Response to Reviewer #2 Comments

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

All page and line numbers refer to the revised manuscript submitted with these responses.

Reviewer Comment 1

Reviewer comment: As mentioned by the authors, there are five parts being improved/revised. However, based on the current methodology, it is not clear how these five parts affect the physical processes included in the module. In addition to a clearer description, a schematic figure showing the structure and improved processes could help. It would also be better to show a comparison of the module structures between the old and modified versions.

Response:

Thank you for this helpful comment. We agree that the physical role of the five updates should be stated more directly. We therefore added a short process-level overview at the beginning of Sect. 2.3 that separates the thermal and hydrological changes and explains which fluxes they mainly affect. The revised manuscript also includes Fig. 1, which directly compares the original and modified model structures and shows the locations of the five updates. We also clarified the purpose of the vegetation-dependent effective surface conductivity.

Changes made in the manuscript:

We added the following overview in Sect. 2.3 (page 7, lines 169–178):

> *"To improve the representation of heat and water exchange in the WRF multi-layer green-roof scheme, we implemented five physically based modifications. The two thermal modifications mainly change how heat moves through the green roof soil and how much energy is stored as Q_G. The revised soil thermal conductivity provides a more realistic representation of heat transfer as soil moisture changes, while the vegetation-dependent surface conductivity reduces excessive heat storage at the soil surface to represent the effect of vegetation shading on heat storage."*
>
> *"The three hydrological modifications mainly affect evapotranspiration and soil water. Soil evaporation allows water to evaporate directly from the substrate surface. Multilayer root uptake allows plants to take up water from several soil layers rather than only from the top layer. Canopy interception allows rainfall to be temporarily stored on the vegetation, evaporated back to the atmosphere, and also allows dew formation. Together, these modifications change Q_G and Q_E and therefore also affect how the remaining available energy is partitioned into Q_H."*

We also clarified the vegetation-dependent conductivity description in Sect. 2.3.2 (page 8, lines 201–205):

> *"In the original green-roof scheme, the model does not include an explicit vegetation canopy, so it does not represent vegetation cover or the shading effect of plants. This means the soil surface receives the full incoming radiation, which can lead to unrealistically large surface heat storage, particularly in the morning, with associated impacts on morning sensible and latent heat fluxes. To make the simulated surface heat storage more realistic, we added a vegetation dependent effective surface conductivity that acts as a simplified representation of the vegetation effect on surface heat storage."*

We also added Fig. 1 in Sect. 2.2 (page 6, around lines 160–165). This figure provides a side-by-side schematic of the original and modified WRF-MLGR schemes. The left panel shows the original model structure and the main simplified or missing processes, while the right panel shows the modified scheme and where the five updates act on the heat and water pathways. We added this schematic because the text description alone made it difficult to see how the individual modifications affect the physical processes. The figure allows the reader to identify the model structure and the role of each update directly.

