Response to Referee #1(Benjamin Stocker)'s comments

We would like to thank Benjamin Stocker and the anonymous referee very much for their constructive comments. In the following, please find our point by point response to the comments.

- Reviewer's comments are in bold
- Modifications done in the revised manuscript are in blue
- All figure numbers, table numbers, and line numbers refer to the initial manuscript version.

Stocker (Referee)

This paper presents and evaluates a global model that simulates the spatial extent of peatlands and their C balance as a function of the environment. The peatland model is implemented as a module within the comprehensive land surface model ORCHIDEE. This is an important addition to this model as it allows to account for the effect of peatlands on the global carbon cycle, which is particularly important for long-term simulations, covering multiple centuries to the millennial time scale. The approach for simulating the spatial dynamics of peatlands across the globe is largely adopted from Stocker et al. (2014) GMD [thereafter referred to as ST14]. I don't want to hide the fact that this is my own work and that I am pleased to see that it has stimulated other researchers to follow the same approach.

The paper by Qiu et al. goes a step beyond ST14 in that it evaluates the model not only by its accurateness in simulating the spatial patterns across the globe and the total northern peatland C storage, but it evaluates peat depth using information from a set of 102 peat cores, distributed across the northern hemisphere (mostly in the boreal zone), and deals with the challenge of accurately simulating the history of peat C accumulation throughout the Holocene, which adds substantial complexity. This work is also a substantial advancement in simulating wetlands and the distribution of flooding. Their comparison to a new observation-based dataset by Tootchi et al. (2018) shows a very good agreement (Fig. S7 - worth including this in the main text?), and seems to suggest that their model works much better in this respect than, e.g., the model presented in ST14. This in itself is a very useful innovation. I was also intrigued by the clever approach to simulate vertical growth of peat as an effective downward transport of soil C (down along the soil profile, across the 32 layers resolved by the model). This is a very useful innovation beyond the models resolved by ST14 and Kleinen et al., 2012. I think this work can be a very valuable addition to the literature and that the model presented here will be a useful addition to the very small set of

comparable models available today (only two models, as I am aware). However, before getting there, I would like to see a few critical (MAJOR) issues addressed. I also think that the paper could gain from a clearer presentation in general. Below, I'm listing specific points. I hope the authors find my suggestions useful and I am looking forward to a revised version of the manuscript, and possibly a revision of the model and evaluation.

We thank the reviewer for his thorough reading of this manuscript and encouraging comments. We include Fig. S7 in the main text of the revised manuscript. Please see below our detailed response to comments.

MAJOR

Q1. * The code is not accessible under the given URL. Although it's not officially required by GMD, I personally try to resist to accept model description papers without having open access code. I also think that the model should be easily reproducible in a simplified setup (without having to run the entire ORCHIDEE) and instructions should be available to do so. Plug and play! Please make an effort to achieve this, it is greatly appreciated by the community and helps science to move forward (and it pays off for you).

The source code is freely available and accessible via the following address: https://forge.ipsl.jussieu.fr/orchidee/wiki/GroupActivities/CodeAvalaibilityPublication/ORCHIDEE_PEAT_V2

Moreover, we agree with the reviewer that a simplified version of the model using some kind of emulator will be helpful for interested readers. However, the ORCHIDEE-PEAT model simulates both carbon and area dynamics of peatland, which consists of the following hydrological and biogeochemical processes and their interactions (non-exhaustive): 1. Physically-based soil water flows and soil moisture constrain area development of peatland. Meanwhile, peatland receives water input from surrounding mineral soils, increases soil water storage and reduces runoff of the grid cell, thus exerts a feedback effect on soil water dynamics; 2. Soil moisture limits phenology, photosynthesis, transpiration and soil thermics, which in turn impact the water cycle; 3. Soil hydrology and soil thermics impact litter and soil carbon decomposition, while the long-term C balance of the peatland limits peatland area development. All those mechanisms feedbacks on each other and the design of an emulator will be a research project as itself.

Q2. * What the paper/model does not tackle/resolve, goes unmentioned. No tropical peatlands are simulated (?) nor evaluated. Are methane emissions from peatlands not resolved by the model? How does peat vs.

mineral soil affect the extent of frozen soils (permafrost!)? The evaluation of inundation, particularly its timing is missing (or hidden in the SI).

We didn't simulate tropical peatlands in this study, because the model is parameterized and calibrated for northern peatlands. To clarify this point, we add sentences on Line657: "Being parameterized and calibrated for northern peatlands, our model can't be used for tropical peatlands. For tropical peatlands, the model needs to be improved to represent its tree dominance, oxidation of deeper peat due to pneumatophore (breather roots) of tropical trees, and the greater water table fluctuations as a result of the higher hydraulic conductivity of wood peats and tropical climates (Lawson et al., 2014). In addition, tropical peat is formed as riparian seasonally flooded wetlands with water coming from upstream river networks, whereas the TOPMODEL equations used here implicitly assume a peatland is formed in a grid cell only from rainfall water falling into that grid-cell.".

The methane module was not activated in this study because it has not been updated and evaluated since many years. We informed readers that methane emissions are not resolved by the model on Line484-485: "CH_4 and dissolved organic carbon (DOC) are not yet included in the model, both of them are significant losses of C from peatland (Roulet et al., 2007).". And then on Line660-661, we recalled the necessity of including methane and DOC emissions from peatland to draw a more complete picture of peatland C budget: "Including CH_4 emissions and leaching of DOC will be helpful to get a more complete picture of peatland C budget.". Actually, in parallel with this study, two projects are ongoing in our group to model CH_4 and DOC fluxes from northern regions with ORCHIDEE.

The model resolves one energy budget for all soil tiles in one gridcell, with soil thermal properties of the gridcell being defined as a weighted average of mineral and organic soil (organic soil fraction is prescribed from NCSCD in permafrost regions and from HWSD in non-permafrost regions) (Guimberteau et al., 2018, GMD). In the model, dynamics of peat vs. mineral soil will only affect soil temperature (and permafrost) indirectly: changes of peat vs. mineral soil in the grid cell impacts gridcell soil water content, then gridcell soil water content and water filled fraction of pores impact fusion and solidification heat fluxes in the soil; changes in soil moisture and its liquid/ice state also impact soil thermal conductivity.

Calibrated by the CW-WTD wetland map (Sect. 2.2.1), we compared simulated maximum inundation area of the Northern Hemisphere with CW-WTD in Sect. 4.2 (Fig. S7), on Line404-411. Now, Following the reviewer's suggestion, we move Fig. S7 to the main text. CW-WTD can't be used to evaluate timing of inundation because CW-WTD is a static wetland map. Therefore, in the following figure, we use GIEMS to evaluate inundation timing (Prigent et al., 2007 and 2012, JGR). Note that because wetland extent in GIEMS (the maximum wetland area for the northern hemisphere over 1993-

2007 being ~7 million km^2 , with lakes are included) are much smaller than in CW-WTD (~13.2 million km^2 after excluding lakes) (Tootchi et al., 2019, ESSD), we normalize the data by dividing the simulated and observed total inundated area of each month by the simulated and observed maximum monthly value, respectively, to highlight seasonality of inundation rather than comparing absolute values. Accordingly, the following discussion is added on Line411: "…The model generally captures the spatial pattern of wetland areas represented by CW-WTD (Fig. 5). The multi-sensor satellite-based GIEMS dataset (Prigent et al., 2007, 2012) which provides observed monthly inundation extent over the period of 1993 – 2007 is used to evaluate simulated seasonality of inundation. Fig. 6 shows that the seasonality of inundation is generally well captured by the model, although simulated seasonal maximum of inundation extent occurs earlier than observations (except in WSL) and simulated duration of inundation is longer than observations.".

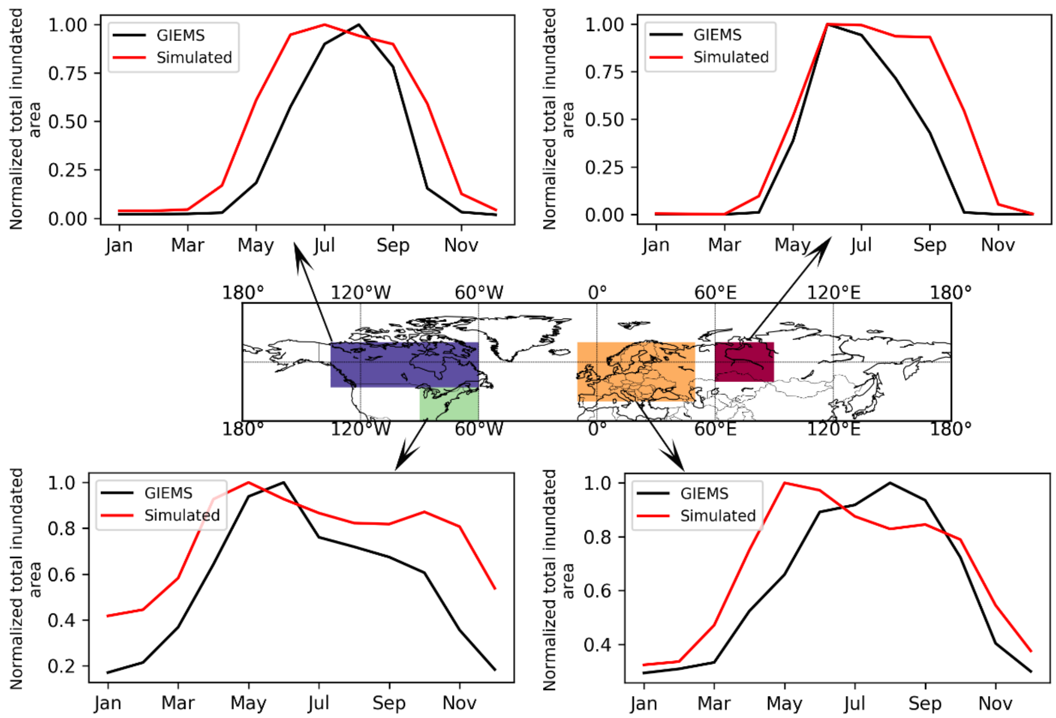


Fig. 6. Simulated and observed (GIEMS, (Prigent et al., 2007, 2012)) mean seasonality (averaged over 1993–2007) of total inundated area. Note that the simulated and observed total inundated area of each month is divided by the simulated and observed maximum monthly value, respectively, to highlight seasonality of inundation rather than comparing absolute values of inundated area.

