Response to the reviewers

General comments

Surface heterogeneity has large impacts on surface energy, water and carbon cycles. This study developed and evaluated a new multi-tile surface energy budget scheme in the ORCHIDEE-MICT model. Expectedly, the improved model indeed shows better performance in some regions, especially the permafrost areas. However, some issues are needed to be resolved first: 1) the research gap is not clear apart from using a different model; 2) many details on the methods are missing, e.g., the vegetation albedo calculation, the unreasonable assumption of 1 for the emissivity, the definition and estimations of surface temperature, the snow cover fraction parameterization, etc. 3) The statistical tests on the significance of the model-model and model-observation differences are needed; 4) The authors just compared the surface temperature between model and observations, and more comprehensive comparisons are needed using the benchmark datasets for all the surface energy balance variables, also the carbon and water cycles-related variables. Please see below for my specific comments.

[Response] Thank you so much for your time in reviewing our manuscript and for providing your constructive comments and suggestions. In response to the reviewer's comments, we 1) reorganized the introduction and discussion to provide a complete description of the research gap and tiling in different land surface models; 2) provided additional details in the methods section, explaining the calculation of albedo, the value of emissivity, the definition of surface temperature, and the calculation of snow cover fraction; 3) explained the calculation and applicability of significance tests for the model-model and model observation differences in this study; and 4) added the comparison of other components of the surface energy budget including albedo and latent flux between the simulations and the MODIS products. Please find detailed point-by-point responses to each major concern and small comment below.

Major concerns

1. In the abstract, I suggest the authors provide some quantitative metrics for the performance of the improved and original models.

[Response] As the reviewer suggested, we added quantitative metrics into the revised abstract (copied as below, L23-30).

"**With the specific values of surface properties for each vegetation type, the new version presents warmer surface and soil temperatures (~0.5 °C, 3%), wetter soil moisture (~10 kg m^{-2}, 2%), and increased soil organic carbon storage (~170 PgC, 9%) across the Northern Hemisphere. … However, the separation of sub-grid energy budgets in the new version improves permafrost simulation greatly by accounting for the presence of discontinuous permafrost types (~ 3 million km^2) …**"

2. In the second paragraph of the introduction section, the authors only used the surface temperature as one example to introduce the background. However, surface temperature is just one import factor in the surface energy budgets. Actually, there are already many existing studies analyzing the impacts of surface heterogeneity on surface energy balance and water cycles, as well as land-atmosphere interaction. I suggest the author reorganize this paragraph to better introduce the existing studies and background.

[Response] Thanks for this comment. We have reorganized the logic of this paragraph and have included more existing studies analyzing the impacts of surface heterogeneity on other components of surface energy balance besides the surface temperature, copied here as below (L41-77).

"**Employing land surface models (LSMs) or earth system models (ESMs) is one of the most common approaches to simulate the surface energy budget and investigate its interactions with hydrologic, atmospheric and biogeochemical processes. The typical spatial resolution of the LSMs varies from 0.5º × 0.5º (~50 km × 50 km at equator) to 2º × 2º (~200 km × 200 km at equator). Significant surface heterogeneity would undoubtedly exist on such large scales. Taking surface temperature (T_{surf}) as an example, in reality, two adjacent landscapes could have significantly different T_{surf} due to their distinct surface properties, including surface albedo, leaf area index, rooting depth, vegetation height at scale not resolved by the models. For instance, the larger latent heat loss via evapotranspiration over deep rooted tropical forests compared to nearby grassland and cropland shows a significant cooling effect, approximately 2.5 °C on a daily basis (Li et al., 2015). The higher albedo across snow-covered areas for short vegetation compared to nearby forest results in a reduction in the absorbed solar energy and lower the T_{surf}, with a magnitude depending on the timing and duration of snow cover (Zhang, 2005). To represent the heterogeneous surface energy balance, some LSMs / ESMs have introduced tiling energy budgets such as the PFT-specific energy budgets in CLASS (Canadian Land Surface Scheme) (Melton and Arora, 2014), the separate energy budgets for snow, soil, and vegetation in ISBA (Soil–Biosphere–Atmosphere LSM) (Boone et al., 2017), the partition of snow-cover and snow-free land units in CLM 5.0 (Community Land Model) (Lawrence et al., 2019), and the sub-grid topographic effects on solar radiation flux in ELM (Energy Exascale Earth System Model (E3SM) Land Model) (Hao et al., 2021). Moreover, three land surface schemes (LSSs) have been adopted to represent the tiling energy budgets including mosaic (use specific surface properties for each land cover type), mixed (grouping certain land cover types with similar surface properties and then having a smaller number of distinct surface types), and composite (using the average properties of one grid cell) (Melton and Arora, 2014; Rumbold et al., 2023). Through the comparison between the "mosaic" and the "composite" LSSs, the CLASS model reported a less than 5% difference in the primary energy fluxes but an up to 46% difference in carbon fluxes and carbon pool size at site level (Li and Arora, 2012), as well as a 19% higher terrestrial carbon sink for**