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

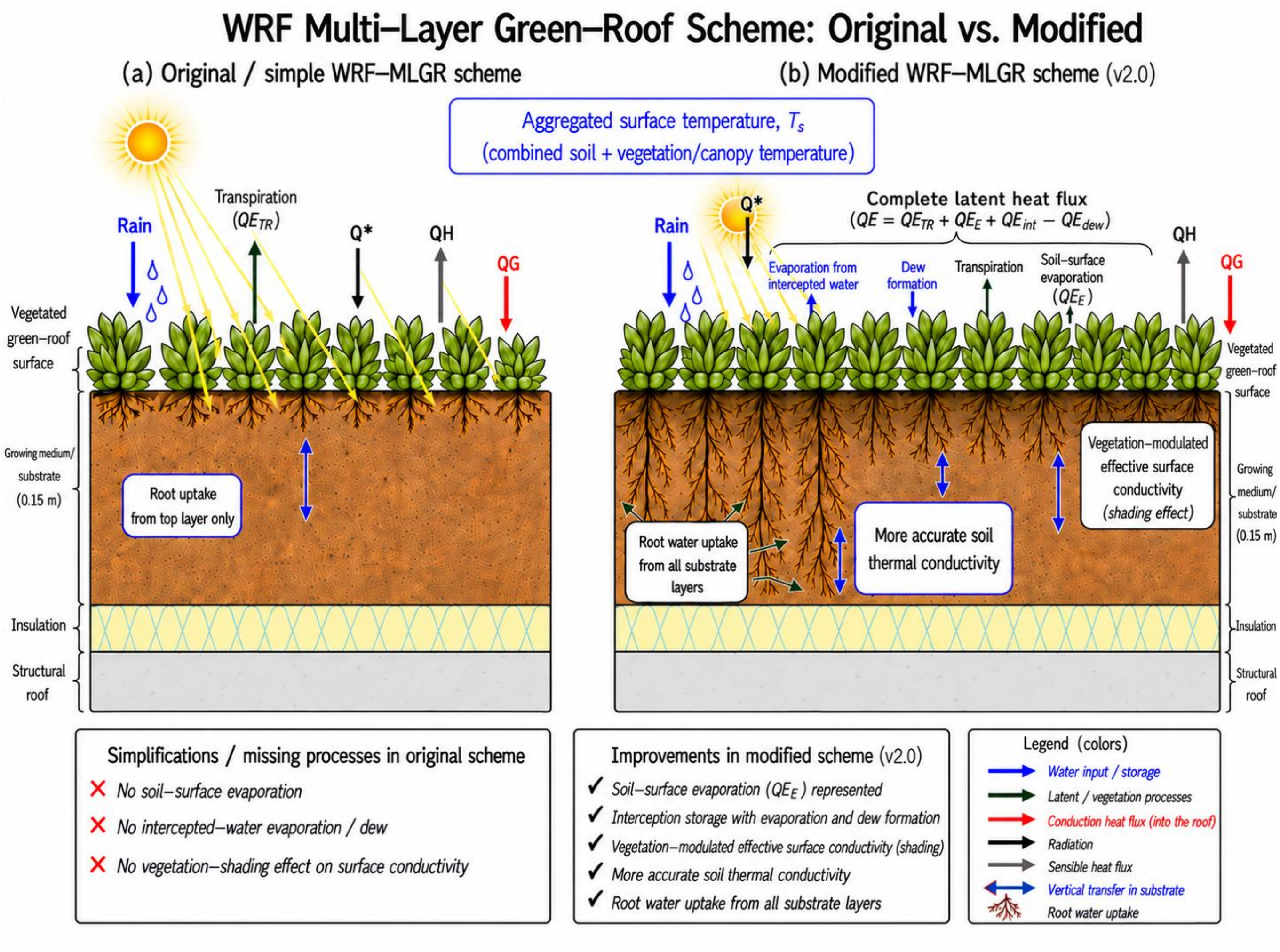

Figure 1. Schematic comparison of the original and modified WRF multi-layer green-roof schemes.

The schematic was included specifically to make the five process changes easier to follow: revised soil thermal conductivity and vegetation-dependent surface conductivity mainly affect Q_G and heat storage, while soil evaporation, multi-layer root uptake, and canopy interception mainly affect soil water and Q_E.

Reviewer Comment 2

> **Reviewer comment:** Some technical details regarding the module improvement: 1) How many layers of soil are below the green vegetation for the roof? 2) Is it possible to show the soil layer temperature and moisture? 3) Does the indoor temperature influence the simulation, especially the storage heat? How does the current model deal with this?

Response:

Thank you for these technical questions. We agree that the model layers and the lower boundary needed to be explained more clearly. The offline model has 10 thermal layers in total. The lower four layers represent the structural roof and have a total thickness of 0.15 m. Above them, six soil layers represent the green roof and also have a total thickness of 0.15 m. Temperature is calculated in all 10 layers, while soil water content is calculated only in the six green-roof soil layers.

