate (SO_4^{2-}), nitrate (NO_3^-), OIN, and organic carbon (OC)) averaged over 10 MEP sites in Hefei. Significant differences emerge in the diurnal variations of these components across multi-resolution simulations. Specifically, the surface concentrations of NO_3^- , OIN, and OC exhibit a consistent diurnal pattern, with lower concentrations during daytime and higher concentrations at night. As resolution increases from 25 km to 5 km and 1 km, the simulated components surface concentrations decrease, aligning more closely with observations.

The total concentrations of $\text{PM}_{2.5}$ and its components demonstrate significant sensitivity to horizontal resolutions. Coarse resolution simulations underestimate turbulent mixing capacity, resulting in overestimated concentrations. Higher resolution simulations more accurately capture vertical mixing within the PBL. For secondary particles such as sulfates and nitrates, formation rates depend heavily on local precursor substance concentrations (SO_2 , NO_x). Higher resolution simulations may enable more realistic representation of precursor substance diffusion, leading to reduced local concentration gradients and consequently slower secondary aerosol formation rates. Additionally, variations in $\text{PM}_{2.5}$ surface concentrations across multi-resolutions may also stem from complex secondary particle generation mechanisms. For instance, liquid-phase oxidation of sulfates in clouds is sensitive to local cloud water distribution, with higher resolutions better capturing small-scale cloud structures that potentially alter sulfate formation efficiency. The formation of ammonium nitrate (NH_4NO_3) is particularly sensitive to temperature and humidity variations. At higher resolutions, temperature and humidity gradients induced by urban heat island effects or topographical variations can be more realistically simulated, influencing the distribution of gaseous nitric acid (HNO_3) and particulate nitrate (NO_3^-). Dry deposition processes may also contribute to resolution-dependent variations, as local differences in surface roughness (including buildings and vegetation) become more apparent at higher resolutions, directly affecting particulate deposition velocity rates. Overall, the simulation results for major air pollutants fall within a reasonable error range compared to observational data, confirming the reliability of the model for this study.”

We also added this additional validation in Section 4 of the revised manuscript: “In addition, the diurnal variation of PM_{2.5} surface concentrations simulated at different resolutions follows the same trend as the observed concentrations at the national monitoring sites, with slight underestimation during daytime and overestimation at night.”

We believe that the inclusion of additional meteorological and pollutant data, as well as the expanded validation analyses, significantly enhance the reliability of our model and its representation of real-world conditions. These improvements address the concerns raised regarding the limited validation in the original manuscript and offer a more comprehensive and rigorous evaluation of the model’s performance.

On the other hand, while model evaluation constitutes an essential component of research, we did not allocate extensive resources to detailed model validation in this study, given our use of WRF-Chem - a well-established and thoroughly validated tool widely adopted for climate and air quality simulations. Our primary objective is to leverage this model to investigate the underlying physical and chemical mechanisms, rather than to conduct a comprehensive performance assessment.

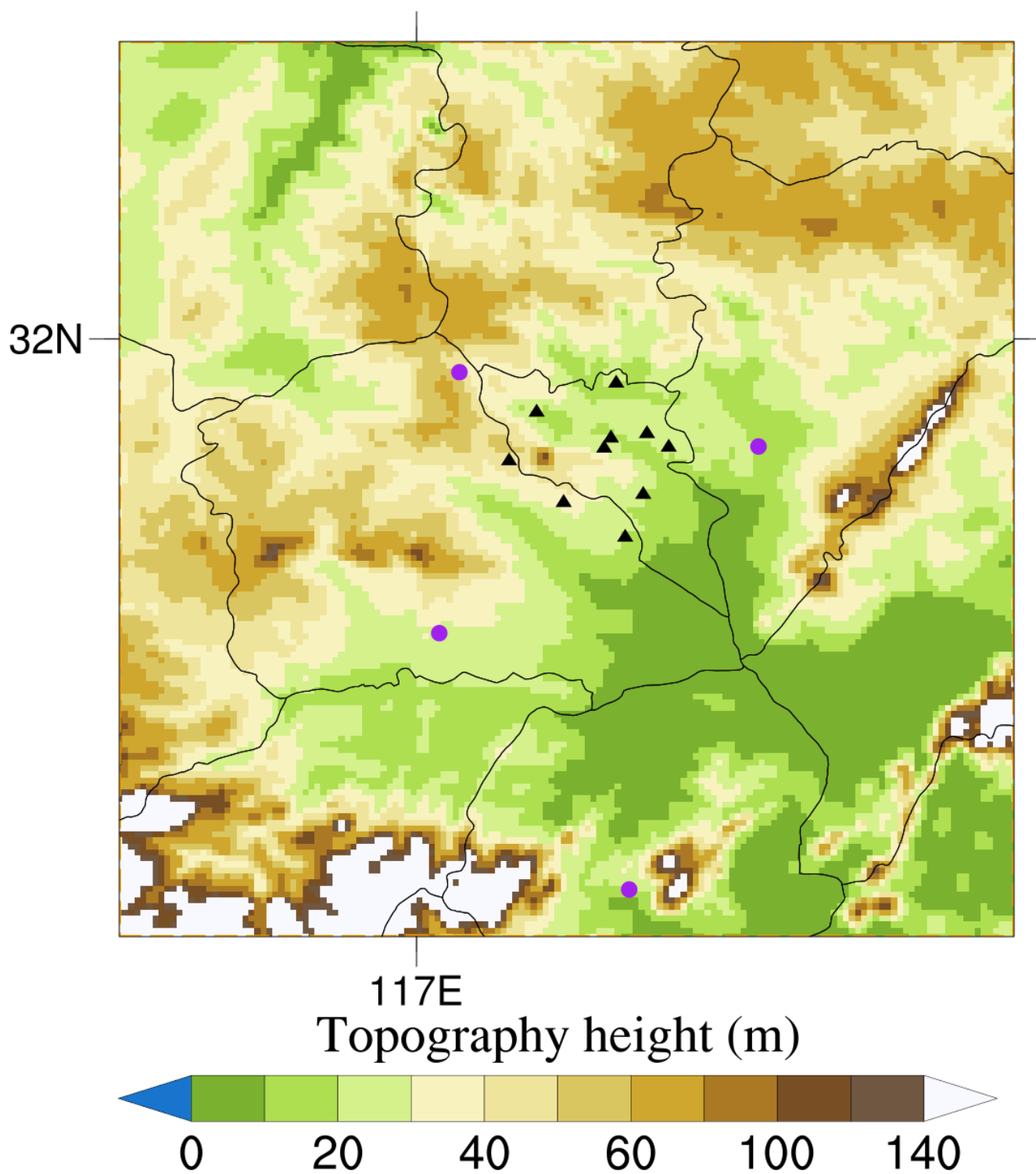


Figure S5. Spatial distributions of 4 MEP and 10 AWSs observational sites used in this study. Solid black triangles indicate MEP monitoring sites, and purple solid dots indicate AWSs locations.

