Response to Reviewer#2

The responses to the reviewers' comments are highlighted in blue, and the revised text is *italicized*.

Zhang et al., 2025: Coupling the TKE-ACM2 Planetary Boundary Layer Scheme with the Building Effect Parameterization Model

The authors present in the manuscript a development and performance of coupling of TKE-ACM2 PBL scheme with BEP urban model in WRF mesoscale model. Although it describes important and interesting topic of improving of WRF model performance, and also the design of the study seems reasonably, the manuscript is not well written. Sometimes it is hardly readable, confused, some parts are too long but other information are missing. The manuscript have to be substantially improved (or re-submitted) before publishing in GMD.

Specific major comments:

1/ The text of the manuscript is not well transparent, some results parts are too long, model formulation could be also shorter or moved into the appendix. Some short sections (e.g. 2.4) could be removed and the number of figures reduced. Further, the manuscript is hardly readable due to often quick switching between ideas and also missing links to figures. It seems that it was not preciously revised by authors before submission.

Dear Reviewer,

Thank you for your thoughtful and constructive feedback on our manuscript titled "*Coupling the TKE-ACM2 Planetary Boundary Layer Scheme with the Building Effect Parameterization Model*." We sincerely appreciate the time and effort you invested in reviewing our work. Your insights have been invaluable in guiding our revisions, and we have made significant changes to enhance the clarity and readability of the manuscript.

Model Formulation: In response to your suggestion, we have condensed the model formulation section by relocating some detailed derivations to the appendix. The numerical solutions to the prognostic equation (Eqn.3) are now removed from **Section 2.1 Numerical method to couple TKE-ACM2 and BEP** and instead detailed in Appendix A.

Removal of non-essential results discussion: Some non-essential parts of the text are removed to help focus on the key findings, e.g., the comparison between BEP and Bulk is removed as it is well investigated.

Removal of Short Sections: We have much shortened the introduction of the Local Climate Zones (LCZ) in the original **Section 2.4** without missing the essential information and reducing the reproducibility of the results.

Readability and Flow: To address the readability issues, we carefully revised the manuscript to ensure smoother transitions between ideas. For instance, we have revised in line 243 to line 305 where any confusion between the descriptions of Figures 4 and 5 is eliminated. The descriptions have been reorganized to clearly differentiate the two figures, ensuring that each is described in its own context without overlap. Meanwhile, we have included active references in Latex to relevant figures within the text when discussing the results. In addition, we have provided a Table B1 in Appendix B to demonstrate the number of available surface stations in each LCZ classification. We have also renamed the three LiDAR sites from USTSS, HT, and KP to USTSS_LCZ5, HT_rural, and KP_LCZ1, respectively according to Reviewer#1's suggestion to remind readers about the characterization of each LiDAR site and thus improve the readability.

Careful Revision: We apologize for any oversight in the initial submission and have conducted a thorough review to ensure the clarity and quality of the manuscript.

2/ Language level is not sufficient, proofreading by English native speaker would be appropriate.

Thank you for your constructive feedback regarding the language quality of the manuscript. We understand the importance of clear and effective communication in presenting our findings. In response to your comments, we have appointed a native English speaker from AsiaEdit (https://asiaedit.com/) to proofread and revise the manuscript. The track changes file shows the corrections to instances where language revision is needed.

3/ Description of model setting is insufficient, BEP parametrization setting of urban canopy parameters in specific LCZ is missing. Author does not consider possible inaccuracy in the setting of such parameters with impact to model performances in specific LCZ.

The BEP parameterization depends on an essential input known as the look-up table for urban morphology parameters (UCP) and thermal and radiative properties (URBPARM_LCZ.TBL when using LCZ). In this study, the look-up table remains as specified in the WRF 4.3.3 GitHub repository. Specifically, thermal properties such as emissivity, albedo, and thermal conductivity retain their default values. Similarly, the distribution of building heights for each LCZ adheres to the default generic values, which are detailed in Table B1 for clarity. These prescribed parameters are consistent with the values recommended by Stewart & Oke (2012).

The major limitation of applying the look-up table method for UCP is that the heterogeneity of UCP for a certain LCZ urban class is not considered, causing it less accurate compared to a gridded UCP approach (Sun et al., 2021). As reported by Shen et al. (2019), one of the crucial UCP, urban fraction, has paramount importance in simulating the horizontal wind speeds. However, the variability of urban fraction or building height distribution for a certain LCZ urban class is not taken into account in the present study.