In the offline simulation, indoor temperature is not calculated. Instead, the model uses a fixed temperature of 23 °C at the bottom of the roof. The fixed indoor temperature of 23 °C was selected as a representative thermal comfort setpoint for occupied buildings. Indoor temperatures in conditioned buildings are typically controlled near this value to maintain human thermal comfort. Therefore, 23°C was used as a constant lower-boundary temperature in the offline simulations. We also added the temperature and soil water content of the individual green roof soil layers as Figs. S2 and S3 in the Supplement.

Changes made in the manuscript and Supplement:

We revised Sect. 2.2 (pages 4–5, lines 120–129) as follows:

> *"The WRF multi-layer green-roof scheme represents a vegetated roof as a one-dimensional (vertical) column of soil (growing medium) placed on top of the structural roof. This column simulates the coupled heat and water balances within the green-roof system. Following the formulations of de Munck et al. (2013) and Gutierrez (2015), as summarized by Zonato et al. (2021), the offline WRF-MLGR configuration contains 10 thermal layers in total. Four layers represent the underlying roof construction, while six layers represent the 0.15 m green-roof soil. Temperature is calculated in all thermal layers, while volumetric water content is calculated for the six soil layers. Layer-resolved soil temperature and moisture diagnostics are provided in Figs. S2 and S3 of the Supplement."*
>
> *"During the offline evaluation, the indoor temperature is not simulated. Instead, the model uses a fixed temperature of 23 °C at the bottom of the green-roof system. representing a typical indoor/building temperature and providing the lower thermal boundary condition for the offline simulations. This temperature affects the amount of heat transferred between the green roof and the underlying roof."*

We added a new Sect. S2 to the Supplement (Supplement, page 2) and two new figures. For clarity, the six soil layers in the plots are numbered from the soil surface downward, with Soil layer 1 as the uppermost layer and Soil layer 6 as the deepest layer.

> *"The offline WRF-MLGR setup used in this study has 10 thermal layers in total. The lower four layers represent the underlying roof construction, while the upper six layers represent the 0.15 m green-roof soil. Temperature is calculated for all thermal layers, while volumetric water content is calculated for the six soil layers. To illustrate the vertical variation within the soil profile, Fig. S2 shows the mean diurnal temperature cycle of the six soil layers during summer 2014, while Fig. S3 shows the daily mean volumetric water content of the six soil layers over the same period. For clarity, the six soil layers in Figs. S2 and S3 are numbered from the soil surface downward, with Soil layer 1 representing the uppermost soil layer and Soil layer 6 the deepest soil layer."*

The two new supplementary figures are reproduced below for clarity:

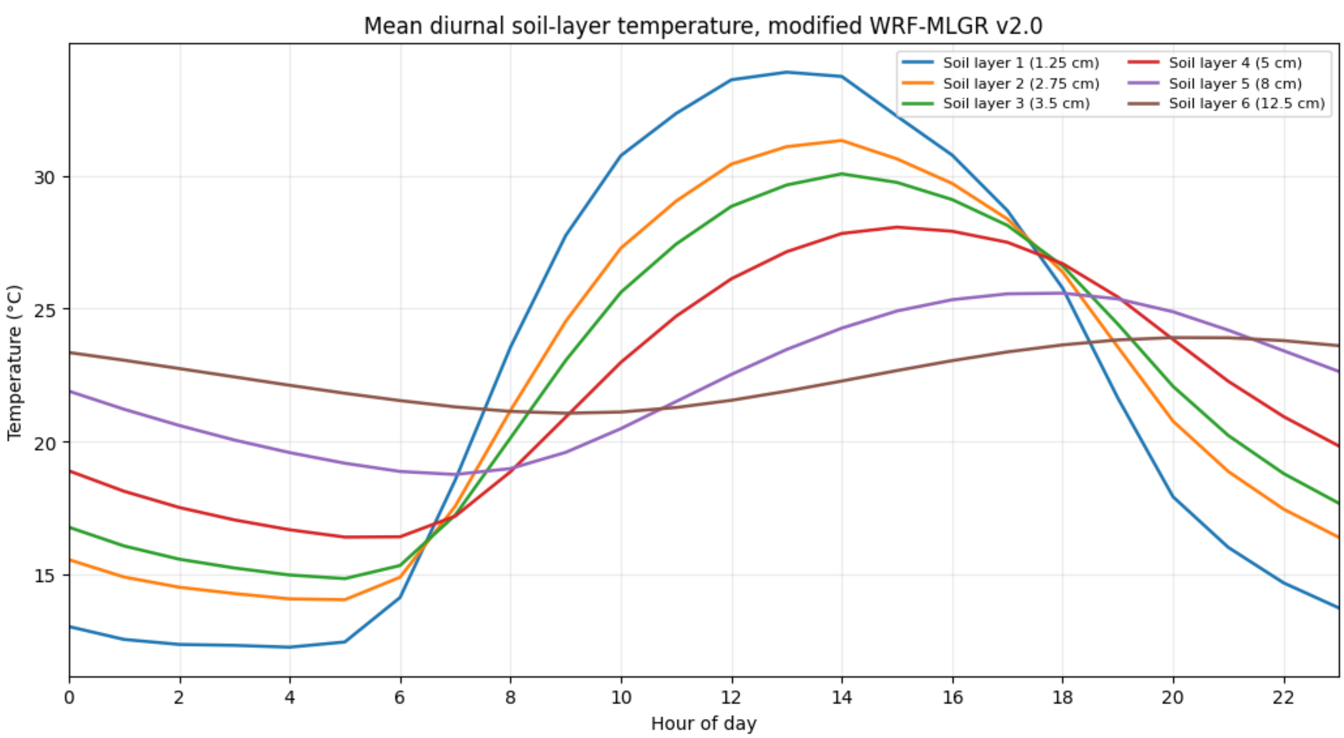

Figure S2. Mean diurnal cycle of temperature for the six green-roof soil layers in the modified WRF-MLGR v2.0 simulation during summer 2014. Soil layers are numbered from the soil surface downward (Soil layer 1 = uppermost soil layer), and labels also give the center depth below the soil surface.