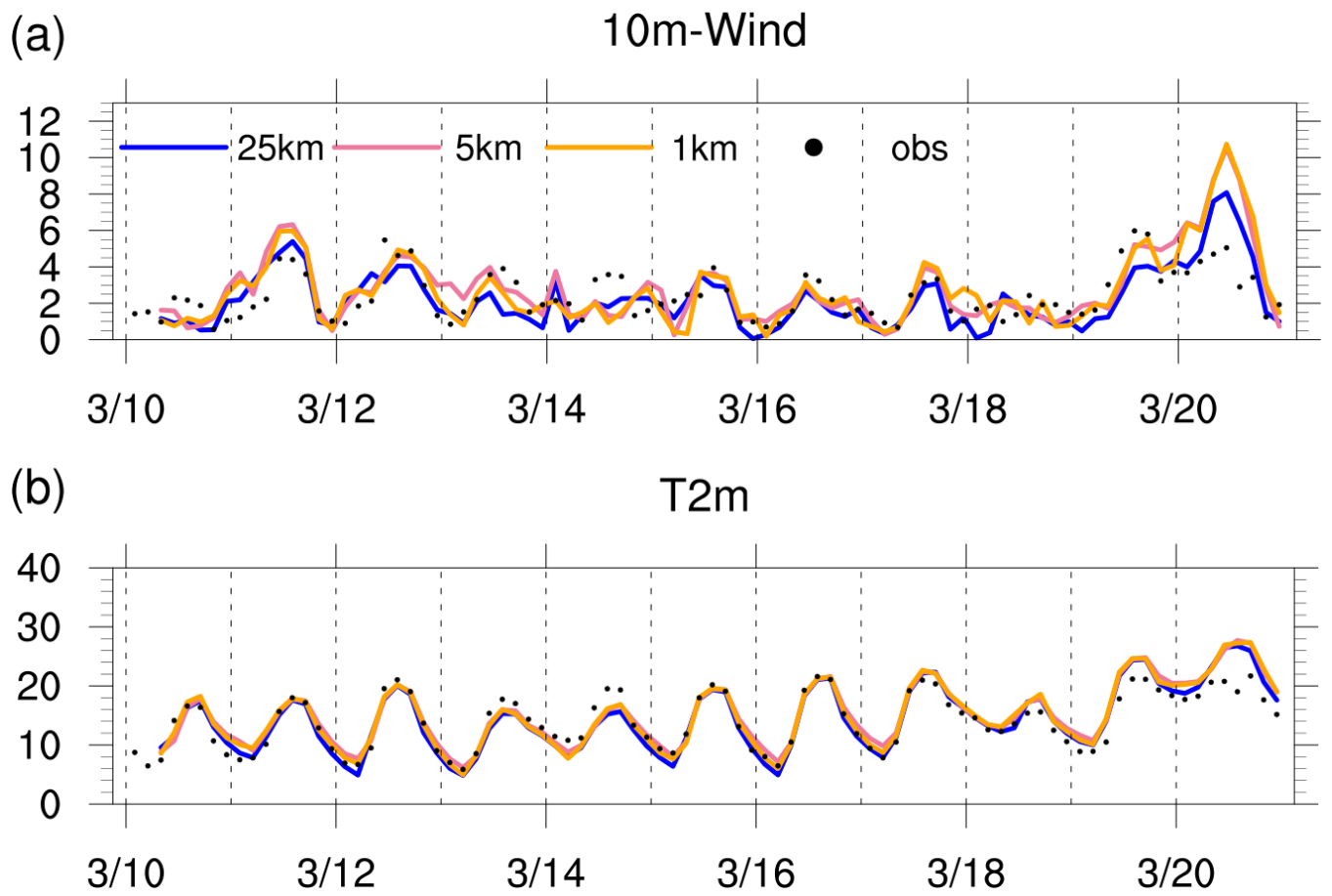


Figure S6. Time series averaged over 4 AWS sites in Hefei of observed (black dot) and simulated wind speed at 8 m (top, unit: m s⁻¹) and temperature at 2 m (middle, unit: °C) for 25-km (solid blue line) resolution, 5-km (solid pink line) resolution, and 1-km (solid orange line), respectively.

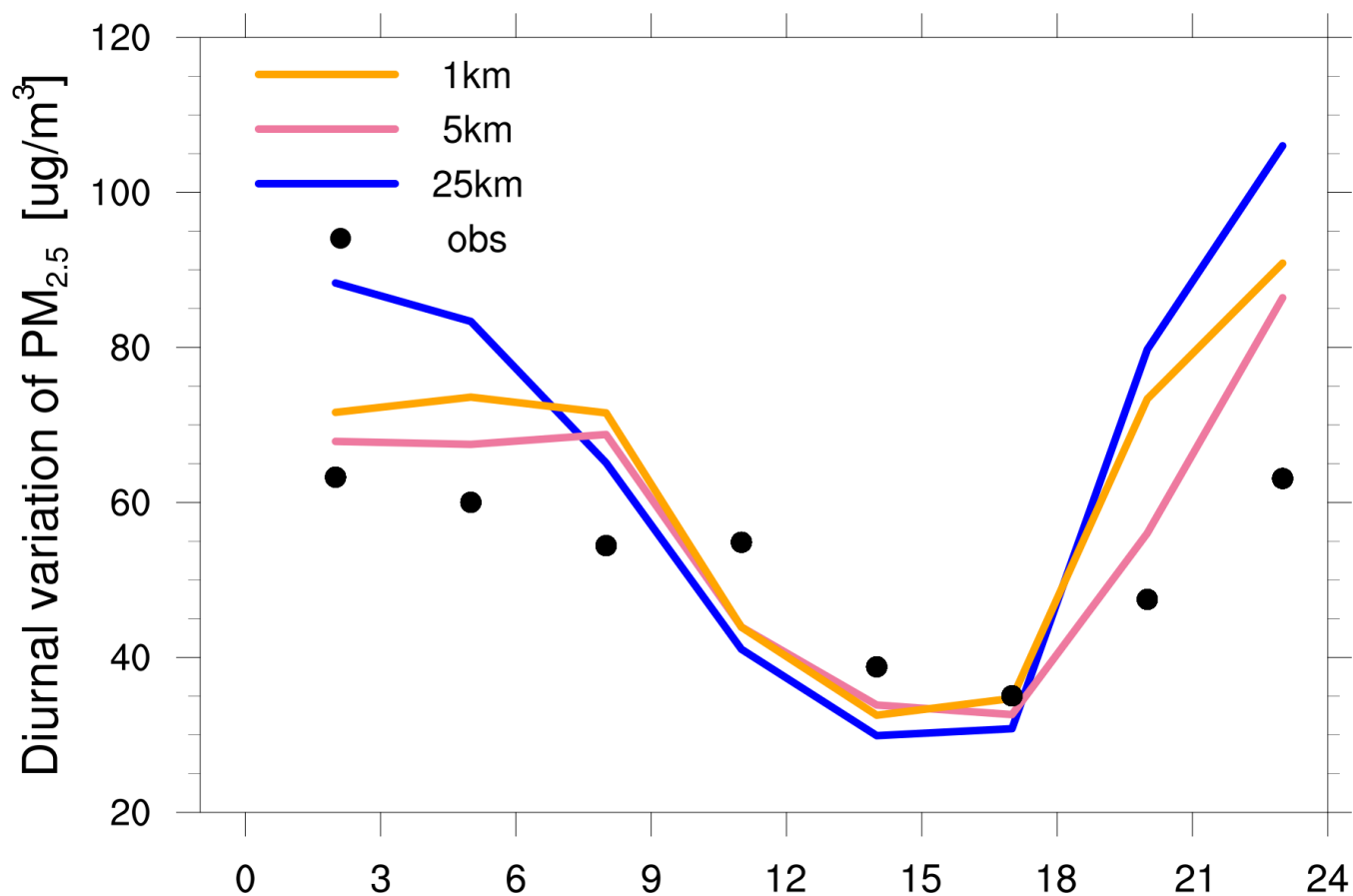


Figure S10. Diurnal variation of $PM_{2.5}$ surface concentrations within 24 h averaged over 10 MEP sites in Hefei during the study period for 25-km (solid blue line), 5-km (solid pink line), and 1-km (solid orange line) resolution simulations and observations (black dot). Both the simulated results and observations are sampled at the model output frequency, i.e., 3-hourly.