Q3. * The simulated distribution of the peatland area fraction (Fig. 4) shows that the model is able to broadly capture the observed pattern,

except that is quite strongly underestimates the peatland extent in the Hudson Bay Lowland (HBL). This reminds me of my own work, where the first version of my model (DYPTOP, ST14) also failed to simulate very high peatland area fractions (over 90%) across this large region. The HBL is, next to the West Siberian Lowland, the largest peatland region and therefore warrants special attention. The failure of the model by Qiu et al. in simulating large peatland fractions may be related to what one may call the "sponge-feedback" – the high efficiency of organic soils in retaining water (small runoff) which in turn increases persistency of flooding and the suitability for peat to accumulate - a positive feedback. I solved this by having (gridcell average) soil parameters that determine the soil hydrology depending on the internally simulated peatland area fraction, rather than using externally prescribed parameters from soil maps. I see that in the present model, some soil parameters are indeed prescribed for each gridcell separately from external data (soil bulk density, soil C fraction; l. 499). I would say that they should be affected by whether the model simulates peatland in the respective gridcell or not. This might be something worth looking into in order to better reproduce the observed Hudson Bay Lowland peatland area fractions. On l.131, it's mentioned that soil thermal (and hydrological?) properties are a weighted average of mineral and organic soils, where organic soil fraction is prescribed from an external dataset (NCSCD and HWSD).

Actually, the "sponge-feedback" was considered in the present model. In the model, each grid cell is divided into four independent sub-grid hydrological soil unit (HSU): one for bare soil, one for all tree PFTs, one for all short vegetations and one for peatland. The peatland HSU is parameterized with peat-specific hydrological parameters (large porosity, large saturated hydraulic conductivity), while hydrological parameters of other non-peatland HSUs are determined by the dominant soil texture (Coarse/Medium/Fine) of the grid cell. This is described on L114-120: "ORCHIDEE-PEAT version 1 was evaluated and calibrated against eddy-covariance measurements of CO_2 and energy fluxes, water table depth, as well as soil temperature from 30 northern peatland sites (Qiu et al., 2018). Parameterizations of peatland vegetation and water dynamics are unchanged from ORCHIDEE-PEAT version 1: …… Vertical water fluxes in peatland tile is modelled with peat-specific hydraulics (Text S1 in the Supplement)."

As for the underestimation of peatland extent in the Hudson Bay Lowland (HBL), Glaser et al. (2004a and 2004b, Journal of Ecology) and Packalen et al. (2014, nature communication) proved that climate alone couldn't explain the initiation and development of peatlands in the HBL, the glacial isostatic adjustment is a more fundamental control of HBL peatlands development. We add sentences on Line434 to address this issue: "……, though the ~~hotspot~~ world's second largest peatland complex at the Hudson Bay lowlands (HBL) is underestimated and a small part of the northwest Canada peatlands is missing. Packalen et al. (2014) stressed that initiation and development of HBL peatlands are driven by both climate and glacial isostatic adjustment (GIA), with initiation and expansion of HBL peatlands tightly coupled with land emergence from the Tyrrell Sea, following the deglaciation of the Laurentide ice sheet and under suitable climatic conditions. The pattern of peatlands at southern HBL was believed to be driven by the differential rates of GIA rather than climate (Glaser et al., 2004a, 2004b). More specifically, Glaser et al. (2004a, 2004b) suggested that the faster isostatic uplift rates on the lower reaches of the drainage basin reduce regional slope, impede drainage and shift river channels. Our model, however, can't simulate the tectonic and hydrogeologic controls on peatland development. In addition, the development of permafrost at depth as peat grows in thickness over time acts to expand peat volume and uplift peat when liquid water filled pores at the bottom of the peat become ice filled pores (Seppälä, 2006). This process is not accounted for in the model and may explain why the HBL does not show up as a large flooded area today whereas peat developed in this region during the early development stages of the HBL complex." .

Unlike the configuration of the model for hydrology, which calculates water budget for each HSU independently. The model can only calculate one energy budget for all HSUs in one grid cell, soil thermal properties are indeed a weighted average of mineral and organic soils (with organic soil fraction being prescribed from NCSCD and HWSD) (Guimberteau et al., 2018, GMD).

Q4. * The explicit depth-dependence of the turnover rates is a bit obscure to me. While the rationale is defensible (l. 160 "priming effects, sorption of organic molecules to mineral surfaces"), it's not clear how important this factor is for the simulations here. Couldn't it be avoided? What's the e-folding scale in Eq. 2? (I see that the z_0 parameter is given later in the manuscript) And shouldn't this be accounted for by oxygen conditions, being subject to water content in different layers where the bottom layers will tend to be water-logged and thus have a very low turnover rate. From text S3, this is not evident.

We understand that in reality, bottom layer of peatland tends to be water-logged and water content of upper soil layers change with time due to the fluctuating water table. While the model resolves water diffusion between soil layers according to the Fokker–Planck equation, shapes of simulated soil moisture profiles depend on soil texture (hydrological parameters), amount and frequency of water input (snowfall, rainfall, runoff from non-peat soils) and water output (evaporation, transpiration, sublimation), water diffusion rates, etc. The figure below shows daily water inputs to a Sweden peatland (68.0°N, 19.0°E) in year1884 and the simulated daily volumetric water content profile for the peat HSU. Simulated soil water content at bottom soil layers are smaller than that at upper layers from Julian days90 to Julian days140, and bottom layers never reach saturation. So, the water content alone can't represent anoxic conditions of peat soil profile.

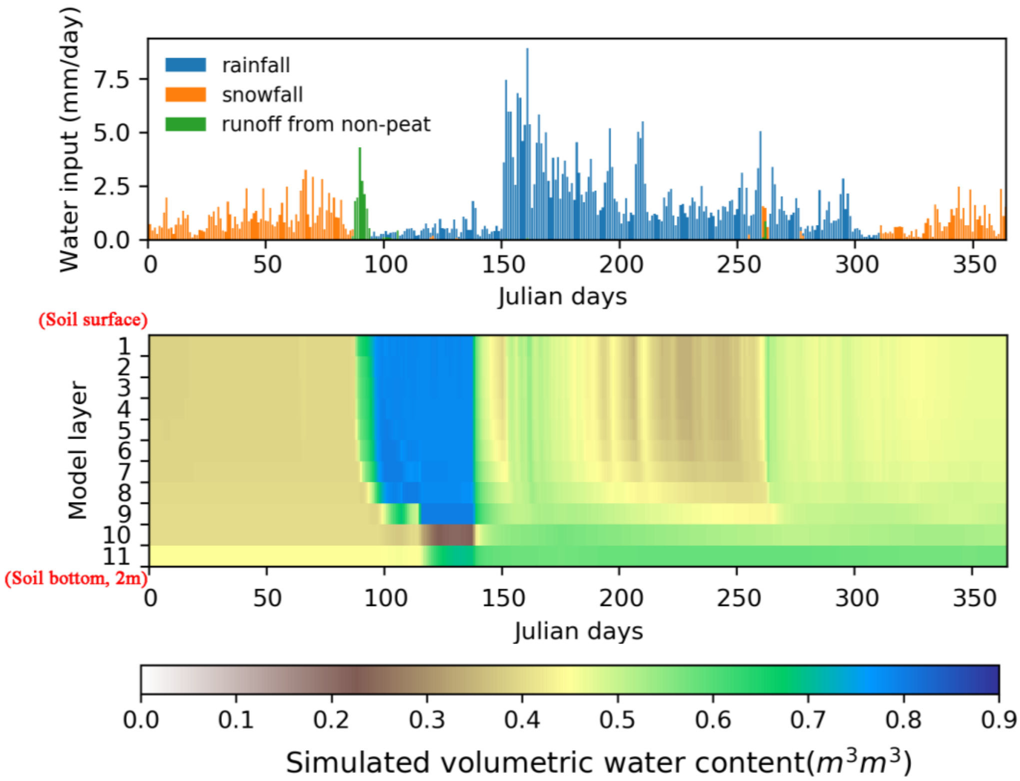
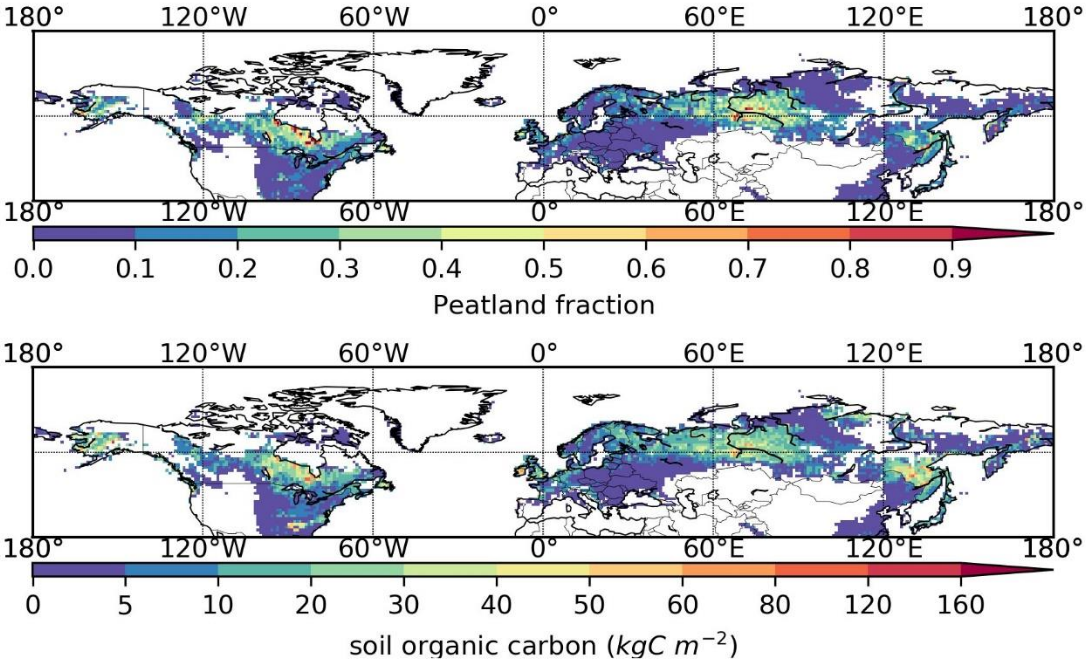


