Response to the reviewer 1

General comments

This paper introduces new model processes to represent old and deep carbon formation in Yedoma and peatland soils. It is an interesting model development, as it is a common issue for many land surface or ecosystem models to simulate these deep and old carbon dynamics explicitly. However, I struggled to understand the model comparisons, evaluation, and calibration due to the current structures and the scattered information.

[Response] Thank you very much for your time and effort in reviewing our manuscript, and for your constructive feedback on our work. We greatly appreciate your thoughtful comments, which have helped us improve both the clarity and structure of the paper. Following your suggestions, we have made the following revisions:

(1) Added summary paragraphs describing the model merging strategy and revised Fig. 1 to provide a clearer graphical overview of the approach, helping readers better understand the overall model development and the rationale for focusing on the evaluation of simulated carbon accumulation.

(2) Reorganized the Results and Discussion sections, and added the explanation of our evaluation strategy to improve the presentation of model comparisons, evaluation, and validation.

(3) Provided additional details on the peatland and Yedoma PFTs, and included a new subsection titled *"Changes in plant and soil carbon pools following conversion from conventional soils to peatlands"* in the Data and Methods section, to clarify the mechanisms underlying changes in peatland areas and peatland inception timing.

Please find our point-by-point responses to each of your comments below.

Major comments

1. *The authors merged different versions of ORCHIDEE models, so it seems unclear if any independent calibration or evaluation has been conducted before comparing carbon accumulations to ensure the model's performance is on the right track before adding new processes.*

[Response] Thank you for raising this important point. In this study, we merged two model versions: ORCHIDEE-MICT-teb (Xi et al., 2024) and ORCHIDEE-MICT-Yedoma (Zhu et al., 2016). The core structure of the improved model is based on ORCHIDEE-MICT-teb, a revised version of the widely used ORCHIDEE-MICT branch (e.g., contributions to the Global Carbon Budget (Friedlingstein et al., 2022), ISIMIP3a simulations, etc.) which targets high-latitude processes (Guimberteau et al., 2018). Compared to the original ORCHIDEE-MICT version, ORCHIDEE-MICT-teb incorporates an improved representation of tiled energy budgets, and has been comprehensively evaluated in our previous work (Xi et al., 2024), including its performance in simulating energy (their Figs. 13–17), carbon (their Fig. 12), and hydrological processes (their Fig. 15) at monthly timescales and across the North hemisphere.

The Yedoma-specific additions from ORCHIDEE-MICT-Yedoma were integrated to simulate carbon accumulation processes specific to Yedoma regions. Because these additions primarily influence soil carbon dynamics, our evaluation in this study (Section 3.1) focuses on carbon-related outputs in Yedoma regions. Given the relatively limited spatial extent of Yedoma (0.47 Mkm^2, 0.7% of areas north of 30°N), our model modifications are expected to have only a minor effect on other regions, and the results from the precursor version hold in this study.

Regarding the peatland processes, the base version already includes peatland carbon accumulation. We did not introduce new process developments, but we significantly revised the way peatland initiation is simulated. Instead of assuming simultaneous peatland formation across all northern peatlands, our new approach uses observation-based, spatially varying, peatland age maps to prescribe the onset of peat formation at each grid cell. This was achieved by prescribing peatland cover maps at different epochs during the Holocene, which the model reads to simulate peatland expansion over time. This approach resolves effects of observed variations in initiation timing on long-term peat carbon accumulation. Since the dataset we used to prescribe peat initiation includes all / most known observations, peat initiation cannot be separately evaluated. We did not further evaluate the hydrological and energy processes of peatlands, as the total simulated peatland soil carbon remains very close to that of the base version (631.4 Pg C vs. 632.0 Pg C), suggesting only minor difference between model versions on regional scale. The primary change of introducing spatially varying peatland initiation lies in the partitioning between fast- and slow-turnover soil carbon pools (see our response to your detailed comment #1 for more details on the soil carbon module), which we have evaluated in detail in Section 3.2.