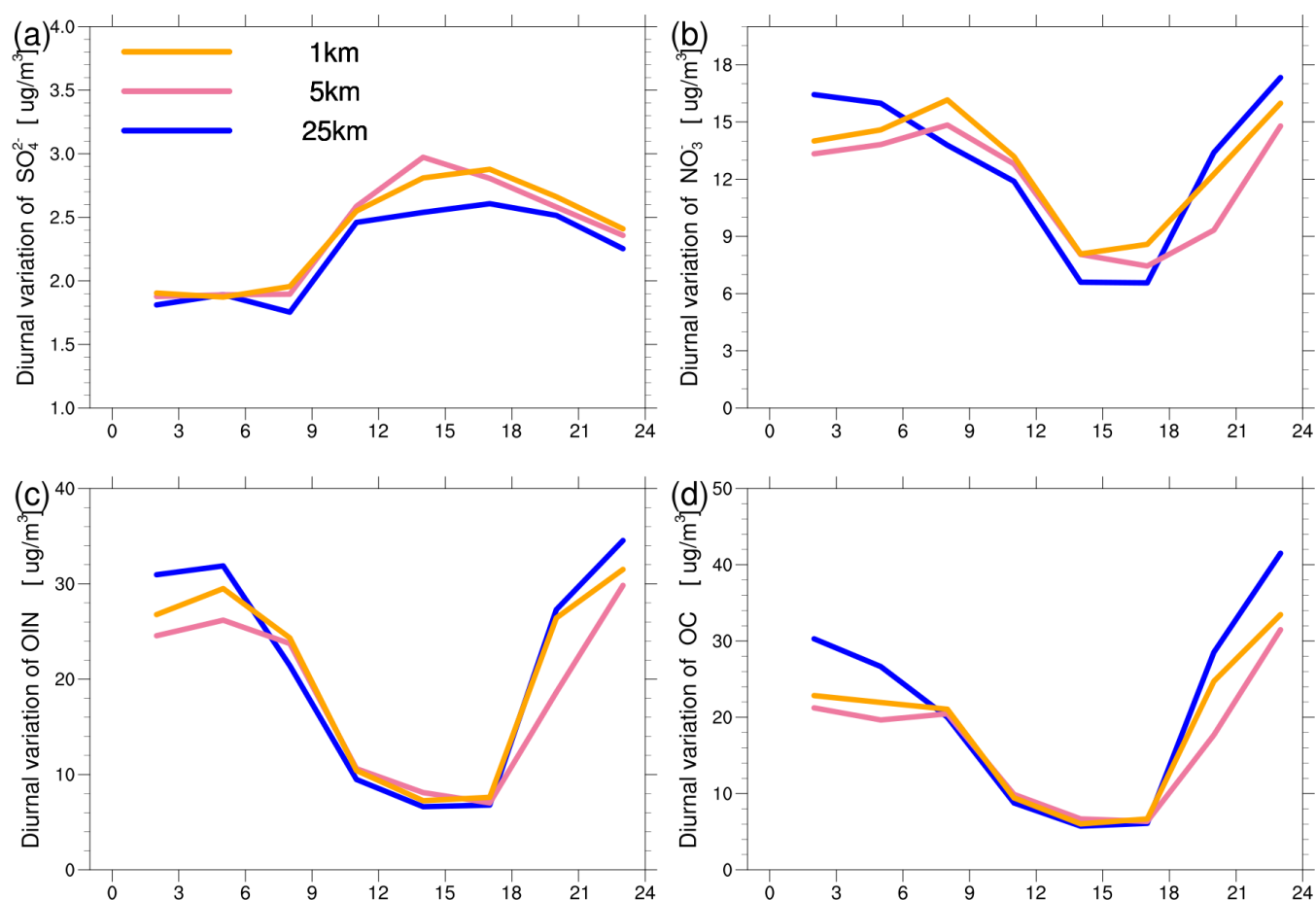


Figure S11. Diurnal variation of (a) SO_4^{2-} , (b) NO_3^- , (c) OIN, and (d) OC surface concentrations within 24 h averaged over 10 MEP sites in Hefei during the study period for 25-km (solid blue line), 5-km (solid pink line), and 1-km (solid orange line) resolution simulations. The simulated results are sampled at the model output frequency, i.e., 3-hourly.

Reference:

CMA, 2018: Technical Specifications for Maintenance of Regional Automatic Weather Stations. QX/T 465–2018. (in Chinese). Available at: <http://cmastd.cmatc.cn/standardView.jsp?id=3076>. Accessed on 5 May 2022.

Estevez, J., Gavilan, P., and Giraldez, J. V.: Guidelines on validation procedures for meteorological data from automatic weather stations, *Journal of Hydrology*, 402, 144-154, <https://doi.org/10.1016/j.jhydrol.2011.02.031>, 2011.

- *2. Furthermore, it would be beneficial to include vertical observations such as PBL height or turbulent fluxes.*
 - *Comparing these with the simulations could better illustrate the mixing processes in the boundary layer. Without such data, it remains unclear whether the mixing is more accurately captured at finer resolutions.*

Response: We sincerely appreciate your insightful suggestion regarding the inclusion of vertical observations (e.g., PBL height or turbulent fluxes) to validate boundary layer mixing processes. Below, we clarify the theoretical framework guiding our approach, address the current limitations, and outline future directions to advance this line of inquiry.

In our model, planetary boundary layer height (PBLH) does not directly represent the turbulence mixing intensity but is

a diagnostic quantity calculated through the boundary layer parameterization scheme. According to the study by Du et al. (2020), the daily variation in surface particulate matter concentration is primarily influenced by the boundary layer mixing coefficient (K_h) rather than PBLH. Previous studies often established a direct relationship between the daily variation of PBLH and pollutant concentrations. However, in reality, the daily variation of PBL mixing coefficients is much more significant than that of PBLH. During the day, when the PBL mixing coefficient is large, emitted pollutants are well mixed and distributed up to the PBL height. However, at night, due to the lower PBL mixing coefficient, atmospheric particulate matter and its precursors tend to stay near the ground and are trapped in the shallow boundary layer, causing higher surface pollutant concentrations. Thus, the PBL mixing coefficient at night becomes the primary determinant of pollutant concentration changes, while PBLH cannot fully reflect the turbulence mixing intensity in the model. Therefore, we believe that comparing the simulated PBLH with observations cannot demonstrate well whether a finer resolution can more accurately capture turbulence mixing.

Furthermore, through kilometer-scale high-resolution numerical experiments, we found that traditional parameterization schemes exhibit systematic bias in representing turbulence mixing intensity, and the boundary layer mixing coefficient does not fully reflect the turbulence mixing intensity in the model. As the resolution increases, the explicitly resolved turbulence mixing intensity in the model increases. Therefore, the total turbulence mixing intensity in the model should be the sum of the boundary layer mixing coefficient given by the parameterization scheme and the directly resolved turbulence mixing intensity.

Regarding your comment about the lack of observational data for turbulence mixing intensity, our study focuses on the Hefei city, a typical mega-city of China, which currently lacks direct observational data for overall turbulence mixing intensity. However, the analysis of turbulence mixing intensity with observations has become an important entry point in our research. While we currently lack direct observational data, we believe this analytical approach holds great potential for understanding the variations in pollutant concentrations in the Hefei area. The primary processes affecting BC concentration are emissions and turbulence mixing, with BC concentration being almost unaffected by chemical processes. In this study, we ensured that pollutant emission details were consistent across all resolutions, effectively isolating the interference of emission heterogeneity on concentration variations. Therefore, under the condition of emission homogenization, the hypothesis that vertical turbulence mixing is the core mechanism driving surface-level BC concentration fluctuations is a reasonable assumption. For future work, we plan to conduct further analytical research in urban areas with pollutant observation towers to validate the assumptions in this study and supplement more field observational data to support the results of our model.

Reference:

Du, Q., Zhao, C., Zhang, M., Dong, X., Chen, Y., Liu, Z., Hu, Z., Zhang, Q., Li, Y., Yuan, R., and Miao, S.: Modeling diurnal variation of surface PM_{2.5} concentrations over East China with WRF-Chem: impacts from boundary-layer mixing and anthropogenic emission, *Atmospheric Chemistry and Physics*, 20, 2839-2863, <https://doi.org/10.5194/acp-20-2839-2020>,

- *3. The model settings and the interpretation of model results should be further elaborated. The vertical level settings in all three domains should be further elaborated. Are these settings sufficient to capture boundary layer turbulence accurately?*

Response: We sincerely appreciate your insightful feedback regarding the elaboration of model settings and vertical level configurations. The concerns about whether our vertical resolution settings adequately capture boundary layer turbulence are critically important for validating the model's reliability. We explicitly emphasize that identical vertical layer distributions are maintained across all three horizontal resolutions (25 km, 5 km, and 1 km), ensuring comparability in turbulent mixing across different horizontal resolutions. In this study, three resolution simulations employ 50 vertical layers (spanning 15 km vertically), with 30 layers allocated below 2 km to resolve the core regions of turbulent mixing. This enhanced vertical configuration ensures that we can resolve the fine details of the Planetary Boundary Layer (PBL) turbulence, which plays a crucial role in the dispersion and vertical distribution of pollutants. The vertical layers are strategically designed with varying thicknesses to provide adequate resolution across different heights. The distribution of layers designed with 7 layers below 200 meters, with each layer approximately 20 meters in height; 3 layers between 200 and 300 meters, each approximately 30 meters in height; 8 layers between 300 and 1000 meters, with each layer approximately 80 meters in height. While the near-surface vertical resolution does not adopt an ultra-fine grid (e.g., 10 m layer thickness), a stretched grid design (gradually increasing resolution near the surface) ensures reasonable representation of surface heat fluxes and turbulent kinetic energy (TKE) transport. Specifically, Jiang et al. (2024) and Jiang and Hu (2023) demonstrated that increasing vertical layers under stable boundary conditions enhances the stability of vertical structures, thereby better resolving boundary layer turbulence. Our configuration (30 layers below 2 km) comprehensively covers the mixed layer development and captures key turbulent processes (e.g., entrainment and surface flux exchange) through layer densification. The finer vertical resolution in our simulations contributes to a more stable vertical distribution of pollutants and enhances the overall performance of the model in simulating dispersion processes.