1959-2005 in the "mosaic" simulation (Melton and Arora, 2014). Rumbold et al. (2023) also found that the tiling soil scheme does have an impact on the water and energy budgets due to the way vegetation accesses soil moisture with the JULES model (Joint UK Land Environment Simulator). Besides, Qin et al. (2023) found that the tiling CLM model provides more accurate simulations of surface air temperature and precipitation than the single-land-cover version when coupled with the WRF model (Weather Research and Forecasting), as validated against in-situ observations. Despite uncertainties in model-specific structures and configurations, these findings highlight the importance of representing explicitly sub-grid surface heterogeneity in current LSMs.

Besides the necessity of representing surface heterogeneity, the incorporation of new landforms and processes also requires the tiling of energy budgets. For instance, Rooney and Jones (2010) identified the challenges in simulating soil temperature under lakes when introducing the lakes into the single-soil-tile JULES, since they have different thermal transfer characteristics due to the higher specific heat capacity of water than adjacent land tiles. When evaluating the impacts of subgrid-scale disturbances such as fires and harvest, Curasi et al. (2023) found the impact of sub-grid heterogeneity is 1.5 to 4 times the impact of disturbances themselves on the carbon cycle with the CLASSIC model (Canadian Land Surface Scheme Including Biogeochemical Cycles). Besides, it's necessary to provide the independent energy budgets, hydrology and carbon cycles when incorporating a series of new processes for permafrost regions such as discontinuous permafrost type (Smith et al., 2022), melting of ground ice (Rumbold et al., 2023), thermokarst thawing and lateral drainage (Nitzbon et al., 2020) in LSMs."

3. Considering that the multi-tiling scheme has been used in other land surface models, please clarify the research gaps apart from the specific model used in the study.

[Response] Following our last response to the reviewer's comment 2, we added more text about the background why we need to represent the tiling energy budgets. To connect with ORCHIDEE-MICT, we have added one sentence in the revised introduction "**To enable the representation of surface heterogeneity and open the door to a series of new landforms and processes,** we implement tiling energy budgets at the surface and subsurface for each plant function type (PFT) in a state-of-the-art LSM, ORCHIDEE-MICT …" (L79-83). We have also added the section 6.3 in the discussion, covering the reason why we performed the improved tiling development in ORCHIDEE-MICT, the extra computation cost of the new version, and the reminder on when and where to tile for the potential users of our version (copied as below, L639-649).

"**6.3 Remarks on the tiling land surface scheme**

The tiling work in this study was initiated because of the planned introduction of new arctic landforms for permafrost regions into ORCHIDEE-MICT that requires independent energy

budgets, carbon and water cycles. The decision to tile by PFT, rather than other units, was determined based on the current model structure. In the new version, additional variables with a new PFT dimension were introduced only for the energy module, rather than all modules, resulting in a 15-20% slower run time compared to the initial version. Recently, several other model groups have also been working on the tiling and the evaluation of its impacts on existing and new processes, such as JULES (Rumbold et al., 2023) and CLASS (Melton et al., 2017). The implementation of tiling in different land surface models can be compared to inspire other groups planning to represent sub-grid heterogeneity of energy budgets in their models. Moreover, for potential users of our new version, it is worth reminding them to carefully consider when and where to apply tiling in their studies to optimize research objectives and computational costs."

4. In section 2, Figure 1: It is unclear how many soil/snow columns are included for each grid cell for the improved and original versions. Whether do different PFTs have different snow cover and soil characteristics or not? These (especially the snow cover) may have big impacts on surface energy balance. Besides, the authors used the standard rectangle grids to represent different PFTs, which may mislead the authors, because the same PFTs may distribute in different sub-grids.

