PARAMETERIZATION OF AERODYNAMIC ROUGHNESS OVER URBAN AREAS FOR WRF-CHEM MODEL BASED ON LCZ AND RADAR INTERFEROMETRY

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ABSTRACT: Aerodynamic roughness is an important parameter for climate and environment simulation using the Weather Research and Forecasting (WRF) model coupled with Chemistry, which is closely related to the surface geometry and thus takes on highly spatio-temporal heterogeneity over urban areas. But in practice the WRF-Chem model usually specifies the appropriate roughness value based on the land use type, that is, land use and land cover classification in urban areas are not precise enough in WRF-Chem default mode, and it sets the aerodynamic roughness of urban built-up areas as 0.5m by default. It is obviously not in accordance with the actual situation in urban areas. Therefore, the WRF-Chem model is less effective in urban areas, and it is necessary to develop suitable parameterization methods for aerodynamic roughness. To address this problem, this paper proposed an urban roughness parameterization method for WRF-Chem model based on Local Climate Zone (LCZ) method and radar interferometry, and compared the PM2.5 simulation results of the WRF-Chem model before and after the roughness update. It showed that the aerodynamic roughness inversion using LCZ combined with TSX/TDX double star interferometry can effectively improve the WRF-Chem model's simulation of PM2.5.

1. INRTODUCTION

Air pollution is one of the major environmental pollution problems in the world at present, and has been gradually paid attention to by the academia, society and government (Fan et al., 2015; Lelieveld et al., 2015). Air quality model is an important mean to quantitatively describe changes in atmospheric pollutants and meteorological conditions, and one of the most commonly used air quality models is the Weather Research and Forecasting Model with Chemistry (WRF-Chem) model that is a complete coupling of the regional climate model and the atmospheric chemical transport model, and is capable of simulating regional-scale climate and environmental elements such as PM2.5, O_3, CO and other chemical elements, as well as meteorological elements such as wind field, temperature and precipitation.

When the WRF-Chem model is used for simulating urban atmospheric environment, it often faces problems such as the insufficient accuracy of the underlying surface and the delay in updating the underlying surface, thus the simulations obtained for the climate environment differed greatly from the actual conditions (Saide et al., 2011). Tie et al. compared the effect of WRF-Chem simulation of CO and O_3 at four spatial resolutions of 3km, 6km, 12km and 24km, and showed that the accuracy of WRF-Chem simulation results improved coupling with the spatial resolution increased(Tie et al., 2010). To address the problem that the WRF-Chem model does not classify urban areas with sufficient precision, Stewart et al. proposed the Local Climate Zone (LCZ) method (Stewart et al., 2014), which aimed to provide a set of objective criteria for local zoning for urban climate and environmental studies, and it is now widely used to improve the simulation effects of meteorological and air quality models. The backscattering intensity obtained by Synthetic Aperture Radar (SAR) is very sensitive to roughness elements, especially to the geometry of buildings. Therefore, with the help of Interferometric Synthetic Aperture Radar (InSAR) technique, it is possible to acquire the height dimensional information of the urban underlying surface, which provides an advantageous tool to extract the aerodynamic roughness of the urban underlying surface on a large scale. Bechtel et al. used InSAR data to extract DTM and DSM information and establish the difference between them, that is, the correlation between feature height information and aerodynamic roughness (Bechtel et al., 2011).

Therefore, this paper used InSAR data on the basis of the LCZ, established a method to parameterize the roughness of the urban underlying surface, which was used to update the input parameters of the WRF-Chem model, and then to optimize the WRF-Chem model. Finally, it analyzed the effect of optimizing the WRF-Chem model using this method with PM2.5 spatio-temporal distribution as a simulation object.

