Response to Reviewer Comments

WRF-MLGR v2.0 / EGUsphere Green-Roof Manuscript

Reviewer Comment 1

Reviewer comment: The green-roof soil depth is only 0.03 m per layer. Please discuss potential numerical stability issues under extreme conditions (e.g., prolonged heat waves) when soil moisture may dry out and temperatures may rise rapidly. Have you tested model behavior under such extremes, and are any timestep or scheme adjustments needed?

Response:

Thank you for this important comment. We agree that numerical stability under dry and hot conditions can be an important consideration for multilayer diffusion schemes, particularly when substrate moisture becomes low and surface temperatures can change rapidly.

First, we would like to clarify that the green-roof substrate layers in our WRF-MLGR configuration are not all fixed at 0.03 m. The multilayer green-roof scheme uses non-uniform layer thicknesses, and the layer depths are specified according to the model configuration rather than being constrained to a constant 0.03 m for each layer.

Second, the model has been evaluated under contrasting environmental conditions, including dry, wet/moist, high-radiation, and warmer periods. In a companion study, Martinez Mendoza et al. (2026) evaluated green-roof model performance, including WRF-MLGR, across different moisture and radiative-forcing regimes using observations from the same green-roof site. That analysis included dry and rainy periods, as well as high- and low-net-radiation conditions. These conditions represent the range available in the observational dataset, although they may not fully encompass more extreme or prolonged multi-day heatwave scenarios. The model remained numerically stable across the tested conditions, and no numerical instabilities associated with rapid substrate drying or rapid increases in surface temperature were observed. Although the version evaluated in the companion study did not include the updates introduced in the present article, the fundamental numerical solution of soil heat and moisture diffusion remains unchanged.

Third, heat conduction and moisture movement within the green-roof substrate are solved using an implicit matrix-based approach. In the heat routine, the temperatures of the soil layers are solved together using a tridiagonal matrix, and in the moisture routine, the soil-water contents are updated using the same type of matrix solution. This makes the model more numerically robust than a purely explicit layer-by-layer update. However, an implicit method does not automatically guarantee accurate results. If the time step is too large compared with the layer thickness and the speed of heat or moisture movement, the solution can become overly smoothed or physically unrealistic. Therefore, reasonable layer thicknesses and time steps are still needed for reliable model performance.

Reviewer Comment 2

Reviewer comment: Section 2.2 describes the original model in text. Consider adding a schematic or flow diagram that contrasts the original scheme and the modified scheme to make the differences clearer (e.g., layer structure, heat flux pathways, and where parameter changes are applied).

Response:

Thank you for this helpful suggestion. We agree that a schematic comparison of the original and modified schemes improves the clarity of the model description. In response, we have added a new schematic diagram as Figure 1 in the revised manuscript. This figure contrasts the structure of the original model with that of the modified model and highlights the main process-based changes introduced in this study. In particular, it illustrates the layer structure, the main heat and moisture flux pathways, and the locations where the parameter and process modifications were applied. We believe this addition makes the differences between the original and modified schemes much clearer for the reader.

Changes made in the manuscript:

We revised Sect. 2.2 of the manuscript, (page 6, lines 160–163), to clarify the structural and process-level differences between the original and modified WRF multi-layer green-roof schemes. Specifically, we added a new schematic as Fig. 1 and added explanatory text introducing the figure. The revised text now reads:

> *"To clarify the structural and process-level differences between the original and modified WRF multi-layer green-roof schemes, Fig. 1 provides a schematic comparison of the two model formulations. The figure highlights the main layer structure, the key heat and water flux pathways, and the locations of the five process-based modifications introduced in Sect. 2.3."*

The new figure added to the revised manuscript is reproduced below for clarity:

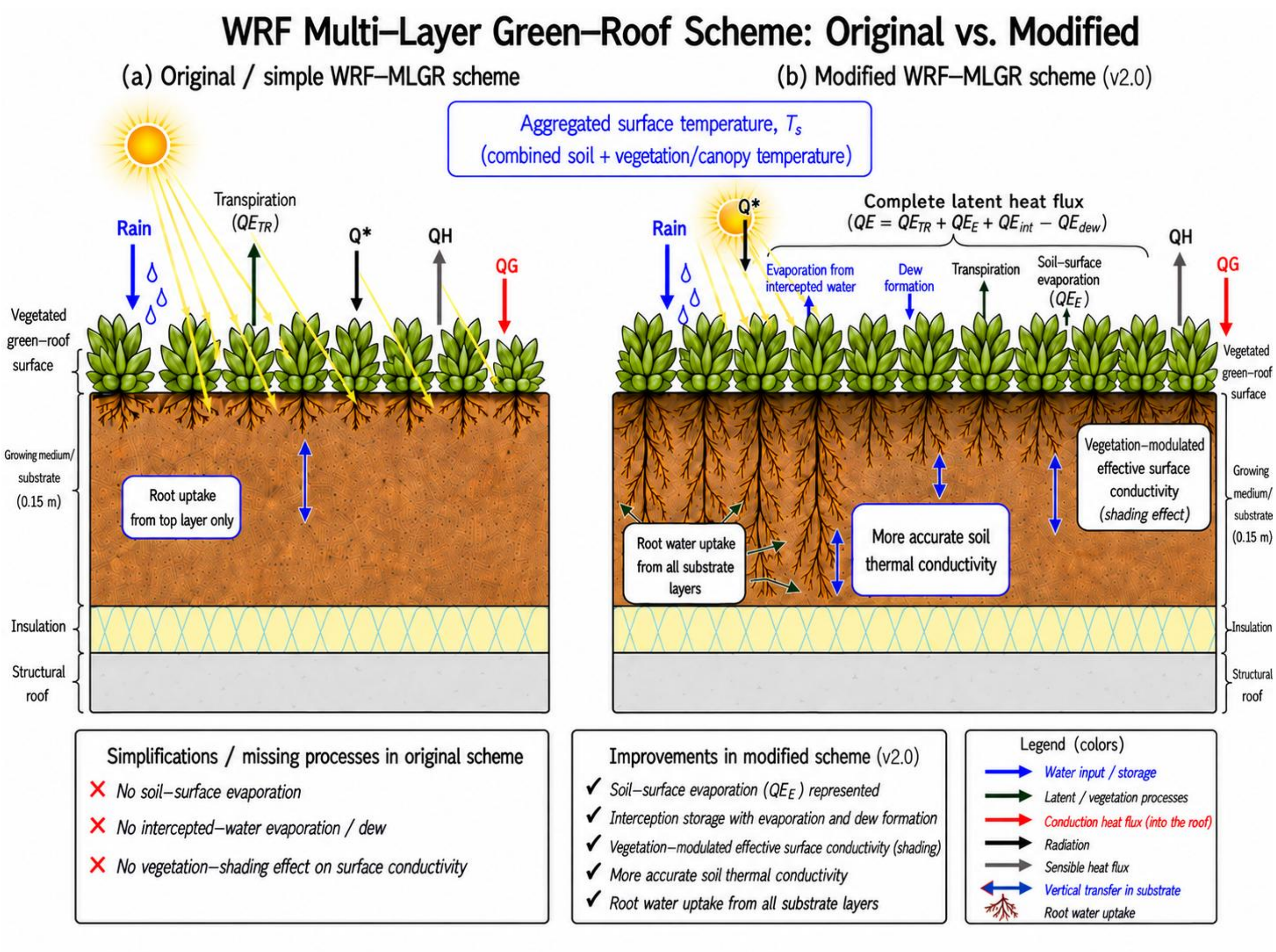

Figure 1. Schematic comparison of the original and modified WRF multi-layer green-roof schemes.

Reviewer Comment 3

Reviewer comment: In Sections 2.3.1 and 2.3.2, please quantify how much the soil and vegetation thermal conductivities were changed relative to the original model. Are the modified values still within physically reasonable/observed ranges? If possible, include a table or figure showing the original vs. modified conductivity values and their sources or justification.

Response:

Thank you for this helpful suggestion. We agree that quantifying the changes in soil and vegetation thermal conductivity relative to the original model improves the clarity of Sections 2.3.1 and 2.3.2.

In response, we have added a new comparison figure as Fig. S1 in the Supplement. This figure compares the depth-averaged soil thermal conductivity simulated by the original and modified model configurations during summer 2014. Because thermal conductivity varies among substrate layers in the multilayer scheme, we calculated and presented the average thermal conductivity across the green-roof substrate layers for both the original and modified models. This allows a clearer comparison of the overall change in effective substrate thermal conductivity between the two model versions.