[Response] In the improved and original version, every PFT has its own snow and soil layers, but the original version used the grid-cell mean energy budgets for all PFTs, and thus the same snow cover fraction for each PFT. As pointed out by the reviewer, the snow cover, as well as many other energy variables are different among different PFTs, especially grasses, shrubs and trees, which is one main reason why we started the tiling work for energy. Now in the improved version, the energy budgets of surface, snow and soil are PFT-specific. Regarding Fig. 1, the big rectangle indicates a grid cell in the model, with each sub-rectangle for one PFT. There are 16 PFTs at maximum (set in our simulation and can be changed in other simulations) existing in one grid cell and one PFT can only be distributed in its sub-rectangle in ORCHIDEE-MICT. Together with the comment from the other reviewer, we made some modifications to this figure (copied here as Figure R1), and we also added some key words in the figure caption to avoid misleading interpretation.

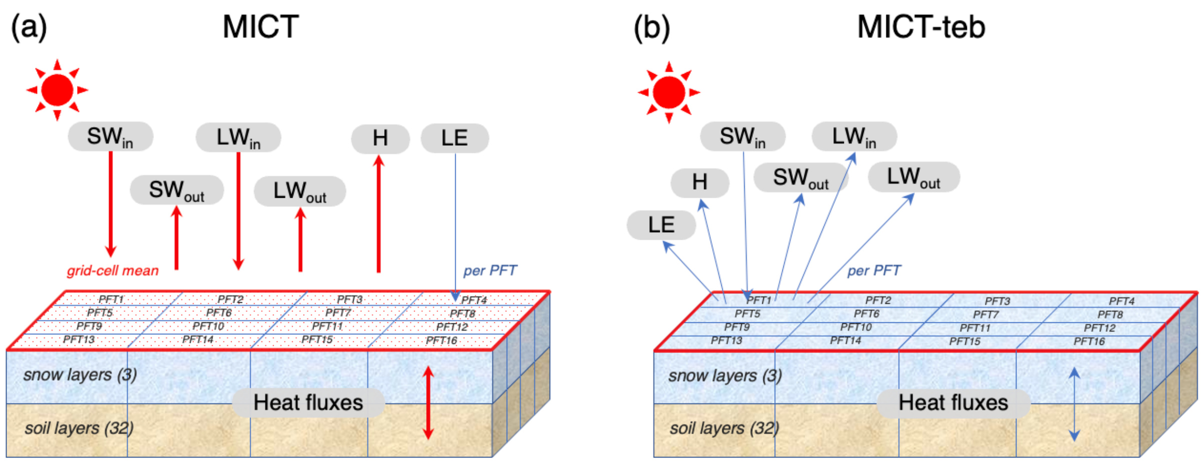

Figure R1 (Figure 1). Schematic representation of energy budgets at the surface, snow layers, and soil layers **in one grid cell** of ORCHIDEE-MICT (MICT) (a) and the new tiling energy budget version (MICT-teb) (b). SW_{in}, SW_{out}, LW_{in}, LW_{out}, H, and, LE represent incoming ShortWave radiation, outward ShortWave radiation, incoming LongWave radiation, outward LongWave radiation, sensible heat flux, latent heat flux, respectively. PFT indicates Plant Function Type. There are 3 layers for snow, and 32 layers for soil **for each PFT** in the model. In MICT, SW_{in}, SW_{out}, LW_{in}, LW_{out}, H, and heat fluxes in snow and soil layers are calculated as grid-cell mean but LE is calculated for each PFT, while in MICT-teb, all of the heat fluxes are calculated for each PFT. **The red and blue arrows distinguish the grid-cell mean and PFT-specific calculation.**

5. In equation 2, the emissivity is assumed to 1, which is not reasonable. For vegetation, the emissivity depends on LAI. Different land types also show very different emissivity.

[Response] The value of 1 for the emissivity is used as default by ORCHIDEE. It is defined as a coefficient describing the capacity of a body to emit radiation. According to the classical geography textbook *Principles of Terrestrial Ecosystem Ecology (2nd Edition)* by F. Stuart Chapin, III, the emissivity is about 0.98 in vegetated ecosystems (page 96). And according to the textbook *Climate Change and Terrestrial Ecosystem Modeling* by Gordon Bonan, most objects have a broadband emissivity of 0.95–0.98 when integrated over all wavelengths (page 42). Thus, using the value of 1 for the emissivity could be rough, but not too unreasonable.

6. In equation 2, I am also confused about how did the authors define the surface temperature here, because the surface temperature can change within the vegetation canopy and understory background. Please clarify how the model calculated surface temperature here as well as the relationship between surface temperature, canopy temperature and ground temperature.

