Dear Anonymous Referee #2,

Thank you very much for your review and your constructive comments. The entire text of your comment is shown (C) together with our authors' responses (A).

Kind regards,

Concetta D'Amato, Niccolò Tubini and Riccardo Rigon.

Reviewer #2

Title: A component based modular treatment of the soil-plant-atmosphere continuum: the GEOSPACE framework (v.1.2.9)

Summary

C17 - This paper presents a modeling framework with three sub-components aiming to improve the simulation capabilities of soil-plant-atmosphere continuum. The paper primarily focuses on presenting the software rather than the science or the specific results.

A: We believe that presenting the software aligns perfectly with the journal's scope. Although it may appear reductive, we contend that meaningful progress in hydrological modeling requires software developed with proper engineering principles. Poor or inaccurate implementations can obscure the underlying physics they aim to represent. Additionally, sound software design enhances code readability, maintainability, and facilitates thorough inspection—a crucial aspect of modern scientific practice. Expanding the paper to include real case studies would have broadened its scope excessively and increased its already substantial length. The current paper is quite comprehensive, and adding approximately 20 pages of case studies, in our opinion, would likely discourage readership. Modifications were made in the introduction under Keyword C17 to convey these concepts.

C18 - I've checked the overall paper for clarity and some of the formulations, but I haven't checked the math in depth since that would be a little out of my domain. I'd recommend that it gets checked in other parts of the review. However, it seems sub-models have been already published and this paper is more focused on the integration.

A:Several GEOSPACE components have undergone substantial modifications beyond their previously published versions. As illustrated in Section 4, GEOET's refactoring represents necessary architectural changes enabling overall integration and future code expansion, not merely cosmetic improvements. Similarly, portions of WHETGEO were modified to serve the same objectives. The treatment of root functioning and evolution, while elementary, is entirely new, as is the BrokerGEO software that facilitates feedback among SPAC components. These contributions have been emphasized in the Conclusions section.

C19 - One overall major comment that didn't fit in the section is that it would help to produce a table of similar class of models, their short descriptions, and key features evaluated against key advances in GEOSPACE-1D.

A: We appreciate the reviewer's suggestion for comparative tables. While understandable, comprehensive model comparisons are more suited to dedicated review articles. For such comparisons, we refer readers to Blyth et al. (2021), Fisher and Koven (2020), and Pal and Sharma (2021) where the Reviewer can also find the Tables they search for. Nevertheless, we have added relevant references to provide additional context in the Introduction.

Model selection involves multifaceted considerations beyond scientific capabilities. These include software architecture, licensing, extensibility, and implementation languages—factors critical to our development decisions. For instance, while HYDRUS is well-validated and widely used in agro-climatology, its FORTRAN implementation and commercial licensing for 2D/3D versions constrained our adoption. Additionally, HYDRUS-1D has technical limitations regarding ponding formation, Richards equation integration, and vegetation representation that we aimed to improve. Similarly, the Community Land Model, though developed by leading researchers, employs software architecture that limits the flexible, component-based modeling framework we envision. Other established models like JULES, ORCHIDEE, and NOAH, despite their valuable features, have grown increasingly complex. This complexity makes understanding, testing, and modifying their implementations difficult—challenges we experienced firsthand with GEOtop, which became unmanageably complex over time. These experiences motivated our shift toward a contemporary, component-based modeling infrastructure that enables better separation of concerns and software accountability. This approach maintains complete control over code evolution while creating a unified framework applicable to both agro-meteorological and hydro-climatological communities. For readers interested in comprehensive model overviews, we recommend Blyth et al. (2021) for LSM comparisons, Fatichi et al. (2016) for process-based model capabilities, and Bonan et al. (2024) for Earth System modeling perspectives. Additional valuable references include Overgaard et al. (2006), McDermid et al. (2017), Vereecken et al. (2019), Bierkens et al. (2015), Graeme et al. (2023), and Miralles et al. (2024).

We have expanded the Introduction to incorporate these considerations.

