Review of egusphere-2025-219

"MLUCM BEP+BEM: An offline one-dimensional Multi-Layer Urban Canopy Model based on the BEP+BEM Scheme"

by Gianluca Pappaccogli, Andrea Zonato, Alberto Martilli, Riccardo Buccolieri, and Piero Lionello

Replies to the Reviewers' remarks

We thank all the Reviewers for the careful revisions and the constructive comments to our work. All suggestions have been appreciated and have been taken into careful consideration in our revision. Below, we provide a detailed reply to all points raised by the reviewers.

Referee: 1

1) It is not clear if the MLUCM BEP+BEM is coupled to a land surface model to simulate land-atmosphere interactions for natural/rural surfaces. What are the sources of latent heat in BEP+BEM? How is the grid-averaged latent heat flux estimated?

R: In order to clarify this point the following sentence has been added to the manuscript in line 157-162:

"MLUCM BEP+BEM is not coupled with an external land surface model. The latent heat flux results from the weighted average of contributions from natural (e.g., green road fractions and street trees.), and wet built surfaces (water from rain on road and roofs). For the green road fraction, the same scheme adopted by green roofs, described in Zonato et al. (2021), is used. For the trees, the latent heat flux is estimated using a simple empirical parameterization that partitions the radiation absorbed by leaves into sensible and latent heat."

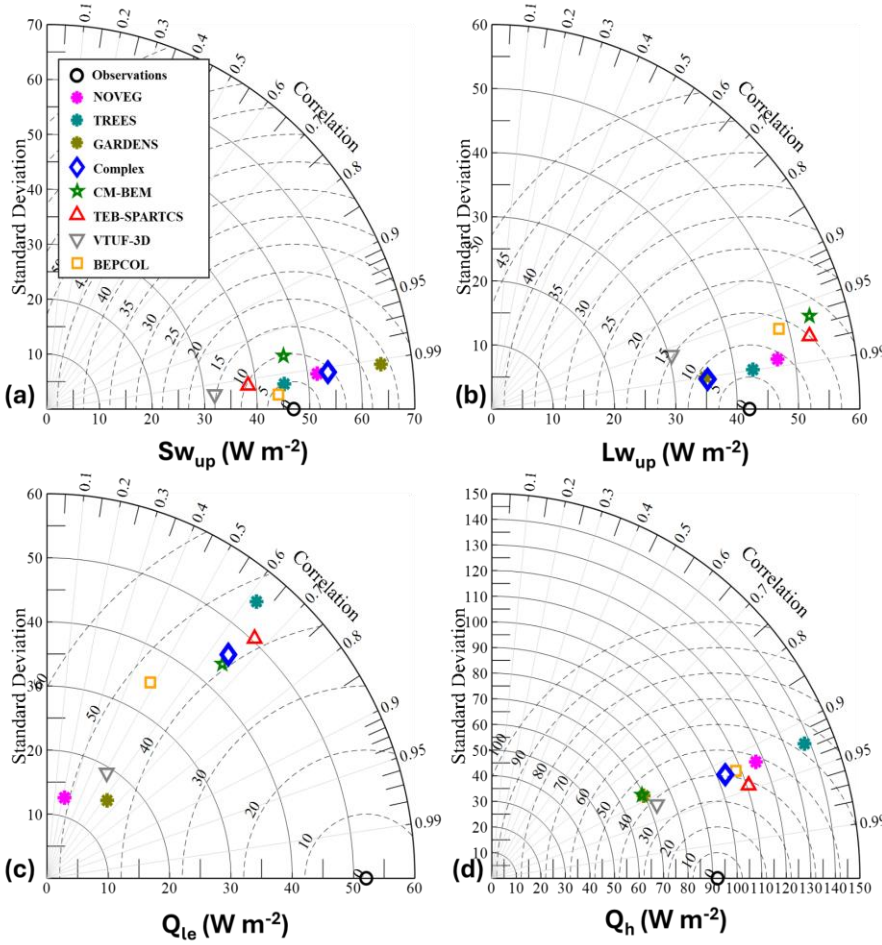
2) Have the street-canyon-trees and street-canyon-gardens models been validated in a previous work? Are trees and gardens (in the street canyon) the unique sources of latent heat in these simulations?