Fig. S14. (Top figure) Daily water inputs to a Sweden peatland (68.0°N, 19.0°E) in year 1884; (bottom figure) simulated daily volumetric water content profile for the peat HSU.

Without the depth modifier, as shown in the figure below, simulated northern peatlands area will not change (3.9 million km^2), but northern peatlands C stock will be underestimated (only 300PgC). We acknowledge that such kind of approach is somehow too empirical but at this stage we can't avoid it. These limitations were presented on Line602: "……The parameter z_0, by contrast, exerts a relatively strong control over C profiles. It is noteworthy that while our model resolves water diffusion between soil layers according to the Fokker–Planck equation (Qiu et al., 2018), simulated soil moisture does not necessarily increase with depth (Fig. S14). z_0 is therefore an important parameter to constrain peat decomposition rates at depth. With smaller z_0, decomposition of C decreases rapidly with depth, resulting in deeper C profile (Fig. S13). Regional scale tests verified these behaviors of the model: When f_{th}=0.9 is used (instead of f_{th}=0.7), changes in peatland area and peat C stock are negligible (Fig. S15). Without z_0, simulated northern peatlands area will not change (3.9 million km2), but northern peatlands C stock will be underestimated (only 300PgC). If z_0=0.5 m is applied (instead of z_0=1.5 m), the simulated total peat C would triple while the total peatland area would only increase by 0.2 million km2 (Fig. S16)."



(Top figure) Simulated peatland area fraction without the depth modifier (z_0), and (bottom figure) simulated peatland soil carbon density without z_0.

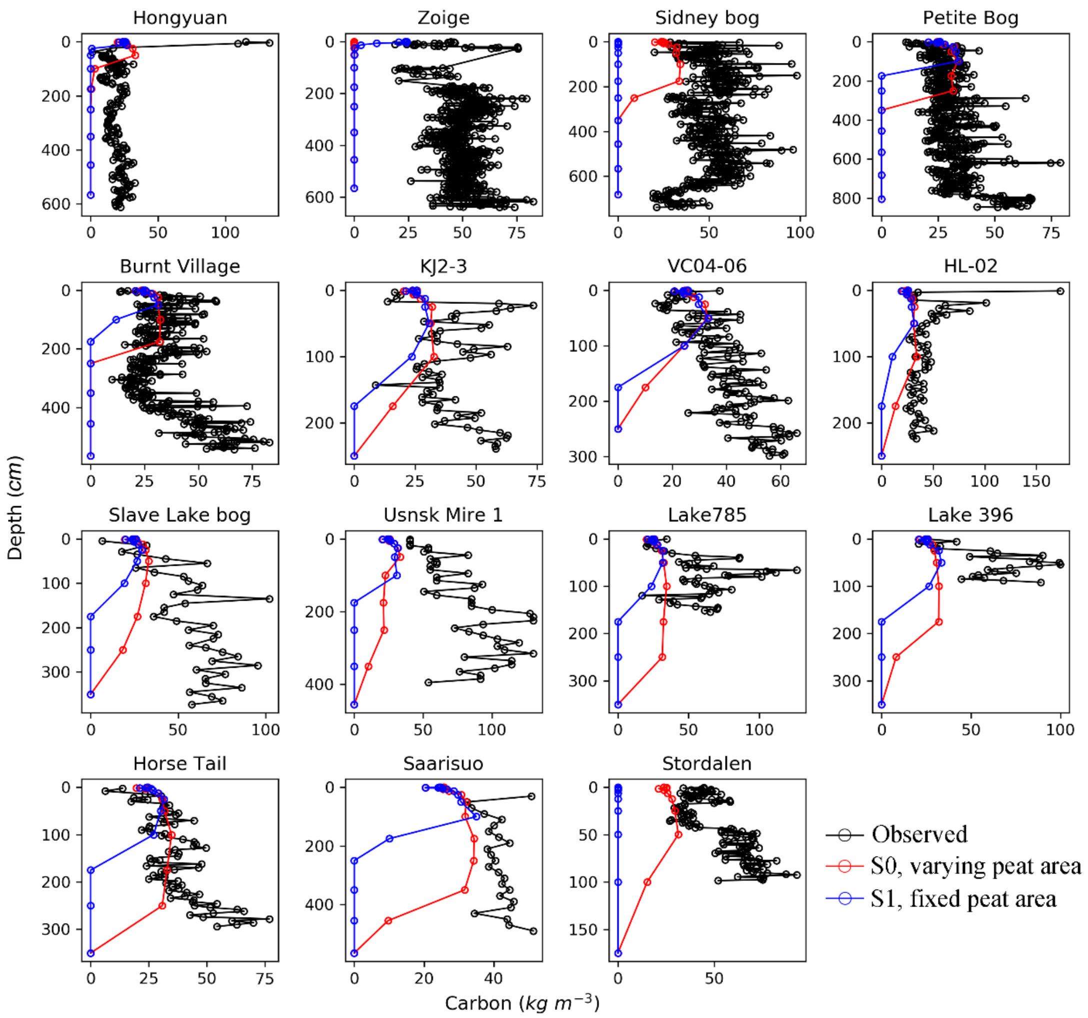
Q5. * Comparison with cores. I am not sure if the model presented here can be compared to peat cores. The reason is that, in order to conserve C mass, an expansion of the peatland area fraction has to imply a reduction of the peat C mass per unit area - peat C is effectively diluted over an increasing area. Hence, the vertical growth of peat should slow upon lateral expansion. This is implied by the simplification that the model doesn't explicitly simulate the horizontal dimension. In reality, a peatland has substantial lateral structure and tends to be deep and have the oldest layers towards the center. That's also where peat cores are commonly taken (in order to maximise the temporal coverage). I am therefore not surprised to see that the model appears to generally underestimate peat depth. I suspect that separate simulations are required for this, where the peatland area fraction is held constant (no dilution!).

We agree with the reviewer that the expansion of peatland area fraction may dilute simulated peat C. Following the reviewer's suggestion, we run simulations with fixed peatland area fraction (with peatland area fraction in each grid cell being derived from the map of Yu et al. (2010, GRL)). However, as shown in the figure below, simulated peat C profiles with varying peatland area fraction (S0 in red line) match better (than S1 with fixed peatland area fraction, in blue line) with observations (black line). This can be due to: (1) in

S0, the simulated peatland area fraction is quite small at first, and then it increases gradually. As we add surface runoff of all non-peatland soils in the gridcell into peatland, with a smaller peatland area fraction, S0 tends to create wetter peat soils than S1. (2) in S0, peatland encroach C from non-peatland soils when expanding, and the C is protected from oxic decomposition subsequently. Point (2) will be presented in a follow up study (Qiu et al., in prep). The below figure is not added in the revised manuscript, for simplicity, we add a section in discussion on Line543 in the revised manuscript to note the dilution issue:

Vertical profiles of peatland soil organic carbon

We note that caution is needed in interpreting the comparison between simulated peat C profile and measured C profile from peat cores (Fig. 3, Fig. 4). In reality, peat grow both vertically and laterally since inception, with the peat deposit tend to be deeper and its basal age tend to be older at the original nucleation sites / center of the peatland complex (Bauer et al., 2003; Mathijssen et al., 2017). As mentioned earlier, field measurements tend to take samples from the deeper part of a peatland complex and shallow peat are underrepresented. The model, however, only simulates peat growth in the vertical dimension and lacks an explicit representation of the lateral development of a peatland in grid-based simulations, thus simulated peat C (per unit peatland area) is diluted when the simulated peatland area fraction in the grid cell increases.