In the revised Methods section (Section 2.1.2), we have added a detailed explanation of the vertical layer configuration: “On the other hand, the vertical configuration within the PBL is also crucial for accurately modeling pollutant dispersion. To better resolve the PBL structure and mixing processes, we implemented a finer vertical resolution within the PBL. Identical vertical layer distributions are maintained across all three horizontal resolutions (25 km, 5 km, and 1 km), ensuring direct comparability of turbulent mixing across different horizontal resolutions. A total of 50 terrain-following vertical eta-layers extending from the surface to approximately 15 km were used in all three resolution simulations, with 30 layers distributed below 2 km above the ground to describe the atmospheric boundary structure in detail. The vertical layer was strategically designed with 7 layers below 200 meters (each approximately 20 meters in height), 3 layers between 200 and 300 meters (each

about 30 meters in height), and 8 layers between 300 and 1000 meters (each approximately 80 meters in height). This configuration comprehensively captures mixed layer development and key turbulent processes (e.g., entrainment and surface flux exchange) through layer densification, which is sufficient to capture PBL turbulent mixing. Jiang et al. (2024) and Jiang and Hu (2023) have demonstrated that the number of model vertical layers primarily influences vertical distribution, with more vertical grid layers producing a more stable vertical structure under stable boundary conditions that better resolves boundary layer turbulence.”

Reference:

Jiang, L. and Hu, J.: Influence of the lowest model level height and vertical grid resolution on mesoscale meteorological modeling, *Atmospheric Research*, 296, <https://doi.org/10.1016/j.atmosres.2023.107066>, 2023.

Jiang, L., Bessagnet, B., Meleux, F., Couvidat, F., Tognet, F., and Hu, J.: The role of vertical grid resolution and turbulent diffusion uncertainty on chemical transport modeling, *Atmospheric Research*, 312, <https://doi.org/10.1016/j.atmosres.2024.107759>, 2024.

- *4. Given that hourly observations for meteorology and BC are available, why is the model output provided at 3-hour intervals? This discrepancy should be addressed.*

Response: We appreciate your astute observation regarding the temporal resolution of model outputs. Now we provide a detailed justification for this design choice and confirm its validity for the study's objectives. First, the outputs of pollutant concentrations in our experiments are sampled every 3-hour to reduce disk storage requirements and increase the computational speed. Hourly output data would provide higher time resolution but significantly increase storage demands. Given that we ran simulations at multi-resolutions (25 km, 5 km, and 1 km), storing hourly data would have resulted in an enormous volume of data storage. To ensure computational and storage efficiency, we opted for a 3-hour output interval. Second, while hourly observational data are available, the primary goal of our study is to analyze the daily variations of pollutants (e.g., BC), rather than focusing on precise hourly variation comparisons. A 3-hour output interval is sufficient to capture the daily trends, and we believe it provides an effective representation of the daily variability without losing significant detail. Therefore, when comparing modeling results and observations, hourly observations are sampled at the model output frequency, i.e., 3-hourly.

In the revised manuscript (Section 2.2.2), we have also added another detailed explanation for this design choice:

“While hourly observations for both meteorology and pollutants are available, model outputs are provided at 3-hour intervals to balance computational efficiency and storage requirements. Hourly output data would provide higher time resolution but significantly increase storage demands. Given that we ran simulations at multi-resolutions (25 km, 5 km, and 1 km), hourly outputs would have generated prohibitively large data volumes. On the other hand, this 3-hour output interval remains sufficient for our primary research objective of analyzing daily pollutant variations (particularly BC) rather than precise hourly comparisons. We believe this approach effectively captures daily variability patterns without losing essential

detail. For direct comparisons, hourly observations were sampled to match our 3-hour model output intervals.”

- *5. The authors claim that the PBL mixing coefficient is crucial for BC surface concentration, which is closely related to land-use type and terrain. Does this imply that high-resolution surface information is more important than high-resolution atmospheric grids? This point needs further clarification.*

Response: We appreciate your insightful comment. We agree that the role of high-resolution surface information and high-resolution atmospheric grids in parameterizing the boundary layer (PBL) mixing coefficient requires further clarification.

In our study, both high-resolution surface information and atmospheric grid resolution contribute to the parameterization of the boundary layer mixing coefficient. In regions with substantial variations in land use and terrain height, high-resolution surface information plays a more dominant role in parameterizing the PBL mixing coefficient. For example, in areas with complex terrain or varying land-use types, more detailed surface information (such as more accurate land use classification at higher resolutions) significantly enhances the calculation of the PBL mixing coefficient. This is because the parameterization of the mixing coefficient is directly influenced by the surface roughness, which is highly sensitive to land-use and terrain characteristics. On the other hand, if high-resolution simulations do not use refined high-resolution surface information (for example, the same low-resolution surface data is used across all three resolutions), the increase in the boundary layer mixing coefficient is mainly due to the higher atmospheric grid resolution. In areas with relatively flat terrain or homogeneous land-use types, the increase in the boundary layer mixing coefficient primarily stems from the higher atmospheric grid resolution. Additionally, high-resolution atmospheric grids help resolve finer atmospheric processes, such as small-scale turbulent eddies. In conclusion, land use and terrain accuracy dominate the simulation of mixing coefficients in regions with significant surface heterogeneity, while high-resolution grids enhance the mixing effect in homogeneous surface regions through numerical and physical mechanisms.

To address this issue more comprehensively, we have conducted an additional set of sensitivity experiments. These experiments utilized the default United States Geological Survey (USGS) land use data in the Weather Research and Forecasting (WRF) model across various resolutions to isolate the effects of grid resolution under uniform land-use conditions, as shown in Figure S2. The default USGS data in WRF's geographical static database represents Chinese land use patterns before the 2000s and reflects land use distribution prior to China's significant urbanization. Consequently, the land use data types have minor variations and remained generally consistent across all three resolutions in the sensitivity experiment. The results clearly demonstrate that in flat urban areas, where land-use types and terrain are nearly uniform across different resolutions, the increase in PBL mixing coefficient is primarily driven by the finer grid resolution. In contrast, in areas with significant terrain height variations, such as rural or hilly regions, the boundary layer mixing coefficient is more sensitive to surface roughness and topographical details, which are better captured at higher resolutions. We have added the specific setup of this additional set of sensitivity experiments with different resolutions in section 2.1.2 in the revised manuscript: “The land

cover dataset is derived from a 1 km horizontal resolution dataset for China (Zhang et al., 2021). The land use categories follow the United States Geological Survey's (USGS) 24-category classification, and the dataset is based on China's land cover conditions as of 2015. This provides a more accurate representation of current land cover, particularly for eastern China, which has experienced intensive urban expansion since the 2000s. Figure 1b shows the land cover data at different resolutions, with detailed descriptions of the legend and land cover classes provided in Table S1. This set of simulations is referred to as the baseline experiment. With the exception of part of Section 3.2.3, all other analyses in this study are based on the results of these baseline experiments. Moreover, to explore the differences in turbulent mixing simulated at multi-resolutions under consistent land use conditions across various resolutions, we conducted an additional set of sensitivity experiments referred to as the sensitivity experiment. The sensitivity experiment was identical to the baseline experiment, except it used the default USGS land use category data in WRF. Notably, this default USGS data in WRF's geographical static database represents Chinese land use patterns before the 2000s, as shown in Figure S2. This default dataset reflects land use distribution prior to China's significant urbanization. Consequently, the land use data types have minor variations and remained generally consistent across all three resolutions in the sensitivity experiment.”

Our results show that in regions with heterogeneous surface types (such as urban areas), high-resolution surface data is critical for accurately parameterizing the PBL mixing coefficient. In contrast, in homogeneous regions or regions with relatively flat terrain, the high-resolution atmospheric grid helps resolve finer-scale turbulent features, further enhancing the mixing effect. In conclusion, while high-resolution surface information is paramount in regions with significant land-use and terrain variations, high-resolution atmospheric grids also play a crucial role in enhancing the mixing effect, especially in areas with more gradual surface changes. Therefore, both components are important, but the relative importance depends on the surface heterogeneity and the complexity of the terrain. We have elaborated on these findings in the newly added Section 3.2.3, which discusses the impact of land use and terrain height on turbulent mixing coefficients at different resolutions: “

Additionally, to explore the differences in PBL mixing coefficients across multi-resolutions under uniform land use conditions, we designed another set of sensitivity experiments across three resolutions. As mentioned earlier, the only difference from the baseline experiment was the use of the default USGS land use classification data in the WRF model. As shown in Figure S2, land use type data at different horizontal resolutions are approximately consistent in this setup. All other settings remained identical to those in the baseline experiment.

