Reply to RC1

We sincerely thank the reviewer for their constructive and insightful comments. The reviewer's original comments are shown in **black**, our detailed responses are provided in **blue**, and the corresponding revisions in the manuscript are highlighted in **grey boxes with red font**.

Comments #1

With the revised manuscript, authors have adequately addressed most of the concerns raised by me and the other reviewer in the first review round, but some concerns remain. The authors have substantially improved the description of the scope and intent of their work, but the applicability of the model for real-world scenarios remains very limited.

As the model components beyond the radiative transfer modelling are much more simplistic than those of other neighbourhood-scale models, I think the manuscript adds only limited novelty beyond the authors' earlier work on modelling the urban radiative transfer using MCRT (https://doi.org/10.1016/j.uclim.2025.102363). The work's positioning with one of the journal's main review criteria "Does the manuscript represent a substantial contribution to modelling science within the scope of Geoscientific Model Development (substantial new concepts, ideas, or methods)?" remains my main concern with the manuscript. The situation would be quite different if the other model components beyond the radiative transfer model would be more complete and comparable to those of modern urban surface models.

Reply:

We greatly appreciate your feedback, which gives us an excellent opportunity to better highlight the novelty and scientific contribution of our work. The main advances of the present study beyond our earlier MCRT-based urban radiative transfer modelling are as follows:

- **GPU-parallelized framework:** We have developed and implemented a fully GPU-parallelized framework that substantially improves computational efficiency, enabling high-resolution urban simulations at neighbourhood scales that were previously computationally prohibitive. The GPU is utilized not only for the MCRT calculations but also for computing longwave radiative exchange between urban surfaces and solving heat conduction using the Monte Carlo Random Walk method. These algorithms were specifically chosen because they are well suited to the GPU computing framework, allowing for highly parallelized and efficient simulations.
- **High-resolution validation:** The model has been evaluated against detailed observational datasets with both high spatial and temporal resolutions. This comprehensive validation demonstrates the model's ability to accurately capture the fine-scale radiative–convective–conductive heat transfer processes within complex urban configurations.
- **Identification of key physical processes:** Through a detailed surface energy budget analysis, we identify which physical processes are most critical in determining urban energy exchange and how radiative processes interact with conduction and convection components. This insight provides valuable guidance for the future development of urban surface temperature models. For example, our analysis reveals that longwave radiative exchange between urban surfaces plays a critical role, yet this process has often been underrepresented or oversimplified in previous models.

In our revised manuscript, we have more clearly highlighted the main contributions of this study.

To accurately reproduce multiple reflections in high-density urban areas, the radiative heat flux is simulated using a reverse Monte Carlo Ray Tracing method. Sensitivity tests show that $10^5 \sim 10^6$ rays are required for each point to accurately model the solar radiation. This large computational demand for ray tracing is addressed using GPU-based parallel computing. In addition, the GPU is utilized to parallelize both the transient heat conduction, which is solved through random-walk algorithms, and the longwave radiative exchange, which is also computed via ray tracing. This integrated GPU-accelerated framework substantially improves the computational efficiency and scalability of the GUST model.

The comparison with the SOMUCH experiment shows that the transient surface temperatures on roofs, walls and the ground are well reproduced. This comprehensive validation demonstrates the model's ability to accurately capture the fine-scale radiative–convective–conductive heat transfer processes within complex urban configurations. By conducting a surface energy balance analysis, this study demonstrates that longwave radiative exchange between urban surfaces plays a critical role across all building density levels. In contrast, convective heat flux becomes significant only in high-density configurations.

In addition to these methodological advancements, the model's applications extend beyond radiative transfer studies. It can be used for:

- Providing boundary conditions for simulations of the urban outdoor thermal environment and heat-related risk assessment.
- Supporting urban energy consumption analysis, as the simulated surface temperature fields offer critical input for estimating building energy demand and anthropogenic heat release.
- Improving longwave radiation parameterization in mesoscale urban surface models, such as SUEWS or urban canopy models (UCMs).

In our revised manuscript, we have made these contributions more explicit and clarify how the present work contributes to the advancement of urban climate modelling.

Although many additional features will be incorporated into the GUST model in future developments, this does not imply that the current version lacks applicability to real-world scenarios. First, by focusing on the coupled radiative–convective–conductive heat transfer processes, GUST effectively identifies the key physical mechanisms responsible for high urban surface temperatures. Second, it provides high-quality building surface temperature predictions, which can be directly utilized for building energy consumption analyses. Third, the inclusion of longwave radiative exchange between urban surfaces enables GUST to be applied in the parameterization of longwave heat fluxes within mesoscale urban climate models.

Comments #2

It also remains unknown for me why the authors have decided not to mention and discuss their earlier published work on using and evaluating the MCRT method for modelling urban radiative transfer, despite being seemingly very much related work. It is mentioned in the revised manuscript, but merely as a side note in the results section.

Reply:

We appreciate the reviewer's comment and the opportunity to clarify this point. Our earlier publication indeed provided the theoretical and algorithmic foundation for the Monte Carlo Radiative Transfer (MCRT) approach, focusing specifically on the parameterization of radiative exchange within the urban canopy layer. However, the present study represents a distinct and independent line of research, with a substantially different objective and model framework.