In additoin, the process of re-gridding the LCZ global map from a 100-m resolution to a 1-km model cell raises concerns about the accuracy of the represented LCZ types (Ribeiro et al., 2021a; Sun et al., 2021). This challenge is further compounded by discrepancies between the land use at local observation stations and the land use depicted by the 1-kilometer model grid. Consequently, the UCP assigned to a specific LCZ type may lack adequate representativeness, especially when a model cell encompasses a variety of LCZ constituents, resulting in an absence of sub-grid variability.

We have added the abovementioned potential uncertainties in line 401.

4/ Description of LIDAR and station data is incomplete. Some special section about observation data is usual in papers, with information about measuring sites, variables, locations and other important characteristics in view of comparison with model data.

We have included an introduction to the LiDAR instrument in the revised **Section 2.4.1**, detailing its resolution, accuracy in measuring wind speed and direction, and operating frequency. Additionally, we have described the characteristics of the three sites where the LiDAR units are installed. Finally, we clarified that the classification of the measurement sites is based on the LCZ landuse associated with the nearest model grid following Ribeiro et al. (2021). Likewise, we have introduced that the surface station data is retrieved from Global Telecommunication System, where the method of classification of each station follows that of the LiDAR unit.

5/ Arrangement of Fig. 7, 8, 14, 15 and 16 shows rather impact of BEP urban scheme compared to Bulk, what is clear and well known fact, but not the impact of TKE-ACM2 PBL scheme compared to Boulac, which is the topic of the paper. Differences between simulations with/without TKE-ACM2 scheme should be rather displayed and also impact of TKE-ACM2 scheme more discussed.

We appreciate your guidance in helping us improve the alignment of our figures with the paper's core topic. We have made the following revisions according to your feedback: Figures 7, 8, 14, 15, and 16 have been updated to display the differences between the TKE-ACM2 and Boulac PBL schemes, both with and without the inclusion of the BEP urban scheme. Meanwhile, discussions in Section 4.1 and Section 4.3 are overhauled. This comparative analysis effectively highlights the impact of the TKE-ACM2 scheme, thereby reinforcing the focus and objectives of this study.

6/ High number of mistakes, typos, wrong use of dashes and connectors (see below). I would recommend to authors to use latex with active references for all figures, sections and tables, to enable better orientation in the text (showing of references by click on) and to prevent mistakes in numbering of figures, sections and tables.

Thanks for the careful evaluation. We have addressed all the identified mistakes in numbering and corrected the use of dashes and connectors. We also improved the phrasing and wording with the assistance from the native English proofreader. Additionally, we have ensured clickable references for all figures, sections, and tables are properly compiled in Latex. Detailed corrections can be found in the response below or in the track changes file.

Other comments and technical corrections:

L 12 – comparison to Bulk method, similarly L 27, that's not clear if Bulk is meant as some simple PBL scheme or simple urban scheme

Thanks for your comment. We have clarified the meaning of Bulk as 'without any urban scheme'. The sentence in line 10 has been revised to:

'*High-resolution wind speed LiDAR observations suggest that TKE-ACM2+BEP reduces overestimation in the lower part of the boundary layer compared with the Bulk method, which lacks an urban scheme, at a LiDAR site located in a densely built environment.*'

L 19 – brace near brace doesn't look well (L 32)

We have revised line 19 and line 33 as follows:

Line 19: … 'and the overlying roughness sub-layer, or RSL (Rotach, 1999).'

Line 32: 'The single-layer urban canopy model (SLUCM) pioneered by Kusaka et al. (2001); Kusaka and Kimura (2004) is …'

L 23 – 10-50

We have revised '10-50' to '10 to 50'.

L 35 – mathematical formula as Fi is superfluous in introduction (similarly L 41)

Agreed. We have removed the mathematical representation of multi-layer fluxes Fi in the introduction.

L 44 – what is urban heat island circulation? UHI or circulation in urban areas.

We have rephrased 'urban heat island circulation' to urban heat island effect' according to the cited work, i.e., Wang et al. (2017), stating that the urban heat island effect is well captured using BEP/BEM in Hong Kong.