[Response] Since ORCHIDEE-MICT is not capable of calculating the leaf energy budgets, there's only one surface temperature (i.e., without height dimension) in the model. This surface temperature is used to calculate all surface energy fluxes. We added one sentence to avoid confusion in the revised version:

"**Since MICT is not capable of calculating leaves energy budgets separately from soils and stems, there's no vertical-layered temperature from the ground surface to the top of the canopy, and thus the T_{surf} here is used to calculate all surface energy fluxes.**" (L138-140).

7. Line 117: How did the authors retrieve the soil albedo for the vegetated regions from remote sensing data?

[Response] The bare soil albedo used in the model is not directly retrieved from remote sensing data. The solar radiation absorbed by the vegetation layer and the background is separated using the Joint Research Centre Two-stream Inversion Package (JRC-TIP). ORCHIDEE uses the background albedo as bare soil albedo. More details about the package, JRC-TIP can be found in Pinty et al., (2011). We have added the reference in the revised manuscript.

8. Section 2.3: How did the authors set the empirical values for different snow-related parameters?

[Response] These empirical values come from the PhD thesis of Sophie Najm Chalita (1992) and the corresponding journal article (Chalita et al., 1994), where the parameterization of the snow albedo has been evaluated with site measurements from Robinson and Kukla, (1984). We added the reference in the revised version.

9. Section 2.1: It is unclear how the model calculates the surface albedo.

[Response] In ORCHIDEE-MICT, the grid-cell surface albedo is calculated as the area-weighted average of the albedo across all PFTs in this grid cell. When snow is free, the area-weighted average calculation only considers the albedo of bare soil (prescribed with remote sensing data) and vegetated regions (prescribed with constant values, Table S1). When snow is covered, the albedos of snow-covered bare soil and the vegetated area use the prescribed values as listed in Table S3. We have revised the description of the calculation of surface albedo following the last two comments of the reviewer.

10. what is the reference of this equation? Are the impacts of topography on snow cover fraction considered in this equation?

[Response] The references for this equation (Niu and Yang, 2007 and Wang et al., 2015) have been added to the revised manuscript. The impacts of topography on snow cover fraction have not been considered in this equation yet.

11. Section 3.3: There are already high resolution (e.g., 250m) SOC datasets at the global scale, e.g., soilgridv2.

[Response] Thanks for this comment. The soilgrid v2 does have a high resolution, but it only provides the SOC for 0-2 m. We cannot use it because the maximum depth of the soil layer is as deep as 38 m in the model and the maximum depth for SOC in most permafrost regions, especially for peatlands, can be as deep as 10 m.

12. Section 4: I am curious about why did the authors run the simulations cycling the forcing from 1901-1920 rather than the present-day simulations? The present-day simulations can be more suitable for the comparisons with the available remote sensing data.

[Response] We ran both simulations with the forcing cycling 1901-1920 and with the present-day forcing in the model in fact, but the present-day simulation was not mentioned in the original Section 4, but was put in Section 6 when we were comparing the improved version with the remote sensing data. As described in Section 4, the simulations during periods A and B were run to accumulate a SOC stock under the same conditions as observed in reality while the simulation during period C was run to achieve near-equilibrium carbon and water cycles. The three periods are indispensable before running a present-day simulation. If we only aim to compare the muti-tiling energy budgets from the improved version and the single-tiling energy budgets from the original version, it is enough to run the simulations by period C. But if we want to compare the improved version with remote sensing data, we need to extend the simulation to the present day. To make the description clearer, we have rearranged the text (copied as below, L281-286) and Table 1, to add period D (Transient simulation) in Section 4.

"All of the three groups are run for the NH (0°-90°N) at a spatial resolution of 2° × 2°, with **four** simulation periods: A) Spin-up1, 100 years of the full ORCHIDEE with a looped 1901-1920 climate, CO_2 level of 1901 at 296.80 ppm, and the land cover map of 1901; B) SubC, 10,000 years of the soil carbon sub-model (offline) to accumulate SOC; C) Spin-up2, 50 years of the full ORCHIDEE to reach equilibrium with a looped 1901-1920 climate, CO_2 level of 1901, and the land cover map of 1901; **and D) Transient simulation, the full ORCHIDEE with varying climate, CO_2 level and land cover maps from 1901 to 2020.**"

13. Figure 4-5 and 7-8: Please show whether the differences are significant or not for each grid cell. Table 2: Please also clearly define the magnitude of one arrow and two arrows. The statistical tests on the case differences are also needed in section 5.2 for all variables.

