To what extent is the description of streets important in estimating local air-quality? A case study over Paris (EGUSPHERE-2024-1043 — Research article)

Discussion

We thank the reviewers for their questions and comments on our work and appreciate the time spent to review our manuscript. In the text below, the questions raised appear in brown, followed by our responses and the modifications made to the paper. The sentences added are in blue and the sentences removed are in red .

1 Reply to anonymous referee #1's comments

- My only concern is that the study is presenting a fairly lengthy analysis of a rather trivial fact, namely, that the differences in concentrations at individual stations estimated by the subgrid and MUNICH methods strongly depend on the differences in local emissions at the respective road segment. This is a trivial observation because the "subgrid method" treats all streets within a grid cell in the same way, whereas the MUNICH approach accounts for the different emissions in each street segment separately. Another factor potentially affecting the differences is the street width:building height aspect ratio, but Figure 7 suggests that this factor is much less important. A more detailed (and again very lengthy) analysis then suggests that there must be an influence but that it is hardly discernable against the emissions influence. I recommend to (substantially) shorten the respective sections and possibly put some results in an appendix. This would make the paper more easily accessible and attractive.

We understand that this remark mainly concern the section 4.2, but we have also reviewed section 4.3 of our manuscript. We fully agree that the qualitative observation in the paper highlighting the strong impact of spatial heterogeneities in traffic emissions on the differences observed between the two approaches was easy to anticipate. The main goal of this section is not only to confirm this impact but also to quantify it. It aims to understand the extent to which the two approaches converge or diverge based on these heterogeneities concerning emissions and other factors. Following the reviewer comment we chose to focus more on this last point.

Below are the detailed modifications made in Section 4.1.1:

> An overarching problem with the description of emissions arises due to the heterogeneity between SOULT and BP_EST, located in the same cell. Indeed, this area is crossed by the heavily trafficked Paris ring road, which introduces significant urban spatial heterogeneity (see Figure 4). This is extensively discussed in Section 4.2.

Therefore, the beginning of Section 4.2 has been simplified. We decided to move Figure 7 to the Appendix and shorten the analysis related to it. Additionally, we moved Equation 6 to the Appendix along with its corresponding analysis. Below are the precise modifications made in Section 4.2.

~~The case of stations BP_EST and SOULT, both located inside the same grid cell, illustrates an expected limitation of the Subgrid method in comparison to MUNICH. The BP_EST station is located on the heavily trafficked Paris ring road, while the SOULT station is on a much less busy boulevard, further away from the highway. The presence of a highway traversing this cell introduces significant urban spatial heterogeneity (refer to Fig. ??).~~

~~The grid-cell that contains the stations BP_EST and SOULT, displayed with BDTOPO database: buildings are represented in grey, the open street in blue, the intermediate street in yellow, and the canyon street in brown.~~

By definition, the Subgrid method is supposed to represent a portion of a neighborhood, whereas the MUNICH model generates concentrations for every single street. To emphasize the impact of this conceptual difference, in Fig. 6, we compare the concentrations simulated with MUNICH for each street to the corresponding CHIMERE/Subgrid grid cell (area of $1\,km^2$), but also with the mean of all the streets of the MUNICH road network located inside this CHIMERE grid cell. This new averaged MUNICH output is noted as MUNICH_cell in Fig. 6. The fractional bias generated by [MUNICH_cell - Subgrid] (depicted by the blue barplot) is significantly lower than that of [MUNICH - Subgrid] (brownn barplot) at all stations for each pollutant. This outcome underscores the similarity in the average behaviour of each method.

~~Cells~~ Stations located in cells intersected by the Parisian ring road exhibit the most substantial ~~fractional biases~~ difference between the two approaches for NO_X, NO_2, and $PM_{2.5}$. Additionally, when examining AUT and RN2, two stations with ~~close~~ comparable emissions ($13.3\,\mu g.s^{-1}.m^{-2}$ and $11.0\,\mu g.s^{-1}.m^{-2}$ respectively), their FB significantly differs for the three pollutants. ~~This indicates that the~~ The observed discrepancies are then not solely attributable to traffic emission levels ~~. As anticipated from the statistics in ??, discrepancies between the two approaches appear more pronounced for NO_X estimations than for NO_2.~~

~~Notably, Fig. ?? highlights a significant observation: the fractional bias generated by MUNICH_cell - Subgrid(depicted by the blue barplot) is significantly lower than that of MUNICH - Subgrid(brownn barplot) at all stations for each pollutant. This outcome underscores the similarity in the average behaviour of each method~~ and justifies the performance disparities as a consequence of urban heterogeneity tied to emissions and urban topography.