R: The street-canyon-trees and street-canyon-gardens models, although previously proposed and applied in the studies of Stone et al., (2021) and Zonato et al., (2021), respectively, had not been validated with respect to the latent heat flux. While the street-canyon gardens model is inspired by the parameterization proposed by De Munck et al. (2013), which was validated in their original study, the street-canyon trees model has not undergone specific validation until now. The results presented in this study are the first direct validation against in situ observations of latent heat flux and show a quality comparable to other models.
Street-canyon-trees and gardens are the main latent heat source in the three experiments analyzed in this study, but these simulations also consider the contribution from artificial wet surfaces. Further our model can include other sources, such as air conditioning systems and green roofs (not active in the simulations presented in this paper), as well as evaporation of rain water accumulated on roofs and roads.

de Munck, C. S., Lemonsu, A., Bouzouidja, R., Masson, V., and Claverie, R.: The GREENROOF module (v7.3) for modelling green roof hydrological and energetic performances within TEB, Geosci. Model Dev., 6, 1941–1960, https://doi.org/10.5194/gmd-6-1941-2013, 2013.

3) Table 1 shows that tree area fraction is 0.225 for this neighborhood. How do sensible and latent heat fluxes change when this fraction is set to 0? In other words, is the role of trees important for mesoscale simulations? Was the impact of trees on near-surface air temperature and/or specific humidity modeled in the numerical experiments?

R: Simulations were conducted for the "complex" experiment, considering three scenarios: one including only street trees (referred to as **TREES**), one including only gardens (**GARDENS**), and one excluding both types of vegetation (**NOVEG**). These configurations were designed to address this and the following research question. Additionally, we identified an error in the previously used tree area fraction value of 0.225. This value should have been weighted by the street fraction according to the model's infrastructure settings. For further clarification, please refer to the general comment, also provided in response to Reviewer 2. The interpretation of the changes of variability in the Taylor results indicates that excluding trees significantly reduces the latent heat flux and at the same time it decreases the reflected shortwave flux. Concerning the sensible heat flux the latter effect prevails determining its increase.
Near-surface air temperature and humidity measurements are not included in the Urban-PLUMBER protocol, making it difficult to establish a reliable reference for validating model output and answering the last question of the Reviewer.



Q_{le}				
	Complex	NOVEG	TREES	GARDENS
BIAS	-4.60	-28.62	-0.69	-22.49
NME	0.88	5.11	0.86	2.58
SLOPE	0.56	0.05	0.66	0.19
COR	0.64	0.22	0.62	0.65
Q_h				
BIAS	17.86	21.76	26.6	6.28
NME	0.48	0.47	0.48	0.64
SLOPE	1.03	1.17	1.39	0.67
COR	0.92	0.92	0.92	0.89

4) Similarly, table 1 shows that grass area fraction is 0.15 for this neighborhood. How do sensible and latent heat fluxes change when this area fraction is set to 0? Was the impact of grass area fraction on near-surface air temperature and/or specific humidity modeled in the simulations?

R: The interpretation of the changes in variability in the "GARDENS" simulation in the Taylor results (olive stars) indicates that excluding gardens reduces the latent heat flux (but to a lower extent than excluding trees) and has a small effect (increase) on the reflected shortwave flux. The sensible heat flux decreases to compensate for the increased latent heat.

5) Overall, the baseline experiment produced good results compared to the other two experiments, which could indicate that some urban parameters are more important than others to accurately simulate the urban climate. Could you explain what is the added value of considering site-specific observations for six/seven additional urban parameters (compared to the baseline experiment) for mesoscale climate simulations?

R: The results indicate that "detailed" and "complex" experiments, incorporating more detailed morphological parameters, lead to better estimates of sensible and latent heat flux, often exhibiting smaller errors than the "baseline" experiment.
However, the added value of incorporating detailed urban descriptors would become evident when addressing aspects such as building energy demand or the effectiveness of urban mitigation strategies (which are not considered in this study that refers to the Urban-PLUMBER protocol). As emphasized in previous work (Pappaccogli et al., 2021), accurately representing urban morphology, particularly the volumetric structure of the built environment and the exchange surfaces between built-up areas and the urban boundary layer is crucial for

simulating energy demand. This is directly linked to anthropogenic heat emissions, which are a key component of urban climate dynamics.