[Response] Thanks for the comment. In Figures 4-5 and 7-8, the differences between MICT-teb and MICT were calculated using the 10-year mean results from period C. That is, there's only one value for each model. Thus, the significance testing is not applicable for these figures. For Table 2, it is a qualitative summary of the change in surface temperature and the changes in surface properties. We provided this summary, hoping it helps readers understand the modifications done in the new version i.e., the changes in surface properties and the consequences after modifications i.e., the change in surface temperature. The significance testing is not applicable, either, but the quantitative difference in the variables in Table 2 can be found in Figs. 4-5 for grid scale and in Figs. 9-11 for the whole NH.

14. Section 6.1: When comparing with MODIS data, did the authors extract the model values in the MODIS overpass time? Besides, also show whether the differences between model estimates and MODIS are significant or not. Did the improved version show better performance than the original version?

[Response] We only compared the average from 2001 to 2020 between the model and MODIS data, so significance testing is not applicable. Including the representation of PFT-specific energy budgets alleviates the LST bias from MICT in some areas such as western North America and northern Europe and in some seasons such as autumn in high latitudes, but at the same time, it aggravates the LST bias in some areas and some seasons such as all seasons in tropical regions (Fig. 13(f)).

15. The authors just compare the surface temperature. I suggest the authors compare all the surface energy balance components with the available remote sensing data or reanalysis data, e.g., surface albedo, net radiation, etc. Comparing all of them can give more hints on the model improvement and potential drawbacks.

[Response] Thanks for the constructive comment. Since the comparison of surface temperature has mirrored the comparisons of outward longwave radiation (LWout) and sensible flux (H), we further compared the albedo (mirroring net shortwave radiation) and the latent heat flux (LE) between the model and MODIS data, including the spatial patterns and the seasonality, to give a complete evaluation of the simulated surface energy balance as the reviewer suggested. The revised text and figures were copied as below (L500-552):

"To evaluate the simulated surface energy budgets, we compare T_{surf} (surface temperature, mirroring outward longwave radiation and sensible heat flux), albedo (mirroring outward shortwave radiation), and LE (latent flux) from period D (the transient simulation, 1901-2020) with satellite-derived land surface temperature (LST), albedo, and LE from MODIS (the Moderate Resolution Imaging Spectroradiometer), respectively. The MODIS LST product is obtained from MOD11C3 Version 6.1 (https://lpdaac.usgs.gov/products/mod11c3v061/), which records the monthly radiative skin temperature of the land surface at 0.05° × 0.05° spatial resolution, spanning from 2000 to the present (Wan, 2013, 2014). Compared to the MODIS product, MICT and MICT-teb reproduce the spatial pattern of mean annual satellite-derived LST for 2001-2020 (Figs. 13(a)-(c)), but with an overestimation of up to 3 °C in wet regions such as tropical regions, Europe, and eastern North America, and an underestimation of up to 3 °C in dry areas and northeastern Asia (Figs. 13(d) and (e)). Regarding the seasonality of T_{surf}, the two model versions show an overestimation of summer and autumn LST (by up to 3 °C) but an underestimation of winter LST (by up to 3 °C) in mid-high latitudes, while an up to 3 °C overestimation throughout the year for tropics (Figs. 13(g) and (h)). Including the representation of PFT-specific energy budgets alleviates the LST bias from MICT in some areas such as western North America and northern Europe and in some seasons such as autumn in high latitudes, but

at the same time, it aggravates the LST bias in some areas and some seasons such as all four seasons in tropical regions (Fig. 13(f)).

The MODIS albedo product is obtained from MCD43C3 Version 6.1 (https://lpdaac.usgs.gov/products/mcd43c3v061/), including the daily black-sky and white-sky albedo at 0.05° × 0.05° spatial resolution. To compare with albedo from the model, we calculate the blue-sky albedo using the black-sky and white-sky albedo for the shortwave band (0.3-5.0 µm) from MODIS, weighted by the diffuse skylight ratio derived from the direct and total shortwave radiation from the fifth generation ECMWF reanalysis product (ERA5, https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=form) (Hersbach et al., 2023). We found that except a ~0.2 overestimation of winter and spring albedo in northern high latitudes, the simulated albedo from MICT and MICT-teb show a very small bias, no more than 0.04 (Fig. 14). The considerable albedo biases in winter and spring could be related to the bias of simulated leaf area index and snow cover fraction by the model (Li et al., 2016). The MODIS LE product is obtained from MOD16A2GF Version 6.1 (https://lpdaac.usgs.gov/products/mod16a2gfv061/), providing the 8-day LE at 500 m × 500 m spatial resolution. Compared to the MODIS LE, the simulated LE tends to be smaller (-6 - -24 J m^{-2} s^{-1}) in most areas except for some arid regions over the NH (Fig. 15). Same as the evaluation for T_{surf}, the representation of PFT-specific energy budgets doesn't reduce the albedo / LE biases significantly (Figs. 14(g) and (h), 15(g) and (h)).