Q6. * The authors aim to model peat C dynamics during the Holocene (see title), but relatively little focus is given to forcing and evaluating the model with respect to this palaeo perspective. As far I understood, the model is forced with constant pre-industrial climate (although insolation and summer temperatures varied substantially during the Holocene, especially at high latitudes). Was a changing sea level accounted for? For applications in palaeo climate and -carbon cycle studies, the model is expected to reliably simulate the net C balance of peatlands. I am not convinced that the evaluation of C content across the soil profile, as presented in the paper, provides sufficient information to evaluate this aspect. Shouldn't a comparison be done against dated peat cores, where the amount of C (left today) per age bin is given? The model doesn't track age bins explicitly, but could be extended to simulate C14 decay and transport across the soil layers (so that lower layers would have an older C14 age, which could then be compared to the C14 age across depth in dated cores). Alternatively, one could write out soil C inputs and decomposition rates at all time steps and resolve age cohorts explicitly offline (diagnostically). I understand that this is a substantial challenge,

but I am not fully convinced that the evaluation presented here is sufficient. At least a discussion of these points should be added.

Considering that there are significant variations in both proxy-based reconstructions of Holocene climate and climate models simulated Holocene climate by models, and a significant model-data discrepancy exists (Mann et al., 2008, PNAS; Liu et al., 2014, PNAS), we simply used looped 1961-1990 climate in this study to approximate the higher Holocene temperatures relative to the ‘pre-industrial’ period (Marcott et al., 2013, Science). Uncertainties induced by the climate forcing has been discussed on Line532-540, and one of our future work is to study impacts of different Holocene climate forcing data.

ORCHIDEE is a land surface model simulating CO_2, water and energy fluxes of terrestrial ecosystems. It is the land component of the IPSL-CM5 (Atmosphere-Land-Ocean-Sea ice) earth system model. In this study, ORCHIDEE-PEAT was run offline, sea-level changes were not accounted for. But changes in the exposed land area after the retreat of ice sheet were considered (see Sect. 3.2).

The reviewer is right that we can’t compare simulated peat C profile against dated peat cores because our model doesn’t track age bins explicitly. Tifafi et al. (2018, GMD) incorporated 14C dynamics in the soil into the ORCHIDEE-SOM model. Their work is in parallel with our model, but could be merged together in the future developments. A discussion on this issue is added following Q5: “……, thus simulated peat C (per unit peatland area) is diluted when the simulated peatland area fraction in the grid cell increases. In addition, while a dated peat core tells us net burial of peat C during time intervals, the model can’t provide a peat age-depth profile because it simulates peat C accumulation based on decomposition of soil C pools, rather than tracking peat C as cohorts over depth/time (Heinemeyer et al., 2010).

The above-noted discrepancies between the simulation and the observation highlight both the need for more peat core data collected with more rigorous sampling methodologies and the need to improve the model. In parallel with this study, ^{14}C dynamics in the soil has been incorporated into the ORCHIDEE-SOM model (Tifafi et al., 2018), which may give us an opportunity to compare simulated ^{14}C age-depth profiles with dated peat C profiles in the future after being merged with our model.”.

Q7. * I simply did not understand Fig. 1.

Fig.1 was used to show the RMSE of simulated and measured peat depth at 60 peatland sites. The transition from green to white indicates the measured mean depth of all 60 sites. Since information showed by this figure was already informed by Table1, we replaced it with a figure for modelled vs. observed depth at these sites. And the text from Line369 to Line 372 were modified accordingly: "…… Peat depths are underestimated for most sites (Fig. 1). Simulated depth of these 57 sites ranges from 0.37 m to 6.64 m and shows a median depth of 2.18 m, while measured peat depth ranges from 0.96 to 10.95 m, with the measured median depth being 3.10 m (Table 1). The root mean square error (RMSE) between observations and simulations is 2.45 m."

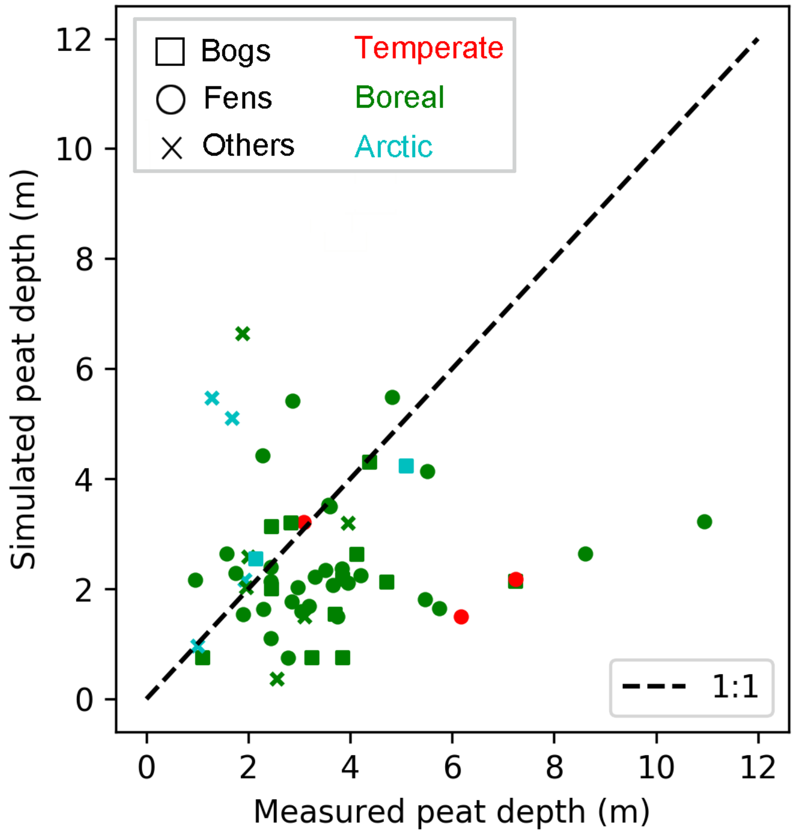


Fig. 1. Measured and simulated peat depth at 60 peatlands sites (Table S1). Shapes of markers indicate peatland types (bogs, fens, others), colors of markers imply climatic zones (temperate, boreal, arctic) of sites' location.

Q8. * Should become clear upfront what parameters are calibrated and what observational targets are used for calibration.

We add the following table to show parameters used and calibrated in the model. We generally described the model parameter, its calibration and observational target simultaneously in the main text. To retain readability (and not having to add redundant descriptions), we keep these descriptions as presented in the initial manuscript.

Table 1. Parameter values in peatland modules of ORCHIDEE-PEAT v2.0.

Parameter	Value	Description
$k_{0,i}$		the base decomposition rate of carbon pools, Eq. 1
$k_{0,i}$: i=*active*	1.0 a^{-1}	the base decomposition rate of the active pool at 30 °C, Eq. 1
$k_{0,i}$: i=*slow*	0.027 a^{-1}	the base decomposition rate of the slow pool at 30 °C, Eq. 1
$k_{0,i}$: i=*passive*	0.0006 a^{-1}	the base decomposition rate of the passive pool at 30 °C, Eq. 1
z_0	1.5m	The e-folding depth of base decomposition rate, Eq. 2
f	0.1	The fraction of carbon content in the model layer to be transported to the layer below, Eq. 4
f_{th}	0.7	The amount (fractional) of carbon content that the model layer need to hold before transporting carbon to the layer below, Eq. 5
m	gridcell specific	TOPMODEL parameter (the saturated hydraulic conductivity decay factor with depth), Fig.1, TextS4
CTI_{min}	gridcell specific	TOPMODEL parameter (the minimum CTI for floodability), Fig.1, TextS4
Num	gridcell specific	The total number of growing season months in the preceding 30 years, Fig.1, Sect. 2.2.2
SWB	6 cm	Minimum summer water balance, Fig.1, Sect. 2.2.2
C_{lim}	50.3 kg C m^{-2}	Minimum peat C density , Fig.1, Sect. 2.2.2

LESS MAJOR (BUT NOT MINOR)

Q9. * Better define the scope of the model and the evaluation, the scale at which the model is expected to yield reliable results, what simplifications have taken to get there, and where the model is not applicable. This can be achieved by more clearly stating upfront for what research questions the model is expected to be applied, and what it therefore needs to simulate with fidelity (and why these quantities). And then present the results with a focus and structure to address these quantities. This is largely done so already, but it would greatly help the reader to improve the structure of the paper in this sense. I would expect the following key quantities:

*** total (northern) peat C: ok**

***spatial patterns of peatland extent: ok, although the particularly extensive peat area in the Hudson Bay Lowland is largely missed by the model.**

*** basal age/inception, compared to first year of peatland establishment in model: It would be good to evaluate simulated and observed basal ages across space, e.g. with a map showing the simulated basal age across space and dots on top of it for observed basal ages from different cores.**

*** peat C accumulation/respiration history: The net C balance through time is what is relevant for the C cycle (what the atmosphere "sees"). I am not convinced that the evaluation presented here, looking at C content across depth, is giving us the right information to evaluate the model in this respect. The dimension time is missing (as mentioned above); there is no age scale of the cores factored into the analysis.**

We revise the summary on Line657-Line661 to make the scope of the study clearer for readers (not stating upfront because we don't want to cause confusion to readers, they need to get an idea of the model and the simulation protocol first): "As a large-scale LSM which is designed for large-scale gridded applications, ORCHIDEE-PEAT v2.0 cannot explicitly model the lateral development of a peatland. The model therefore aims to simulate average peat depth and C profile in a grid location rather than capturing peat inception time and age-depth profiles of peat cores. For tropical peatlands, the model needs to be improved to represent its tree dominance, oxidation of deeper peat due to pneumatophore (breather roots) of tropical trees, and the greater water table fluctuations as a result of the higher hydraulic conductivity of wood peats and tropical climates (Lawson et al., 2014). In addition, tropical peat is formed as riparian seasonally flooded wetlands with water coming from upstream river networks, whereas the TOPMODEL equations used here implicitly assume a peatland is formed in a grid cell only from rainfall water falling into that grid-cell. Further work to improve this simulation framework is needed in areas such as an accurate representation of the Holocene climate, higher spatial resolution, distinguish bogs from fens to better parameterize water inflows into peatland. Including CH4 emissions and leaching of DOC will be helpful to get a more complete picture of peatland C budget.".