It is interesting to quantify the influence of these two factors separately on the differences observed. However, it's worth noting that they~~these two factors~~ are not entirely independent: in our domain, a highway with substantial traffic emissions generally corresponds to a broad and open road. Moreover~~in MUNICH~~, in MUNICH, the impact of the aspect ratio α_r on street concentrations is more ~~visible for street~~ pronounced for streets with high emissions than for ~~street~~ those with low emissions. Additionally, a third factor could

impact these discrepancies. Because the Subgrid method has information only about the street area, we could expect some contribution from the wind direction. Its influence on the discrepancies observed between the approaches has been studied and does not reveal any significant impact in our case. But this could be due to the fact that the wind direction barely changes over the studied period, making it challenging to analyze its influence.

Figure ?? shows the between our two approaches for NO_x on all the streets inside two chosen cells, depending on the aspect ratio on x-axis, and the mean of the emissions on y-axis. The results displayed in this figure confirmed the strong correlation between the emissions and the disparities observed between MUNICH and the Subgrid method.

Bias between MUNICH and the Subgrid method for NO_x, as a function of the α_r (X axis) and the average emissions of MUNICH (Y axis, in $\mu g.s^{-1}.m^{-2}$) of all the streets (point) of a cell, over February and March 2014. The left panel shows the results for the cell containing stations BP_EST and SOULT, the right one for the cell containing HAUS.

The impact of emission heterogeneity on model discrepanciesis clearly observed by comparing the two panels of Fig. ??. The cell containing a part of the Paris ring road, leading to a wide range of emission values, presents a significantly greater range of bias values than the cell inside the city (the scatter plot of the right in Fig. ??). Indeed, we observed that for stations near the Paris ring road, namely BP_EST, AUT, and RN2, the minimum fractional bias averages at -0.61, while the maximum reaches 1.08. In contrast, for stations within the city, the fractional bias ranges between -0.29 and 0.53 on average. This observation confirms that the discrepancies between As expected, through an extension of the approaches are significantly less pronounced in areas with a more homogeneous distribution of emissions compared to those adjacent to highways, which introduce heterogeneous emissions.

The Spearman's rank correlation coefficient (defined in ??) between 1) the FBs in the mean concentrations (for the two months studied) calculated by the two approaches and 2) the differences, $E_{diff}(i)$, between the local emission in street i (E_i) and the average of emissions over the N_S analyze on all the streets in the corresponding cell (weighted by street surfaces $\{S_j\}_{j=1,N_S}$) is used to quantify the strength of the relationship. $E_{diff}(i)$ is then defined as:

$$E_{\text{diff}}(i) = E_i - \sum_{j=1,N_S} E_j \frac{S_j}{\sum_{k=1,N_S} S_k}$$

For NO_x, NO_2, and $PM_{2.5}$, the coefficients are 0.88, 0.85, and 0.87, respectively. These values confirm a significant correlation (potentially non linear)between the emission heterogeneity and the observed disparities between the modelling approaches.

cells calculated by the Subgrid method (see Appendix B, it is easy to show that emission heterogeneities is an important factor in the discrepancies observed between the two approaches. The other cell illustrated in Fig. ?? , which include HAUS station, represents an area with more homogeneous emissions. In this type of urban area (such as the cells containing ELYS and BONAP), However, as observed in Figure B1 (b), comparing

concentration differences with the aspect ratio of the ~~impact of emission heterogeneity is less prominent but the influence of streetaspect ratio on the differences observed between the two methods remains difficult to discern. We made the same observation for NO_2 and $PM_{2.5}$.~~

~~Comparing concentration differences with~~ street, the aspect ratio seems not very relevant. This can be explained by the absence of a direct use of the aspect ratio ~~of the street is less relevant as this variable is not directly used~~ in the Subgrid approach, which only considers the surface area of the street.

