Response to Reviewer #2:

The authors present a study coupling the 3D variably saturated groundwater surface water model with the ecosystems model LPJ-GUESS. The rational is that applying coupling groundwater processes are improved which in turn improve the representation of land surface and ecosystems' processes. The coupled model is applied over the Danube basin at the climate time scale. A comprehensive evaluation of the model with observations is performed that shows that indeed the coupled model is able to represent elevation processes much better even without calibration.

This is an interesting and timely study. The terrestrial system constitutes a continuum with respect to the coupled water, energy and matter cycles. It models it should be treated as such, in order to arrive at interpretable results and allow extrapolation into future climates. It is curious that the comparison to observations results in excellent statistical metrics especially considering the no calibration was applied. This has been observed in previous coupled modeling studies (also with ParFlow). It would be interesting to hear the authors' opinion why this is.

Below I provide general and specific comments and suggestions. The study can be published following moderate to major revisions.

Thank you for your positive evaluation. We will carry out major revisions and improve the paper comprehensively.

Response: We are most grateful to the reviewer for the constructive comments and encouraging assessment of our work, acknowledging it as an interesting and timely study, and noting that our coupled model demonstrates excellent simulation of hydrological variables without requiring calibration. This characteristic reflects the physics-based nature of the coupled model, where hydrological and ecological fluxes are explicitly represented and constrained by observed boundary conditions and physical parameters. The river network within the catchment evolves organically through the evolution of infiltrating surface water and groundwater flows, rather than through empirical adjustments. Considering the complexity and physical realism of the input data, the results were obtained without calibration. We will carry out major revisions following your suggestion and improve the paper comprehensively.

Introduction

[Comment 1] Given the plethora of work that as been done with physics-based groundwater flow models, in particular with ParFlow with reagard to coupling with land surface and also atmospheric processess, the introduction is not only incomplete, but misses to contextualize the novelty of the presented study. The gap mentioned on line 70 has been bridged in many other previous studies.

Response: Revised, thanks to the reviewer for pointing out the need to better contextualize the novelty of our study. Following the reviewer's suggestion, we have revised the introduction to include details on ParFlow's current coupling status and remaining process gaps. In particular, we added discussions of previous coupling efforts of ParFlow with land surface and atmospheric models such as WRF, CLM, LIS, and Noah-MP, and clarified the remaining research gaps. Specifically, most prior studies focused on coupling ParFlow with land surface processes but employed static vegetation parameters, which do not adequately represent dynamic vegetation growth and ecosystem processes (e.g., vegetation mortality, interspecific competition, phenology, and carbon-nitrogen cycling).

The novelty of our study lies in: Coupling groundwater-soil water processes with dynamic vegetation and ecosystem processes through bidirectional feedback; Treating vegetation as an active participant providing feedback to the hydrological system, rather than as a passive recipient of water flux; Capturing nonlinear feedbacks of vegetation dynamics on soil moisture, groundwater, and transpiration.

These additions are now reflected in lines 67-70 of the revised manuscript.

[Comment 2] ParFlow: Which type of shallow water equation was used, kinematic of diffusive?

Response: The overland shallow flow in ParFlow is computed using the Overland Kinematic Wave equation.

Coupling modeling approach

[Comment 3] Is the coupling directed at the existing coupling of ParFlow with e.g. the Common Land Model? Is daily coupling sufficient? What's the total depth of the ParFlow model?

Response: Thanks to the reviewer for these insightful questions. Our responses are provided below:

1. Coupling framework: In our coupled model, the coupling is implemented directly with ParFlow 3.13, which does not directly couple with ParFlow-CLM but only with ParFlow itself. we have effectively replae the typical ParFlow-CLM coupling to couple Parflow with a new ecosystem model, (dynamic vegetation process model LPJ-GUESS. This allows the coupled system to explicitly simulate both hydrological and ecological processes (updated in the revised paper, please see line 159).

2. Temporal discretization: ParFlow operates on an hourly timescale to capture fast

hydrological processes, while LPJ-GUESS updates daily to reflect vegetation growth processes. In practice, LPJ-GUESS reads ParFlow outputs every 24 timesteps (1 day) to compute daily water fluxes. These daily P-ET values are disaggregated into hourly values according to diurnal patterns and passed back to ParFlow for the next simulation day. This strategy preserves hydrological fidelity while maintaining realistic ecological dynamics (updated in the revised paper, please see lines 173-175).