References

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Vereecken, Harry, Lutz Weihermüller, Shmuel Assouline, Jirka Šimůnek, Anne Verhoef, Michael Herbst, Nicole Archer, et al. 2019. “Infiltration from the Pedon to Global Grid Scales: An Overview and Outlook for Land Surface Modeling.” *Vadose Zone Journal: VZJ* 18 (1): 1–53. https://doi.org/10.2136/vzj2018.10.0191;

C20 - Other major comments include no assets being available for review/links not working, big wiring diagram is missing, case implementation and validation could be improved, performance metrics to be included etc. Our detailed comments, including minor and major, are organized below in the order of appearance in the manuscript. Most of these comments are going to be applicable throughout the manuscript but I’ve highlighted them at only a few places.

A: We appreciate the reviewer's detailed comments and address each point below:

• Review/links not working: We have systematically reviewed all manuscript links and verified their functionality in the revised version.

• Missing wiring diagram: Figure 3, whilst a simplification, is such a diagram. Please see answer to #1 reviewer C4 for more details.

• Case implementation and validation: As previously discussed (Response C5 to the first Reviewer), implementing and validating a detailed case study represents a substantial undertaking that could merit a separate publication. Including a comprehensive case study would add approximately 20 pages to an already extensive manuscript (50 pages, expanding to hundreds with supplementary material). We would be happy to address any specific concerns about our current case implementation.

• Performance metrics: We maintain that mass conservation during integration is the most relevant performance metric for this paper, as previously detailed. Code efficiency comparisons would require benchmarking against other software packages, which—as noted in Response C19—would be both technically challenging and potentially inappropriate given the differences in software architectures and objectives.

We are committed to addressing the reviewer's concerns thoroughly and look forward to more specific feedback in the detailed comments below.

Specific comments

Abstract

C21 - Line 3 - specify matter? do you mean organic matter?

A: Thank you for pointing this out. We have removed the word “matter” from the sentence to avoid ambiguity.

C22 - Line 4 and throughout the text: deemphasis interdisciplinary aspects. This paper is still a very specific product of ecohydrologists, without any input from, let’s say, economists. It is fine to mention the need for interdisciplinary science and products but probably don’t frame this as an interdisciplinary product.

A: Thank you for the comment, as it likely indicates that our perspective was not clearly conveyed. What we aim to emphasize is that modeling the soil-plant-atmosphere system encompasses a wide range of disciplines, including hydrology, ecology, meteorology, climatology, geology, agronomy, environmental chemistry, environmental engineering, remote sensing, and, not least, numerical modeling and computational science. Given this context, a physically-based approach to studying the SPAC system inherently requires an interdisciplinary intellectual effort. To better clarify this concept, the text has been revised as

follows: “Modeling the SPAC system involves multiple disciplines, including hydrology, ecology, and computational science, making a physically-based approach inherently interdisciplinary and essential for capturing the complexity of the system.”

C23 - Line 24 – It is important to make sure it produces some kind of results. Or a prototype model or case implementation is critical for this paper to be strong. I see Section 7 speaks to it but there are some concerns there as described later. Also, better to mention the case implementation and discuss some results/over model behavior here in the abstract as well.

A: We thank the reviewer for highlighting this important point. In response, we have revised the abstract to include a clear reference to the case implementation. Specifically, we now mention the virtual simulations presented in Section 7, which demonstrate the model’s ability to simulate the coupled dynamics of infiltration and evapotranspiration within the soil–plant–atmosphere continuum. These additions aim to strengthen the overall contribution of the work and emphasize the operational capabilities of the GEOSPACE-1D framework. Moreover, to understand better we’ll look at the concerns that follow.

C24 - Intro

It is unclear from the introduction what this paper is contributing. I see many motivations being described such as better SPAC modeling, going beyond traditional "models", MBC etc, but the description of the unique contribution is lacking. I'd suggest not only specifying that comprehensively but also including an overarching "vision" statement for the model covering its scope, specifications and significance.

A: This approach (i.e., MBC) maintains complete control over code evolution while creating a unified framework applicable to eco-hydrological, agro-meteorological, and hydro-climatological communities. In addressing these concepts, we also aim to develop codes that strictly adhere to FAIR principles of openness and availability. Last, but not least, we also address algorithmic limitations that we have identified in similar software, such as inadequate treatment of transitions between saturated and unsaturated conditions, and the use of improper solvers. We have added to the new manuscript text to convey these concepts.