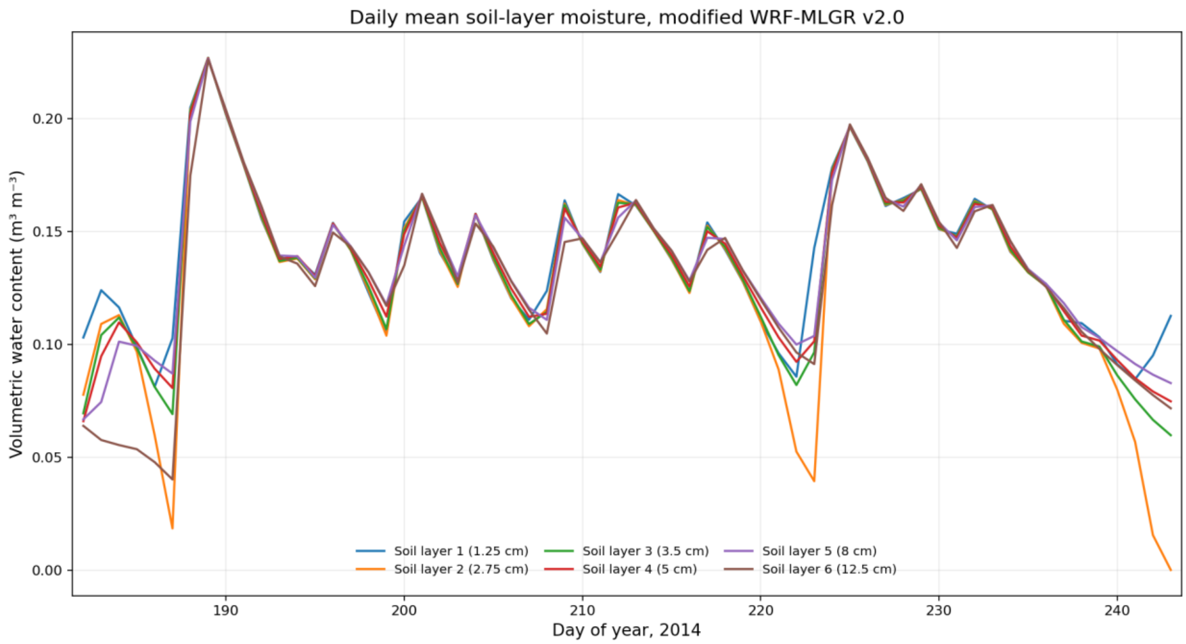

Figure S3. Daily mean volumetric water content of the six green-roof soil layers in the modified WRF-MLGR v2.0 simulation during summer 2014. Soil layers are numbered from the soil surface downward (Soil layer 1 = uppermost soil layer), and labels also give the approximate center depth below the soil surface.

Reviewer Comment 3

Reviewer comment: A clarification is needed for the reason for the included validation variables. Why are the sensible heat flux and near-surface 2-m air temperature not included? Is it because of the limits of the field measurement dataset? Since the field measurement description is very limited in the current manuscript, I suggest adding a bit more detail, along with the previous reference; this would be more rigorous and comprehensive for the current focus.

Response:

Thank you for this comment. We agree that the choice of validation variables and the limitations of the field measurements should be explained more clearly.

Q_E, Q_G, T_s, and soil water content were selected as the main validation variables because they were directly measured and are closely related to the processes modified in this study. The 2-m air temperature was also measured, but in the offline model it is used as forcing data. Because the green-roof model was separated from the full WRF atmospheric model for this evaluation, it does not calculate its own 2-m air temperature. Therefore, the observed 2-m temperature is an input to the model and cannot also be used as an independent validation variable.

Sensible heat flux (Q_H) was not measured directly. Instead, it was calculated as a residual of the surface energy balance, using net radiation, Q_E, and Q_G. Therefore, any uncertainty or error in these measured fluxes, especially Q_G, also affects the calculated Q_H. As discussed in the manuscript, the 2014 green-roof modules were located on an elevated platform with an air space below them, and the individual modules could also lose heat through their sides. This makes the Q_G measurements, especially at night, more difficult to interpret. For this reason, Q_H is used mainly to discuss changes in energy partitioning rather than as an independent validation variable.

We have clarified these points in the manuscript. Additional details about the field instruments, measurement setup, data processing, and quality-control procedures are provided in Martinez et al. (2026), which we cite for the complete description of the observational dataset.

Clarifications in the manuscript:

The field setup and data processing are described in Sect. 2.1.1 (pages 3–4, lines 81–96), including the instrumented green-roof array, Sedum vegetation, 0.15 m soil depth, quality control, hourly processing, and the reference to Martinez et al. (2026). The revised text includes:

> *"Raw measurements were quality controlled, and time periods affected by instrument malfunction, maintenance, calibration events, or missing data were excluded. For this paper, both the observational time series and the corresponding model output were processed to hourly resolution (hourly means for state variables and fluxes, and hourly totals for precipitation). Further details on the site instrumentation, observational processing, and quality-control procedures are provided in Martinez et al. (2026); readers are referred there for a complete description of the observational dataset."*

Sect. 2.1.2 (page 4, lines 101–104) makes clear that near-surface air temperature is prescribed forcing:

> *"Atmospheric forcing data were prescribed from observations collected on the roof at, or near, the green-roof array. The forcing time series includes incoming shortwave radiation (W m^{-2}), incoming longwave radiation (W m^{-2}), near-surface air temperature (°C), relative humidity (%), wind speed (m s^{-1}), precipitation (mm; hourly accumulation), and surface air pressure (Pa)."*

