Reviewer 1

General comments:

The paper presents the modelling of the methane dynamics into the LPJmL6 land surface model which includes already a representation of the energy, water, carbon and nitrogen cycles. For that purpose, a modelling of the water table depth and wetland extent were included based on the CTI-TOPMODEL framework. Methanogenesis and methanotrophy were parameterized, land use and rice management effects alongside inundation-tolerant vegetation were also represented. Model results evaluated against global datasets show consistent and realistic fluxes, showing the potential of the developed framework to support climate-mitigation strategies.

The paper is well-structured, well-written and easy to read. The parameterisations developed and the results are clearly presented, the figures are of good quality. The paper falls within the scope of GMD and presents a very rigorous and substantial advance in the modelling of the soil methane processes. Therefore, I recommend its publication after the authors address my main concerns.

We thank the reviewer for the positive and constructive feedback. We appreciate the recognition of the novelty, rigor, and clarity of our work, as well as its relevance for GMD.

We carefully addressed all main concerns and provide detailed responses below. Corresponding revisions were made in the manuscript. For transparency, we also provide PDF diff files for both the revised manuscript and the Supplement, documenting all changes made during the revision.

Specific comments:

- The introduction should present the state of the art of the soil methane processes in Earth System Modeling, especially the previous works which focused on the representation of methane cycle in land surface models. All the bibliography on this topic is missing in the present paper.

  We thank the reviewer for this comment. We revised the introduction by adding a concise paragraph on previous process-based representations of soil and wetland CH_4 processes in land-surface and Earth system models. The added text summarized earlier work on CH_4 production, oxidation, and transport pathways and their implementation in models such as LPJ-WHyMe, ORCHIDEE-based methane formulations, CLM4Me, WETMETH, and WETCHIMP/WETCHIMP-WSL intercomparison studies.

- It is important to validate the model on local fluxes. A comparison against site measurements of carbon and methane fluxes is required to show the model performances and give error metrics.

  We agree that site-level validation provides an important constraint on simulated carbon and methane fluxes. The original manuscript already included a site-level evaluation of carbon fluxes using NEE measurements, shown in Fig. 7, together with error metrics. In response to the reviewer's comment, we added a supplementary comparison of simulated CH_4 fluxes against available methane flux tower observations to evaluate model performance for local-scale methane exchange.

- To better highlight the performances of the model developed, a spatial representation of the methane emissions need to be added (not only latitudinal averages as done here). Maps should be added to present the spatio-temporal variability of the fluxes. A presentation of the contributions of the various processes and ways of transportation would be interesting also.

  We thank the reviewer for this helpful suggestion. We agree that latitudinal averages alone did not sufficiently describe the spatial structure of simulated CH_4 emissions. In response, we added a new spatial comparison of wetland CH_4 emissions to the revised manuscript. The new figure shows maps of LPJmL6 wetland CH_4 emissions, the WetCHARTs ensemble median, and the spatial anomaly between LPJmL6 and WetCHARTs, together with the corresponding latitudinal profiles. This allowed the reader to assess both the zonal agreement and the regional spatial deviations between LPJmL6 and the observation-based ensemble.
  The added analysis showed that LPJmL6 reproduced the broad latitudinal distribution of wetland CH_4 emissions reasonably well, including the dominant tropical maximum. However, the spatial anomaly map also showed that similar latitudinal totals could arise from different regional emission patterns. We discussed these differences explicitly, noting that the comparison was made against the WetCHARTs ensemble median and that the ensemble spread reflected substantial uncertainty in wetland extent and CH_4 flux estimates. We also discussed limitations related to the coarse model resolution, which restricted the representation of narrow floodplains and riparian wetlands, and the absence of explicit bank infiltration and river--floodplain exchange processes in the current model version.
  Regarding the requested presentation of the contributions of the various processes and transport pathways, these diagnostics were already included in the manuscript in Sect. 5.3 and Table 3. There, we reported the global CH_4 budget separated into atmospheric flux pathways, including diffusion, plant-mediated transport, ebullition, and fire emissions, as well as source categories such as natural wetlands, rice fields, grasslands, and other croplands. We also provided soil CH_4 oxidation and the resulting net methane sink. We revised the text to make this connection clearer and to emphasize that these data provided a process-level comparison of the different emission pathways and source categories.

Technical comments:

- Line 75: grid cell mean water table depth: is it the annual mean? Precise please.