Additional clarification has been included in the Section 5 of the manuscript in lines 460-463 as follows:

"*Results show that the integration of detailed, site-specific information on urban elements such as building geometry and vegetation generally improves the simulation of energy fluxes. This level of detail is particularly important for applications involving building energy demand or urban mitigation strategies, where accurate representation of urban morphology, especially the volumetric structure, is essential (Pappaccogli et al., 2021).*"

Pappaccogli, G., Giovannini, L., Zardi, D., & Martilli, A. (2021). Assessing the ability of WRF-BEP + BEM in reproducing the wintertime building energy consumption of an Italian Alpine city. Journal of Geophysical Research: Atmospheres, 126, e2020JD033652. https://doi.org/10.1029/2020JD033652

General comments for reviewer 1

The Reviewers' comments offered an opportunity to conduct a more in-depth investigation into the representation of latent heat flux in our model. This led to the discovery of a significant error: the tree and garden area fractions used in the three experiments were only 55% and 76%, respectively, of the correct values. This discrepancy systematically underestimated both the magnitude and variability of the latent heat flux.
Furthermore, the recently proposed UT-GLOBUS database by Kamath et al. (2024) was employed to enhance the representation of building distributions in the "complex" experimental setup, producing a generalized increase of the height of buildings. These two changes have led to a reduction of the negative latent heat bias of our former simulations. The updated simulations yield results that are consistent with those obtained from similar parameterization schemes.

Additional clarification has been included in the manuscript in lines 277-278 as follows:
"*For the "complex"* experiment*, the UT-GLOBUS database (Kamath et al., 2024) was employed to derive this parameter.*"

Please note that Sections 4.1 and 4.2 have been completely rewritten in the revised manuscript to fit with the results of the new simulations.

Kamath, H.G., Singh, M., Malviya, N. et al. GLObal Building heights for Urban Studies (UT-GLOBUS) for city- and street- scale urban simulations: Development and first applications. Sci Data 11, 886 (2024). https://doi.org/10.1038/s41597-024-03719-w

Referee: 2

1) Is it a good assumption to not let longwave radiation interact with the tree canopy processes? Longwave radiation should be absorbed, transmitted, and emitted from the tree canopy like all other structures, which would then affect the radiative temperature and therefore heat flux partitioning. Please clarify what you mean by "The canopy interacts only with short-wave radiation and does not affect long-wave radiation components." on line 187

R: We fully agree with the reviewer's observation regarding the role of longwave radiation in tree canopy processes. Since the main objective of our work is to develop an efficient and lightweight modelling tool, we chose not to describe long-wave interactions with the tree canopy.

Nonetheless, we acknowledge the importance of this aspect, and additional clarification has been included in the manuscript in lines 195-199 as follows:

"*The interaction of the canopy with radiation is limited to shortwave components, as a modelling simplification. In the current version, longwave interactions with the tree canopy are neglected. This includes the (computationally expensive) omission of longwave reflection and exchange between multi-layer 2D assemblages of buildings, roads, and tree foliage. Remarkably, the observed thermal radiation fluxes are accurately reproduced despite this simplification.*"

2) Why use an empirical formulation for the partitioning of heat fluxes dependent on the shortwave radiation? Do street trees not have their own soil moisture stores that are similar to the street canyon gardens? Not taking into account the changes in soil moisture induced by urban trees, and the reduction in latent heat and subsequent changes to sensible and ground heat fluxes, could be biasing the results of this study (e.g. a reason why there are such large discrepancies in the latent heat results).

R: In the proposed model, street trees do not have a dedicated soil moisture reservoir. Instead, the transpiration process is explicitly represented as a function of downward short-wave radiation and this approach does not account for dynamic changes in soil moisture beneath trees.

We recognize this as a limitation of the current model version, and ongoing work aims at including BEP-Tree (Krayenhoff et al. 2020) in the model for a more complete representation of the role of vegetation. However, in most densely built urban areas, latent heat flux represents a relatively minor component of the surface energy budget. It is worth noting that, in the updated simulations, the latent heat flux values are consistent with those obtained from other modelling approaches.

A clarification has been added to the manuscript in lines 180-183 to explain this assumption and its implications more clearly.

"*In the current configuration, street trees are not assigned a dedicated soil moisture reservoir, limiting the representation of tree-induced soil moisture dynamics and potentially introducing biases in the partitioning of turbulent heat fluxes. On the other hand, in most dense urban areas, the latent heat is a small component of the surface energy budget.*"

3) Do you believe that the LCZ6 parameters you chose are representative for this space? Did you check the albedo and emissivity against remotely sensed averages? To my knowledge, LCZ give a range of values to select from, but these are likely to change given the age and type of architecture chosen for the study region.

R: We agree with the reviewer's observation regarding the representativeness of the LCZ6 parameters and the importance of validating albedo and emissivity values against remotely sensed data. However, in order to maintain internal consistency across the three different experiments presented in the paper and to align with the standardized framework proposed by the Urban-PLUMBER project, we chose to adopt the same set of LCZ6 parameter values across all experiments.
This decision was made to ensure comparability between experiments and to stay consistent with the reference configurations defined in the Urban-PLUMBER protocol. We acknowledge that some variability exists depending on the local architecture's age and typology, and this is indeed an important consideration for future model refinements.