In response to your comments, we have added two paragraphs at the beginning of Section 2 *Data and Methods* (L101-123, copied as below) to summarize our model development strategy, including the details of each model version and our previous evaluation work. In addition, we have revised Fig. 1 (shown as Fig. R1 below) to provide a clearer graphical summary of our approach, and have cited Fig. 1 in the text where the old and new spin-ups are introduced. We believe these changes will help readers, particularly those less familiar with model development, better understand which aspects of the improved model require evaluation.

"To implement the model development, we used a branch version of ORCHIDEE-MICT, namely ORCHIDEE-MICT-teb (r8205), from Xi et al. (2024) as our base model. This version has PFT-specific (plant functional type-specific) energy budgets, soil thermics, and their interactions with carbon and hydrological processes, and has been comprehensively evaluated for its performance in simulating carbon, energy, and hydrological processes (Xi et al., 2024). To simulate Yedoma

carbon accumulation, we incorporated sedimentation processes from Zhu et al. (2016), adapting them to be compatible with the PFT-specific framework of the new model. The model version used by Zhu et al. (2016) relied on grid-cell-averaged energy budgets, which meant that Yedoma carbon was mixed with coexisting PFTs (bare soil, tree, grass, crop) to regulate the average energy budget. Given that Yedoma soils typically have much higher carbon densities than general soils, accounting for their distinct carbon-energy-water feedbacks such as the thermal insulation effect of SOC (Koven et al., 2009; Zhu et al., 2019) is essential for realistically simulating both their historical development and future evolution. Regarding peatland processes, the base version already included peatland carbon accumulation. We thus did not develop new peatland processes, but we revised the way peatland initiation is simulated during the Holocene. Instead of assuming a homogeneous peatland age across northern peatlands starting in early Holocene, we employed spatially explicit peatland age maps based on observational data to define the onset of peat development at each grid cell. This was achieved by prescribing peatland cover maps at different epochs during the Holocene, which the model uses as a forcing to simulate realistic peatland expansion over time. As a result, the improved model allows for the independent simulation of Yedoma carbon, peatland carbon, and conventional soil carbon dynamics within a single grid cell.

In Section 2.1, we describe the soil carbon models in detail, including the general soil carbon processes and the peatland carbon accumulation scheme in the base version (Xi et al., 2024), as well as the Yedoma carbon accumulation processes from Zhu et al. (2016). Section 2.2 then presents the setup of the carbon accumulation simulations, using both the base version (without Yedoma carbon accumulation and with uniform peatland inception timing) and the improved version (with Yedoma carbon accumulation and spatially varying peatland inception).”