  We agree that this should be stated more precisely. Here, the grid-cell mean water-table depth referred to the annual mean water-table depth simulated for the 0.5° grid cell. Since the saturated area was derived annually in our implementation, we clarified this in the text.

- Table 1, 2 and 3 should be moved to an annex or supplementary document

Done; Table A1 was therefore also moved to the Supplement.

- Liner 169: equation number is missing

  This was corrected.

- Line 181: Remove the article “the” at the beginning of the line

  This was corrected.

Reviewer 2

General Comments

This article presents an implementation of the main terrestrial mechanisms governing CH_4 fluxes, covering both anthropogenic sources and natural sources, with well-represented links to the carbon, nitrogen, and water cycles. A particular focus is placed on water table depth modeling to estimate wetland extent using the CTI-TOPMODEL framework. The new model is first evaluated against wetland observations, then used to simulate CH_4 fluxes compared with observational data.

The paper is well constructed and clearly written. The description of the new model is complete, and the number of mechanisms implemented represents an impressive and comprehensive effort within a single framework. However, the introduction would benefit from explicitly listing the newly implemented mechanisms as well as those not yet implemented, rather than leaving the reader to discover them progressively through the model description section. The article only requires a few minor clarifications on missing details, as outlined below.

We thank the reviewer for the positive assessment of the manuscript and for this helpful suggestion. We agree that the introduction can more explicitly state which CH_4-related mechanisms were newly implemented and which related processes were outside the scope of the present study. We therefore revised the introduction to list the main implemented components, including dynamic water-table depth, CTI-TOPMODEL-based wetland extent, soil-layer O_2 and CH_4 concentrations, methanogenesis, CH_4 oxidation, and CH_4 transport to the atmosphere through diffusion, ebullition, and plant-mediated transport. We also clarified that these processes were coupled to the simulated carbon, nitrogen, and water cycles and were applied to natural wetlands and rice systems.

In addition, we explicitly stated that livestock-related CH_4 emissions had been implemented in a previous LPJmL5.0 development (Heinke et al. 2023), but were not evaluated or further described in the present study. We further clarified that sub-grid open-water CH_4 emissions from lakes, ponds, and river networks were not explicitly represented in the current implementation.

Specific Comments

- **Time stepping and numerical scheme**: The main time step used with climate forcing data, and consequently with each model component, is not explicitly stated. Section 2.3 mentions "an adaptive sub-stepping scheme that refines the time step when local CH_4–O_2 concentration gradients become steep", but the baseline time step remains unclear, as does the criterion governing the adaptive refinement. It would be beneficial to either explicitly state these details or provide a reference where this information can be found. Furthermore, regarding the numerical scheme selection (Line 355), the authors mention that only the backward Euler scheme provided sufficient stability. However, stability alone does not guarantee accuracy. It would strengthen the methodological justification to provide the CFL number ($CFL = v\Delta t/\Delta z$) for the vertical water and gas transport equations.

  We thank the reviewer for pointing out that the time-stepping procedure and numerical scheme required further clarification. We therefore added a dedicated subsection describing the time stepping and numerical scheme used for the methane and oxygen balance in more detail. The revised text explicitly stated the baseline time step used by the model, the sub-time step used for the CH_4-O_2 calculations, and the criterion used for adaptive refinement when local concentration gradients became steep.

We also agree that numerical stability alone did not guarantee accuracy. To address this point, we performed an additional simulation at higher temporal resolution and compared the results with the default setup. This sensitivity test was reported in the revised manuscript. Because the vertical gas transport was solved with an implicit backward Euler scheme, the CFL number was not a stability criterion for this part of the model. Instead, we assessed the adequacy of the selected time step through the high-resolution sensitivity experiment. We clarified this distinction in the revised text.

- **Slope distribution and wetland fraction validation**: The assumptions underlying the chosen hypothesis for slope distribution construction used in the CTI-TOPMODEL framework are not evaluated against observational constraints. It would be valuable to briefly discuss whether these assumptions remain valid across different climatic or topographic regions, particularly where the hypothesis may be too crude. The latitudinal comparison presented in Section 5.2 is pertinent, but a spatial evaluation would further strengthen the validation. Adding supplementary maps of wetland fraction anomalies against multiple observational databases would allow the reader to better assess the sensitivity of the results to the chosen hypothesis for slope distribution construction, and to identify whether systematic errors correlate with topographic characteristics, wetland fraction, or other physically meaningful variables.