Changes made in the manuscript and Supplement:

We revised Sect. 2.3.2 of the manuscript, (page 8, lines 215–221), to quantify the effect of the revised thermal treatment and to explain why the modified conductivity values are physically reasonable. We also added a new supplementary figure, Fig. S1, to show the depth-averaged soil thermal conductivity simulated by the original and modified schemes during summer 2014. The revised manuscript text now reads:

> *"To quantify the effect of the revised thermal treatment, we compared the time-varying average soil thermal conductivity produced by the original and modified green-roof schemes during summer 2014 (Fig. S1 in the Supplement). The original formulation produced unrealistically large and highly variable conductivity values, with peaks exceeding 49 W m^{-1} K^{-1}, indicating excessive conductive heat transfer under wet conditions. In contrast, the modified formulation produced conductivity values mainly within the range 0.32 to 0.98 W m^{-1} K^{-1}, which is physically more reasonable for engineered green-roof growing media, for which thermal conductivity has been shown to vary strongly with substrate moisture content and composition (Barozzi et al., 2017; Shao et al., 2021)."*

The new supplementary figure is reproduced below for clarity:

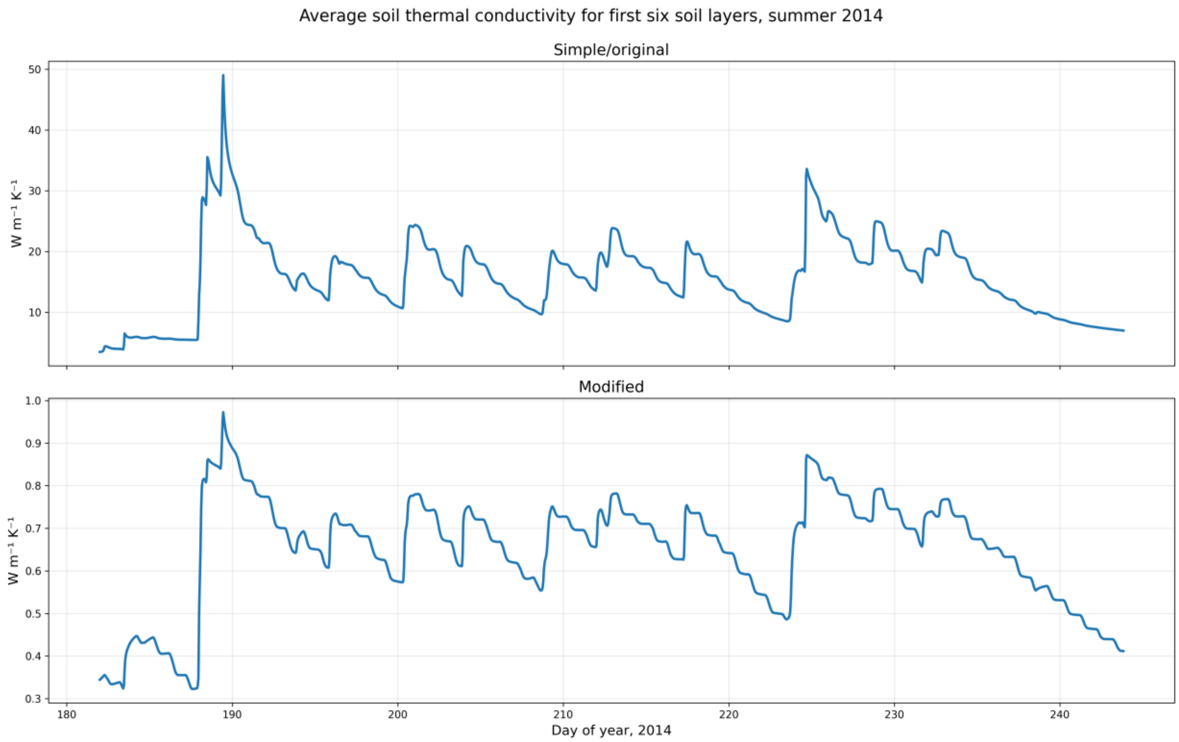

Figure S1. Comparison of depth-averaged soil thermal conductivity between the original and modified WRF multi-layer green-roof schemes during summer 2014.

The modified values remain within physically reasonable ranges reported for green-roof substrates and vegetation materials. We have also revised the text in Sections 2.3.1 and 2.3.2 to clarify the magnitude of the changes and to explain the physical basis for the modified parameter values. Because several additional diagnostic figures are already included in the Supplementary Material, we placed this comparison there rather than in the main manuscript.

Reviewer Comment 4

Reviewer comment: Table 1 and Fig. 1 show degraded performance in Ts prediction across all cases. Please discuss possible causes. Clarify which surface temperature is reported (soil surface, vegetation canopy surface, or some aggregated surface skin temperature). You mention two thermal conductivity calculations-how do those relate to the reported Ts, and might they explain the degradation? Consider adding separate diagnostics for soil-surface and vegetation-surface temperatures if available.

Response:

Thank you for this important comment. We agree that the small drop in model performance for surface temperature prediction requires further clarification and discussion.