Section 2

C25 - Line 108 and throughout the text – “with flexibility and minimal effort”: Major: Since this is primarily a software paper, I'd like to see performance metrics included in the SI or the appendices. A comparison with other models/software or previous versions would also be nice. It is understandable if those are not available for other models but a comparison to the preceding version would help the reader see the value of this contribution more clearly.

A: Benchmarking against other software is in our opinion a matter for specialized community papers that focus on standardized benchmark simulations. Since this software is novel in parts of its components and their connections, there is no previous version to compare with regarding execution velocity. The benchmarks we have performed focus on water mass budget conservation. The value of this contribution is described more clearly in our responses to comments C19.

C26 - Line 114 and throughout the text – I see a few critical citation are referencing to authors own previous work. No issues with that but it would make the paper stronger if some of the formulations/key statements could also be supported by other citations. Just a suggestion

A: The implementation of the Casulli-Zanolli algorithm is not only unique to WHETGEO (and GEOSPACE) thus far, but according to the original authors, apparently represents the only method that guarantees solver convergence in all cases without requiring external controls, like, for instance in our GEOtop model (e.g Endrizzi et al, 2014) that uses a Newton-Krylov method. At line 114 we have added a reference to the Casulli and Zanolli paper (Casulli and Zanolli, 2010). Because we are convinced that the statement made by the mathematicians we cite, while strong, is true, we are reluctant in this specific case to cite other papers, such as Celia 1990 or Paniconi and Putti 1994, that apparently use incomplete integration methods. Moreover, models like CATHY (Paniconi and Putti), while certainly valuable, depend on ad hoc treatments of surface saturated and ponding conditions that we avoid. However, we have added additional citations to other authors where appropriate.

References

Casulli, Vincenzo, and ZANOLLI. 2010. “A Nested Newton-Type Algorithm for Finite Colume Methods Solving Richards’ Equation in Mixed Form.” *SIAM Journal of Scientific Computing* 32 (4): 2225–73.

Celia, M. A., E. T. Bouloutas, and R. L. Zarba. 1990. “A General Mass-Conservative Numerical Solution for the Unsatured Flow Equation.” *Water Resources Research* 26 (7): 1483–96.

Endrizzi, S., S. Gruber, M. Dall’Amico, and R. Rigon. 2014. “GEOtop 2.0: Simulating the Combined Energy and Water Balance at and below the Land Surface Accounting for Soil Freezing, Snow Cover and Terrain Effects.” *Geoscientific Model Development* 7 (6): 2831–57. https://doi.org/10.5194/gmd-7-2831-2014.

Paniconi, C., and M. Putti. 1994. “A Comparison of Picard and Newton Iteration in the Numerical Solution of Multidimensional Variably Saturated Flow Problems.” *Water Resources Research* 30 (12): 3357–3333. https://doi.org/10.1029/94WR02046.

C27 - Fig 1 - Are these components developed as a part of this effort/paper. it is not clear so far

A: We have clearly specified in the revised manuscript which contributions are developed in this paper, beginning with the introduction. The primary innovation presented is the establishment of bidirectional connectivity between infiltration and transpiration processes, enabling dynamic feedback mechanisms between soil conditions and atmospheric states. To achieve this integration, significant portions of the existing software were refactored, particularly the transpiration modules, and to a lesser extent, the infiltration components. The root growth and behavior modeling framework represents an entirely novel contribution. We have added the following clarification to the new manuscript introduction:

"The GEOSPACE framework presented here was developed by composing and extending existing GEOframe components: WHETGEO (Water Heat and Transport) (Tubini and Rigon, 2022), GEOET (EvapoTranspiration), and BrokerGEO to simulate complex soil-vegetation-atmosphere interactions in the Critical Zone. While GEOSPACE builds upon existing components in GEOframe, this work contributes three main innovations: (i) the development of GEOET, a new evapotranspiration module evolved from the established ETP-GEOframe component (Bottazzi, 2020); (ii) the implementation of BrokerGEO, a new coupler component enabling the dynamic interaction between evapotranspiration and infiltration processes; (iii) the extension of WHETGEO (Tubini and Rigon, 2022) to allow modular and seamless coupling with GEOET and BrokerGEO. These contributions represent both algorithmic and structural advances over previous models, such as the monolithic GEOtop framework (Rigon et al., 2006), and establish GEOSPACE as the ecohydrological core of GEOframe."