We agree that the assumptions associated with the CTI-based TOPMODEL representation should have been discussed more explicitly. We clarified that wetland fractions were not prescribed directly from the CTI values. The CTI fields were used as a sub-grid topographic template within the TOPMODEL framework, while the actual wetland extent was determined dynamically from the simulated water-table position and the hydrological state of each grid cell. Thus, the CTI distribution constrained the spatial probability of saturation within a grid cell, but temporal wetland dynamics and regional wetland extent also depended on simulated water balance, precipitation, evapotranspiration, runoff generation, and soil-water storage.

Nevertheless, we agree that the prescribed CTI representation may have introduced regional uncertainties. Its assumptions may have been less valid in very flat lowlands, where small elevation or slope errors could strongly affect the inferred saturation distribution, and in steep terrain, where narrow valley-bottom or riparian wetlands may not have been resolved at the model resolution. Moreover, wetland occurrence in floodplains, coastal zones, and managed landscapes could depend on processes not fully represented by a static topographic index, such as river inundation, groundwater convergence, backwater effects, or water management.

We revised the methods to clarify this point. In addition to the latitudinal comparison in Section 5.2, we included supplementary maps of wetland-fraction anomalies relative to multiple observational wetland datasets. These maps provided a spatial diagnostic of regional biases and helped assess whether deviations were associated with specific topographic or hydrological settings. While this analysis did not constitute an independent validation of the CTI dataset itself, it evaluated the consequences of using the prescribed CTI representation within the dynamic CTI-TOPMODEL wetland scheme. In addition, we added binned diagnostics of the wetland-fraction anomaly against mean grid-cell slope and CTI (Figs. S3 and S4). These figures allowed the reader to assess whether model-data differences were spatially coherent and whether they were systematically related to topographic controls used in the wetland parameterization.

- **Sensitivity analysis and conclusion:** Given the large number of parameterizations introduced, the conclusion would benefit from an additional perspective on sensitivity analysis. A discussion of the relative influence of key parameters on wetland extent and CH_4 flux estimates would be a valuable addition, even as a stated future direction.

  We agree with the reviewer that the large number of newly introduced and modified parameterizations warranted a systematic sensitivity analysis. Such an analysis was important to quantify the relative influence of individual parameters and their interactions on simulated wetland extent, agricultural CH_4 emissions, and total land-atmosphere CH_4 exchange. However, a full global sensitivity analysis was beyond the scope of the present model-description and evaluation study, as it would have required a dedicated experimental design and substantial additional simulations. We therefore expanded the conclusion to discuss this point more explicitly.

Technical Comments

- Line 104: The variable Ψ_inf is used but not defined. Please provide its definition.
  We added the definition of Ψ_inf.
- Line 106: The expression "at a time" should be clarified — does this refer to a daily time step if the model operates at daily resolution?
  We clarified this as follows: “To improve numerical stability during vertical soil-water routing, precipitation was internally partitioned into increments of at most 4 mm, which were sequentially routed through the soil column within the daily time step.”

- Line 119: The value of 2.0 m^{-1} is used without justification. Please provide the source for this parameter value.
  We thank the reviewer for pointing this out. We revised the manuscript to explicitly cite the source of this parameter value. The decay factor f = 2.0 m^{-1} followed the default CLM 2.0 parameterization described by Niu et al. (2005).

- Line 124: The threshold of 100 mm day^{-1} for agricultural water input requires a reference or justification.
  We agree that this threshold should not be presented as an empirically constrained parameter. We have therefore revised the methods to clarify that the value of 100 mm d^{-1} was used as an effective upper limit for managed agricultural water removal, rather than as a directly observed

drainage parameter. e motivation is that agricultural areas are commonly subject to enhanced drainage or water management (see e.g. Valayamkunnath et al. 2020, https://doi.org/10.1038/s41597-020-00596-x for the USA, but global data are missing), so that short-term water fluxes can be substantially larger than in unmanaged natural stands. We have also mentioned this assumption as a limitation and noted that future model developments could replace this globally uniform threshold with spatially explicit information on drainage infrastructure and soil hydraulic properties.

- Line 496: Please add the time step of the GSWP3-W5E5 forcing dataset for completeness.
  We revised the manuscript to specify that the GSWP3-W5E5 forcing data were applied at a daily time step.