2. METHOD

2.1 Overview

This paper used the InSAR technology and the geometric morphology method, and proposed a parameterization model of urban aerodynamic roughness for WRF-Chem model optimization. Figure 1 is a flow chart for extracting the aerodynamic roughness of the urban underlying surface suitable for WRF-Chem mode. First, we used Landsat-8 data to finely classify urban land based on the LCZ method, and then used InSAR technology to generate surface DSM using TSX/TDX data. On this basis, we used the MSD algorithm to obtain the height information of urban buildings and describe the height dimension characteristics of roughness elements; then, according to the urban land types obtained by the LCZ method, the average height of different urban land types was obtained, and the average height of different urban land types was combined with the geometric morphology method to finally determine the corresponding aerodynamic roughness of different urban land types in Beijing .

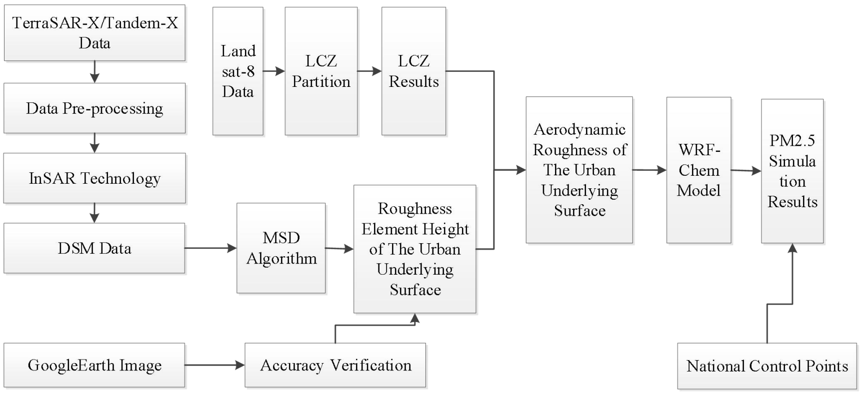


Figure 1 Flow Chart of Aerodynamic Roughness Inversion

2.2 LCZ method

After pre-processing the Landsat-8 data, training samples were selected for each type with reference to Google Earth imagery and streetscape data. The urban land types in the experimental area were actually divided into seven categories, such as compact high-rise building area (LCZ1), compact mid-rise building area (LCZ2), compact low-rise building area (LCZ3), open high-rise building area (LCZ4), open mid-rise building area (LCZ5), open low-rise building area (LCZ6) and large low-rise building area (LCZ8), and the natural environment land types were divided into five categories, such as densely wooded area (LCZA), sparse wooded area (LCZB), low lying vegetation area (LCZD), hardened ground area (LCZE) and water (LCZG). Finally, about 20 training samples were selected for each type, and the random forest algorithm was used to classify the images to obtain the LCZ classification result map of the experimental area as shown in Figure 2. Fifteen samples were selected for each category on Google Earth images to verify the LCZ classification results, and the confusion matrix of the seven urban area categories in the experimental area is shown in Table 1.

Table 1 LCZ Classification Result Accuracy Verification

LCZ Classification Category	Producer accuracy	User Accuracy
LCZ1 Compact High-rise Building Area	60.47%	86.67%
LCZ2 Compact Mid-rise Building Area	80.60%	70.13%
LCZ3 Compact Low-rise Building Area	85.94%	90.91%
LCZ4 Open High-rise Building Area	72.22%	55.32%
LCZ5 Open Mid-rise Building Area	63.33%	86.36%
LCZ6 Open Low-rise Building Area	75.90%	81.82%
LCZ8 Large Low-rise Building Area	97.27%	56.32%

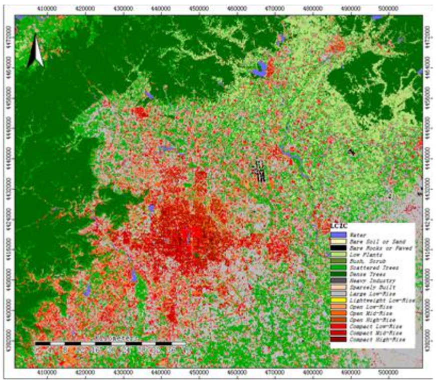


Figure 2 Local Climate Zone Graph

Table 2 shows the area proportions of each type of LCZ obtained by statistics. Among the results, the built-up area has the largest proportion of large low-rise buildings, mainly industrial buildings located in the suburbs of Beijing. Although the area of the other urban types is lower than the area of large low-rise buildings, they are mainly distributed in the central of Beijing with dense human activities, which is the key area for roughness calculation in this paper.