In the current WRF-MLGR formulation, the reported surface temperature, T_s, represents a simplified bulk/skin surface temperature of the green-roof system. The model does not explicitly solve separate temperatures for the vegetation canopy surface, the air space within the canopy, and the soil/substrate surface. Instead, these components are represented in a simplified manner through a single surface temperature. Therefore, Ts should be interpreted as an aggregated surface skin temperature rather than a separately resolved soil-surface or vegetation-canopy temperature.

We believe this simplified representation is one of the main reasons for the weaker T_s performance. Because the current model does not explicitly resolve these separate thermal components, improvements in substrate heat transfer and vegetation-related parameterizations do not necessarily translate directly into improved Ts prediction.

The two thermal conductivity calculations discussed in Sections 2.3.1 and 2.3.2 affect the heat transfer within the substrate. These changes improve the representation of heat storage and ground/substrate heat fluxes, but they do not introduce a fully separate canopy energy-balance model. Therefore, they may influence Ts indirectly, but they do not fully address the structural limitation associated with representing the green roof using a single bulk surface temperature.

Although T_s remains an important diagnostic variable, improving the surface energy-flux partitioning has higher priority at this stage of model development, because Q_G, Q_E, and Q_H are more directly influential in the coupled WRF climate-model system. These fluxes control the exchange of heat and moisture between the urban surface and the lower atmosphere and can therefore affect the broader atmospheric response simulated by the model. While Ts affects upward longwave flux, the latter is less influential in terms of surface climate than Q_H (and Q_E and Q_G).

We have revised the manuscript to clarify the definition of T_s and to discuss this limitation more explicitly. Separate diagnostics for soil-surface temperature, vegetation-surface temperature, and canopy-air temperature are not available in the current WRF-MLGR formulation. Addressing this limitation will require future model development in which canopy temperature, substrate/soil-surface temperature, canopy-air exchange, and their separate energy interactions are represented explicitly rather than being aggregated into a single bulk skin temperature. Such a formulation would allow the respective contributions of vegetation and substrate processes to be computed separately and would provide a more physically consistent basis for evaluating T_s. It is largely for this reason that we identified the separation of canopy and substrate thermal processes as an important direction for future development of the WRF-MLGR scheme in the final section of the manuscript.

Changes made in the manuscript:

We revised Sect. 2.2, (page 5, lines 135–137), to clarify that the reported surface temperature, T_s, should be interpreted as a bulk or aggregated green-roof skin temperature rather than as a separately resolved soil-surface temperature, vegetation-canopy temperature, or canopy-air temperature. The revised text now reads:

> *"Therefore, the reported surface temperature Ts in the current WRF-MLGR formulation should be interpreted as a bulk or aggregated green-roof skin temperature, rather than as a separately resolved soil-surface temperature, vegetation-canopy temperature, or canopy-air temperature."*

We also revised Sect. 4.1, (page 24, lines 521–527), to explain why biases in T_s remain after the model updates. The revised text now reads:

> *"A key reason for this remaining T_s bias is that the current WRF-MLGR formulation calculates only a single bulk surface skin temperature for the green-roof system. Separate computation of the soil/substrate surface temperature, vegetation/canopy surface temperature, and canopy-air temperature is not available in the present formulation. As a result, T_s cannot be directly interpreted as either a soil-surface temperature or a vegetation-canopy temperature, but instead represents an aggregated surface temperature produced by the simplified bulk representation of the green roof. This limits the ability to diagnose whether the remaining T_s bias arises primarily from the substrate thermal state, vegetation thermal response, or both."*

Finally, we revised Sect. 4.1, (page 25, lines 535–540), to identify this limitation as an important direction for future model development. The revised text now reads:

> *"Future development should therefore separate the vegetation canopy, canopy air, and soil/substrate surface in the model, instead of representing them with one bulk surface temperature. This would allow the model to calculate their heat exchange processes separately, including radiation, turbulent heat exchange, and heat conduction into the substrate. It would also make it possible to identify whether any remaining errors in T_s come mainly from the vegetation or the soil surface, and to improve the inaccurate model component."*

Reviewer Comment 5

Reviewer comment: The resolution of all figures is quite low. Please replace figures with higher-resolution versions and ensure axes, legends, and labels are clearly legible.

Response:

Thank you for this helpful comment. In response, we have revised all figures and replaced them with higher-resolution versions. We also improved the readability of the axes, legends, labels, and text to ensure that all figures are clear and legible in the revised manuscript.

References

Martinez, M., Saeedi, A., Voogt, J., and Krayenhoff, S.: Process-based evaluation of green roof models for assessment of heat mitigation efficacy in WRF (v4.3.1) and EnergyPlus (v8.6.0), Geosci. Model Dev., under review, 2026.

We thank the reviewer for these comments and hope the revisions are satisfactory.

Sincerely,

Alireza Saeedi