Reviewer 2

Responses to the reviewers are shown in red.

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 are newly implemented and which related processes are outside the scope of the present study. We therefore revise the introduction to list the main newly 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 clarify that these processes are coupled to the simulated carbon, nitrogen, and water cycles and are applied to natural wetlands and rice systems.

In addition, we explicitly state that livestock-related CH_4 emissions have been implemented in a previous LPJmL5.0 development (Heinke et al. 2023), but are not evaluated or further described in the present study. We further clarify that sub-grid open-water CH_4 emissions from lakes, ponds, and river networks are 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 require further clarification. We therefore add a dedicated subsection describing the time stepping and numerical scheme used for the methane and oxygen balance in more detail – explicitly stating the baseline time step used by the model (daily), the sub-time step used for the CH_4-O_2 calculations, and the criterion used for adaptive refinement when local concentration gradients become steep.

We also agree that numerical stability alone does 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 will be reported in the revised manuscript. Because the vertical gas transport is solved with an implicit backward Euler scheme, the CFL number is not a stability criterion for this part of the model. Instead, we assess the adequacy of the selected time step through the high-resolution sensitivity experiment. We clarify 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 be discussed more explicitly. We thus clarify that wetland fractions are not prescribed directly from the CTI values. The CTI fields are used as a sub-grid topographic template within the TOPMODEL framework, while the actual wetland extent is determined dynamically from the simulated water-table position and the hydrological state of each grid cell. Thus, the CTI distribution constrains the spatial probability of saturation within a grid cell, but temporal wetland dynamics and regional wetland extent also depend on simulated water balance, precipitation, evapotranspiration, runoff generation, and soil-water storage.

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

We revise the methods to clarify this point. In addition to the latitudinal comparison in Section 5.2, we have now prepared supplementary maps of wetland-fraction anomalies relative to multiple observational wetland datasets. These maps provide a spatial diagnostic of regional biases and help assess whether deviations are associated with specific topographic or hydrological settings. While this analysis does not constitute an independent validation of the CTI dataset itself, it evaluates the consequences of using the prescribed CTI representation within the dynamic CTI--TOPMODEL wetland scheme. In addition, we add binned diagnostics of the wetland-fraction anomaly against mean grid-cell slope and CTI (Figs. S3 and S4). These figures allow the reader to assess whether model--data differences are spatially coherent and whether they are 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 warrants a systematic sensitivity analysis. Such an analysis is 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 is beyond the scope of the present model-description and evaluation study, as it would require a dedicated experimental design and substantial additional simulations. Nonetheless, we expand the conclusion to refer to this point more explicitly.

Technical Comments

- Line 104: The variable Ψ_inf is used but not defined. Please provide its definition.
  We add 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 clarify the expression as follows: “To improve numerical stability during vertical soil-water routing, precipitation is internally partitioned into increments of at most 4 mm, which are 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 revise the manuscript to explicitly cite the source of this parameter value. The decay factor $f=2.0m^{-1}$ follows 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 thank the reviewer for pointing this out. We agree that this threshold should not be presented as an empirically constrained parameter. We therefore revise the methods to clarify that the value of 100 mm d-1 is used as an effective upper limit for managed agricultural water removal, rather than as a directly observed drainage parameter. The 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 also mention 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 revise the manuscript to specify that the GSWP3-W5E5 forcing data are applied at a daily time step.