Finally, we have also shortened section 4.3 (Analysis of daily cycles), as detailed below :

~~About the station AUT~~ In areas with significant emission heterogeneity (such as AUT and BP_EST), the Subgrid approach underestimates ~~the~~ gas concentrations at each hour of the day~~unlike the street-network model, an area with an characterized by significant emission heterogeneity. This underestimation is especially~~ , with the discrepancies compared to MUNICH being particularly marked during the concentration peaks corresponding to ~~the~~ rush hours (from 5 am to 9 am and from 5 pm to 8 pm). ~~It's also at these moments that the discrepancies between the two approaches are more pronounced. This is also true~~ This pattern is also observed for $PM_{2.5}$ concentrations. ~~The behaviour is different for stations located in~~ In areas with less emission heterogeneity (HAUS and BONAP)~~. In these cases~~, the two methods exhibit alternating periods of over- and under-estimation of NO_X and NO_2 concentrations throughout the day, ~~and~~ with the dispersion of the bias of each approach ~~is~~ being quite similar. Specifically, the spreads of these biases (the difference between the maximum and minimum bias) for the two methods remain fairly similar for a given hour of the day. This underscores the similarity in the daily variability of the methods. The other stations are displayed in Appendix E.

~~The Fig. 9 illustrates~~

Figure 9 shows the averaged 24-hour profiles of the bias between MUNICH and the Subgrid approach at each hour of the day for the same three stations. It ~~confirms that the differences are more pronounced during the daylight, and the significant influence of the emission heterogeneity (BP_EST has the same behavior as AUT). The NO_X bias at BONAP station slightly exceeds that of HAUS, possibly attributable to the effect of α_r, given that the street, where the BONAP is localated, is among the narrowest in its urban area.~~

~~However,~~ illustrates that the discrepancies between the two approaches become more pronounced at certain times of the day. These differences are minimal during nighttime and escalate with traffic. Regarding NO_X concentrations, the bias between the two methods remains positive and increases slightly throughout daylight hours. This indicates that for these streets, MUNICH retains traffic emissions for longer than ~~Subgrid~~the Subgrid approach. Conversely, for NO_2 concentrations, the sign of the bias varies ~~along~~ throughout the day. ~~Indeed, while~~ While in most cases the street-network model generates higher concentrations of NO_2 than the Subgrid method, ~~this~~ the latter generates higher concentrations during the morning. ~~Note~~ It is noteworthy that all the other stations (apart from AUT and BP_EST) behave in the same way as HAUS and BONAP, ~~which are~~ as shown in Fig. 9.

- The "subgrid method" seems to require multiplying the number of species in the chemistry scheme by the number of sectors considered, which seems very expensive. Please clarify whether really all species (including secondary) are treated n times (where n is number of sectors) and whether this is done in the whole 3D grid of CHIMERE or only in the lowest few layers. If this is done only in the lowest layers, how is the transition to the upper layers handled, where each species is represented only once?

As indicated in lines 117-118 of the original manuscript, the subgrid method processes all species (including secondary ones) for all sectors considered in the approach. The sentence has been modified to clarify this point :

> The advantage of this approach is that the full chemical mechanism operates over each subgrid-scale volume, i.e. for each sector specifically considered, leading to subgrid scale concentrations for all model species.

Although this method can be applied to multiple cells, it is only implemented at the surface cell. Tests performed for the publication of the approach (Valari and Menut, 2010) that are not discussed showed negligible differences in concentrations when applied to all vertical cells versus only the surface cell. Moreover the application of the method is only local, meaning it can be used for one chosen subset of cells. There is no specific transition between cells using this method and those using the classic approach (without sectors) because the classic approach remains applied to the entire grid.The additionnal computational burden remains therefore affordable in a general case. In the present study the subgrid approach is not computationally expensive because it is applied for two sectors to only a few cells, where measurement stations are located. To clarify this point, the following sentences have been added at the end of the section 3.2.2 :

> The approach is applied only to cells containing a traffic station, representing a total of 8 cells. Their locations within the grid are illustrated in Figure 1d.

- Similarly, for the "MUNICH method" it seems that the number of species (per CHIMERE grid cell) has to be multiplied by the number of street segments in that cell. Within a 1 km x 1 km grid cell this number must be quite large, making the scheme potentially very expensive. Again, it is unclear to me whether all species of the chemistry and aerosol schemes are treated in this way or only a subset. And is this done for all CHIMERE cells in Paris or only for the handful of cells containing the measurement stations? Please clarify!