L 48 – braces in braces doesn't look well (L 63 similarly, L 154)

We have revised line 69 as follows:

'*They showed that the TKE-ACM2 outperformed two other operational PBL schemes, Boulac (Bougeault and Lacarrere, 1989) and ACM2 (Pleim, 2007b), in simulating the vertical profiles of wind speeds.*'

We have revised line 154 as follows:

'*The prescribed height of building arrays is justified by that it is commonly seen in Hong Kong according to Kwok et al. (2020).*'

L 49 – word order … added recently by H…

Revised accordingly.

L 51 – motivation better explained

We have added a few sentences from line 48 to better emphasize our motivation in coupling a 1.5-order non-local closure PBL model with the BEP model:

'*However, multi-layer BEP/BEP+BEM models are adopted less widely than the Bulk scheme or SLUCM because they have only been tentatively coupled to a few planetary boundary layer (PBL) schemes [e.g., Boulac (Bougeault and Lacarrere, 1989), MYJ (Janjic, 1994), and YSU (Hong et al., 2006) added recently by Hendricks et al. (2020)]. This is primarily due to ´ the challenges associated with incorporating the transformation of mean kinetic energy into TKE within a first-order closure PBL scheme, such as the YSU scheme. As a result, the eddy diffusivity can only be adjusted in response to surface fluxes, limiting its ability to account for the generation and dissipation of TKE through other boundary layer processes, such as the generation of TKE by wind shear and buoyancy. Additionally, the other two PBL schemes (MYJ and Boulac) model the vertical mixing of momentum between two adjacent layers, but lack the non-local mixing driven by large-scale eddies under convective conditions. For instance, Coniglio et al. (2013) reported that MYJ produces PBLs that are too shallow and moist PBLs in the evening, and Xie et al. (2012) found that the PBL height diagnosed by Boulac may be too short to be realistic.*'

L 160 – the horizontal resolution of WRF+BEP in idealized case is not clear

The horizontal resolution of WRF+BEP was described in line 157:

'*WRF+BEP runs at ta building-parameterized scale ($\Delta x = \Delta y = 1$ km)*'

L 175 – WRF+BEP other setting is not described

The configuration of idealized WRF+BEP in Section 2.3 (line 149) is rather simplistic because the simulations are prescribed with idealized initial and boundary conditions, where physics such as microphysics and radiation scheme are turned off.

Specifically, the initial condition of wind speed is described in line 161 with the Coriolis parameter being $10^{-4}s^{-1}$ and that of potential temperature has analytical expression following Eqn.10 and Eqn.11. The landuse of all model cells is prescribed as urban type. The parameterization of cumulus and microphysics are turned off in WRF+BEP to keep it consistent with the LES setting. The short/long wave radiation schemes are also turned off because the net heat flux is prescribed with user-specified values. Additionally, the land surface model/surface layer schemes are not used for calculating surface fluxes for the same reason. However, the namelist options for these two physics (sf_surface_physics and sf_sfclay_physics) are still assigned with 8 and 1, respectively, otherwise BEP subroutines cannot be called.

An implication of this idealized configuration is that the thermal properties of buildings and streets specified in the look-up table (URBPARM.TBL) become ineffective because the radiation transfer is essentially prescribed by the idealized heat flux. The key parameters defined in the look-up table are a uniform building height of 40 meters, a street width of 30 meters, and a building width of 20 meters which are reported in the manuscript.

Chap. 2.4 – why is it separated? Is is used in idealized case, or is it belonging rather to real case?

We have reorganized Section 2.4.1 to describe the Local Climate Zones (LCZs) used in real case simulations. In addition, we have introduced the wind LiDAR observation network in this section, where we clarified the approach to classify the landuse type of the LiDAR unit.

L 186 – you talk firstly about 10 LCZ and here about 17 classes

The LCZ classification scheme has in total 17 classes, consisting of 10 urban classes and 7 non-urban classes. We have clarified in line 183 as follows:

'*The distribution of LCZ 1 to 10 (urban) grids and LCZ A to G 180 (non-urban) grids is depicted in Fig.2c. Each class is defined in Table B1*.'

Additionally, we have clarified the definition of 17-class LCZ in Appendix B Table B1 where the 10 urban classes along with the 7 non-urban classes are explicitly defined.

L 198 – the formulation "July 18 20 o'clock" is unclear, need reformulate. Similarly the following sentence.