Table 2 Statistics on the Area Proportion of Different Types of LCZ

LCZ Classification	Large Low-rise Building	Open Low-rise Building	Open Mid-rise Building	Open High-rise Building	Compact Low-rise Building	Compact Mid-rise Building
Proportion	12.98%	3.28%	2.77%	1.76%	2.75%	1.77%
LCZ Classification	Compact High-rise Building	Water	Hardened Ground	Low Lying Vegetation	Sparse Wooded	Densely Wooded
Proportion	0.70%	1.21%	0.13%	6.52%	16.78%	49.36%

2.3 Roughness element height extraction based on InSAR technology and MSD algorithm

This paper used InSAR technique to obtain digital surface model (DSM) data based on TSX/TDX data, and then calculate the roughness element height using MSD algorithm as shown in Figure 3.

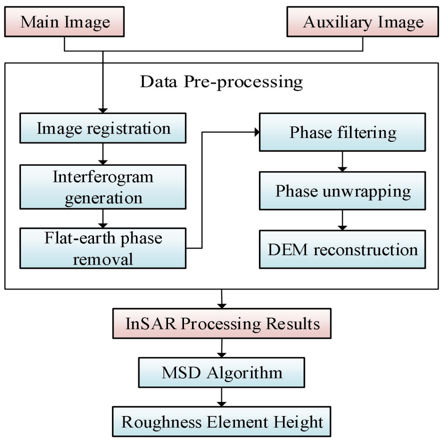
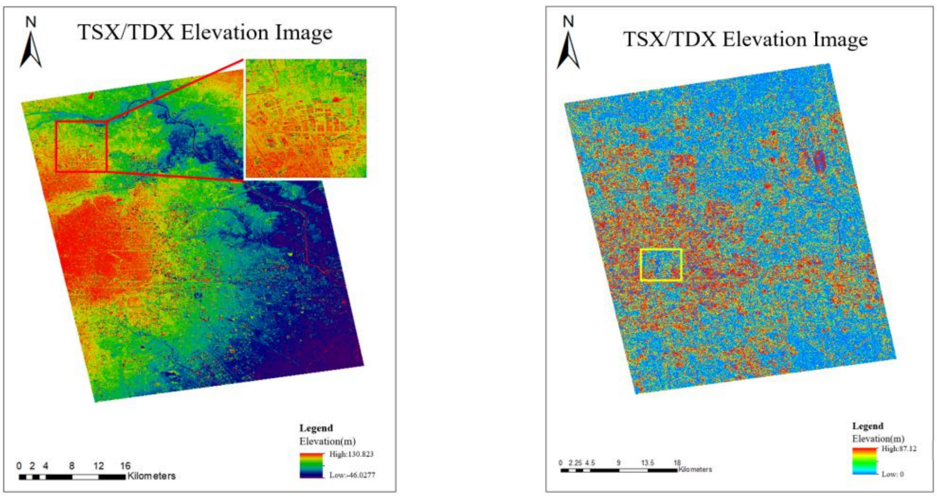


Figure 3 InSAR Technical Flow Chart

The DSM of the experimental area obtained by using TSX/TDX data is shown in Figure 4 (a), which is consistent with the actual topographic distribution of Beijing showing highs in the northwest and lows in the southeast. The maximum height of the building in the experimental area by the inversion of TSX/TDX data is 130.823m, which is significantly higher than the 107m extracted by SRTM. Compared with partial enlarged images, it shows that the method in this paper obtains a richer information of DSM details. It was found that the elevation range within the third ring of Beijing urban is between 35m and 108m, with an elevation variation of more than 70m; the elevation range in the southeastern region is between 21m and 50m, with an elevation variation of 29m. In order to eliminate the influence of the undulating terrain, the MSD algorithm was used to extract the building height ΔH.