Additional clarification has been added in the text in lines 261-263 to reflect this rationale.
"*To ensure internal consistency across experiments and alignment with the Urban-PLUMBER protocol, a standardized set of LCZ6 parameters was adopted, enabling compatibility while acknowledging the need for future refinements to capture local variability.*"

4) Upon reading the street canyon gardens section, I think that clarification is needed to discuss whether street trees are treated similarly (e.g. using ecohydrologic principals) or not.

R: Street trees are not treated in the same way as gardens.
Please note the clarification within section 2.2.2, reported in the revised manuscript in lines 180-182 as follows:

"*In the current configuration, street trees are not assigned a dedicated soil moisture reservoir, limiting the representation of tree-induced soil moisture dynamics and potentially introducing biases in the partitioning of turbulent heat fluxes.*"

5) I think that a more detailed investigation of the "why" behind sensible and latent differences in the single layer BEP BEM model is needed. For instance, why is the baseline doing better in the sensible heat flux compared to the more detailed versions of the model presented? Is there a lack of sensitivity/too much sensitivity to the parameters that were introduced? For the latent heat flux, it is tricky to tell what is going on without a better explanation of how green areas are represented. Is there soil moisture/ hydrology being simulated? Or is this the ratio that was mentioned in the methods section? Examining the code shows that partitioning between sensible and latent heat fluxes for trees, which would be the major contributor to the latent heat signal, is using this ratio. More justification is needed on why this is appropriate given the biases that it introduces, given that urban trees do increase latent heat fluxes to be higher than those shown (even in modeling experiments, like related work with BEP-Tree (https://doi.org/10.1016/j.uclim.2020.100590) or tiling approaches in Noah-MP HUE that represent ecohydrology (https://doi.org/10.1029/2023WR035511)).

R: The results of the "baseline" experiment are broadly consistent with those of the "detailed" and "complex" experiments; however, it exhibits greater variability and an elevated cRMSE. This difference in performance is a consequence of variations in urban geometry. According to the LCZ classification, the "baseline" features a more compact and lower urban structure. This arrangement of buildings leads to less heat accumulation and release, resulting in lower BIAS for sensible heat fluxes.
Green areas are not explicitly treated according to the tree canopy cover ratio. Indeed, as described in Section 2.2.2, soil moisture and hydrological processes are represented, including a soil layer where moisture content evolves dynamically based on surface energy balance and precipitation inputs.
Regarding latent heat flux and its representation, we recognize this as a limitation of the current model version, and ongoing work aims at including BEP-Tree (Krayenhoff et al. 2020) in the model for a complete representation of the role of vegetation. However, despite the use of simplified descriptions of street trees, the model yields results that are consistent with those from similar parameterizations. This demonstrates the robustness of the approach, even when driven by relatively coarse urban input data.

Further discussions have been included in the revised manuscript in lines 444-447:

"*The "baseline" experiment shows a mixed behaviour in reproducing sensible heat fluxes (Q_h), with reduced BIAS but overestimated variability compared to the more detailed experiments. This is mainly attributed to its representation of a compact and low urban structure derived from the LCZ classification, which reduces heat accumulation and release dynamics.*"

6) Authors could give a more detailed breakdown of what they hypothesize is going wrong than "whose cause deserves further investigations, are present for latent heat flux (Qle)." As stated on line 414.

R: We acknowledge the lack of detail in the original version of the manuscript regarding this point. Please note that the revised version of the manuscript has been adapted to fit the new results. However, in response to the reviewer's suggestion, we have included additional and more specific details in lines 448-453 in the revised version of the manuscript.

"*The discrepancies observed in both sensible (Q_h) and latent heat flux (Q_{le}) is probably attributable to the limitations of the current model setup, which omits the presence of trees in green areas. As a result, the model does not account for the full extent of vegetative cover, particularly in areas with dense greenery. In addition, street trees may receive limited solar radiation due to shading effects and potential inaccuracies in urban geometry representation, which can further reduce their transpiration capacity. The absence of a dedicated soil moisture reservoir for trees also limits the simulation of their evapotranspirative contribution. These factors can contribute to an imbalance in the surface energy budget.*"

7) What is going on with the ground heat flux? I am assuming there are no measurements, but do the results from this flux look believable? I would think that because of the errors in Qh and Qle, Qg would be also too high, and thus could cause a warming feedback when introduced into weather or climate models like suggested in the discussion.