Line 206 has been revised to:

'*30-day simulations are performed between 1200 UTC+0 on 18th July to 1200 UTC+0 on 18th August of year 2022.*'

L 204 – this sentence is without any notice about moving to WRF setting

We have made the introduction to the physics settings of WRF a separate paragraph following the sentence "We used NCEP GFS analysis data at 6-hourly input intervals to provide the initial and lateral boundary conditions."

The separate paragraph in line 213 reads,

'*Identical physics schemes are chosen in the four simulations: unified Noah scheme (Chen and Dudhia, 2001) for the land-surface model, WSM 3-class simple ice scheme (Hong et al., 2004) for microphysics, RRTMG scheme (Iacono et al., 2008) for longwave/shortwave radiation, and Grell-Freitas ensemble scheme (Gall et al., 2013) for cumulus.*'

L 205 – Bulk scheme is usually not considered as a canopy model (UCM), because there is no canopy

Agreed. We have clarified that the Bulk scheme refers to the configuration where the surface layer fluxes are computed using Noah land-surface model without any UCM.

Lines 215 is revised to:

'*The TKE-ACM2 PBL scheme was coupled with the BEP UCM (referred to as TKE-ACM2+BEP) and evaluated alongside the TKE-ACM2 scheme in isolation (TKE-ACM2+Bulk), where the surface layer fluxes were computed using the Noah land-surface model. The Boulac PBL scheme underwent the same evaluation, being coupled with the BEP UCM (Boulac+BEP) and assessed in isolation with the Noah land surface model (Boulac+Bulk).*'

L 215--220 – acronyms are unclear, all sentences should be written better

The mathematical symbols and acronyms are revised and the sentences are re-written in line 233 as:

'*Quasi-equilibrium was achieved in the two LES cases after approximately 10.2 convective turnover times (τ), where $\tau = h/w^*$, and $w^* = \left(\beta \overline{w'\theta_0'} h\right)^{1/3}$ represents the convective velocity scale. The duration of 10.2 large-eddy turnover times is considered a reasonable indicator of well-developed dynamic fields over the domain with buildings, especially when compared to other studies that have used factors of 5 (Ayotte et al., 1996; Pleim, 2007b; Zhang et al., 2024) and 6 (Shin and Dudhia, 2016) for flat domains.*

The horizontal averages of the velocity and potential temperature fields are calculated at 10.2τ and serve as initial conditions for driving mesoscale WRF simulations for an additional 20τ . Subsequently, the results from the final 6τ, corresponding to either 3600 seconds or 2400 seconds, are averaged both horizontally and temporally. Table 1 summarizes the key turbulence characteristics of the convective flow and the runtime parameters.'

Fig. 4 – dotted line is not well visible in plots

Thanks for the comment. We have connected the dots representing the LES results with lines.

Fig. 5 – blue dotted and dashed lines are not in the legend

We have added the legend for the TKE-ACM2+BEP momentum flux which consists of the non-local (dashed) and the local (dotted) components in Fig.5.

L 240–250 and further – links to figures are missing, the text is still switching between description of Fig. 4 and 5

We have added necessary links and active references to figures from line 248 To line 309 to ensure that the references are clear and easily accessible for the reader. Additionally, we have revised the text to eliminate any confusion between the descriptions of Figures 4 and 5. The descriptions have been restructured to clearly distinguish between the two figures, ensuring that each figure is described in its own context without overlap.

L 256 – prorportion → proportion

Revised accordingly.

L 274 – is blue dashed line non-local or local component? (sentence vs. Fig. 5 caption), there is also no red dashed line

We have revised Fig.5 and also the texts so that the blue dashed line represents the non-local component and the blue dotted line denotes the local component.

L 275–276 – the sentence not clear

We have revised the sentence in line 295 as follows:

'Compared with Case 10WC, the larger prescribed $\overline{w'\theta'}_0$ in Case 24SC suggests that TKE-ACM2+BEP achieved a closer match in the magnitude and shape of $\overline{w'u'}$ at and immediately above roof level compared with Boulac+BEP. '

L 283 – fount → found

Revised accordingly.