The common method to obtain ΔH is to determine the elevation information of ground points and to make the difference with the elevation of non-ground points. The difference between the two is the value of ΔH, thus distinguishing ground points and non-ground points is the key problem to be solved in ΔH extraction. This paper used a method-MSD (Multi-directional Processing and Slope-dependent Filtering) filtering that is applicable to a large-scale building height extraction (Misra et al., 2018). We set parameters that the windows size was 300×300m, the height was 2.5m, and the slope was 30°.

The height of buildings in Beijing is shown in Figure 4 (b), in which the height range of the roughness elements in Beijing is 0m~87.12m. The area in yellow box in Figure 4 (b) is the central area of Beijing with mostly elements in blue, which indicates that the height of roughness elements in this area is significantly lower than that in the surrounding area. We divided the buildings into high-rise buildings (above 15 floors), mid-rise buildings (3 to 15 floors) and low-rise buildings (1 to 3 floors), and used Google Earth and ground survey results to obtain 20 groups of high-rise buildings, mid-rise buildings and low-rise buildings data to verify the accuracy of the building height obtained by this method. The root mean square error (RMSE) and the normalized mean error (NME) of the height inversion result of this method were shown in Table 3.It indicates that the method has a large error when used for extracting the height of low-rise buildings, but the height inversion results and errors are within reasonable limits, thus the result can be used for roughness calculations.



(a) TSX/TDX Elevation (b) MSD Filtering Result

Figure 4 Elevation Map of Beijing

Table 3 TSX / TDX Extraction Building Height Accuracy Verification

Building Type	NME	RMSE
High-rise Building	0.155	8.355
Mid-rise Building	0.194	5.861
Low-rise Building	0.374	3.291

2.4 Aerodynamic roughness calculation based on morphological method

In this paper, aerodynamic roughness calculations were performed using the building height-based method proposed by Raupach, et al. (Raupach et al., 1991)：

$$Z_0 = f_0 \Delta H \tag{1}$$

where ΔH is the height of roughness elements, and different f_0 are corresponded to different land types (Raupach et al., 1991). To address the complex internal structure and high spatial heterogeneity of the underlying surface in urban areas, Langkamp proposed a formula (Langkamp, 2013):

$$\ln(\Delta H) = 3.56 Z_0^{0.08} \tag{2}$$

Table 4 Average Height and Aerodynamic Roughness of Urban Underlying Surface

Urban Underlying Land Use	ΔH(m)	Aerodynamic Roughness(m)	LCZ Z_0(m)
Compact High-rise Building Area	57.27	1.738188	≥2
Compact Mid-rise Building Area	39.37	0.751563	0.5-1
Compact Low-rise Building Area	10.54	0.016235	0.5
Open High-rise Building Area	41.26	0.838508	1-2
Open Mid-rise Building Area	35.01	0.56787	0.25-0.5
Open Low-rise Building Area	7.26	0.00367	0.25-0.5
Large Low-rise Building Area	12.58	0.030334	0.25

We extracted the average height of the roughness elements obtained by TSX/TDX interferometry according to the ground classes determined by LCZ method, and calculated the aerodynamic roughness results of different urban land types underlying surface using the formula. WRF-Chem has a default aerodynamic roughness of 0.5m for urban underlying surface, and the results obtained by this method is showed in Table 4. The LCZ method recommends different range of aerodynamic roughness for different land types, and the values of aerodynamic roughness calculated in this paper for low height building classes are somewhat different from the aerodynamic roughness ranges provided by the LCZ method, while the aerodynamic roughness calculations for high-rise and mid-rise buildings all show good agreement with the aerodynamic roughness ranges provided by the LCZ method. Therefore, the aerodynamic roughness of the urban underlying surface obtained in this paper described the vertical characteristics of the urban underlying surface in more detail, which was beneficial to improve the accuracy of WRF-Chem model simulation.

