Dear Anonymous Referee #1,

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 #1

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

C1 - Summary:

The manuscript introduces a novel modeling framework that focuses on modeling the interactions within the soil-plant-atmosphere continuum (SPAC). Rather than using a single, rigid model, the authors propose a modular approach called GEOSPACE-1D, built on object-oriented programming principles. GEOSPACE-1D is a flexible, open-source framework with self-contained components. This modular design allows for easy customization, reuse, and extension of the model without disrupting existing parts to integrate new processes seamlessly. Instead of offering a single definitive model. The manuscript thoroughly describes the framework's components, providing information about modularity, process representation and interaction between components. The authors further discuss the implementation of the system with a case study, describe the setup, and present the results.

A: Thank you for your thorough and accurate summary of the manuscript. We appreciate that you have highlighted the modular structure and object-oriented design of GEOSPACE-1D, as well as its potential for customization and integration of new processes. This feedback confirms that the intended framework structure and its key features have been clearly explained.

General Comments:

C2 - While supplementary materials provide detail on the GEOFRAME system, the main body could include a brief description of the system. Clearly establish GEOFRAME as the overarching framework and explicitly define GEOSPACE as the specific ecohydrological model within it. This clarification will significantly improve the reader's understanding of the present work and contextualize it.

A: We appreciate the reviewer's suggestion since it is important to clearly establish that GEOframe is a modular framework that allows users to build custom modeling solutions to

address various hydrological challenges, inside which GEOSPACE was born. GEOSPACE mainly represents the ecohydrological model of GEOframe due to it simulates the water transport in the soil-plant-atmosphere continuum, by using models available in GEOframe. We modified the abstract and introduction. Please refer to C9 and C10 comments.

C3 - Consider adding a brief introductory paragraph or section in the main body that explains the purpose and architecture of the GEOFRAME system, and how GEOSPACE fits within it.

A: We have modified the abstract and the introduction accordingly. Please see the C9 and C10 answers for more details.

C4 - The captions of the figures need to be more descriptive to meet the author's intention. Some figures have very descriptive captions and some others lack detail. Despite providing a description in the main body, it is important that the figures are self-explanatory or at least that the author helps the reader in their interpretation. Take, for example, Figure 3, where the width of the arrows is explained in the text but should also be included in the caption.

Instead of simply stating "[arrow] thickness reflecting the volume of exchanged variables" rewrite Figure 3's caption to include: "Arrow widths represent [specific meaning, e.g., water flow volume]."

A: The diagram depicts the component relationships within our modeling framework, highlighting parameter dependencies through weighted arrow representations. For instance, the "Stress Factor" component establishes connections with both Prospero components and ETBrokerSolver, delivering multiple parameters to these components (shown by arrows three times thicker than baseline). Conversely, it provides only a single parameter to the soil ET component, represented by a correspondingly thinner arrow. During model execution, WHETGEO initializes the computational sequence. The figure necessarily omits several auxiliary components that manage input/output operations and buffer processes essential for parallelizing component output writing, as including these would compromise diagram clarity and readability. Complete operational details are available in the simulation files (.sim files) included in the supplemental material. We direct reviewers' attention particularly to the `geospace1D_ProsperoPM.sim` file, which serves as an illustrative example of our framework's structure and functionality. Additionally, we have prepared a concise presentation with accompanying slides that demonstrate how .sim files are organized and interpreted which will be added to the supplementary material.

In response to reviewer feedback, we have substantially revised the manuscript text to better convey this information and expanded figure captions throughout the document to provide more comprehensive explanations of the modeling framework components and their interactions.

The text has been modified to include the following: “For a comprehensive understanding of the complete workflow, we direct readers to examine the simulation configuration files provided in the supplemental material, particularly the `geospace1D_ProsperoPM.sim` file. These .sim files, a standard feature of the OMS framework, serve as executable documentation that precisely records the model workflow, component connections, and parameter settings. The supplemental material also includes a concise presentation with accompanying slides that provide detailed guidance on interpreting .sim file structure, component relationships, and execution sequence, offering valuable insights for both new users and those seeking to modify existing simulations.”

C5 - While the number of figures in Section 7 is appropriate, the analysis and interpretation of the simulation results are insufficient. Provide a more thorough evaluation of the model's performance, including quantitative metrics (if possible) and qualitative assessments relative to the experiment setup.

A: The simulations presented here are not intended to investigate a particular experimental setup, which would require a longer paper and open a topic better addressed in dedicated research. Instead, these simulations serve as a proof of concept, demonstrating that the system functions correctly without integration errors across all tested conditions. This represents only a small subset of the comprehensive simulations performed by the Authors to evaluate GEOSPACE's robustness. Water budget closure was verified for all simulations, with supporting documentation provided in the supplemental material, even for challenging situations involving transitions between unsaturated and saturated conditions as apparent, for instance, in Figure 13. We have modified Section 7 to clarify these aspects and have furthermore improved all figure captions.

The text has been modified under the label C5, to include the following:”

To demonstrate the capabilities of the model, we present two "virtual"simulations: the first called as "baseline simulation" (BSL) which simulates the coupled dynamics of infiltration and evapotranspiration, while the second one focuses only on the infiltration process. The simulations are not intended to investigate a particular experimental setup, which would require a longer paper and open a topic better addressed in dedicated research. Instead, these simulations serve as a proof of concept, demonstrating that the system functions correctly without integration errors across all tested conditions. This represents only a small subset of the comprehensive simulations performed by the Authors to evaluate GEOSPACE's robustness. Water budget closure was verified for all simulations, with supporting documentation provided in the supplemental material. All the simulations are readily available in the supplemental material which contain a series of Jupyter notebooks which allow to re-execute them and inspect their results more deeply. **“**

C6 -Also, the authors could describe the processes represented in the simulations and explain the logic behind the observed model behavior. What can be considered limitations?