Questions concerning these quantities had already been disclosed previously (or later) by the reviewer, please see our responses to Q3, Q6 and Q13:

*spatial patterns of peatland extent in the HBL – Q3
* basal age/inception – Q13
* peat C accumulation/respiration history – Q6

Q10. * Vertical peat growth model: I didn't intuitively understand the rationale for using bulk density data to formulate the vertical growth/downward transport model. Why didn't you use volumetric C content? Can your approach be described as a sequence of C-buckets that fill up by receiving inputs from the layer above (once this "spills over")? Then, spill-over is happening when the typical empirical volumetric C density at the respective depth, as measured in your 102 cores, is achieved. I'm just thinking out loud here, trying to make sense of the model. But maybe you can include such an intuitive description of your approach in the paper.

Actually, we did use volumetric C content in the vertical downward transport model. In Eq.3 (on Line182), we used observed bulk density and observed C concentration (%) to calculate an empirical amount of C (kg C/m^2) that each model layer can hold (M_l), then simulated C content is compared with $f_{th}*M_l$ (f_{th} is a prescribed value, f_{th} = 0.7) to start downward transport of C. The reviewer's description generally matches our initial idea, although we calibrated the threshold to start downward C transfer and the amount of C to be transferred according to peat cores. Please see our responses to Eq. 4 and Eq. 5.

Q11. * While the striking performance in simulating inundation is definitely a plus, it remains unclear how this improvement over earlier publications (e.g., ST14) is achieved. Is it related to resolving the soil hydrology across layers instead of using a simple bucket model? The inundation sub-model is key for the peatland extent model and warrants a bit more attention in the paper.

We would like first to note that the soil hydrology scheme is not the only difference between our model and ST14. Representation of peatland vegetations, the soil thermal regime, and snow processes are all very different between the two models (Guimberteau et al., 2018; Stocker et al., 2014, GMD; Sitch et al., 2013, GCB; Ekici et al., 2015, The Cryosphere). All the above-mentioned processes can more or less have an influence on both the water fluxes and water content of a grid cell, and also affect simulated inundation.

In addition, we use peat-specific soil hydrological parameters for peatland, while using another set of parameters (which depend on the dominate mineral texture of the grid cell) for mineral soils. In contrast, ST14 used grid cell average soil parameters in soil hydrology. De Rosnay et al. (2002, JGR) evidenced that a single ‘‘average’’ textured soil couldn’t adequately represent the “averaged” water fluxes for heterogeneous regions, a subgrid-scale representation of soil type is relevant for modeling of soil water movement and surface fluxes.

For reasons indicated above, we feel that a comparison between ST14 and our model would be unfair, and we couldn’t attribute the better performance of our model in simulating inundation than ST14 only to the multi-layer physically-based soil hydrology.

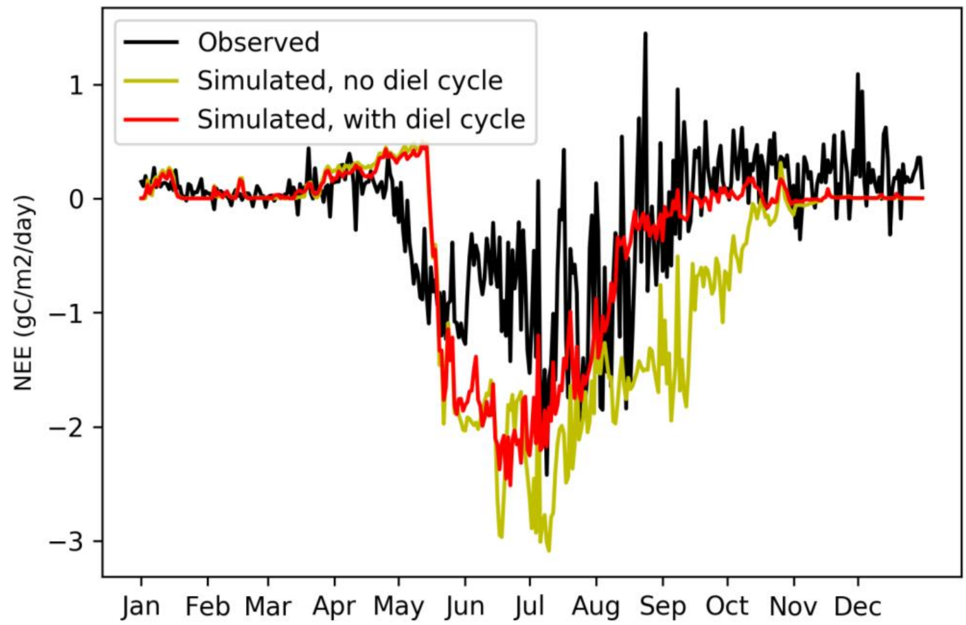
As for impacts of the 2-layer bucket scheme vs. the 11-layer physically-based diffusion scheme, while a comparison between the two schemes is out of the scope of this paper, we can get an idea of it from the study of De Rosnay et al. (2002, JGR) and Guimberteau et al. (2014, GMD). De Rosnay et al. (2002, JGR) showed that compared to the 2-layer bucket approach, the multi-layer diffusion scheme together with a subgrid-scale representation of soil type allow a more realistic representation of surface water fluxes, soil moisture profile and root water uptake, resulting in a better spatial and seasonal representation of evapotranspiration. Guimberteau et al. (2014, GMD) applied both the simple 2-layer scheme and the 11-layer diffusion scheme over the Amazon Basin, and showed that the 11-layer diffusion scheme simulates more dynamic soil water storage variation and improves simulation of soil water storage when compared with satellite observations.

Q12. * I don’t think it’s appropriate to require every model presented in GMD to be fundamentally novel. Furthermore, the model presented by Qiu et al. is largely an adoption of an existing model (ST14), which itself is

based on Kleinen et al., 2012. Sufficient reference is made by Qiu et al. to this earlier work. However, the authors introduce and motivate their work with (l.94) "While both studies made pioneering progresses in the modelling of peatland ecosystems, they adopted a simple bucket approach to model peatland hydrology and peatland C accumulation, and neither of them resolved the diel cycle of surface energy budget." However, it is unclear why the diurnal surface energy budget needs to be explicitly simulated in this context, and what limitations the simple bucket model approach incurs. It definitely needs more clarification what the model adds to our knowledge and our predictive power and I am skeptical that resolving the diurnal cycle of surface energy exchange adds a great deal. I am more curious about whether resolving soil hydrology across multiple layers helps better simulating relevant peatland-related processes, but the paper doesn't provide this insight. I think it is important that it becomes better clear what the merit of this model (over existing ones) is.

Actually, the diurnal cycle of surface energy exchange matters. We ran two simulations (with diel cycle vs. without diel cycle) to show the model performance in simulating peatland NEE and C stock at the Degerö Stormyr peatland site (Peichl et al., 2014). ORCHIDEE-PEAT v2.0 resolved energy processes in 30min time steps. In the first simulation (with diel cycle), we used measured half-hourly meteorological variables from the flux tower to force the model; in the second simulation, to mimic a run without diel cycle of meteorological variables, the daily mean of measured meteorological variables is used. In the figure below, observed peatland NEE (negative NEE: CO_2 sink) of the site in 2002 is shown in black, simulated NEE with diel cycle is shown in red, and simulated NEE without diel cycle is shown in yellow. Simulated NEE with diel cycle matches better with observations. Meanwhile, in the simulation without diel cycle, simulated C density is 50% greater than the simulation with diel cycle.

Regarding impacts of the multi-layer, physically-based soil hydrology scheme, please see our responses to Q11



Q13. * Observed (Mc Donald et al., 2006) and modelled inception age could be compared across space rather than just showing the numbers across time in Fig. 10. Actually, this comparison is subject to a possible sampling bias in Mc Donald. You want to test whether the model simulates the right inception time at a specific location, and not only the fraction of total number of simulated against the total number of sampled peatlands sampled in each age bin.

We couldn't transiently run the model due to the limitation of computational resources, so we spun up the model at discrete Holocene intervals with the soil C only part of the ORCHIDEE LSM being forced by archived litter input from a 100 years simulation with full ORCHIDEE (2000 yr each time) in this study. In other words, we first calculated peatland areas at 12,000 BP (Area0), then we assumed that peatland areas will not change in the following 2000 years, and we simulated C accumulated by Area0 in the following 2000 years. Then we updated peatland areas (Area1, at 10,000 BP) and simulated C accumulated by Area1 for another 2000 years…… As a result of this crude spinup acceleration procedure, we aimed to reproduce peatland areas and peat C stocks at discrete Holocene intervals rather than to capture inception time of peat cores. On the other hand, the inception time of peat cores couldn't represent the area development of a peatland, i.e. the simulated first initiation of peatland in a specific grid cell could be quite early, while the lateral expansion occurred much later. As the model was simulating peat C accumulation based on peatland areas (Area0, Area1…) at discrete Holocene intervals, we feel that the comparison at 2000-yr age bins is informative.