2.5 WRF-Chem model optimization and PM2.5 simulation

We set up the parameter scheme for WRF-Chem simulation shown in Table 5, and selected two days, February 13, 2015 and February 14, 2015, as the validation time period when the national control points data showed that the monitoring results at all stations in Beijing reached the heavy pollution level these days, to compare and analyze the simulation results of the WRF-Chem model before and after the roughness update of the underlying surface. The simulation used a layer of nesting, the simulation spatial resolution was set to 1km, and the nested area grid points was 327 * 327.

Table 5 WRF-Chem Physical and Chemical Parameter Scheme Setting

Parameter Name	Selection	Parameter Name	Selection
Land-based processes	Noah	Aerosol mechanism	MOSAIC
Boundary layer	YSU	Anthropogenic emissions sources	EDGAR-HTAP
Gas-phase chemical	MOZART	Biological emission sources	MEGAN

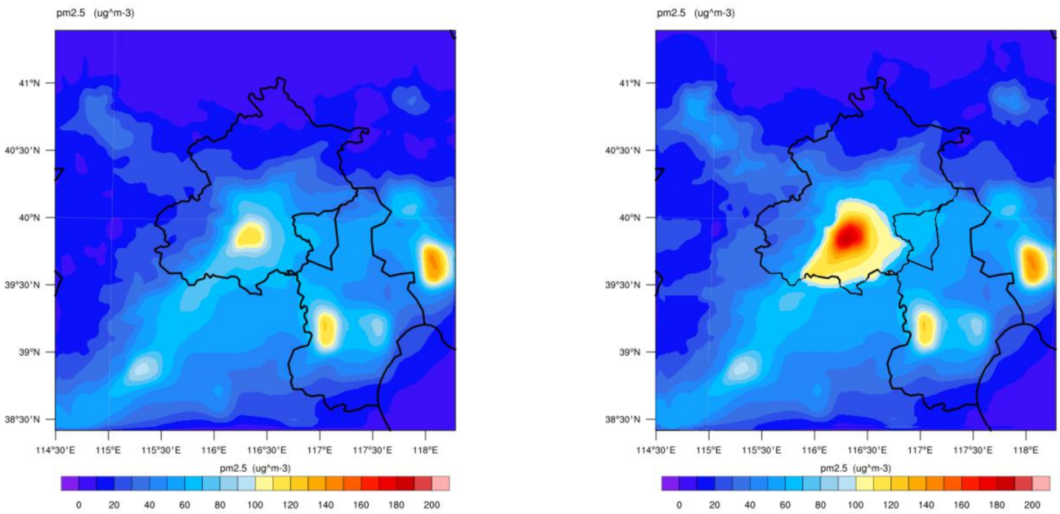
In experiment 1, we used the default settings of the WRF-Chem model, that is, using a lookup table method to assign values to roughness based on MODIS land use and land cover data. The Noah land surface process scheme was used in this paper, and the corresponding lookup table for this scheme was VEGPARM.TBL. It was shown that the urban and built-up areas correspond to only one land class with an aerodynamic roughness of 0.5. In Experiment 2, according to the roughness calculation in this paper, the aerodynamic roughness of the urban underlying surface was refined by modifying the VEGPARM.TBL lookup table, and the added contents of the modified lookup table were shown in Table 6.

Table 6 Modification of VEGPARM.TBL Lookup Table

	Z_{0MIN}(m)	Z_{0MAX}(m)	Encoding
34	1.74	1.74,	LCZ1 Compact High-rise Building Area
35	0.75	0.75	LCZ2 Compact Mid-rise Building Area
36	0.02	0.02	LCZ3 Compact Low-rise Building Area
37	0.84	0.84	LCZ4 Open High-rise Building Area
38	0.57	0.57	LCZ5 Open Mid-rise Building Area
39	0.004	0.004	LCZ6 Open Low-rise Building Area
40	0.03	0.03	LCZ8 Large Low-rise Building Area

3. RESULTS

According to the above two methods, the distribution of PM2.5 was simulated using the WRF-Chem mode before and after the update of the underlying surface roughness. Figure 5 (a) and (b) show the characteristics of low PM2.5 concentration in the northwest and high in the southeast. Compared with Figure 5 (a), the PM2.5 concentration in Beijing's main urban area after the update of the urban underlying surface roughness using this method is higher than the value before the update of the underlying surface, and the spatial difference is more significant.