C28 - Line 136 – Major comment: There are many modules/components within the GEOframe suite. I see Fig 1 and Fig 3 attempt to list a few but a bigger wire-diagram showing all components with their connection is critically needed to follow what's going on and how everything works together. I suggest including that as a separate Fig at the start. It is fine if that fig gets complex, sometimes looking everything in one place is much better than trying to connect across pages

A: Same as in C20: While we could create a comprehensive wiring diagram, it would be extremely large and potentially counterproductive to readability. Instead, we direct interested readers to the geospace1D_ProsperoPM.sim file, which provides a readable workflow representation of the entire model. This file is included in the supplementary material, with clear comments to help readers understand the implementation. Besides, we

have prepared a concise presentation with accompanying slides that demonstrate how .sim files are organized and interpreted.

C29 - Section 4

Major: In this section, I would suggest highlighting the strengths of the formulation in this paper compared to Penman-Monteith and Priestley-Taylor since you describe them as simplified approaches in the intro. "Traditional PBM-based land surface models, widely used in hydrology and agronomy, often employ simplified governing equations, such as the Penman-Monteith equation (Pereira et al., 2015) or the Priestley-Taylor approach". Alternatively, you can repurpose to better highlight Prospero.

A: As suggested by the Reviewer, we have repurposed the Prospero model and more clearly specified its implementation details at the beginning of Section 4. We have included reference to a recent paper co-authored by two members of our team (D'Amato and Rigon, 2025) that provides a comprehensive derivation of Prospero's governing equations and thoroughly addresses its limitations.

Reference

D'Amato, Concetta, and Riccardo Rigon. 2025. "Elementary Mathematics Helps to Shed Light on the Transpiration Budget under Water Stress." *Ecohydrology: Ecosystems, Land and Water Process Interactions, Ecohydrogeomorphology* 18 (2). https://doi.org/10.1002/eco.70009.

C30 - Line 334: "GEOET, developed as part of this paper": Too far into the paper to mention this. Suggest being upfront about the key unique contributions of the model/paper

A: We appreciate the reviewer's suggestion. In the revised manuscript, we have anticipated the description of the key contributions of this work by including them in the Introduction section, as recommended. Specifically, we now state:

"While GEOSPACE builds upon existing components in GEOframe, this work contributes three main innovations: (i) the development of GEOET, a new evapotranspiration module evolved from the established ETP-GEOframe component (Bottazzi, 2020; (ii) the implementation of BrokerGEO, a new coupler component enabling the dynamic interaction between evapotranspiration and infiltration processes; (iii) the extension of WHETGEO (Tubini and Rigon, 2022) to allow modular and seamless coupling with GEOET and BrokerGEO. These contributions represent both algorithmic and structural advances over previous models, such as the monolithic GEOtop framework (Rigon et al., 2006), and establish GEOSPACE as the ecohydrological core of GEOframe."

We believe this change clarifies the scope and novelty of the paper from the outset, in line with the reviewer's recommendation.

C31 -Lines 560-575: non-critical writing style check: suggest making proper paras

A: In the revised text we have modified the structure of the paragraphs. Hopefully now, everything is more readable.

C32 -Page 30 and Figs 12-19 – Major: no validation of any sorts is presented to confirm the behavior of the model's outputs. I'd highly recommend a comparison with data and in the worst case an expert-based evaluation of the model diagnostics.

A: We are addressing applications of our model in separate forthcoming papers, as the experimental setups require detailed descriptions, particularly regarding evapotranspiration measurements, which often present their own methodological challenges and uncertainties. However, following Reviewer #1's suggestion in comment C5, we have incorporated additional expert commentary throughout the manuscript to enhance the interpretability of our simulation results and make their significance more accessible to readers.

C33 - No assets were available for review. SPIKE II data is available on zenodo but no links in Section 8 or the code available are functions. I would recommend including them as texts too: https://github.com/geoframecomponents/GEOSPACE-1D

A: We thank the reviewer for this valuable observation. In the revised manuscript, we have provided all relevant links in full, both in Section 8 and in the Code and Data Availability section. These include direct access to the GEOSPACE-1D code repository, the corresponding OMS3 project, the Zenodo archive containing all materials required to reproduce the simulations and the SPIKE II experimental dataset. All assets are now explicitly referenced and accessible to ensure full transparency and support reproducibility.