Figure 10 presents the spatial distribution of PBL mixing coefficients in the sensitivity experiment. Figure 10a illustrates the results across multi-resolutions averaged over the whole day. Similar to the baseline experiment, increasing resolution resolves more spatial details. For example, in the area where the USTC site is located, the PBL mixing coefficient in the 25 km resolution simulation of the sensitivity experiment is approximately $4.3 \text{ m}^2/\text{s}$, significantly lower than the $8 \text{ m}^2/\text{s}$ observed in the baseline experiment. This pattern is consistent across higher resolutions (5 km and 1 km). This finding aligns with the spatial distribution of land use types used in both sets of experiments (Figure 1b and Figure S2). The decrease in mixing

coefficients in the sensitivity experiment stems from its land use data failing to resolve urban land types in urban areas. Figures 10b and 10c show the PBL mixing coefficients of the sensitivity experiment during daytime and nighttime, respectively. Consistent with the baseline experiment, the turbulent mixing coefficients during the day are substantially higher than at night. The PBL coefficients in the nighttime simulations are higher at 5 km and 1 km resolutions compared to the 25 km resolution.

Additionally, Figure S16 further illustrates the differences in the parameterized PBL mixing coefficient between the 25 km resolution and the two higher-resolution simulations under roughly uniform land use conditions. Figure S16c shows that in the city center, the boundary layer mixing coefficient parameterized at 5 km and 1 km resolutions is higher than at the 25 km resolution during nighttime. Since urban areas are primarily flat, topographical differences between different resolutions in urban areas are minimal, almost negligible. Furthermore, because the land use types in the sensitivity experiment are approximately consistent across different resolutions, the main factor responsible for resolution-related differences in the PBL mixing coefficients in urban areas is the grid size. Notably, in areas with significant topographic variations, such as suburban and rural regions, the difference in boundary layer mixing coefficients between 25 km and 5 km/1 km resolutions in the sensitivity experiment strongly correlates with the spatial distribution of topographic differences. This directly demonstrates that topographic height is also a key determinant of boundary layer mixing coefficient distribution. Qian et al. (2010) indicated that the terrain affects the transport and mixing of aerosols and trace gases, as well as their concentrations across multi-resolutions, through its impact on meteorological fields such as wind and the PBL structure. These terrain-related effects are particularly significant in regions with more variable topography. Additionally, Figure S17 shows that the turbulent mixing intensity parameterized at 5 km resolution in the sensitivity experiment is greater than at 1 km resolution. Further analysis of the latitude-pressure cross section of BC concentrations and vertical wind speed flux, as shown in Figure S18, indicates that, similar to the baseline experiment, the 1 km resolution of the sensitivity experiment resolves more small-scale turbulent eddies, capturing more prominent vertical wind speed flux, thus resulting in stronger turbulent mixing.

Through comprehensive analysis of both baseline and sensitivity experiments, we found that within the resolution range of 25 km to 5 km and 1 km, the spatial distribution accuracy of land use types plays a decisive role in parameterizing the PBL mixing coefficient. Finer land use type information at higher resolutions directly alters the spatial distribution of the boundary layer mixing coefficient, with urban surfaces significantly increasing the parameterized PBL mixing coefficient. Therefore, accurately representing land use types, particularly urban surfaces, is critical for parameterizing the PBL mixing coefficient. On the other hand, in the sensitivity experiment, complex terrain areas with significant elevation (such as suburban, rural, and hilly regions) increase mixing coefficients by enhancing surface roughness, whereas this effect is weaker in flat urban areas. Consequently, differences in PBL mixing coefficients across multi-resolutions strongly correlate with terrain precision. Higher resolutions can resolve finer terrain variations, affecting local turbulent mixing (such as terrain-induced mechanical turbulence). This confirms the dominant role of high-resolution terrain and land use information in PBL mixing coefficient parameterization. Notably, in regions where land use types and terrain height remain relatively flat and consistent across different horizontal

resolutions in the sensitivity experiments, increasing resolution still leads to enhanced boundary layer mixing coefficients, highlighting the importance of grid size for parameterizing the boundary layer mixing coefficient. In the resolution range from 5 km to 1 km, higher resolution slightly reduces the parameterized boundary layer mixing coefficient. However, the 1 km resolution model resolves more small-scale turbulent eddies, resulting in stronger turbulent mixing at night. In summary, for parameterization of boundary layer mixing coefficients across multi-resolutions, high-resolution surface information is more important in regions with significant changes in land use types and terrain height. Grid size is also crucial in regions with more gradual changes, where higher-resolution grids consistently enhance boundary layer mixing representation. Therefore, to improve PBL mixing coefficient simulation, priority should be given to ensuring accuracy of land use data (especially spatial representation of urban types), precise terrain representation in complex regions, and appropriated grid resolution to enhance turbulent mixing simulation.”

We also added these findings in the Section 4 of the revised manuscript: “Further analysis reveals that the spatial distribution of PBL mixing coefficients is influenced by both land use types and terrain heights. The turbulent mixing coefficient correlates with the spatial distribution of land use types at smaller scales, with urban underlying surfaces notably increasing the parameterized PBL mixing coefficient. The mixing coefficient also strongly correlates with terrain heights at larger scales, particularly in regions with complex topography and significant elevation differences, where higher terrain substantially enhances mixing coefficients. This correlation can be attributed to the interrelationship among turbulent mixing coefficients, friction velocity, terrain, and land use types. The static database of terrain and land use types employed as model input determines the surface roughness. Higher surface roughness typically leads to greater friction velocity, subsequently increasing the PBL mixing coefficients. Moreover, in regions where land use types and terrain height remain relatively flat and consistent across multi-resolutions, increasing resolution still enhances boundary layer mixing coefficients, highlighting the importance of grid size. Thus, both surface information and grid resolution are crucial for accurately parameterizing PBL mixing coefficients, with priority given to accurate land use data, precise terrain representation, and higher grid resolution to improve turbulent mixing simulations.”

Finally, we also added these finding in the “Abstract” of the revised manuscript: “Variations in mixing coefficients are partly attributed to differences in land use and terrain, with higher resolutions providing more detailed information that enhances PBL mixing coefficients, while grid size remains crucial in regions with more gradual terrain and land use changes.”

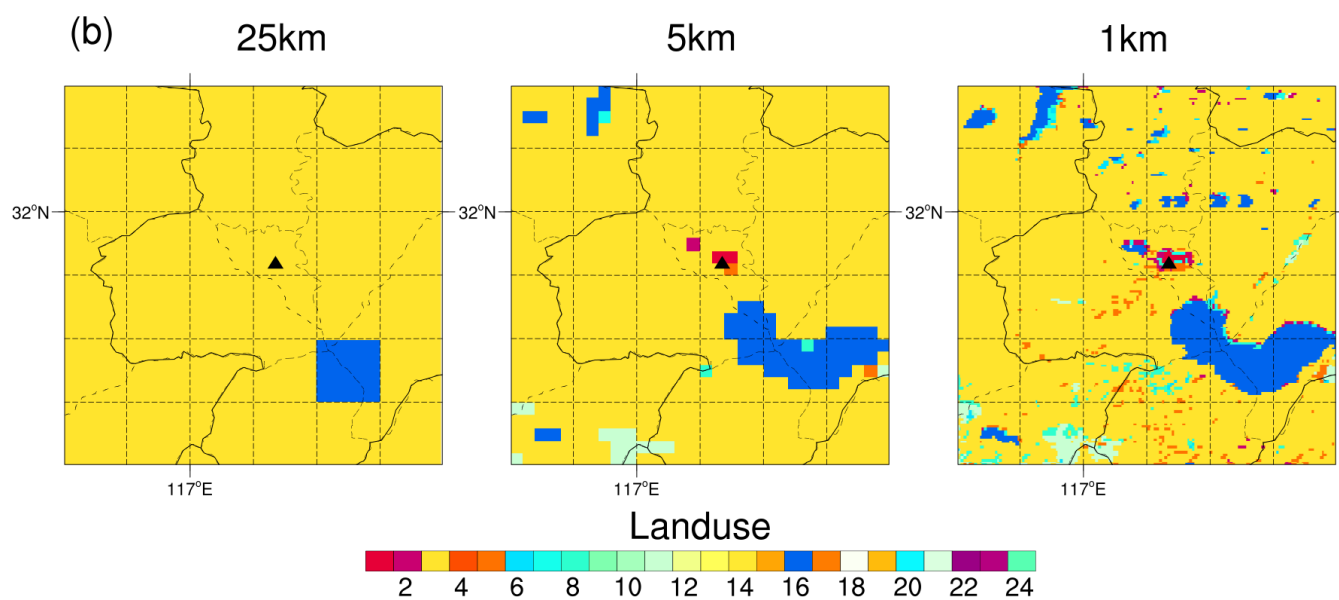


Figure S2. The spatial distribution of the default USGS land use category data in WRF in the study area for 25-km (left), 5-km (middle), and 1-km (right) resolution simulations, respectively. The solid black triangle indicates the location of the USTC site.