R: The Reviewer is correct in noting that no measurements of ground heat flux (Q_g) are available, which poses a challenge for directly evaluating the accuracy of this component. Nonetheless, we recognize the limitations of this approach and have clearly stated in the manuscript that the lack of observational data for Q_g represents a constraint in evaluating model performance for this specific flux.
This limitation has been explicitly addressed in the revised text in lines 453-455.

"*The absence of observational data for ground heat flux (Q_g) prevents direct validation, limiting the evaluation of model performance for this component and warranting caution in interpreting its impact in coupled simulations.*"

8) The final point of this paper, "Further research includes experiments forcing the MLUCM BEP+BEM model with the ERA5 reanalysis to assess its sensitivity to various input parameters, including urban morphology and vegetation characteristics. Moreover, the model will be forced with climate projections to investigate the impact of climate change on the different urban processes, such as overheating, building energy demands, outdoor thermal comfort, and the efficacy of adaptation strategies, including urban greening, green and cool roofs, photovoltaic panels and hybrid sustainable infrastructure." is a lofty goal, and I would agree that this model is able to look at urban morphology pretty neatly. The issue is coming from the vegetation characteristics, urban greening, green and cool roofs, and the interactions with urban comfort and other applications. As of right now, the latent heat flux and sensible heat fluxes are wrong, which would then cause these to be erroneous. This model is on the right track, but there needs to be more justification/investigation/discussion on how we could use this model to look at urban climate adaptation with the errors that are present within the model right now.

R: We appreciate the reviewer's recognition of the model's potential in representing urban morphology and we fully agree that the future applications outlined in the paper are ambitious. As part of our ongoing development efforts, we acknowledge the need to further improve the representation of vegetation and the associated hydrological processes.
While on one hand, it is important to acknowledge the current limitations of the model, particularly in the representation of vegetation processes and the discrepancies observed in thermal fluxes, on the other hand, as demonstrated in our results, the model's performance is in line with or in some cases superior to other similar urban parameterizations.
Our primary objective has been to develop a computationally efficient tool capable of representing key urban processes, with a special focus on morphology and its influence on the urban energy balance assessing the effectiveness of urban mitigation strategies, such as greening or cool roofs, over broader spatial and temporal scales. We believe that the inaccuracies of the model do not prevent achieving a useful estimate of long term trends of projections at the urban scale and their uncertainties, initiating to provide some crucial information that is requested by city planners and stakeholders.
In response to the reviewer's suggestion, we have revised and expanded the discussion in lines 469-474 in the manuscript to reflect these important considerations and to clearly communicate both the strengths and limitations of the current model framework.

"*Although the current model adopts simplified representations of vegetation and hydrological processes, the results demonstrate good agreement with, and in some cases outperform,* *other comparable urban parameterizations. These findings suggest that the model can provide a reasonable representation of key urban climate dynamics, even when driven by limited input detail. Its computational efficiency makes it particularly suited for exploring long-term trends and assessing large-scale mitigation strategies. Therefore, the framework represents a promising tool for supporting urban-scale climate analyses and informing decision-making processes.*"

9) When investigating the model code, the code is clean but there are some missed opportunities to give an indication of what each of the subroutines are doing. Consider adding those so that folks who want to add/modify this code base will know what is going on in each routine and call to the routine!

R: We agree that providing clearer documentation within the code is essential to support users who wish to understand, modify, or extend/implement the model. To address this, we will prepare a user guide that outlines how to properly set up and use the model, including descriptions of its main components and configuration options. In addition, we plan to release a second version of the code that includes more detailed and specific comments within each subroutine, as suggested. This will improve transparency and usability, making the model more accessible to the broader research community.

Minor points:
1. Line 59: missing a space between "1 Dimensional"

R: The error has been fixed

General comment for Review 2
The Reviewers' comments offered an opportunity to conduct a more in-depth investigation into the representation of latent heat flux in our model. This led to the discovery of a significant error: the tree and garden area fractions used in the three experiments were only 55% and 76%, respectively, of the correct values. This discrepancy systematically underestimated both the magnitude and variability of the latent heat flux.
Furthermore, the recently proposed UT-GLOBUS database by Kamath et al. (2024) was employed to enhance the representation of building distributions in the "complex" experimental setup, producing a generalized increase of the height of buildings. These two changes have led to a reduction of the negative latent heat bias of our former simulations. The updated simulations yield results that are consistent with those obtained from similar parameterization schemes.

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