3. Model depth: The total depth of the ParFlow model in the Danube River Basin is set at 92 meters below the surface (depending on the specified bedrock depth of the Danube River Basin) and divided into 10 layers with variable thicknesses (from bottom to top: 50, 25, 10, 10, 10, 5, 1, 0.6, 0.3, 0.1 m). Layer thicknesses can be adjusted according to the hydrogeology and research objectives on the specific study area (updated in the revised paper, please see lines 255-257).

[Comment 4] Soil data: Why not use Soil Grids instead?

Response: We thanks to the reviewer for this helpful suggestion. We have revised the description of the soil dataset for greater clarity and consistency with the subsurface-data explanation. Although Soil Grids provides global, high-resolution soil information, LPJ-GUESS requires soil input that is directly compatible with the WISE soil texture dataset, which is used in its parameterization. In addition, the WISE-derived soil texture fractions better reflect the spatial variability of soil properties. Therefore, we used 10-km soil grids derived from the WISE database, where each grid contains sand, silt, and clay percentage fractions. These revisions have been updated in the revised paper, please see lines 197-205.

Subsurface data:

[Comment 5] Is soil data not subsurface data? For each hydrogeologic unit an indicator is required not an indicator file. To which depth was he subsurface represented in the model.

Response: We thanks to the reviewer for raising these important points, and we have substantially revised our description of the subsurface data. Soil data alone does not fully represent subsurface characteristics. In the coupled model, subsurface properties are assigned using a 3-D indicator array, which specifies the hydrogeologic unit for each grid cell and depth level.

Soil layers (0-2 m; codes s1-s12): Derived from WISE soil texture fractions (sand, silt, clay). Twelve soil classes were defined using the soil texture classification code. Each soil class is linked to predefined hydraulic parameters, including hydraulic conductivity, porosity, and relative permeability curves.

Bedrock layers (2-92 m; codes g19-g28): Derived from GLHYMPS v1.0 permeability data and grouped into classes based on hydraulic-conductivity distributions.

Each unit class has a set of hydraulic properties. The 10 vertical subsurface layers (soil + bedrock) in the model are therefore defined through these indicator codes, which are read by the model to assign parameter values. All relevant revisions appear in lines 197-215.

[Comment 6] 54: These references to not show influence of groundwater on boundary layer development. An example is Rahman, M., Sulis, M., Kollet, S.J., 2015. The subsurface–land surface–atmosphere connection under convective conditions. Advances in Water Resources 83, 240–249. https://doi.org/10.1016/j.advwatres.2015.06.003.

Response: Revised, thanks to the reviewer for the professional comment. The suggested reference has been added to the revised manuscript (please see line 53).

[Comment 7] 116: It is not the jacobian matrix that is solved but a system of equations.

Response: Corrected, thanks to the reviewer for pointing this issue out. Following the reviewer's suggestion, we have corrected the sentence to clarify that the Newton-Krylov framework in ParFlow solves the Jacobian-based linear system using GMRES, rather than directly solving the Jacobian matrix itself (please see lines 120-121).

[Comment 8] 216: The slope was calibrated? Perhaps calculated.

Response: Yes, we appreciate the reviewer's insightful comment. As clarified in lines 239-241 of the manuscript, the slope variable is derived from the priority flow algorithm, which calculates slope values in both the x and y directions for each grid cell based on regional topography and river network data. The algorithm uses a D4 flow direction scheme, and the resulting drainage area was validated against the 0.1° drainage area dataset from the IHU publication (Eilander et al., 2021). Details of the terrain preprocessing and algorithm implementation are provided in the priority flow algorithm and topographic preprocessing references (Zhang et al., 2021).

Eilander, D., van Verseveld, W., Yamazaki, D., Weerts, A., Winsemius, H. C., and Ward, P. J.: A hydrography upscaling method for scale-invariant parametrization of distributed hydrological models, Hydrol. Earth Syst. Sci., 25, 5287-5313, https://doi.org/10.5194/hess-25-5287-2021, 2021.

Zhang, J., Condon, L. E., Tran, H., and Maxwell, R. M.: A national topographic dataset for hydrological modelling over the contiguous United States, Earth Syst. Sci. Data, 13, 3263-3279, https://doi.org/10.5194/essd-13-3263-2021, 2021.

[Comment 9] Equation 6 is redundant.

Response: Corrected. Thanks to the reviewer for the professional suggestion, the redundant Equation (6) has been removed in the revised manuscript.

Results and Discussion

[Comment 10] 323: ParFlow-CLM

In order to show uncertainty in ET observations, it would be nice to include more than one product in the analyses. In figure 4h, please include the results from LPJ-GUESS.