MINOR

*** l.21: I wouldn't subscribe to 'recently'.**

Deleted now from the text.

*** l.34: "270-540 PgC" Seems to be at the low end. What's the reference? On l. 44 references are given. But I suggest to use the latest (Yu, 2010) as the benchmark.**

We thank the reviewer for the suggestion. Considering that there are still large uncertainties in peat C stock estimates (Yu et al., 2012, Biogeosciences) and there is still no consensus in the soil (peat) science community, we feel that using only one benchmark is not rigorous enough (although the estimate by Yu (2010) is indeed the latest). We decide to report the range of peatland C stock estimates, as presented in the initial manuscript.

*** l.48 "in environments…" Make a new sentence, as this is not related to the first part of the sentence**

We rephrase this sentence as: "Due to water-logged, acidic and low-temperature conditions, plant litter production exceeds decomposition in northern peatlands. More than half of northern peat carbon was accumulated before 7000 years ago during the Holocene (Yu, 2012)."

*** l.49: Change 'despite' to 'while'.**

Changed in the text

*** l.64/65: Weird sentence. The depth itself doesn't prevent oxygen supply.**

We rephrase this sentence as: "Water table is one of the most important factors controlling the accumulation of peat, because it limits oxygen supply to the saturated zone and reduces decomposition rates of buried organic matter (Kleinen et al., 2012; Spahni et al., 2013)."

*** l. 69: Unclear: "critical level [of WTD???]"**

We rephrase this sentence as: "…However, some studies showed that changes in soil water content could be very small while the water table was lowering, the drawdown of the water table caused only small changes in soil air-filled porosity and hence exerted no significant effect on ER (Lafleur et al., 2005; Parmentier et al., 2009; Sulman et al., 2009)."

*** l. 70: Isn't WTD linearly related to soil moisture content? Why the threshold?**

It is intuitive that WTD is closely related to soil moisture content. However, we were not talking about the total soil moisture content of the peat profile here. We were considering the relationship between WTD and the moisture content of soils above the WT, because oxic respiration above the WT contributes more to the heterotrophic respiration of peat than anoxic respiration below the WT.

The figure below (Figure 2 of the study of Lafleur et al. (2005, Ecosystems)) shows measured WTD and soil water content at the Mer Bleue peatland site (soil water content was measured with a profile of TDR probes). As shown by Figure2a, the soil water content at 0.28m depth decreased rapidly when WTD drops from -25cm to -33cm, however, it only decreased marginally with further drops of WTD (from -33cm to -70 cm).

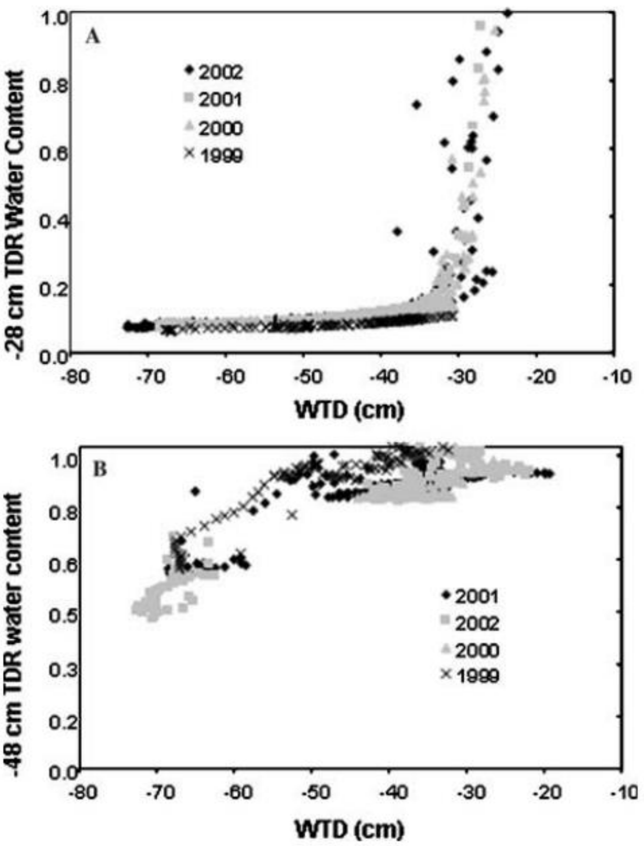


Figure 2. Relationship between peat moisture content as a percent by volume and water-table depth, WTD, below the hummock surface at **A**) −28 cm soil depth and **B**) −48 cm soil depth.

*** l.69-74: This sounds like the authors highlight a unresolved challenged here that the model/paper is going to address. However, it's unclear what is meant here (of course, WTD determines soil moisture or vice-versa), and how the model and results presented here address this particular challenge.**

Yes, here we highlighted the fact that ecosystem respiration didn't always depend on WTD, there could be only small changes in soil moisture in the unsaturated part of the peat profile while WTD was significantly lowered (Lafleur et al., 2005, Ecosystems; Parmentier et al., 2009, Agric. For. Meteorol.; Sulman et al., 2009, Biogeosciences). Founded on a physically-based representation of hydrology of our model, the decomposition of peat C at each model layer is controlled by peat soil moisture (the soil volumetric water content - respiration relationship for organic soils from the meta-analysis of Moyano et al. (2012, Biogeosciences) were used), rather than by WTD.

We haven't ran a control simulation with decomposition controlled by WTD, and the aim of this study was to evaluate if the model can reproduce present-day peatland areas and C stocks, thus we didn't address this in the results. This particular issue (two-layered model vs. multi-layered model, WTD controlled vs. moisture controlled decomposition) can be addressed in future studies.

*** l.76: Style: don't refer to 'groups'.**

"groups" is deleted in the text.

*** l. 92: I would say that the key in ST14 was to account for peatland-specific water storage capacity in typical organic soils ("sponge" feedback) which enabled to accurately simulate the particular patter of peatland areas across the globe.**

We add a sentence to highlight this key improvement on Line92: "Stocker et al. (2014) extended the scope of Kleinen et al. (2012) in the LPX model. In their model, soil water storage and retention were enhanced and runoff was reduced by accounting for peatland-specific hydraulic properties. A positive feedback on the local water balance and on peatland expansion was therefore exerted by peatland water table and peatland area fraction within a grid cell. Areas that are suitable for peatland development were distinguished from wetland extent according to temporal persistency of inundation, water balance and peatland C balance."

*** l. 98: Unclear what "discrepancies" are referred to.**

Here, "discrepancies" referred to issues mentioned above; On Line54-Line74: decomposition doesn't always depend on WTD, soil moisture controls decomposition. On Line75-85: vertical heterogeneities in soil temperature, moisture and soil freezing can't be captured by two-layered bucket model. On Line86-Line97: previous models used two-layered bucket approach to model peatland hydrology and C decomposition without diel cycle of energy and water budget. To keep it as simple as possible (and not having to add redundant descriptions), we only rephrase this sentence on Line98 as: "To tackle these above-mentioned discrepancies and estimate the C dynamic as well as the peat area, we used the ORCHIDEE-MICT land surface model incorporating peatland as ……".

*** l.121: 'multi' instead of 'many'**

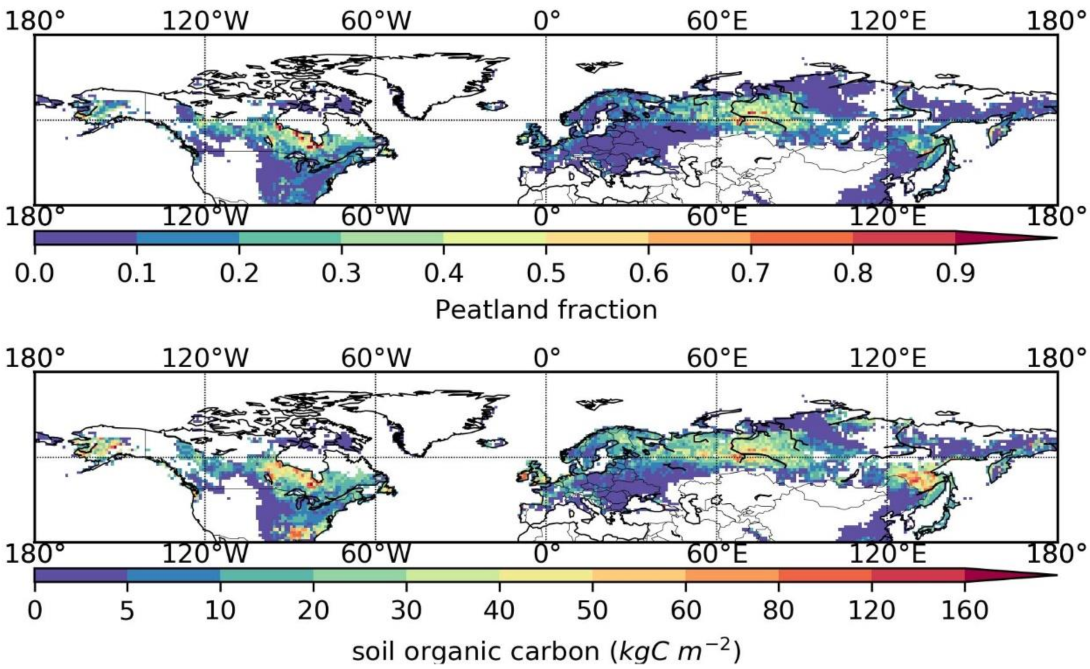
Corrected in the text.