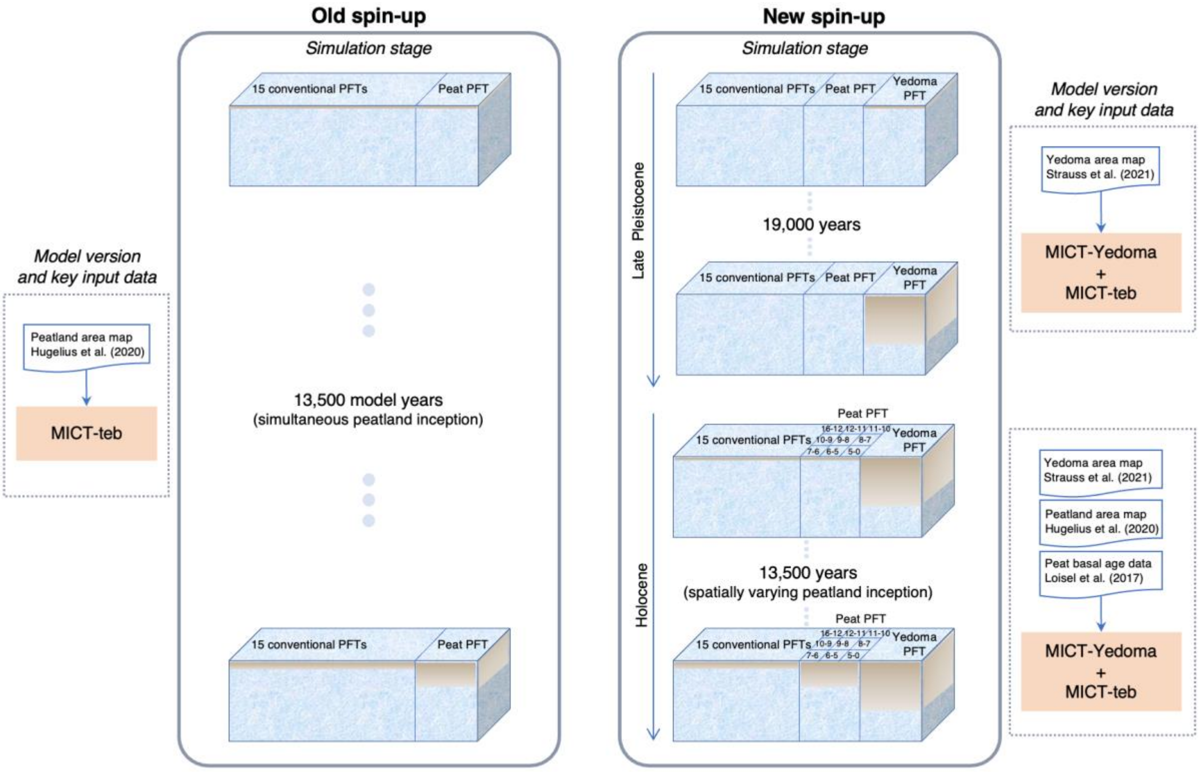

Fig. R1 (also shown as Figure 1). Schematic representation of soil carbon accumulation across different simulation stages in the old and new spin-up simulations. The old spin-up uses the ORCHIDEE-MICT-teb (MICT-teb) model version, includes 16 plant functional types: 15 conventional PFTs (bare soil, 8 tree PFTs, 4 grass PFTs, and 2 crop PFTs) and one peatland PFT (C3 grass) within a grid cell (Table S1). In the old spin-up, the cover fraction of peatland is fixed throughout the simulation, and all peatlands are assumed to have formed simultaneously, 13,500 years ago. By contrast, the new spin-up merges ORCHIDEE-MICT-Yedoma (MICT-Yedoma) with MICT-teb, enabling the model to simulate Yedoma carbon accumulation during the late Pleistocene and subsequent carbon accumulation in peatland and conventional soils during the Holocene. The new spin-up includes the same 15 conventional PFTs, one peatland PFT, and an additional Yedoma PFT (C3 grass) within a grid cell (Table S1). Peatland cover varies dynamically across nine Holocene epochs (shown in the peat PFT domain), based on prescribed maps constructed from peat basal age observations and present-day peatland distribution.

2. *It is a bit confusing for me what has been developed in this study in terms of yedoma deposits. In the method section, it states that this study merged yedoma process from Zhu et al., 2016, and then in the Results section on L275, the authors used the same survey to evaluate the model performance. In Figure 4, why not compare the simulation outputs between the old and new spinup to show the model differences?*

[Response] As mentioned in our last response to your comment, for Yedoma deposits, we merged processes from Zhu et al. (2016), but adapted them to be compatible with the PFT-specific framework in the base version (ORCHIDEE-MICT-teb). We did not directly compare simulation outputs between the original and improved versions for two main reasons:

(1) Model structure changes: While the conceptual representation of Yedoma-specific processes remains similar, their implementation differs due to structural updates in the improved version. In Zhu et al. (2016), energy budgets were calculated at the grid-cell level, whereas the improved version employs PFT-specific energy budgets. This shift affects not only carbon accumulation but also soil thermal and hydrological processes, particularly in high-carbon-density Yedoma soils. Furthermore, ORCHIDEE-MICT-teb includes several updates and bug fixes not present in the Zhu's version. For example, we used a newly introduced PFT (boreal C3 grass) to better represent Yedoma-region vegetation, while Zhu et al. relied on a generic C3 grass type. This change alters vegetation parameters and may influence simulated carbon dynamics. Accurately isolating the specific impact of our developments would require substantial effort to ensure strict comparability between versions, which is not justified given the high workload.

(2) Lack of original outputs: The simulation output files from Zhu et al. (2016) are no longer available, which prevents direct comparison of simulation outputs between the original and improved versions. Although we still have access to the model code, reconstructing all the input files and rerunning the outdated version would be time-consuming and of limited value, especially given that an improved model version is already available.