L 283–285 – the sentence is not consistent to claim in L 244. I think a different order of variables in Fig. 4 and 5 vs. Fig. 6 caused it. I would recommend to change the order of variables in Fig. 6

Thanks for the comment. We have revised the order of variables in Fig.6 such that the order follows that in Fig.4 and 5, which reads $\theta, u, \overline{w'\theta'}, \overline{w'u'}$. The sentence in line 303 draws conclusions for Case 24SC where line 252 describes the results for Case 10WC.

To avoid confusion to readers, we have revised line 303 as:

'*This indicates that the two PBL schemes coupled with BEP performed similarly in simulating momentum profiles below the PBL height in Case 24SC and outperformed the Bulk methods*.'

L 289 – what does mean "other natural landuse" – is it any crop, forest or pasture?

We intended for 'other natural landuse' to refer to the landuse that is non-urban (LCZ 1 to 10) and also not water surface (LCZ G). To enhance clarity, we revised all instances of 'other natural landuse' to 'rural land cover' throughout the texts and figures.

L 299 – besides urban grid-boxes, the BEP model is not used over natural and water grid-boxes in simulation, so it cannot produce any direct difference in U, only as an impact of neighbouring grid-boxes

Agreed. We have rephrased the texts in line 311 as:

'*Both BEP simulations had less pronounced differences in U over water surfaces and rural land cover compared with urban grids, primarily because the BEP model was not directly applied in these non-urban areas. Any observed differences in U in these regions resulted from the neighboring urban grids*.'

L 302 – the sentence is not correct, there are other mechanisms except anthropogenic heat (e.g. shadowing of solar radiation by buildings), which cause lower temperature in BEP simulation in comparison to Bulk

Agreed. We realize that the total heat flux can consist of shortwave/longwave radiation received by the surface, and sensible heat through conduction computed in BEP, ultimately resulting in the lower temperature in our case. We have rephrased the sentence in line 319 as:

'*Finally, complex interactions between the atmosphere and buildings, including radiative transfer (direct and reflected solar radiation and net longwave radiation), and thermal exchange between solid surfaces and the atmosphere, collectively led to the lower temperature in BEP simulations*.'

Fig. 7 – there is no direct comparison of model and observation data

In response to your major comment #5, Figures 7 and 8 now focus on illustrating the impact of TKE-ACM2 on the vertical profiles of potential temperature and wind speed as compared to Boulac, both with and without the BEP. Additionally, the effects on 10-meter wind speed, 2-meter temperature, and 2-meter relative humidity are depicted in Figures 14, 15, and 16, respectively. This shift in focus better aligns with the core topic of our paper, moving away from the well-known comparison between BEP and Bulk methods.

We have also incorporated a comparison with observational data, including wind speed LiDAR measurements and surface station data, as detailed in Sections 4.2 and 4.3. Given the relatively sparse distribution of observation units in relation to the model grid, simulations are evaluated exclusively at grid points that encompass any measurement stations.

L 309 – there is no Fig. A51 in the manuscript

This sentence is deleted to avoid confusion.

L 331 – rather "the lowest RMSE and the lowest negative MB"

Revised accordingly.

L 335 – there is no Section 44.1

We have removed the duplicated number and revised as 'Section 4.1'.

L 369 – in the supplementary Zhang (2024) → rather in the supplementary material of Zhang (2024) … or similarly

We have revised it as '… in the supplement material of Zhang (2024)'.