*** Eq. 4: Why isn't it flux = f * (C_l - M_th,l)? The way it's formulated, the C content may drop below the threshold after transfer. Shouldn't it stay "saturated" after accounting for downward transport?**

This question and the question following this one are actually asking the same question: why didn't we keep the soil layer "saturated" after downward C transfer. Please see our responses to the question following this one.

*** Eq. 5: What's the rationale for introducing parameter f_th? Why isn't it 1?**

We calibrated f and f_{th} in Eq.4 and Eq.5 to match the simulated vertical C profiles with peat cores. Actually, we have also tried to formulate the flux as flux = C_l-M_l so that the layer stay "saturated" after C transfer, in this case, simulated vertical C profiles in site level simulations don't match with peat cores as well as with Eq. 4 and Eq5; and in regional simulations, the simulated peatland C in West Siberia and southeastern US are worse than with Eq.4 and Eq.5 (see the figure below). The formulations of the downward C transfer model will be tested for the next steps of model application and development.



*** l. 216: …than what? Explanation would be helpful: More computationally efficient than determining water table depth for each sub-grid pixel.**

We improve the sentence on Line216 as suggested: "……, which is more computationally efficient than determining water table depth for each sub-grid pixel (Stocker et al., 2014)."

*** l. 227: Ambiguous formulation. Do you mean max(monthly values)?**

Yes, we meant max(monthly values). We correct the text on Line 227 as: "…… We therefore compare simulated maximum monthly mean wetland extent over 1980−2015……."

*** Section 2.2.2.: Put Fig. S2 into main text and highlight difference to ST14.**

We move Fig. S2 into the main text in the revised manuscript, its difference to ST14 is highlighted on Line284: "The difference between our model and the DYPTOP model in simulating peatland area dynamics can be summarized as follows: (1) TOPMODEL calibration: TOPMODEL parameters are globally uniform in the DYPTOP model, but grid cell-specific in ORCHIDEE-PEAT v2.0. (2) Criteria for peatland expansion: In the DYPTOP, the "flooding persistency" parameter is globally uniform, being 18 months in the preceding 31 years. And the ecosystem water balance is expressed as annual precipitation-over-actual-evapotranspiration (POAET). In ORCHIDEE-PEAT v2.0, the flooding persistency parameter is grid cell-specific, being the total number of growing season months in the preceding 30 years. And peatland expansion is limited only by summer water balance. The relative areal change of peatland is limited to 1% per year in DYPTOP, but not limited in our model. (3) Peatland initiation: DYPTOP prescribes a very small peatland area fraction (0.001%) in each grid cell to simulate peatland C balance condition. Peatland can expand from this "seed" once water and carbon balance criteria are met. In ORCHIDEE-PEAT v2.0, no "seed" is needed because only the flooding persistency and summer water balance criteria need to be met for the first initiation of peatland (Fig. 1b), carbon balance is only checked after initiation (Fig.1c)."

*** l. 238: Not quite correct. I don't know what the authors refer to here.**

We revised the sentence on Line238 as: "Stocker et al. (2014) introduced a 'flooding persistency' parameter (N in Eq.12, Eq.13 in Stocker et al. (2014)) for the DYPTOP model to represents the temporal frequency of inundation. N is a globally uniform parameter in DYPTOP, being set to 18 months during the preceding 31 years."

*** l. 249: Question: Are non-growing season months discarded or do they count towards N?**

Non-growing season months are counted.

*** l. 254: What's the difference to ST14? Using only water balance during summer months instead of entire year? Might be worth mentioning explicitly. What's the rationale for this choice? Note that winter precipitation is relevant too as summer snow melt is effectively delayed winter precipitation.**

Yes, only water balance during summer months are used in the ORCHIDEE-PEAT v2.0 model. This difference to ST14 now is added on Line284 in the revised manuscript (please see our response to the previous question regarding Section 2.2.2.). Summer dryness was proved to be a key factor in limiting *Sphagnum* growth and peatland expansion in western Canada (Gignac et al., 2000, Journal of Biogeography) and in Western Siberia (Alexandrov et al., 2016, Scientific Reports). Based on the abundance of *Sphagnum* species on 640 peatland sites located in western Canada, Gignac et al. (2000) evidenced that *Sphagnum*-dominated peatlands do not occur in areas having summer moisture index (P–PET) values ≤ -6 cm. A similar climate characteristic, warm precipitation excess (P-0.7PET), was reported by Alexandrov et al. (2016), to explain the present-day distribution of peatlands in Western Siberia, their absence during the Last Glacial Maximum, and their expansion during the mid-Holocene.

*** l. 258 "May-September": Warning: this would mean that the model is not applicable in the south.**

A warning is added on Line261: "……SWB = 6 cm is selected so that the model captures the southern frontier of peatland in Eurasia and western North America (Text S5). Note that the definition of summer (May-September) and *SWB* are not applicable for tropical regions and the Southern Hemisphere."

*** l. 270: Clarify: C_lim "is defined here as…"**

C_{lim} is clarified on Line270 in the revised manuscript: "…… C_{lim} is defined here as long-term peatland C balance condition, it's a product of……"

*** l. 278: "SubC": What's this?**

SubC is a stand-alone soil carbon sub-model of ORCHIDEE, it simulates only soil carbon dynamics using monthly litter and soil C input, soil water and thermal conditions from the preceding full ORCHIDEE run. This part is described in Sect.3.2, L312-315.

*** l. 280-283: Add reference to ST14 as this is the same procedure as chosen by them.**

Reference is added in the text: "Therefore, parameterizations of the "old peat" pool is identical to mineral soils, following the study of Stocker et al. (2014). When peatland expansion happens, the peatland will first expand into this 'old peat' area and inherit its stored C (Stocker et al., 2014)."

*** l. 350: Missing references**

References are added: "Simulated peatlands SOC is evaluated against: 1. The WISE database (Batjes, 2016); 2. The IMCG-GPD (Joosten, 2010)."

*** l. 371: Figure for modelled vs. observed depth would be instructive.**

A figure for modelled vs. observed depth is added, please see our response to Q7.

*** Fig 1/Sect. 4.1: I didn't understand Fig. 1 and how I can read the RMSE from that figure. I expected a comparison of modelled and observed peat**

depth (or total column C), possibly split by temperate/boreal/arctic and/or bog/fen.

A figure for modelled vs. observed depth is added, please see our response to Q7.

*** l. 411: Worth including figure in main text.**

The figure (Fig. S7) is moved to the main text now.

*** l. 425: Are leptosols and agricultural peatlands simply deducted from simulated peatland areas?**

Leptosols and agricultural peatlands were deduced from both simulated areas and simulated C stocks. To clarify it, we modify the sentence on Line425: "After masking Leptosols and agricultural peatlands from the simulated peatland areas and peatland C stocks, ……"

*** l. 440: Abbreviations introduced?**

These Abbreviations were introduced on Line357: "……, from literature data on peatlands in North America (NA) and in the West Siberian lowlands (WSL)."

*** l. 455: "we can only make the..." I don't understand this part.**

We couldn't do transient spinups due to the limitation of computational resources with the full ORCHIDEE LSM, so we designed an accelerated multiple spin-up strategy (Sect. 3.2): For regions that were unglaciated during Holocene, we ran SubC (a stand-alone soil carbon sub-model that only simulates soil C dynamics, without having to run the full ORCHIDEE) for 6 times, with SubC simulates C decomposition and accumulation over 2000 years each time. Therefore, we only know simulated peat depth at 2000-year intervals in regional simulations, and we can only make the comparison (observed vs. simulated peat depth) at 2000-year intervals. For example, for a peat core with its age being 8500 years, we compare its observed depth with simulated peat depth after the fourth SubC run.

*** l. 489: "several": delete**

Deleted.

Response to Referee #2's comments

We would like to thank Benjamin Stocker and the anonymous referee very much for their constructive comments. In the following, please find our point by point response to the comments.

- Reviewer's comments are in bold
- Modifications done in the revised manuscript are in blue
- All figure numbers, table numbers, and line numbers refer to the initial manuscript version.

Anonymous Referee #2

Qiu et al. present their new peatland model, ORCHIDEE-PEAT (v2) and use it prognostically simulate peatland C, extent, and depth over the Holocene. Their work borrows from previous efforts using TOPMODEL based approaches but they extent the field by allowing their model to determine where peatlands will initiate and expand. I find the work to be on the whole sound and interesting. The problem they are tackling is far from trivial and I am surprised it does as well as it does. I am a little concerned about the poorer performance in the major peatland complexes of the world (Hudson's Bay and West Siberia) which I get to in my comments. The paper is generally easy to follow and has relatively few typographical/grammatical errors. I think the paper is publishable in GMD but would like to see my comments addressed prior to that.

Main comments:

1. The paper seems to sometimes confuse wetlands and peatlands. While peatlands are a type of wetland, in the paper the distinction can be at times very fuzzy. For example, in the abstract it says 'A cost-efficient TOPMODEL approach is implemented to simulate the dynamics of peatland area, calibrated by present-day wetlands areas that are regularly inundated or subject to shallow water tables' (lines 28 - 30). Since it is very possible to have a non-peatland wetland be 'regularly inundated or subject to shallow water tables' this makes it confusing at a minimum. Later in the supplementary material some model parameters are tuned, grid cell by grid cell, to 'select the combination that matches with the CW-WTD wetlands map'. So it appears quite unclear that this is indeed a peatland specific parameterization. I realize that there are other steps to determine if peat will begin to form at the site (e.g. Fig S2) but the implementation of the wetland/peatland determination scheme is confusing. Why tuned to wetland area if that will include many non-peat wetlands? Is the idea that the peatland initiation scheme can handle the rest? Can the authors try and bring a bit more clarity to that aspect of their technique?