Response: Added, thanks to the reviewer for the constructive suggestion, and have revised the manuscript accordingly. We have added a comparison with the LPJ-GUESS seasonal variability in Figure 4h.

Regarding the use of additional ET products, we carefully considered incorporating MODIS16 as an extra observational benchmark. However, our evaluation shows that MODIS16 systematically produces higher ET values (typically 600-800 mm yr^{-1} across most parts of the basin) and exhibits spatial patterns that differ substantially from GLEAM, LPJ-GUESS, and PF-LPJG. Because these differences largely reflect known structural biases in MODIS16 rather than model-observation discrepancies, including MODIS16 would complicate interpretation without providing a consistent reference for model evaluation.

Given that GLEAM has been extensively validated with flux tower observations and is widely recognized as one of the most reliable global ET datasets, we use it as our primary benchmark in this study. Nevertheless, we acknowledge that MODIS16 may offer complementary insights for future multi-product intercomparison analyses.

[Comment 11] Interestingly, ParFlow simulates too shallow water tables. What are the reaons? Coarse resolution, hydrogeologic heterogeneity, etc.? Perhaps it's worthwhile considering anisotropy in the hydraulic conductivity, where Kxx, Kyy > Kzz.

Response: Thanks to the reviewer for the professional suggestion. In our coupled simulations, the relatively coarse 10-km model resolution (ensure computational feasibility) tends to smooth topographic gradients and river channel geometry. This smoothing promotes soil moisture accumulation in low-slope areas, leading to locally excessive saturation and consequently shallower simulated water table depths compared with observations.

With respect to hydraulic conductivity, PF-LPJG already applies an anisotropic scheme in which horizontal conductivity ($K_x = K_y$) exceeds vertical conductivity (K_z), with K_z typically set to $0.01 \times K_{x,y}$ to represent flow-restricting layers. In future work, we plan to explore increasing K_x and K_y to better represent the lateral spreading of groundwater and improve the simulation of water table depth in low-gradient terrains. These limitations and potential improvements have been incorporated into the revised manuscript (please see section 4.3).

Insight

[Comment 12] Can the authors provide some insight on the computational or HPC aspect of the simulations since the computational burden of coupling ParFlow with LPJ GUESS increases considerably in the context of decadal scale simulations.

Response: Thanks to the reviewer for raising this important point, which is indeed a common concern among users of high-resolution coupled models. In our current setup, the coupled PF-LPJ-GUESS model runs at a resolution of 10 km using 80 + 100 CPU cores, requiring approximately 6-7 hours of computation per simulated year. Both ParFlow and LPJ-GUESS support large-scale parallel computation on HPC systems. In future work, we plan to adopt the GPU-accelerated version of ParFlow, which combines MPI and GPU parallelization, potentially improving computational efficiency by a factor of 2-3 compared to the current setup.

[Comment 13] What does the coupling of ParFlow with LPJ-GUESS do wrt to non-linear interactions and the boundary value problem of the terrestrial hydrologic cycle and how it is generally treated in land surface models? What are the implications for Earth system modeling?

Response: Thanks to the reviewer for these thought-provoking questions. In the ParFlow-LPJ-GUESS configuration, LPJ-GUESS dynamically simulates vegetation growth, competition, and carbon cycling in response to hydrological conditions, while ParFlow resolves the three-dimensional variably saturated flow that governs soil moisture and groundwater dynamics. Through this coupling, the terrestrial hydrologic cycle is formulated as a dynamic boundary value problem (BVP), where both upper and lower boundaries evolve interactively in time, rather than being treated as static parameters or externally prescribed fluxes. Such a formulation allows nonlinear feedback between vegetation physiology (e.g., transpiration, rooting depth, leaf area) and hydrological states (e.g., soil moisture, groundwater level) to emerge explicitly.

In contrast, the ParFlow-CLM coupling mainly emphasizes the exchanges of surface energy and water fluxes associated with land-atmosphere interactions. The coupling of ParFlow-LPJ-GUESS focuses on representing the two-way interactions between vegetation dynamics and subsurface-surface hydrological processes. Although both coupling frameworks exchange similar variables, the processes that generate and respond to these fluxes differ fundamentally.

This integrated approach provides a more realistic representation of vegetation–water interactions, especially across arid and humid regions, and improves the physical consistency of land carbon-water coupling. Consequently, it enhances the representation of terrestrial processes in Earth System Models (ESMs) and strengthens the simulation of long-term (decadal) water-carbon-energy feedbacks. The discussion on these questions has been included in the revised manuscript (sections 3 and 4).