As a result, instead of a direct comparison, we reproduced similar figures to those in Zhu et al. (2016) and used the same survey to evaluate the model performance, an indirect way to compare the two versions. Despite structural and parameterization differences, our simulation produced similar results: a total soil carbon stock of 141 Pg C and an average Yedoma soil carbon depth of ~20 m, closely matching the 125-145 Pg C and ~20 m depth reported by Zhu et al. (2016). This consistency suggests that the core mechanism driving vertical carbon accumulation (Eq. (2)), governed by measurement-derived deposition rates, remains robust and effective in capturing Yedoma soil carbon dynamics. Also, it indicates that our improved model version successfully integrates Yedoma-specific processes without conflating them with existing components of the base model (ORCHIDEE-MICT-teb).

We did not add further explanations on this point in the revised manuscript, given that including overly detailed descriptions of the model merging might distract from the overall understanding of the model developments. However, together with your next comment, we have reorganized the Results and Discussion sections and added a paragraph at the beginning of Section 3 (L317-323, copied as below) to summarize and clarify our evaluation strategy.

"**In this section, we present the simulated Yedoma carbon accumulation from the improved model version in Section 3.1. In Section 3.2, we examine how peatland soil carbon accumulation responds to the implementation of spatially varying peatland initiation timing. Since the vertical carbon**

transfer process in Yedoma is driven by deposition rates derived from site-level measurements, and peatland development is informed by prescribed maps extrapolated from point-based peat age data, we evaluate model performance by comparing simulated soil carbon from both the old and new spin-up schemes, as well as against site-level observations. In Section 3.3, we provide a spatial evaluation using the deepest available gridded soil carbon map (to our knowledge), although it only covers the top 0-3 m of soil."

3. *When comparing the spatial distribution of simulated carbon accumulation and maximum depth, why not compare the existing datasets to illustrate whether the changes make the simulations closer to the observation-based patterns? I later saw the comparison of the new spinup output with the existing database in Figure 9 in the Discussion section, which makes it difficult to judge the performance of these new model developments.*

[Response] Thank you for your comment. In our previous Results section, we showed only the spatial distribution of simulated Yedoma carbon accumulation and maximum depth, without comparing with existing observation-based spatial patterns. Our logic was that, since we used deposition rates derived from site-level measurements (1.0 mm yr^{-1}) and a specified accumulation period (19,000 years), the most direct validation was to test whether the model—driven by dynamic carbon cycle processes, observation-based deposition rates, and the specified duration—could reproduce the observed Yedoma carbon depths and total carbon stocks.

In Fig. 9, we used a gridded SOC map that combines WISE30sec (global soils, 0-2 m) (Batjes, 2016) and NCSCD (northern permafrost regions, 0-3 m) (Hugelius et al., 2013) datasets to evaluate our model's performance in simulating soil carbon within the top 3 m only. To our knowledge, this is currently the deepest available gridded SOC map. However, it remains insufficient for representing deep carbon in Yedoma and peatlands which reach depths of up to ~20 m and ~10 m, respectively. Our model improvements were explicitly designed to capture such deep carbon storage. Therefore, using a 0-3 m SOC dataset for evaluation is not sufficient enough. In the absence of gridded observational data for deeper SOC deposits we argue that the dedicated site-level deep soil core measurements which we used offer more appropriate and informative benchmarks for assessing the performance of our improved version.

In the revised manuscript, we still provide a spatial comparison using the 0-3 m SOC map at the end, along with a note on its limitations in representing deep soil carbon stocks. In response to your last comment, we have added a paragraph at the beginning of Section 3 (L317-323) to summarize and clarify our evaluation strategy. In addition, we revised the title of Section 3 as "**Results and evaluation**", and moved the evaluation against the spatial SOC map from the previous Discussion section into this Section, as Section 3.3 (L424-457). We apologize again that our previous manuscript did not clearly separate the Results and Discussion sections, which may have made our evaluation strategy difficult to follow.

4. *The authors may want to consider merging the Results and Discussion sections, as some content in the Discussion were in the Results section and vice versa.*

[Response] We agree and following our response to your major comments #2 and #3, we have merged the simulated results and their evaluation in Section 3 of the revised manuscript. Section 4 is now dedicated to the discussion, including Section 4.1, which provides a further interpretation of the differences between the old and new spin-up simulations, and Section 4.2, which discusses the implications and limitations of our development.