Thank you for pointing out the absence of this important precision. Indeed, all the species in the chemistry and aerosol schemes are accounted for in the MUNICH model. To clarify this point the following sentence has been added in the section 2.2 :

> As with the CHIMERE subgrid-scale model, the full chemical mechanism is applied to each street, leading to street scale concentrations for all the species in the model.

The MUNICH model was applied to the entire street network representing the city of Paris and its close suburbs, as explained in section 3.2.1.

The final street network comprises 4655 streets and extends over the city of Paris and its nearby suburbs

MUNICH operates as an Eulerian model and, in the present study, independently of the CHIMERE simulation. The computing time of the concentrations in the street network is divided equally according to the number of processors used, ensuring a reasonable computing time of around 72 h with 50 CPUs for a two-month simulation (we have not specifically optimised this computing time).

- Finally, it should be briefly explained how wind along the different street segments is computed. I assume that the wind in segments perpendicular to the mean flow (from WRF) is lower than in segments oriented along the mean flow. I assume that the orientation of a street canyon relative to the mean flow is another factor potentially contributing to differences between the two methods, because the "subgrid method" cannot take this into account. Please comment on this point and eventually add a corresponding analysis.

Thank you for pointing out this point. The Section 2.2 has been expanded to precise how wind speed is taken into account in the street network, as detailed below :

~~Finally, the computation of the wind profile within streets is inspired from Wang (2011, 2014). To estimate the wind speed at roof level, the parametrization of Macdonald et al. (1998) has been used. The implementation of these parametrizations in MUNICH is detailed in Maison et al. (2022).~~ The implementation of the different parameterizations available in MUNICH to determine the average wind speed in a street is detailed in Maison et al. (2022). The first step is to compute the wind speed at the mean height of the building, u_H. It can be derived in MUNICH from a representative wind speed above the urban canopy or from the friction velocity u_*. This second option and the parameterization of Macdonald et al. (1998) are used in the current work, allowing an estimation of u_H based on an average vertical profile at the scale of a neighborhood. Then only the component of the wind in the direction of the street is taken into account to reconstruct the wind vertical profile in the street. It has been represented in the current study following the work of Wang (2011, 2014). Finally the average wind speed in the street is obtained by integrating the chosen wind profile between the soil roughness and the building height.

As the Subgrid method only has information about the street area, we indeed assumed that wind direction could be one of the factors contributing to the differences observed between the two approaches. Nevertheless the study of the influence of wind direction on these discrepancies does not reveal any significant impact in our case. We noticed that the wind direction barely changes over the studied period, making it challenging to analyze its influence. To clarify this point, some comments have been added in the Section 4.2. The modifications have been detailed above, but are briefly reminded below :

It is interesting to quantify the influence of these two factors separately on the differences observed. However, it's worth noting that they~~these two factors~~ are not entirely independent: in our domain, a highway with substantial traffic emissions generally corresponds to a broad and open road. Moreover~~in MUNICH~~ , in MUNICH, the impact of the aspect

ratio α_r on street concentrations is more ~~visible for street~~ pronounced for streets with high emissions than for ~~street~~ those with low emissions. Additionally, a third factor could impact these discrepancies. Because the Subgrid method has information only about the street area, we could expect some contribution from the wind direction. Its influence on the discrepancies observed between the approaches has been studied and does not reveal any significant impact in our case. But this could be due to the fact that the wind direction barely changes over the studied period, making it challenging to analyze its influence.

Reply to minor comments

Below, we answer to one of the minor points, the others have been corrected as proposed.

- Assumption that traffic profile is representative for anthropogenic heat flux in February is fairly questionable, since heat release from heating is likely much larger in this month than traffic.

We agree that this modeling choice is questionable. The paper emphasizes traffic measurement for the current comparison. Given that the resutls of the approaches studied are strongly influenced by traffic emissions and that we have access to traffic data provided by Airparif, we decided to use this type of profile for our simulations, as explained in Section 3.1.3. And this approach appears to be better than using the default profile provided by WRF. We guess from this result that a temporal profile corresponding to heating, or ultimately to the total anthropogenic heat flux, would not be very different.

2 Reply to anonymous referee #2's comments

- It is not clear how "double counting" of the street traffic emissions is avoided. The emissions Ei are used in CHIMERE (eq. 1) as well as in MUNICH (eq. 2). This might lead to double counting and additional (too high) urban background contributions in CHIMERE caused by the street that is considered in MUNICH. On the other hand, if the street traffic emissions are only included in MUNICH, then the effect of neighboring streets is not included as contribution to the background concentration for the street considered. It is not clear how this is accounted for.