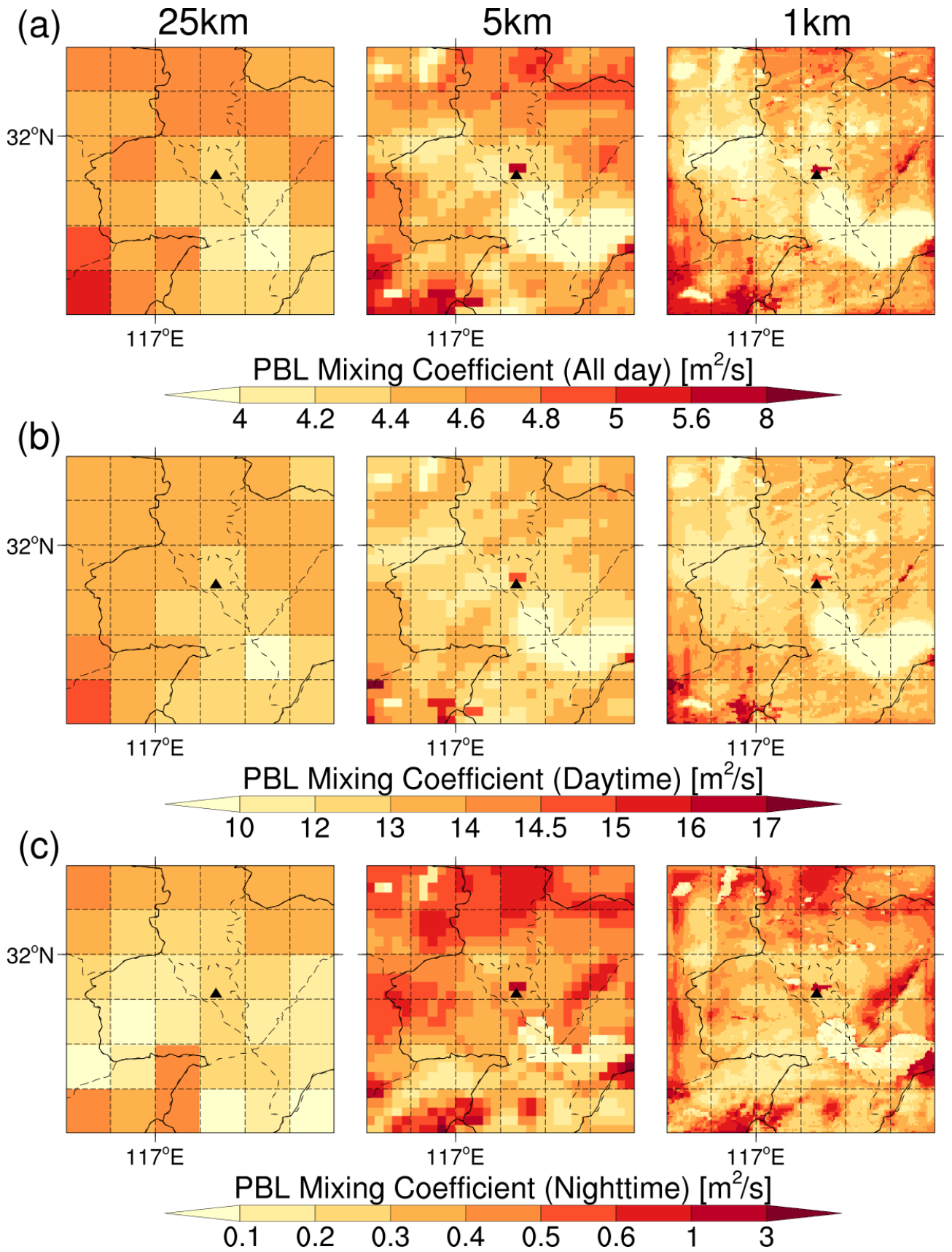
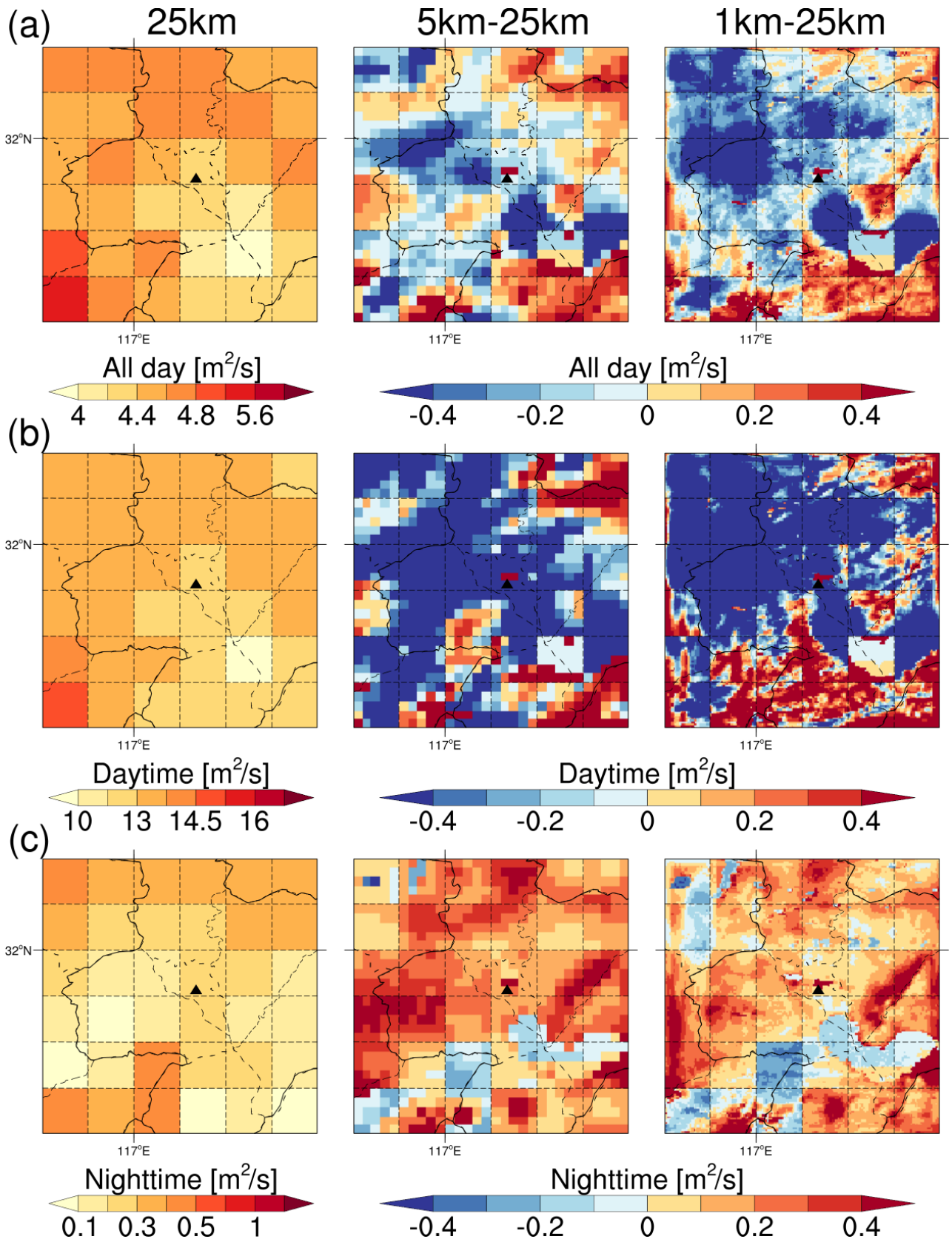


Figure 10. Spatial distribution of PBL mixing coefficients in the study area for 25-km (left), 5-km (middle), and 1-km (right) resolution simulations of the whole day (top), the daytime (middle), and the nighttime (bottom), respectively. The solid black triangle indicates the location of the USTC site. The simulation results are from the three sensitivity experiments.