A: Answering to this question is part of the modifications we made in section 7. Please, in the new manuscript with highlighted additions, refer to modifications with keyword C5.

C7 - Consider improving the structure of the manuscript regarding sections and subsections. The paragraph preceding each subsection should provide a clear introduction and establish the connection to the subsequent content. For example, in Section 4, the unnumbered subsections (Priestley-Taylor ET estimator, Penman-Monteith FAO estimator, Prospero Model) should be introduced with a unifying paragraph that explains their relevance.

A: We modified the introduction to Section 4 to accomplish the Reviewer's requests. Please refer to C4 modifications.

C8 - The transition into sections 4.1 and 4.1.1 should be handled with more clarity.

A: We have modified the initial part of section 4.1.1 by adding: “A primary objective in the software engineering of the GEOSPACE system was to enable feature expansion through class addition rather than code modification, adhering to the open-closed principle of object-oriented design.”

Specific Comments:

C9 - Abstract**:** Include a couple of sentences describing the GEOFRAME system and the gap that GEOSPACE is filling. Add a mention of the processes that can be represented in the GEOSPACE framework.

A: We have modified the abstract by adding: “GEOSPACE leverages and extends selected components from the GEOframe modeling system, while also integrating newly developed modules to comprehensively simulate water transport dynamics in the SPAC system.”

C10 - Introduction**:** Add details about the GEOFRAME system, and the relevance of including SPAC process representation. Include details on the performance of the framework when tested as presented in section 7. Clarify that GEOSPACE is a framework within the GEOframe system.

A: As mentioned previously, it is important to clearly establish that GEOSPACE is an integral component of GEOframe. The main text has been modified in the introduction to also specify the main contributions of this paper, as follow:

“The GEOSPACE framework functions as an integral component of the GEOframe system and it uses some of the components available in GEOframe to simulate the water transport

in the continuum SPAC, thus being the ecohydrological model of GEOframe. GEOframe is an open-source, component-based hydrological modelling system (Formetta et al., 2014; Bancheri et al., 2020). Rather than being a single model, GEOframe is a modular framework, where each part of the hydrological cycle is implemented in a self-contained building block, an OMS3 component (David et al., 2013). Models available in GEOframe cover a wide range of processes, including geomorphic and DEM analysis, spatial interpolation of meteorological variables, radiation budget estimation, infiltration, evapotranspiration, runoff generation, channel routing, travel time analysis, and model calibration. It allows users to build custom modeling solutions to address various hydrological challenges. 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."

In addition, a reference to Section 7 simulations was included in the introduction as requested by the reviewer. Modifications were made in the introduction under Keyword C9

C11 - GEOSPACE-1D System Overview and its perceptual model - There is a mention to "*multiple stress functions mentioned in the introduction"* but such reference is missing in the introduction

A: OK. We have corrected it by deleting the sentence.

C12 General notes about the software organization of GEOSPACE-1D - Figure 3 could be improved by including a description/functionality of each component within the SPAC. The thickness of the arrows represents the number of variables, but it is not described in the caption or the number. Is there a sequence in the computing of each component, if so, is there a starting point?

A: The modification of the caption was accomplished in the revised manuscript. Please see the C4 answer.

C13 - GEOET

Considering improving the structure of this section. **The Priestley-taylor ET estimator; The Penman-Montheith FAO estimator; The Prospero Model**

A: According to what already said in answering C7 and C8 we have modified the introduction of the section and the text in the revised manuscript.

C14 - The GEOET informatics organization- How to add a new model?: Is this section only referring to new models for GEOET?

A: Thank you for the question. The section is not limited to models for GEOET, but refers to the integration of new models into any component of the GEOSPACE framework. We have clarified this point in the revised manuscript under label C8.

C15 - Unveiling GEOSPACE-1D capabilities on practical applications - Figure 12 is not very clear. Consider using a different scale or color scheme to better show the temporal variability. Additionally, incorporating the rainfall timeseries could help interpret the variation shown in this figure while tracking the the occurrence of rainfall events. Consider providing a side by side comparison between the most relevant aspects of the two experiments.

We thank the Reviewer for this valuable comment. Following the suggestion, we have substantially revised Figure 12 to improve clarity and interpretability. Specifically:

1. We incorporated the precipitation–irrigation time series as Panel (a), which now allows direct temporal comparison between rainfall inputs and soil water potential responses in the two simulations.
2. We ensured that the color scales are consistent and diverging where appropriate: Panel (b) presents absolute soil water potential (ψ) with a perceptually uniform scale, while Panel (c) uses a diverging colormap centered at zero to effectively highlight both positive and negative differences in $\Delta\psi = \psi_R - \psi_{BSL}$.
3. To enhance the comparison between scenarios, we now show:
    - The full spatio-temporal evolution of ψ in the baseline case (Panel b),
    - The direct difference between the two scenarios (Panel c), thus enabling a side-by-side assessment of the processes driving divergence (e.g., absence of evapotranspiration in the infiltration-only simulation).

We also revised the figure caption to better explain the physical meaning of the color scales and the relevance of the differences. Hopefully this meets the Reviewer's request.

C16 - User information: Input and output - This information should be included in code and data availability. Section 8

A: We appreciate the reviewer's suggestion. To improve clarity regarding the open-source structure and usage of the code, we decided to separate the information related to input and output into a dedicated section (Section 8) rather than incorporating it into the Code and Data Availability section. This choice was made to provide users and developers with a more accessible and detailed overview of how the components interact at runtime, including input requirements, output formats, and integration aspects. We believe this structural decision enhances readability and usability, while preserving the coherence of the manuscript.