The limitation of Q_H as an independent validation variable is stated in Sect. 4.2 (page 26, lines 564–569):

> *"A related limitation is that the "observed" sensible heat flux (Q_H) is not measured directly. Instead, it is calculated as a residual: net radiation minus the sum of measured Q_E and measured Q_G. This means that any bias in Q_G, during the day and especially at night—will automatically appear as a bias in the residual Q_H, which makes nighttime Q_H comparisons harder to interpret. Importantly, this does not change one of the main conclusion of this study: the modified model dramatically reduces the large Q_G errors seen in the original scheme. Rather, the residual nature of Q_H mainly limits how confidently we can interpret the remaining nighttime Q_H differences as resulting from model physics."*

Reviewer Comment 4

> **Reviewer comment:** As mentioned by the authors, the green-roof scheme in the single-layer urban canopy model, I would like to ask how its performance compares to the previous scheme and the current modified scheme. Because the green-roof scheme itself has been quite intensively studied, it is essential to show why and how the current improvements are significant.

Response:

Thank you for this important comment. We agree that the difference between the single-layer and multi-layer green-roof schemes needed to be explained more clearly. In response, we added further explanation to the revised manuscript to clarify that these are two different model implementations.

The single-layer and multi-layer green-roof schemes are two different model implementations with different structures and physical processes. The single-layer green-roof scheme was developed for the WRF single-layer urban canopy model and has been evaluated in previous work. In contrast, our study uses the multi-layer green-roof scheme developed by Zonato et al. (2021) for WRF-BEP+BEM. This model represents the green roof and underlying roof using multiple vertical layers and is therefore different from the single-layer scheme.

A direct numerical comparison between the two models would not be fully appropriate because the previous single-layer study used a different site, climate, forcing data, simulation period, and model configuration. Therefore, differences in their reported performance cannot be attributed only to the green-roof model itself. For this reason, we compare their structures and previously reported performance, rather than directly comparing their numerical statistics.

The focus of the present study is the Zonato et al. (2021) multi-layer scheme. This scheme had not previously received comprehensive process-level evaluation and development against long-term field observations. In this study, we evaluate the original multi-layer scheme against observations, identify its main problems, introduce five process-based modifications, and then evaluate the modified WRF-MLGR v2.0 using exactly the same forcing and observations. We also use the one-at-a-time sensitivity tests in Figs. 8 and 9 to show which of the new processes are responsible for the changes in Q_E and Q_G. This direct original-versus-modified comparison provides the main evidence for the importance of the improvements introduced in this study.

Changes made in the manuscript:

We revised Sect. 4.1 (page 22, lines 447–456) to make this distinction explicit:

> *"It is relevant to additionally compare other green-roof models. A separate WRF green-roof scheme has also been developed for the single-layer urban canopy model (Yang et al. 2015). This scheme is different from the multi-layer WRF-BEP+BEM green-roof scheme of Zonato et al. (2021) evaluated and modified in the present study. The single-layer scheme does not document a dedicated interception storage and evaporation process; however, it was shown to reproduce surface temperature and turbulent energy fluxes within a reasonable range when evaluated against observations over a 6-day period. Another approach is that the TEB-GREENROOF model directly couples the vegetated substrate to the roof layers without a canopy air space. When evaluated, it showed underestimated substrate moisture, overestimated drainage, and larger than observed temperature amplitudes, reflecting a warm bias and discrepancies in moisture dynamics (de Munck et al., 2013). In the following, we assess the behavior of the modified WRF multi-layer green roof scheme and its strengths, weaknesses, and the impacts of the applied updates."*

The following paragraphs in Sect. 4.1 then quantify the improvement of the modified multi-layer scheme relative to its original version using the same observations (e.g., Q_G RMSE decreases from 105.9 to 24.0 W m^{-2} in summer and from 94.2 to 24.0 W m^{-2} in fall; Table 1).