In this work, we developed an urban surface temperature model that couples radiative, conductive, and convective heat transfer processes within a unified surface energy balance framework. While the MCRT module remains an essential component, the scientific focus has shifted toward understanding and quantifying radiative–convective–conductive interactions and their implications for urban surface temperatures. Therefore, we limited discussion of the earlier MCRT study to avoid redundancy and confusion, as the two works address different scientific questions: the previous one concentrated on methodological developments in urban radiative transfer, whereas the current one emphasizes model coupling and physical process analysis.

In the revised manuscript, we have expanded the references to our previous study to better illustrate the conceptual continuity while maintaining the scientific focus of the current work.

Our previous work (Mei et al., 2025) demonstrated that the MCRT can accurately predict solar radiation in high-density urban configurations, while also achieving high computational efficiency through GPU-based acceleration. In that study, we compared the albedo of the urban canopy layer and of street canyons across a range of urban layouts with in-situ measurements, achieving excellent agreement. The previous study also serves as an independent validation of the ray-tracing component within the modeling framework. Although the ray-tracing procedure in the present study differs from that in our previous work, the core computational framework remains the same. In the previous study, solar rays were emitted directly from the sun and sky, whereas in this study, we adopted a reverse ray-tracing technique, in which rays are emitted from building surfaces toward the surrounding environment.

Comments #3

Despite a short extension in the revision, I think the description of the model's limitations still does not clearly communicate the scarcity processes represented in the model compared to more comprehensive urban representations at neighbourhood-scales. Therefore, I think that the statement "This model is a building-resolved urban surface temperature model, focusing on detailed neighborhood-scale processes", especially the usage of the word "detailed" in this context, is not justifiable. I also think the following sentence, "Therefore, its application to full city-scale simulations remains limited by computational cost and is currently best suited for neighborhood-scale", underestimates the model's limitations, although some of them are covered in the following sentences.

Reply:

We thank the reviewer for this constructive comment. We also fully understand the concern regarding the necessity of developing a new model when several existing neighbourhood-scale tools, such as PLAM-4U, ENVI-met, and UrbanMicroClimateFoam, already can simulate urban surface temperature and include many physical processes (e.g., vegetation, glazing, and anthropogenic heat).

The motivation for developing our model is fundamentally different. Rather than aiming to replicate the full complexity of existing urban models, our objective is to systematically validate fundamental physical processes under controlled conditions. The model is built upon the SOMUCH database, which is derived from reduced-scale outdoor measurements in a simplified urban environment. This experimental setup provides an ideal opportunity to isolate and validate individual processes one by one.

For example, the current version demonstrates that the radiative–convective–conductive heat transfer scheme performs very well when compared against detailed SOMUCH observations. In contrast, comprehensive urban models are typically validated only against full-scale urban measurements, where numerous processes occur simultaneously. Such validation approaches often make it difficult to diagnose which sub-models contribute to discrepancies or errors. Therefore, by developing a simplified yet physically explicit model and validating it under controlled, reduced-scale conditions, we can identify which physical processes are most influential and which require further refinement. This process-based understanding is essential for guiding improvements in larger, more comprehensive urban models and for deepening insight into the mechanisms driving the urban heat island effect.

In response to the reviewer's concern, we have clarified our motivation and model positioning in the revised manuscript. We now explicitly state that the purpose of this study is not to compete with or replace existing urban climate models, but to provide a physically consistent, experimentally validated framework that helps to improve the representation of key processes in more complex urban modelling systems.

> The main objective of GUST is to resolve the coupled radiative–convective–conductive heat transfer processes occurring across complex urban geometries. These coupled processes represent one of the core physical mechanisms driving the urban heat island effects (Manoli et al., 2019). The model is developed based on reduced-scale outdoor measurements conducted within a simplified urban environment (Hang and Chen, 2022). In this experimental setup, complex glazing systems and green infrastructure are intentionally excluded to isolate and validate the core radiative–convective–conductive heat transfer mechanisms. GUST uses a time-dependent heat conduction model to couple radiative, convective, and conductive heat transfer processes, as illustrated in Fig. 1.

Comments #4

The introduction has been extended to contextualise the study with relevant prior literature. The authors have also improved the presentation of technical and implementation aspects of the model. The authors did also identify a bug in the model code that caused the spurious wall temperatures. The issue with the lack of user guide has been mitigated. They also provided a small-scale validation case.

Reply:

We thank the reviewer for the valuable feedback provided in this and the previous round, which has greatly helped us to improve the clarity, accuracy, and overall quality of the manuscript.

Comments #5

Technical comments:
L52: Asia cities → Asian cities
L146: insensitivity → insensitive
L473: The convective contributes → The convective heat flux contributes
L359: plotted the measurement data → shows the measurement data

Reply:

We thank the reviewer for carefully checking the manuscript. All suggested corrections have been implemented.

Reply to RC2

Comments #1

Please correct the following statement:
L66-67: the complex three-dimensional geometry of urban environments leads to multiple reflections, which reduce reflected solar radiation.
Suggested correction:
The complex three-dimensional geometry of urban environments leads to multiple reflections, which enhance the absorption of solar radiation by surfaces and reduce the net reflected radiation escaping to the atmosphere."

Reply:

We thank the reviewer for carefully checking the manuscript. All suggested corrections have been implemented.

Secondly, the complex three-dimensional geometry of urban environments leads to multiple reflections, which enhance the absorption of solar radiation by surfaces and reduce the net reflected radiation escaping to the atmosphere.