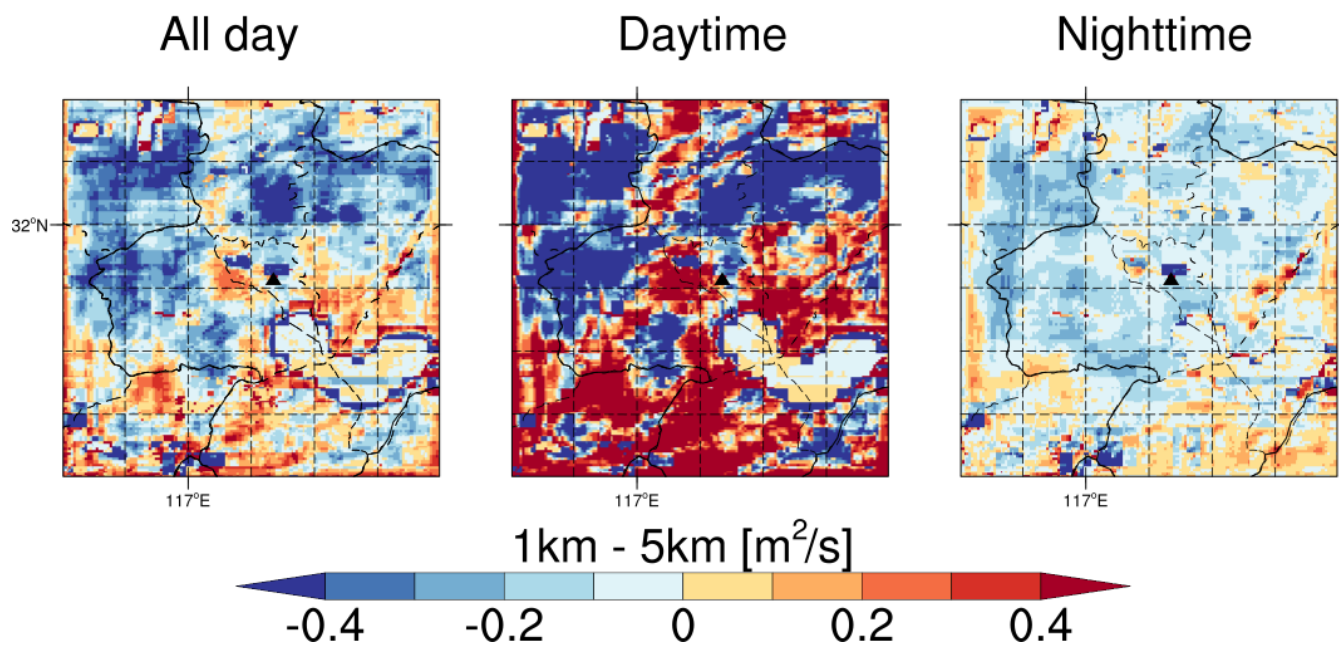


Figure S17. Spatial distribution of the differences in PBL mixing coefficients between 1-km and 5-km resolutions in the study area of the whole day (left), the daytime (middle), and the nighttime (right), respectively. The solid black triangle indicates the location of the USTC site. The simulation results are from the sensitivity experiments.

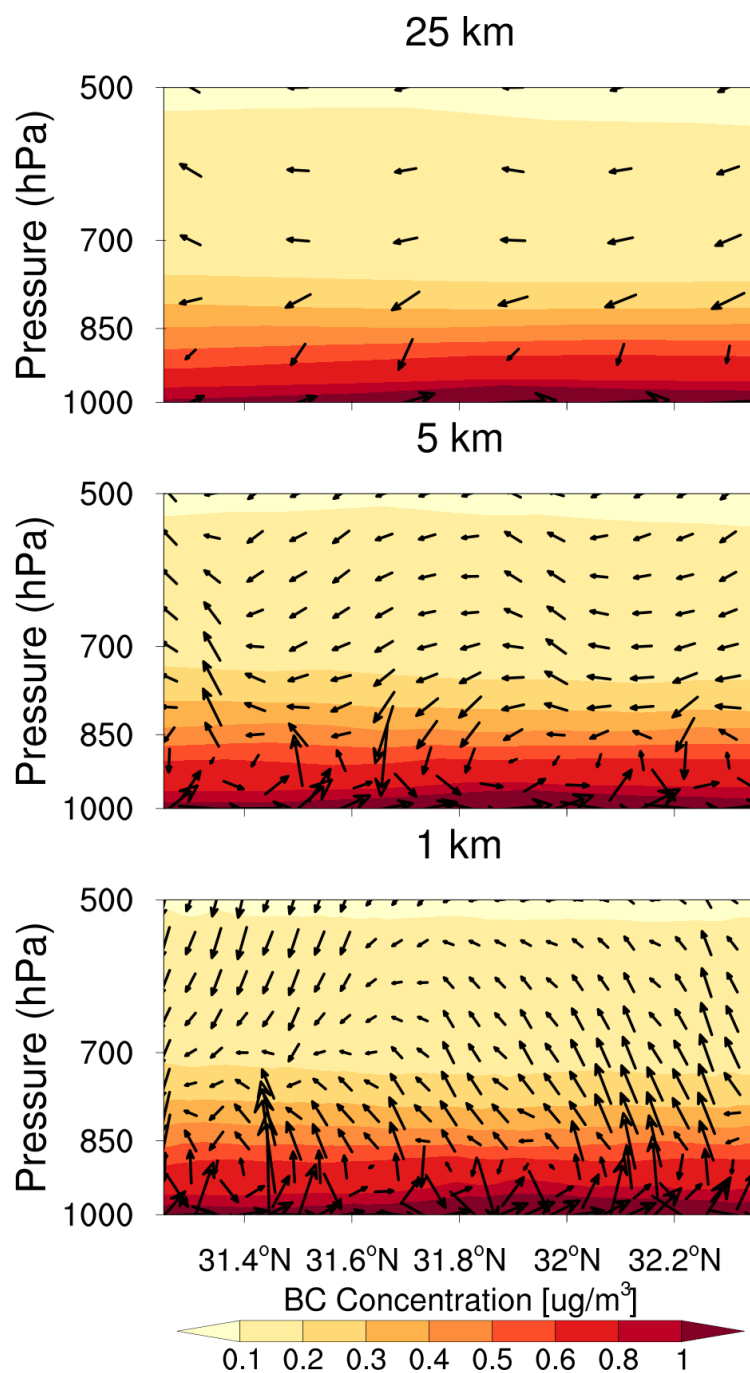


Figure S18. The latitude-pressure cross section of BC concentrations and wind speed flux along the USTC site for 25-km (top), 5-km (middle), and 1-km (bottom) resolution simulations of the whole day, respectively. Vector arrows are the combination of wind speed fluxes v and w , with the vertical wind speed flux being multiplied by 100 for visibility. The shaded contours represent BC concentrations at each pressure level. The simulation results are from the sensitivity experiments.

Reference:

Qian, Y., Gustafson, W. I., Jr., and Fast, J. D.: An investigation of the sub-grid variability of trace gases and aerosols for global climate modeling, *Atmospheric Chemistry and Physics*, 10, 6917-6946, <https://doi.org/10.5194/acp-10-6917-2010>, 2010.

- *6. Lastly, vertical grid resolution may play a more significant role in resolving eddies of different scales. The authors should discuss this aspect in more detail.*

Response: We appreciate the reviewer's insightful comment regarding the potential role of vertical grid resolution in resolving eddies of different scales. We agree that vertical resolution can indeed influence the representation of turbulent processes and boundary layer dynamics in numerical models. Below, we provide a detailed discussion to clarify our experimental design and justify the vertical grid configuration in this study.

Our study aims to investigate differences in pollutant concentrations across different horizontal resolutions and explore how the turbulent mixing plays as a crucial role affecting pollutant concentrations at various horizontal resolutions. Therefore, we performed nested simulations using WRF-Chem's Ndwon method, where the three different resolutions refer to horizontal resolution, while the vertical resolution remains consistent across all experiments. The layer thicknesses in our boundary layer configuration are sufficient for capturing sub-kilometer-scale eddies and vertical mixing processes. Jiang et al. (2024) and Jiang and Hu (2023) have demonstrated that the number of model vertical layers primarily influences vertical distribution, with more vertical grid layers producing a more stable vertical structure under stable boundary conditions that can better resolve boundary layer turbulence. In our WRF-Chem downscaling simulations, the vertical grid structure was designed with a total of 50 terrain-following vertical eta-layers extending from the surface to the height of 15 km in all three resolution simulations, with 30 layers distributed below 2 km above the ground to describe the atmospheric boundary structure in detail. The vertical layer was strategically designed with 7 layers below 200 meters, each approximately 20 meters in height; 3 layers between 200 and 300 meters, each about 30 meters in height; 8 layers between 300 and 1000 meters, each approximately 80 meters in height, which is sufficient to explicitly resolve boundary layer turbulence.