There are several reasons that could explain the disagreements of surface energy budgets between the MODIS products and the models. On the one hand, 1) the under-representation of some important processes in the model such as the parameterization of ET (LE) and snow insulation, as well as the uncertainties of climate forcing data (Guimberteau et al., 2018; Peng et al., 2016; Domine et al., 2016) and 2) missing data across dry areas and cloudy-weather days in the MODIS products, e.g., a ± 2 °C LST bias compared to ground-truth data found in dry areas (Li et al., 2014; Wan, 2014; Westermann et al., 2012) could partly account for disagreements between the MODIS products and the models. On the other hand, the considerably different land cover maps used by MODIS and the simulations (Fig. S18) and the difference in one specific variable from MODIS and the simulations could contribute to the systematic biases / gaps. For instance, the LST from MODIS reflects more the radiative skin temperature, i.e., canopy temperature, while the canopy energy budget is absent in ORCHIDEE-MICT, which could result in a higher T_{surf} from the models compared to the MODIS LST in forest ecosystems (Fig. 13) (Gomis-Cebolla et al., 2018)."

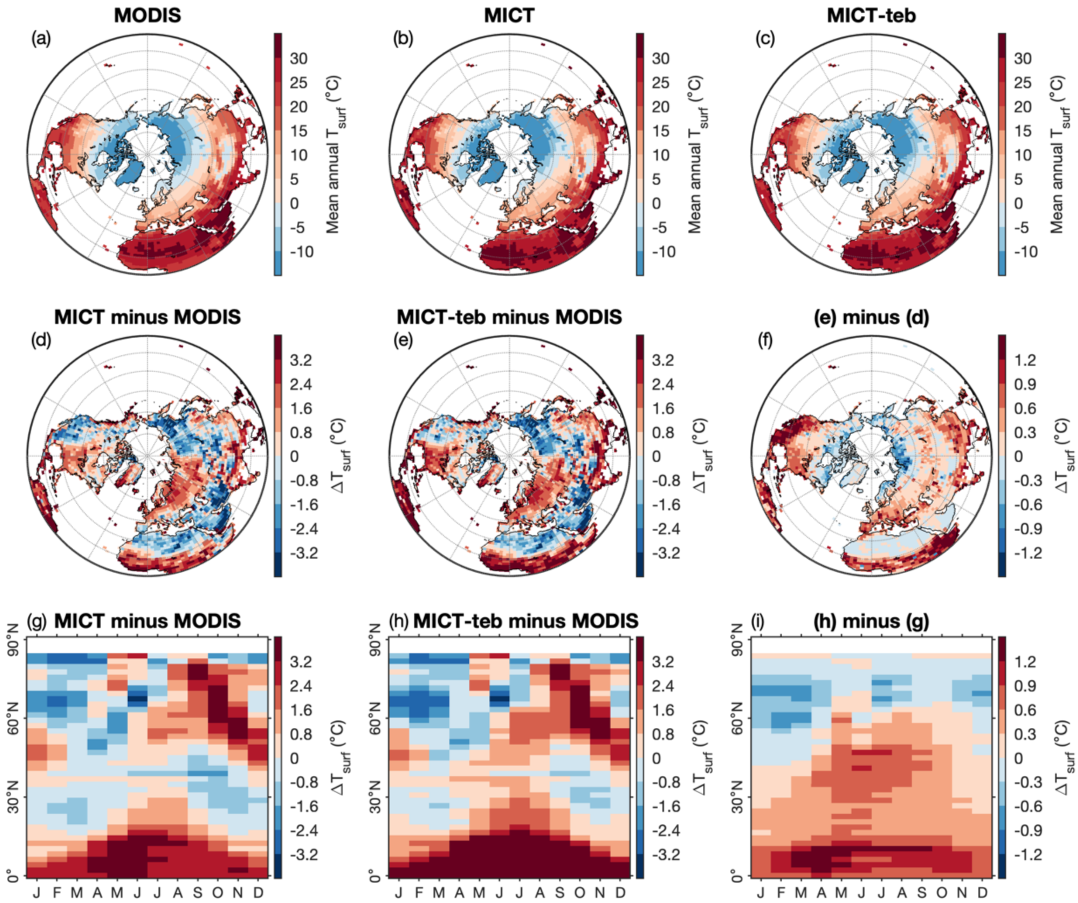

Figure R2 (Figure 13). Evaluation of simulated surface temperature (T_{surf}) with land surface temperature (LST) from MODIS. (a)-(c), Spatial pattern of mean annual LST for 2001-2020 from MODIS, MICT, and MICT-teb. (d) and (e), Spatial pattern of the difference in mean annual T_{surf} for 2001-2020 between MICT (d) or MICT-teb (e) and MODIS. (f), Spatial pattern of the difference in (e) and (d). (g) and (h), Seasonal cycle of the difference in T_{surf} calculated over each latitude band between MICT (g) or MICT-teb (h) and MODIS. (i), Seasonal cycle of the difference in (g) and (h).

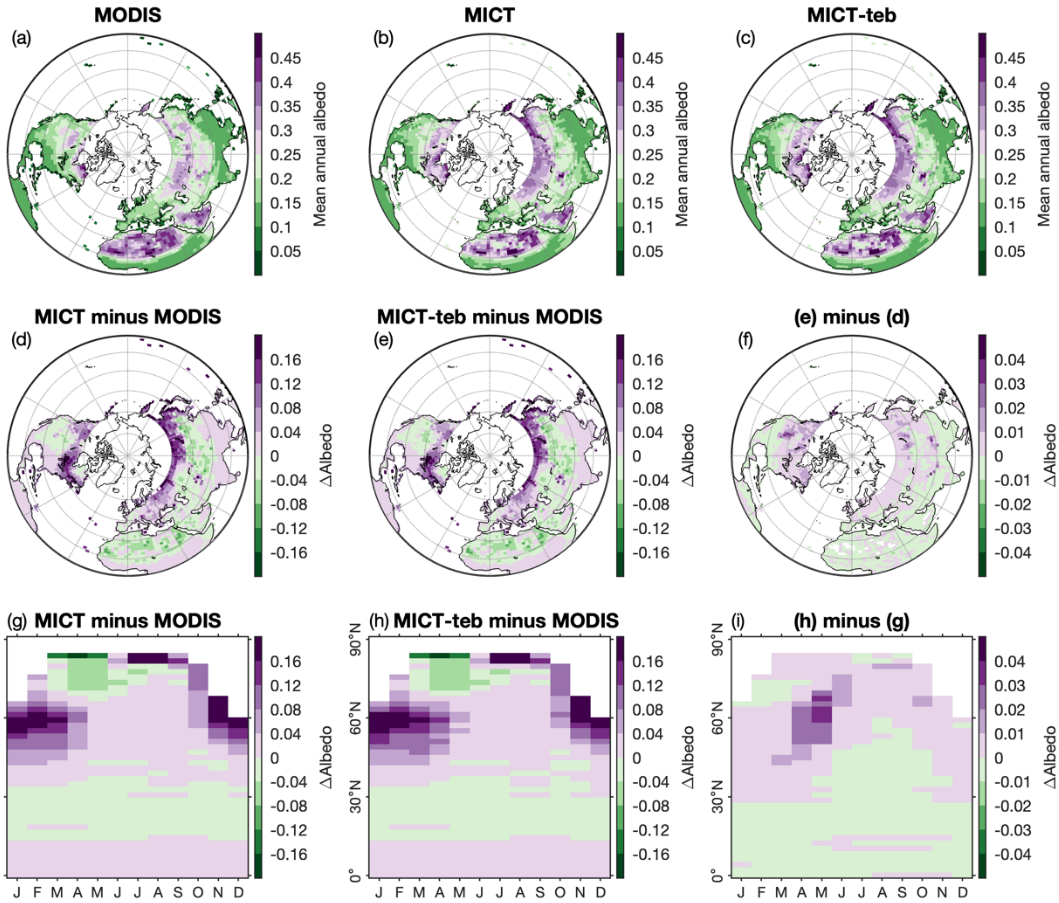

Figure R3 (Figure 14). Same as Figure 13, but for the evaluation of simulated albedo with blue sky albedo from MODIS.