5. *What happens in the model (regarding plant and soil carbon pools) when converting an upland cell fraction to a peatland fraction? It could be good to describe so readers can better understand the mechanism of these new changes in dynamic peatland areas and peatland inception time.*

[Response] Thank you very much for this constructive suggestion. In the ORCHIDEE-MICT model, when an upland cell fraction is converted to a peatland cell, the new peatland fraction first inherits the plant and soil carbon pools from the displaced upland cell in order to conserve mass. After this transition, the newly formed peatland begins to grow peatland-specific PFT and accumulate soil carbon according to peatland soil characteristics. Compared to conventional PFTs (e.g., forest or grass), the peatland PFT features a shallower rooting depth and is prescribed with distinct soil hydrological properties, including specific values for hydraulic conductivity and diffusivity. Moreover, the peat soil tile does not allow drainage at the base of soils and receives lateral surface water input from other upland PFTs within the same grid cell. These water-logged soil conditions substantially suppress decomposition, promoting the accumulation of soil organic carbon.

Regarding vertical soil carbon transfer, conventional PFTs accumulate soil carbon to a maximum depth of 3 m through three main processes: (1) root-density-dependent organic carbon inputs, (2) depth-dependent decomposition regulated by vertically stratified soil temperature and moisture, and (3) carbon diffusion via bioturbation by animal and plant activity and via cryoturbation in permafrost soils. By contrast, the peatland PFT employs a more efficient scheme for vertical carbon transfer (as described in the second paragraph of Section 2.1), enabling substantial carbon accumulation down to depths of up to 10 m.

In the revised manuscript, we have added a new subsection in Section 2.2.2 (L303-315, copied as below) to describe the changes in plant and soil carbon pools that occur when a fraction of an upland cell (i.e., conventional soils) is converted into a peatland fraction.

"• **Changes in plant and soil carbon pools following conversion from conventional soils to peatlands**

In the starting MICT version from Xi et al., (2024), when conventional soils are converted to peatlands within a grid cell, the newly established peatland fraction initially inherits the plant and soil carbon pools from the displaced conventional soils to ensure mass conservation. After this transition, the peatland fraction begins to grow peatland-specific PFT and accumulate soil carbon according to peatland soil characteristics. As described in Section 2.1, compared to conventional PFTs (e.g., forest or grass), the peatland PFT features a shallower rooting depth and is assigned distinct hydrological properties. Moreover, the peat soil tile does not allow drainage at the base of the soils and also receives lateral surface water input from other non-peatland PFTs within the same grid cell. These water-logged soil conditions substantially suppress decomposition, promoting the accumulation of soil organic carbon. Peatland tiles also differ regarding vertical soil carbon transfer. Conventional PFTs can accumulate carbon down to a depth of 3 m through root-distributed inputs, depth-dependent decomposition, and vertical diffusion via bioturbation and cryoturbation (see the first paragraph of Section 2.1). In contrast, the peatland PFT employs a more efficient scheme for vertical carbon transfer (detailed in the second paragraph of Section 2.1), enabling substantial carbon accumulation down to depths of up to 10 m."

Some detailed comments:

1. *Abstract:*

   L21: "A passive soil carbon pool" could be rephrased. For Non-specialists in this field, we won't know what "passive" means here. It can be easily misunderstood as it is not biologically active or is not contributing to any fluxes. The same goes to L27..What does "less passive" really mean?

[Response] Sorry for this very technical phrasing. In the ORCHIDEE-MICT model, there are three conceptual soil carbon pools, 'active', 'slow', and 'passive' pools, defined by their turnover rates. The turnover time at 5 °C without moisture limitation for the three carbon pools is 0.84, 31, and 1,363 years, respectively. The 'passive' soil pool turns over much more slowly than the 'active' and 'slow' pools, but it is still biologically active and contributes to CO_2 fluxes. To improve clarity, we have revised "**a passive soil carbon pool**" as "**a passive soil carbon pool (a conceptual soil carbon pool with longest turnover time)**" at L22 and have revised "**less passive**" as "**a smaller passive soil carbon pool (by 35 Pg C, 43%)**" at L28. Moreover, we have added the specific turnover times of five carbon pools (three soil carbon pools and two litter carbon pools) in the Methods (L127-128), where the soil carbon model is described: "**The turnover times at 5 °C without moisture limitation for the five carbon pools is 0.37, 1.4, 0.84, 31, and 1,363 years, respectively.**"