The issue of "double counting" of emissions and its concrete consequences when models are coupled together strongly depend on the nature of the models and the coupling strategy. The MUNICH model belongs conceptually to the class of Eulerian approaches. When runnning the street-network model MUNICH in stand-alone mode, as is the case in this work, it is mandatory to provide background concentrations as boundary condition at the top of the buildings' roofs. In the current work, these background concentrations are provided by the regional scale CHIMERE model, an evaluation of which against urban background measurements is given in Appendix D. This evaluation shows that CHIMERE is able to provide boundary conditions that are representative of the background concentrations observed, which is what is actually expected.

Street concentrations are computed in MUNICH as the result of the integration of the mass conservation equation (see Lugon et al., 2020), taking into account emissions in the street network and exchange fluxes between the street volume and its boundary conditions at roof level, as is done in

regional Eulerian chemical transport model. It is important to keep in mind that the street concentrations are never estimated as the direct sum of the background concentrations with a local concentration only due to sources in the simulated domain.

We believe that the issue of "double counting" is more significant when source-oriented models are used, such as Gaussian plume models (e.g. Benavides et al., 2019) or Lagrangian models (e.g. Berchet et al., 2017) for which the constitutive equations do not take into account the contribution of a background via boundary conditions. Gaussian models explicitely assume null boundary condition and Lagrangian models, often implemented as source oriented models to ensure low computing time, do not manage incoming fluxes through spatial boundary conditions. With this type of approach, it becomes necessary to estimate the street concentration as a composition, generally a sum (e.g. Stocker et al., 2012), of a local contribution and a background contribution. From our point of view, it is mainly this composition that raises the question of "double counting".

However, we recognise that the "one-way" nesting coupling strategy used in this work and in many others with MUNICH (e.g. Sarica et al., 2023; Kim et al., 2022; Lugon et al., 2021; Wang et al., 2022), but more generally with any local Eulerian model (e.g. Alam et al., 2024; Lauriks et al., 2021) , leads to some coupling errors. And some of these errors are indeed due to the fact that "local" emissions are taken into account in both the local and regional models. We intend to provide a comprehensive analysis of the nature of these errors in the case of coupling the MUNICH street network model with the CHIMERE model, and of their consequences, in a separate paper presenting the "two-way" coupling strategy we have implemented between MUNICH and CHIMERE. We believe that this "two-way" coupling strategy is the most appropriate way of dealing with this issue for our approach.

The following sentence is added in our manuscript in section 2.2 to clarify further this point:

> In the framework of the one-way coupling strategy applied in this work, as in many previous studies (e.g. Sarica et al., 2023; Wang et al., 2022), the background concentrations ~~(compared to observations in Annex C)~~ are not modified by MUNICH. These background concentrations are evaluated against observations in Appendix D. This comparison shows that CHIMERE is able to provide boundary conditions for MUNICH that are representative of the background concentrations observed.

- Secondly it is not clear if or how the O3-NO-NO2 chemistry is modelled differently in MUNICH compared to CHIMERE. This is important because the time scales might be different.

The O3-NO-NO2 chemistry in both models is represented by the same chemical mechanism MELCHIOR2 (Derognat et al., 2003), as explained in section 3.1.4 (lines 262-265). In both cases the temporal integration is explicitly solved and does not rely on a stationarity assumption. This paragraph has been reworded to clarify further these points :

> ~~These background concentrations were evaluated by comparing them with observations from the background stations operated by Airparif, as shown in Appendix C.~~For CHIMERE~~/~~ and MUNICH simulations, a same configuration of SSH-aerosol is used ~~at every scale, which is described in 3.2.1. Finally,~~. Both simulations use the same chemical module

for gas chemistry, the MELCHIOR2 mechanism (Derognat et al., 2003; P.L.Carter, 1990) and the H2O (Hydrophilic/Hydrophobic Organics) reduced mechanism for the SOA (Secondary Organic Aerosol) formation from VOC (Volatile Organic Compounds Couvidat et al., 2012). For both models the time integration of the gas-phase chemistry is solved explicitly and is not based on a stationarity assumption, which means that different time scales can be taken into account .