That being said, we acknowledge that vertical grid resolution may play a more significant role in resolving eddies of different scales. Excessively coarse vertical grids (e.g., greater than 100 m layer thickness) could artificially suppress vertical mixing and misrepresent energy cascades across scales. When the vertical resolution is not sufficient to correctly resolve the vertical gradient, the chemical transport model usually fails to maintain the fine structure of the plume resulting in their over-dilution compared to observations (Eastham and Jacob, 2017; Zhuang et al., 2018). Studies confirm that high vertical resolution configurations substantially reduce system errors compared to lower resolution settings, making it suitable for both long-term average simulations and transient characteristics such as blocking events (Liu et al., 2022; Pelucchi et al., 2021; Teixeira et al., 2016; Tang et al., 2006; Roeckner et al., 2006).

While the vertical resolution is held constant in our study, we do recognize that it could influence the interpretation of the turbulence processes in certain scenarios, especially in regions with complex vertical structures. However, due to the already sufficient vertical resolution in our simulations, we focused on the effect of horizontal resolution on turbulence mixing, which remains the dominant factor in our experiments. While vertical resolution is important for resolving stratified flows and boundary layer instabilities, horizontal resolution predominantly controls representation of turbulent mixing in mesoscale

simulations when vertical mixing schemes are well-configured. We have added a brief discussion on the role of vertical resolution in the end of section Discussion of the revised manuscript: “Finally, while the vertical resolution is held constant in our study, we do recognize that it could influence the interpretation of the turbulence processes in certain scenarios, especially in regions with complex vertical structures. Therefore, future work should systematically explore the interplay between vertical resolution and pollutant concentration or aerosol-boundary layer feedbacks.”

Reference:

Jiang, L. and Hu, J.: Influence of the lowest model level height and vertical grid resolution on mesoscale meteorological modeling, *Atmospheric Research*, 296, <https://doi.org/10.1016/j.atmosres.2023.107066>, 2023.

Jiang, L., Bessagnet, B., Meleux, F., Couvidat, F., Tognet, F., and Hu, J.: The role of vertical grid resolution and turbulent diffusion uncertainty on chemical transport modeling, *Atmospheric Research*, 312, <https://doi.org/10.1016/j.atmosres.2024.107759>, 2024.

Eastham, S. D. and Jacob, D. J.: Limits on the ability of global Eulerian models to resolve intercontinental transport of chemical plumes, *Atmospheric Chemistry and Physics*, 17, 2543-2553, <https://doi.org/10.5194/acp-17-2543-2017>, 2017.

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Roeckner, E., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kornblueh, L., Manzini, E., Schlese, U., and Schulzweida, U.: Sensitivity of simulated climate to horizontal and vertical resolution in the ECHAM5 atmosphere model, *Journal of Climate*, 19, 3771-3791, <https://doi.org/10.1175/jcli3824.1>, 2006.

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Teixeira, J. C., Carvalho, A. C., Tuccella, P., Curci, G., and Rocha, A.: WRF-chem sensitivity to vertical resolution during a saharan dust event, *Physics and Chemistry of the Earth*, 94, 188-195, <https://doi.org/10.1016/j.pce.2015.04.002>, 2016.

Minor comments:

- 1. Line 23-28: ‘higher resolution’ in key points, what resolution? Vertical or horizontal? Please be specific.

Response: Thank you for your constructive feedback. In this context, we are referring to the “horizontal resolution”. We have updated the manuscript to clearly specify “horizontal resolution” in the Key Points section, as well as in all relevant parts of the manuscript where the resolution is mentioned. This clarification ensures that the resolution type is explicitly defined throughout the article.

- 2. Line 418: what is the diurnal variation of BC emissions?

Response: Thank you for your constructive feedback. The diurnal variation of BC emissions refers to the pattern in which emissions from all sectors peak during the daytime and are lower at night, as illustrated in Figure 1. The diurnal profiles of emissions from the five individual sectors (agriculture, industry, transport, energy, and residential) all show this same pattern. However, the diurnal variations are much stronger for agriculture, residential, and transportation sectors compared to industry and power plants (Du et al., 2020). We have added a brief introduction of the diurnal variation of BC emissions in section 3.2.1 of the revised manuscript: “The diurnal variation of BC emissions peak during the daytime and are lower at night.”

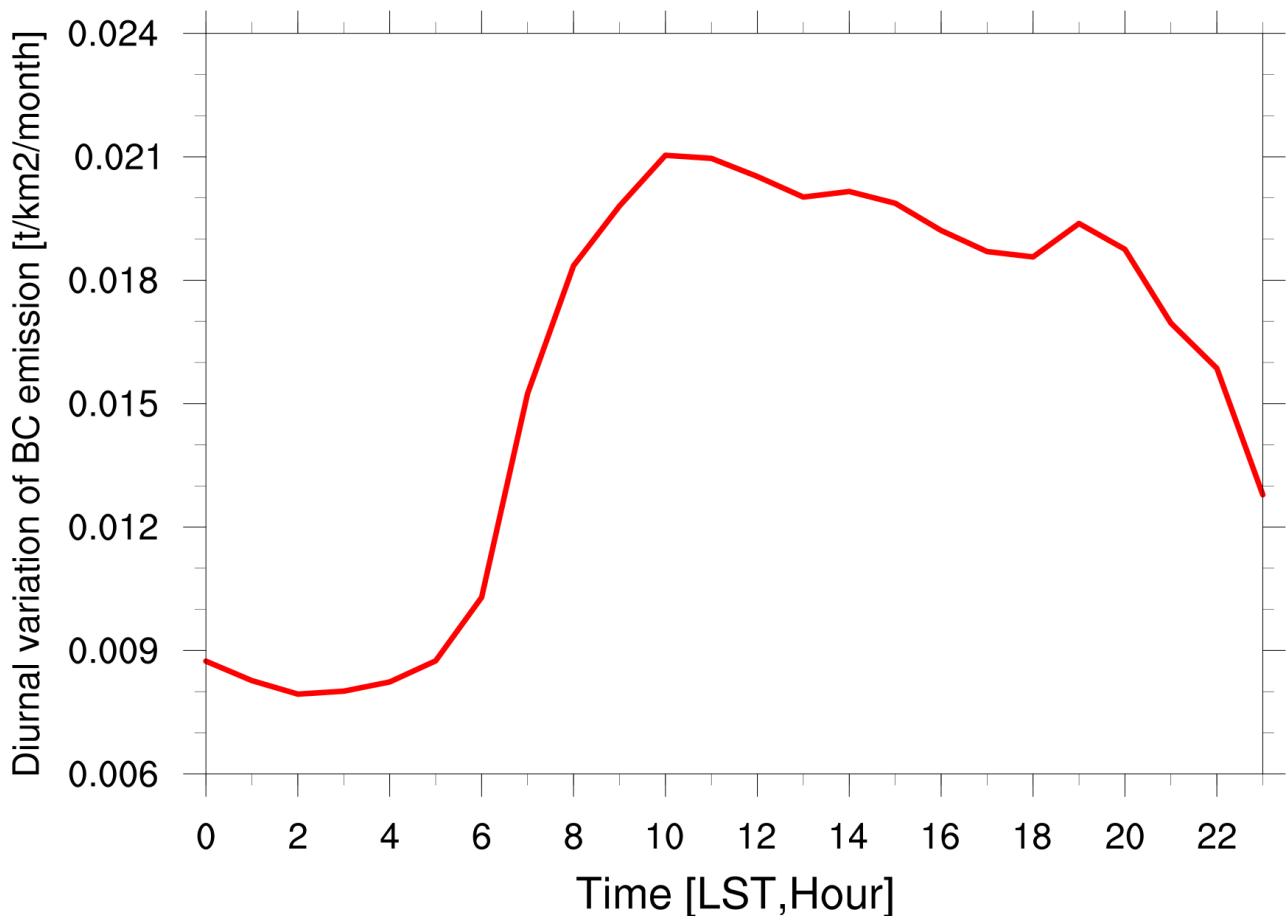


Figure 1. Diurnal variation of the total BC emissions from five individual sectors (agriculture, industry, transport, energy, and residential).

Reference:

Du, Q., Zhao, C., Zhang, M., Dong, X., Chen, Y., Liu, Z., Hu, Z., Zhang, Q., Li, Y., Yuan, R., and Miao, S.: Modeling diurnal variation of surface PM_{2.5} concentrations over East China with WRF-Chem: impacts from boundary-layer mixing and anthropogenic emission, *Atmospheric Chemistry and Physics*, 20, 2839-2863, <https://doi.org/10.5194/acp-20-2839-2020>, 2020.

- *3. I noticed a few spelling errors, such as 'parametrized' (should be 'parameterized') on page 17, line 474. Please review the manuscript for similar issues.*

Response: Thank you for pointing out the spelling error. We have carefully reviewed the manuscript and corrected all similar issues, including the change from 'parametrized' to 'parameterized'. We appreciate your attention to detail and have ensured that the manuscript is free from such errors.