2. *Figure 1, &L148, what are peat PFT and Yedoma PFT? What are the main differences between these two PFTs? So why only one PFT is allowed to grow on peatland or Yedoma? How PFT chose could influence carbon accumulation over this study's long temporal scales?*

[Response] Yedoma is ice-rich, organic-rich permafrost deposits formed during the late Pleistocene, primarily distributed across Arctic Siberia and Alaska (Fig. 1). Peatlands are wetland ecosystems where water-saturated conditions inhibit decomposition, resulting in the accumulation of organic-rich peat layers over thousands of years, mainly distributed in northern high latitudes (Fig. S2p). In our simulations, both the peat PFT and the Yedoma PFT are based on the existing C3 grass PFT (Table S1), with rooting depth as the only structural difference—shallower for the peat C3 grass. This framework allows for further refinement of these PFTs in future developments. The main differences between the two PFTs in current model lie in their associated soil hydrology characteristics and the schemes used for vertical transfer of soil organic carbon, as mentioned earlier and described in Section 2.1. Specifically, peatland soils incorporate specific processes to retain water and maintain water-logged conditions, which are important for peat formation. The vertical transfer of soil carbon in peat and Yedoma soils is simulated by distinct schemes, with Eq. (1) for peat carbon and Eq. (2) for Yedoma carbon, respectively.

For the number of PFTs, it's flexible and technically possible to represent multiple PFTs for peatlands and Yedoma within one grid cell in our simulation. However, the peatland / Yedoma map we used provides only the fractional coverage of peatlands and Yedoma in each grid cell, without specifying vegetation types or biomes. Given that C3 grass is the dominant vegetation type in boreal peatlands and Yedoma regions, we chose to represent each with a single C3 grass PFT in our simulations. We acknowledge that using different PFTs could affect carbon accumulation by influencing several processes, including CO_2 assimilation rates, surface characteristics (e.g., albedo and roughness), surface energy budgets, and the associated soil thermal and hydrological dynamics.

To clarify this point, we have added the explanation of each PFT in the caption of Fig. 1 (L187-193).
"... **The old spin-up uses the ORCHIDEE-MICT-teb (MICT-teb) model version, includes 16 plant functional types: 15 conventional PFTs (bare soil, 8 tree PFTs, 4 grass PFTs, and 2 crop PFTs) and one peatland PFT (C3 grass) within a grid cell (Table S1). In the old spin-up, the cover fraction of peatland is fixed throughout the simulation, and all peatlands are assumed to have formed simultaneously, 13,500 years ago. By contrast, the new spin-up merges ORCHIDEE-MICT-Yedoma (MICT-Yedoma) with MICT-teb, enabling the model to simulate Yedoma carbon accumulation during the Late Pleistocene and subsequent carbon accumulation in peatland and conventional soils during the Holocene. The new spin-up includes the same 15 conventional PFTs, one peatland PFT, and an additional Yedoma PFT (C3 grass) within a grid cell (Table S1).** ..."

3. *L276, what is the value of total SOC stock from the old spin-up then?*

[Response] There's no Yedoma PFT or Yedoma carbon accumulation in the old spin-up, so the value is zero (see Table 3).

4. *L306-307, what are the main reasons that two spinup end with different NEP values?*

[Response] The different NEP values between the two spin-up simulations likely result from two main factors:

(1) Differences in PFT composition within a grid cell: The old spin-up includes 15 conventional PFTs and one peat PFT, whereas the new spin-up includes 15 conventional PFTs, one peat PFT, and an additional Yedoma PFT. This leads to different net primary production (NPP) due to variation in vegetation distribution and productivity.

(2) Differences in soil carbon stocks: The new spin-up introduces changes in carbon accumulation, particularly in deep soils, which affects total soil respiration.

The altered balance between NPP and heterotrophic respiration ultimately leads to the difference in NEP.

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