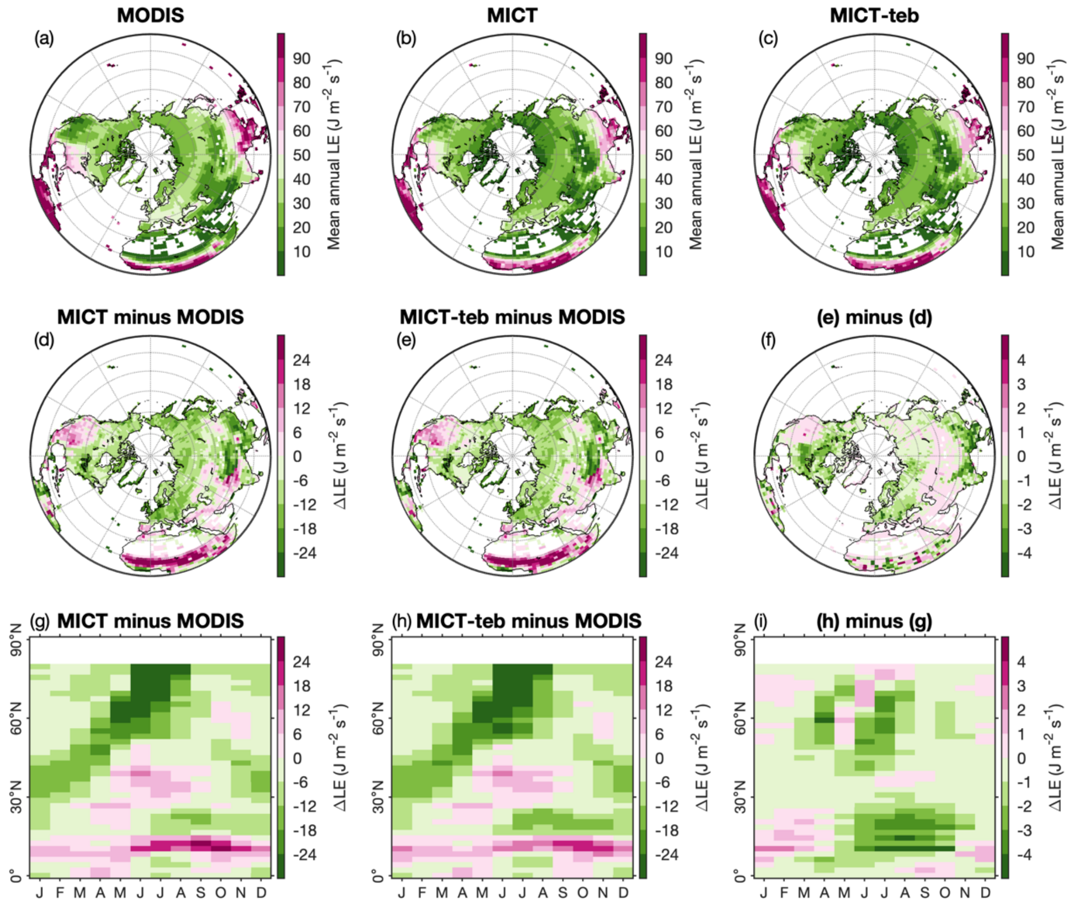

Figure R4 (Figure 15). Same as Figure 14, but for the evaluation of simulated latent flux (LE) with that from MODIS.

To sum up, the two model versions can reproduce the spatial patterns of the three components of surface energy budgets from MODIS basically, but with biases in some areas and some seasons due to the under-representation of some processes in the model and / or the uncertainties in satellite observation. Including the PFT-specific energy budgets can alleviate the bias in some areas and some seasons, but at the same time aggregates the biases in other areas and seasons, which suggests the uncertainties from the model cannot be solved by the representation of PFT-specific energy budgets but relies on the incorporation / refinement of some key processes.

Minor concerns

1. Line 53: In some ESMs, e.g., E3SM, the topography-based tiling scheme has also been used.

[Response] Thanks. We have added it in the revised version (L54-55), as an example how ESMs consider the topography into the tiling scheme.

2. Line 100: Modify the captions of Figure 1.

[Response] It has been corrected.

3. Line 264: what is the meaning of "offline" here?

[Response] It means that the soil carbon module is run independently, not coupled with the hydrology and energy. We have removed it to avoid the confusion with the "offline" used for land surface models.

4. Line 290: why did the author select the three grids?

[Response] They were selected randomly, only to show the results for the three latitudes. We have added "**randomly**" in this sentence.

5. Line 306: Looks like such calculation is not accurate because of neglecting the light interaction between canopy and soil.

[Response] As mentioned earlier, the canopy energy budgets are absent in current ORCHIDEE-MICT. It is under developing for the ORCHIDEE model (Alléon et al., 2023) and has not been included in ORCHIDEE-MICT. This could contribute to the disagreements between the simulations and the satellite datasets in Section 6.1.

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