References

Alam, B., Nkenfack Soppi, R., Feiz, A.-A., Ngae, P., Chpoun, A., and Kumar, P.: CFD simulation of pollutant dispersion using anisotropic models: Application to an urban like environment under neutral and stable atmospheric conditions, Atmospheric Environment, 318, 120 263, https://doi.org/https://doi.org/10.1016/j.atmosenv.2023.120263, 2024.

Benavides, J., Snyder, M., Guevara, M., Soret, A., García-Pando, C. P., Amato, F., Querol, X., and Jorba, O.: CALIOPE-Urban v1.0: coupling R-LINE with a mesoscale air quality modelling system for urban air quality forecasts over Barcelona city (Spain), Geoscientific Model Development, 12, 2811–2835, https://doi.org/10.5194/gmd-12-2811-2019, 2019.

Berchet, A., Zink, K., Oettl, D., Brunner, J., Emmenegger, L., and Brunner, D.: Evaluation of high-resolution GRAMM–GRAL (v15.12/v14.8) NOx simulations over the city of Zürich, Switzerland, Geoscientific Model Development, 10, 3441–3459, https://doi.org/10.5194/gmd-10-3441-2017, 2017.

Couvidat, F., Debry, E., Sartelet, K., and Seigneur, C.: A hydrophilic/hydrophobic organic (H^2O) aerosol model: Development, evaluation and sensitivity analysis, Journal of Geophysical Research: Atmospheres, 117, n/a–n/a, https://doi.org/10.1029/2011jd017214, 2012.

Derognat, C., Beekmann, M., Baeumle, M., Martin, D., and Schmidt, H.: Effect of biogenic volatile organic compound emissions on tropospheric chemistry during the Atmospheric Pollution Over the Paris Area (ESQUIF) campaign in the Ile-de-France region, Journal of Geophysical Research: Atmospheres, 108, https://doi.org/10.1029/2001jd001421, 2003.

Kim, Y., Lugon, L., Maison, A., Sarica, T., Roustan, Y., Valari, M., Zhang, Y., André, M., and Sartelet, K.: MUNICH v2.0: a street-network model coupled with SSH-aerosol (v1.2) for multi-pollutant modelling, Geoscientific Model Development, 15, 7371–7396, https://doi.org/10.5194/gmd-15-7371-2022, 2022.

Lauriks, T., Longo, R., Baetens, D., Derudi, M., Parente, A., Bellemans, A., van Beeck, J., and Denys, S.: Application of Improved CFD Modeling for Prediction and Mitigation of Traffic-Related Air Pollution Hotspots in a Realistic Urban Street, Atmospheric Environment, 246, 118 127, https://doi.org/https://doi.org/10.1016/j.atmosenv.2020.118127, 2021.

Lugon, L., Sartelet, K., Kim, Y., Vigneron, J., and Chrétien, O.: Nonstationary modeling of NO 2 , NO and NO x in Paris using the Street-in-Grid model: coupling local and regional scales with a two-way dynamic approach, Atmospheric Chemistry and Physics, 20, 7717–7740, 2020.

Lugon, L., Sartelet, K., Kim, Y., Vigneron, J., and Chrétien, O.: Simulation of primary and secondary particles in the streets of Paris using MUNICH, Faraday Discussions, 226, 432–456, https://doi.org/10.1039/d0fd00092b, 2021.

Sarica, T., Maison, A., Roustan, Y., Ketzel, M., Jensen, S. S., Kim, Y., Chaillou, C., and Sartelet, K.: Modelling concentration heterogeneities in streets using the street-network model MUNICH, Geoscientific Model Development Discussions, 2023, 1–34, 2023.

Stocker, J., Hood, C., Carruthers, D., and McHugh, C.: ADMS-Urban: developments in modelling dispersion from the city scale to the local scale, International Journal of Environment and Pollution, 50, 308, https://doi.org/10.1504/ijep.2012.051202, 2012.

Valari, M. and Menut, L.: Atmospheric Environment, 44, 3229–3238, 2010.

Wang, T., Li, J., Pan, J., Ji, D., Kim, Y., Wu, L., Wang, X., Pan, X., Sun, Y., Wang, Z., Yang, W., and Du, H.: An integrated air quality modeling system coupling regional-urban and street models in Beijing, Urban Climate, 43, 101 143, https://doi.org/10.1016/j.uclim.2022.101143, 2022.