(a) Experiment1 (b) Experiment2

Figure 5 Experiment 1 and 2 WRF-Chem Simulation PM2.5 Results

The simulation results were verified by the PM2.5 concentration obtained by the national control point observation. As shown in Figure 6, the variation range of the average PM2.5 concentration obtained by the national control point was 118.58ug/m³~254.98ug/m³, and the variation range of the PM2.5 concentration obtained by the default WRF-Chem mode simulation was 30.03ug/m³~85.8ug/m³, which was significantly lower than the observed value of the national control points. After updating the roughness of the underlying surface using the method in this paper, the simulated PM2.5 concentration range was 33.82ug/m³~135.07ug/m³. The simulation effect of heavily polluted areas has been greatly improved. The three points with the highest average PM2.5 concentration obtained by WRF-Chem simulation were Wanshou Xigong, Guanyuan and Dongsi, all of which are located in the main urban area of Beijing, and consistent with the results obtained by national control points. The three points with the lowest average PM2.5 concentration obtained by WRF-Chem simulation were Huairou, Changping and Dingling, which are all located in the suburbs and the corresponding national control points results are also relatively low. The average PM2.5 concentration of the five stations in Shunyi, Huairou, Changping, Dingling, and Gucheng did not change much before and after the roughness update. Because no significant changes in the underlying surface around these sites from 2005 to 2015, the simulated PM2.5 values before and after the underlying surface update do not change significantly.

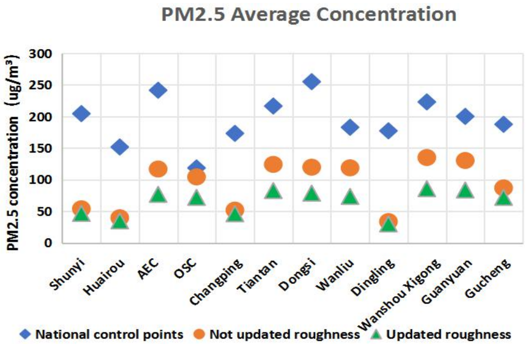


Figure 6 PM2.5 Average Concentration

Due to the problem of instability at the beginning of the WRF-Chem model simulation, the initial time selected for the hour-by-hour analysis of sites with significant changes after the update, such as the Agricultural Exhibition Center (AEC), Olympic Sports Center (OSC), Tiantan, Dongsi, Wanliu, Wanshou Xigong, and Guangyuan, was set at 7:00 on February 13, 2015. Figure 7 shows the hour-by-hour changes in PM2.5 concentration simulated with the WRF-Chem model for these seven national control points observations. Although the measured PM2.5 concentration at the national control points of each site is higher than the PM2.5 concentration obtained by the WRF-Chem simulation, the simulation results and the measured PM2.5 concentration at the national control points show the same change trend. The peak measured PM2.5 concentration at the state control point occurred at approximately 1:00 on February 14, 2015, and the peak PM2.5 concentration simulated by WRF-Chem occurred at approximately 19:00 on the evening of February 13, 2015, with the simulated peak slightly earlier than the measured value. After the measured peak, the concentration of PM2.5 first decreased and then began to increase again around 7:00 on February 14, and the concentration of PM2.5 simulated by WRF-Chem maintained a consistent pattern of change in this time period, but the magnitude of change varied more than the measured value.