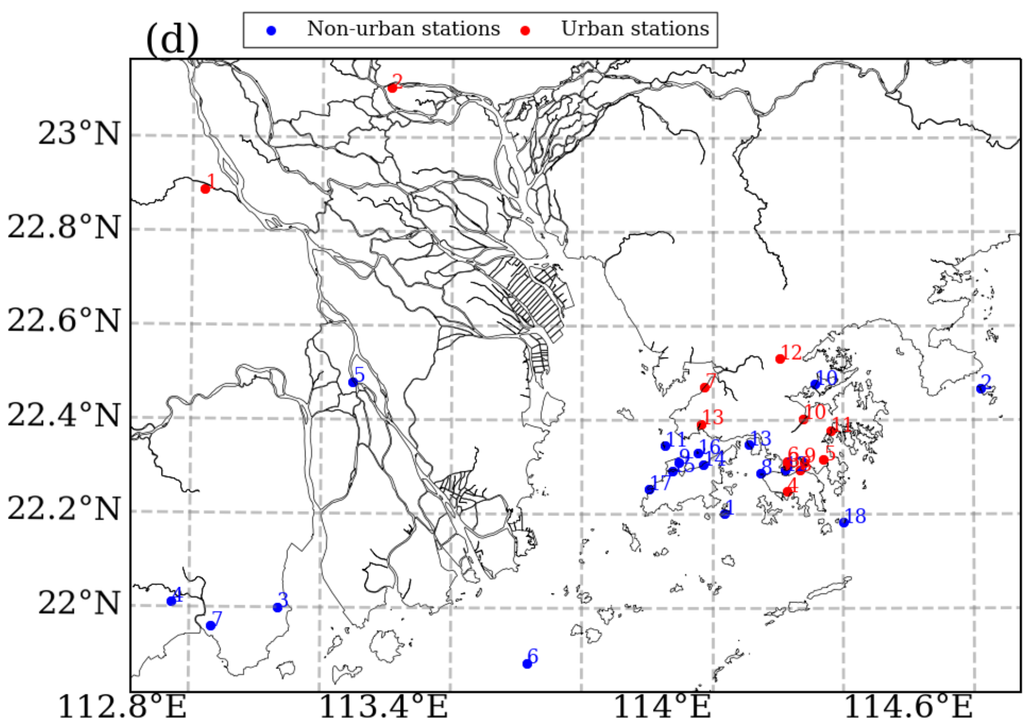
Fig. 17, 18 and 19 – it is not clear, how the stations are assigned to LCZ. Fig. 2 shows only 10 urban stations, but Fig. 17 etc. computes with 23 stations in urban areas.

The classification of each surface station is determined by the LCZ landuse of the nearest model cell center following Ribeiro et al. (2021). There are in total 13 urban stations (LCZ 1 to 10) and 18 non-urban stations (LCZ A to G) in the finest domain 4 (1 km resolution). The breakdown of all types of stations is listed below:

LCZ classification (urban)	Number of stations	LCZ classification (non-urban)	Number of stations
1 Compact high-rise	2	A Dense trees	4
2 Compact mid-rise	1	B Scattered trees	0
3 Compact low-rise	0	C Bush and scrub	3
4 Open high-rise	3	D Low plants	0
5 Open mid-rise	1	E Bare rock or paved	0
6 Open low-rise	2	F Bare soil or sand	1
7 Lightweight low-rise	0	G Water surface	10
8 Large low-rise	3		
9 Sparsely built	0		
10 Heavy industry	1		
Subtotal	**13**	**Subtotal**	**18**

The table above is included in Table B1 for clarity.

Figure 2d illustrates the distribution of surface stations, represented by blue and red circles. However, some stations overlap, making it difficult to assess their individual locations. To enhance clarity, the figure below focuses solely on the distribution of surface stations by removing the LiDAR units. This revised visualization clearly shows a total of 13 urban stations (red) and 18 non-urban stations (blue).



The following text has been added to clarify how the LiDAR unit and surface station is classified: '*We represent the land cover type of each LiDAR unit using the LCZ classification associated with the nearest model grid following Ribeiro et al. (2021).*' in line 186.

L 382 – reported in (Ribeiro et al., 2021) – wrong braces

We have revised line 399 as '*...reported by Ribeiro et al. (2021)*'.

L 400 – "influence of BEP is relatively marginal on RH 2 at non-urban stations" this is quite trivial meaning when BEP is not operating in non-urban grid-boxes.

Agreed. We have deleted the non-essential information.

L 419 – "BEP indicates the buildings act as a sink of heat" – I think this is not a correct statement, there is no sink of energy, the reasons for lower temperature under BEP are different.

Thanks for the careful evaluation. We are aware that the lower temperature simulated by BEP is a net effect from incoming and reflected shortwave radiation, received and outgoing longwave radiation, and conduction between the atmosphere and buildings. The phrasing of the sentence in line 437 has been changed to:

' *Likewise, the effects of BEP considering the radiative transfer and sensible heat fluxes between solid surfaces and the atmosphere ultimately led to a lower θ over all urban grids*.'

References

Ribeiro, I., Martilli, A., Falls, M., Zonato, A., & Villalba, G. (2021a). Highly resolved WRF-BEP/BEM simulations over Barcelona urban area with LCZ. *Atmospheric Research*, *248*, 105220. https://doi.org/10.1016/j.atmosres.2020.105220

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