Reviewer Comment 5

> **Reviewer comment:** The figures shown in the current manuscript are quite unclear, which may be due to the resolution of the figures. In addition, in both Figures 2 and 3b, there are grey lines underlying the figures; what do those lines represent?

Response:

Thank you for this helpful comment. We agree. All manuscript figures have been replaced with higher-resolution versions, with clearer axes, legends, labels, and text. We also clarified the meaning of the gray/light traces in the figure captions. In both Figures 3 and 4b, the gray lines are observed Q_E during rainy days.

Changes made in the manuscript:

The Fig. 3 caption was clarified (page 14, around lines 341–342) to state:

> *"In panel (b), gray lines indicate observed latent heat flux during rainy days."*

In addition, all figures throughout the revised manuscript were regenerated/replaced at higher resolution.

Reviewer Comment 6

> **Reviewer comment:** For the results, I have one major question. As shown by the current results, the storage heat is largely improved; the error improved from around 100W/m2 to around 20 W/m2, but the surface temperature results are comparable. This means the energy partitioning in the previous and current/modified modules is quite different. This part of the results needs further and deeper explanation and discussion. I suggest a comprehensive analysis of each energy partitioning and an explanation of the reasons/possible reasons behind it. Figure. 6 has addressed this partially, but it is still a bit superficial and only describes the differences.

Response:

Thank you for this important comment. We agree that the previous discussion was too descriptive. We expanded the energy-partitioning discussion to explain why Q_G improves strongly while T_s changes much less. Net radiation (Q^*) is very similar in the two simulations, so reducing excessive Q_G leaves more energy for Q_E and Q_H. Q_G can change substantially without a similar change in Ts because it depends on both the soil temperature difference and the soil thermal conductivity. We also explain how soil evaporation, canopy interception, and multi-layer root uptake affect Q_E and therefore the remaining energy available for Q_H. The energy-partitioning figure referred to as Fig. 6 by the reviewer is now Fig. 7 after figure renumbering.

Changes made in the manuscript:

We expanded Sect. 4.1 (pages 23–24, lines 482–498) with the following explanation:

> *"Reducing the unrealistic daytime Q_G peak changes how the available energy is divided between the different heat fluxes. Net radiation (Q*) is very similar in the original and modified simulations. Therefore, when Q_G becomes smaller in the modified model, more energy is available for Q_E and Q_H."*
>
> *"The main reason for the large change in Q_G is the improved soil thermal conductivity. Ground heat flux depends on both the temperature difference within the soil and the soil thermal conductivity. Therefore, Q_G can change a lot even if the modeled surface temperature does not change very much. In the original model, the soil thermal conductivity became unrealistically high in the morning, which caused too much heat to move into the soil. In the modified model, the revised soil thermal conductivity and especially the vegetation-dependent surface conductivity reduce this excessive heat transfer. As a result, more of the available energy is directed to Q_E and Q_H, particularly earlier in the day, shifting the timing of the diurnal cycle of these fluxes."*
>
> *"The hydrological modifications further influence this coupled energy balance. Soil evaporation provides an additional pathway for water loss from the green roof, canopy interception allows stored rainfall to evaporate rapidly after rain, and multilayer root uptake allows plants to access water from deeper soil layers as the upper soil becomes dry. These processes generally enhance Q_E when water is available. The resulting changes in Q_E, Q_G, surface temperature, and moisture conditions also affect Q_H. Therefore, the modified model produces a more realistic overall partitioning and diurnal evolution of the surface energy fluxes, even though changes in surface temperature remain relatively small."*
>
> *"The hydrological modifications also help explain the changes in latent heat flux (Q_E)."*

This expanded discussion is supported by Fig. 7 and by the one-at-a-time sensitivity analysis in Figs. 8–9, which separately shows the effects of the moisture-related and thermal-conductivity modifications.

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.