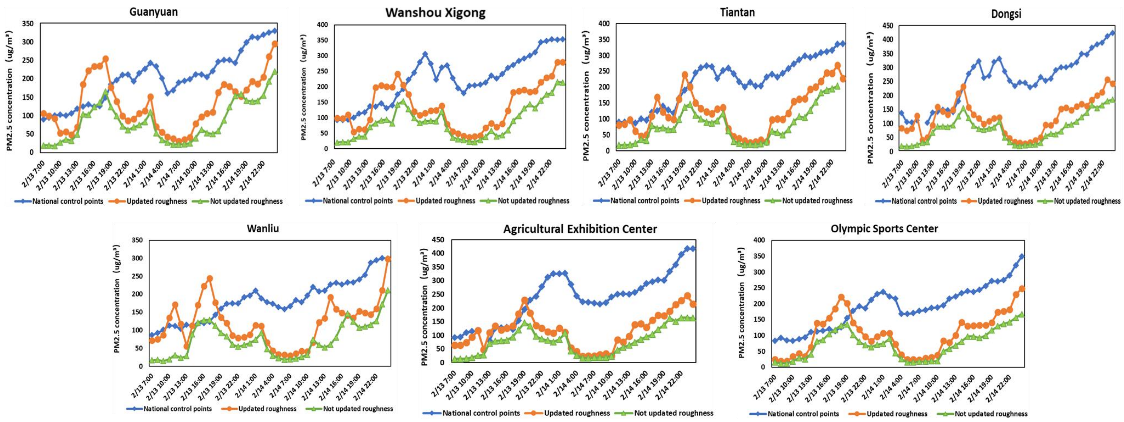


Figure 7 Hourly PM2.5 Concentration

4. CONCLUSION

In this paper, we used multi-source remote sensing data comprehensively to realize the inversion of the aerodynamic roughness of the urban underlying, and evaluated the effect of WRF-Chem model using PM2.5 as the simulated object. The results showed that after updating the aerodynamic roughness of the urban underlying surface using the method in this paper, the PM2.5 concentration obtained from the WRF-Chem model is closer to the observed values at the national control points, indicating that the combination of the LCZ method and radar interferometry can optimize the urban underlying surface roughness parameters and thus improve the simulation performance of the WRF-Chem model.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Bechte, B., Langkamp, T., Ament, F., et al., 2011. Towards an urban roughness parameterisation using interferometric SAR data taking the Metropolitan Region of Hamburg as an example. Meteorol Z, 20(1), pp. 29-37.

Fan, J., Rosenfeld, D., Yang, Y., et al., 2015. Substantial contribution of anthropogenic air pollution to catastrophic floods in Southwest China. Geophysical Research Letters, 42(14), pp. 6066-6075.

Langkamp, T., 2013. Contributions towards a downscaling scheme for urban climate modeling integrating mobile measurements and improved roughness representation for Hamburg(Germany). In: University of Hamburg.

Lelieveld, J., Evans, JS., Fnais, M., et al., 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature, 525(7569), pp. 367-371.

Misra, P., Avtar, R & Takeuchi, W., 2018. Comparison of Digital Building Height Models Extracted from AW3D, TanDEM-X, ASTER, and SRTM Digital Surface Models over Yangon City. Remote Sensing, 10(12), pp. 25.

Raupach, MR., Antonia, RA & Rajagopalan, S., 1991. Rough-Wall Turbulent Boundary Layers. Applied Mechanics Reviews, 44(1), pp. 1.

Saide, PE., Carmichael, GR., Spak, SN., et al., 2011. Forecasting urban PM10 and PM2.5 pollution episodes in very stable nocturnal conditions and complex terrain using WRF–Chem CO tracer model. Atmospheric Environment, 45(16), pp. 2769-2780.

Stewart, Oke & Scott, KE., 2014. Evaluation of the 'local climate zone' scheme using temperature observations and model simulations. International Journal of Climatology, 34(4).

Tie, X., Brasseur, G. & Ying, Z., 2010. Impact of model resolution on chemical ozone formation in Mexico City: application of the WRF-Chem model. Atmospheric Chemistry and Physics, 10(18), pp. 8983-8995.