The reviewer is right that not all wetlands are peatland, non-peat wetland can also be regularly inundated or subject to shallow water tables. In our study, the cost-efficient TOPMODEL was calibrated to reproduce wetland distributions (CW-WTD, which includes non-peat wetlands). Then, based on the study of Kleinen et al. (2012, Biogeosciences) and Stocker et al. (2014, GMD), we assumed that peatland can be distinguished from other wetland, using the peatland initiation condition and development scheme which includes inundation persistency, summer water balance and long-term C balance criteria.

We appreciate the reviewer's suggestion that the distinction between peatland and wetland should be clearer, we thoroughly checked the manuscript and revised the text where the distinction between them was fuzzy:

On Line28-30: ~~A cost-efficient TOPMODEL approach is implemented to simulate the dynamics of peatland area, calibrated by present-day wetlands areas that are regularly inundated or subject to shallow water tables~~. The cost-efficient version of TOPMODEL and the scheme of peatland initiation and development from the DYPTOP model, are implemented and adjusted, to simulate spatial and temporal dynamics of peatland.

On Line92: Stocker et al. (2014) extended the scope of Kleinen et al. (2012) in the DYPTOP model. In their model, soil water storage and retention were enhanced and runoff was reduced by accounting for peatland-specific hydraulic properties. A positive feedback on the local water balance and on peatland expansion was therefore exerted by peatland water table and peatland area fraction within a grid cell. Areas that are suitable for peatland development were distinguished from wetland extent according to temporal persistency of inundation, water balance and peatland C balance.

On Line102-103: ~~A cost-efficient TOPMODEL approach is applied to simulate the dynamics of peatland area extent.~~ Peatlands extent are modelled following the approach of DYPTOP (Stocker et al., 2014) but with some adaptions and improvements (Sect. 2.2).

On Line126-131: Furthermore, the ~~computationally efficient TOPMODEL~~ approach proposed by Stocker et al. (2014) is incorporated into the model to simulate dynamics of peatland area~~, calibrated with a new dataset of wetland areas excluding permanent lakes~~ (Sect. 2.2). This model simulating the dynamics of peatland extent and the vertical buildup of peat is hereinafter referred to as ORCHIDEE-PEAT v2.0.

On Line205-206: ~~Here, dynamics of peatland area is calculated by a cost-efficient TOPMODEL (Stocker et al. 2014).~~ Here, a cost-efficient TOPMODEL from the DYPTOP model (Stocker et al., 2014) is incorporated, and calibrated for each grid cell by present-day wetland area that are regularly inundated or subject to shallow water tables, to simulate wetland extent (Sect. 2.2.1). Then, the criteria for peatland expansion is adapted from DYPTOP to distinguish peatland from wetland (Sect. 2.2.2).

2. I fully understand the authors' point about difficulty in simulating small permafrost complexes (e.g. discussion of Fig 6) but I am concerned about the poorer performance in the major complexes such as the HBL or WSL. Both of these regions have areas of near 100% peatland cover so the model should have a good chance. Also there is an overabundance of peatlands in some regions that are generally devoid of peatlands (e.g. E. USA). Is this 'smearing' of peatlands perhaps a result of how wetlands area is generally determined, i.e. TOPMODEL-based, or is this a result of the peat initiation limits? I think this deserves more discussion in the paper as it is a striking aspect of the result and one that the community would benefit from any lessons learned regarding how to best get the hotspots without overdoing the rest of the domain.

Simulated peatland areas at the WSL (~ 0.6 million km^2) matched with observation-based estimates (in PEATMAP: ~ 0.6 million km^2; in WISE: ~ 0.5 million km^2). But the model indeed underestimated peatland areas at the HBL, and the same question has been raised by Referee1 (his Q3). Below are our responses to the question: As for the underestimation of peatland extent in the Hudson Bay Lowland (HBL), Glaser et al. (2004a and 2004b, Journal of Ecology) and Packalen et al. (2014, nature communication) proved that climate alone couldn't explain the initiation and development of peatlands in the HBL, the glacial isostatic adjustment is a more fundamental control of HBL peatlands development. We add sentences on Line434 to address this issue: "……, though the ~~hotspot~~ world's second largest peatland complex at the Hudson Bay lowlands (HBL) is underestimated and a small part of the northwest Canada peatlands is missing. Packalen et al. (2014) stressed that initiation and development of HBL peatlands are driven by both climate and glacial isostatic adjustment (GIA), with initiation and expansion of HBL peatlands tightly coupled with land emergence from the Tyrrell Sea, following the deglaciation of the Laurentide ice sheet and under suitable climatic conditions. The pattern of peatlands at southern HBL was believed to be driven by the differential rates of GIA rather than climate (Glaser et al., 2004a, 2004b). More specifically, Glaser et al. (2004a, 2004b) suggested that the faster isostatic uplift rates on the lower reaches of the drainage basin reduce regional slope, impede drainage and shift river channels. Our model, however, can't simulate the tectonic and hydrogeologic controls on peatland development. In addition, the development of permafrost at depth as peat grows in thickness over time acts to expand peat volume and uplift peat when liquid water filled pores at the bottom of the peat become ice filled pores (Seppälä, 2006). This process is not accounted for in the model and may explain why the HBL does not show up as a large flooded area today whereas peat developed in this region during the early development stages of the HBL complex." .

As for the overestimation of peatlands in east US, it could be related to past land use change in peatlands. According to the U.S. Fish and Wildlife

Service's National Wetlands Inventory (Tiner Jr, 1984; Dahl, 2011), there were about 215 million acres of wetlands in the lower 48 states of US at the time of the Nation's settlement, but only 110 million acres remained by 2009 due to agricultural development, urban and other development (~50% of wetlands in the conterminous US has been lost to land use change). From 1780's to mid-1980's, 6 states lost more than 85% of their wetlands, and 16 states lost 50%-85% of their wetlands (Dahl and Allord, 1997). Although wetlands are not necessarily peatlands, the reported losses of wetlands in US indicating that a potentially large area of peatlands in US may have been lost to land use. However, historical losses of peatlands due to land use change and the impact of agricultural drainage of peatlands haven't been taken into account by our model. Simulated natural peatland area by 1860 is 0.4 million km^2, if we assume that 50% of simulated natural peatlands have been lost to land use change (the same percentage of historical wetlands losses) and there is no change in peatland area since then, then ~0.2 million km^2 remained as natural peatlands, closer to observation-based estimates (0.05-0.1 million km^2).

We add sentences on Line626 to address this issue: "From early 1600's to 2009, ~ 50% of the original wetlands in the lower 48 states of US have been lost to agricultural, urban development and other development (Dahl, 2011; Tiner Jr, 1984). Although wetlands are not necessarily peatlands, the reported losses of wetlands in US indicating that a potentially large area of peatlands in US may have been lost to land use change. However, historical losses of peatlands due to land use change and the impact of agricultural drainage of peatlands haven't been taken into account by our model."

Minor comments:

1. line 202 - does that mean the peatland PFTs are forced into their gridcells? Can you expand on what peatland PFTs there are? I see that there are some mention in Text S1 but it just says a PFT with shallow roots. Is it a tree? Do you simulate any other peatland specific PFTs? Shrubs? Moss? Sedges?

There is only one peat-specific PFT in this study, it is forced into the gridcell as long as the peatland development criteria are met. This peatland PFT represents an average of all vegetations growing in the ecosystem, not a specific plant type. We discussed this question in the description paper of the ORCHIDEE-PEAT model published by GMD in 2018 (Qiu et al., 2018, GMD: https://www.geosci-model-dev.net/11/497/2018/). Here we cite the discussion in that paper: "*At present, however, ORCHIDEE-PEAT lacks representation of dynamic moss and shrub covers, and we do not know the fractional coverage of different vegetation types at each site in grid-based simulations. Previous studies have shown that there was considerable overlap between the plant traits ranges among different plant functional types, while variations in plant traits within PFTs can be even greater than the difference in means among PFTs (Verheijen et al., 2013; Wright et al., 2005; Laughlin et* *al., 2010). Therefore, for simplicity, we applied the PFT of C3-grass with a shallower rooting depth to represent the average of vegetation growing in northern peatlands. Only one key photosynthetic parameter—V_{cmax} of this PFT has been tuned to match with observations at each site. This simplification may cause discrepancies between model output and observations. Druel et al. (2017) added non-vascular plants (bryophytes and lichens), boreal grasses, and shrubs into ORC-HL-VEGv1.0. Their work is in parallel with our model and will be incorporated into the model in the future. It will then be possible to verify how many plant functional types are needed by the model to reliably simulate the peatlands at site-level and larger scale*."

To address this question, we recall the Qiu et al. 2018 description paper on Line117: "……. Vegetations growing in peatlands are represented by one C_3 grass plant functional type (PFT) with shallow roots (see dedicated section 2.2.1 of Qiu et al. (2018) for additional discussion on peatland PFT) …"

2. line 224 - Since Fan et al. 2013 is a model-based product perhaps add in 'simulated' in the description.

Corrected now in the text on Line224: "……, with areas that have shallow (WT≤20cm) water tables from groundwater modeling of Fan et al. (2013)."

3. line 265 - Does the peatland HSU immediately shrink to the new potential peatland area fraction? No lag or delay?

Yes, the peatland HSU immediately shrink to the new potential peatland area fraction, there is no lag or delay. Please see our response to Q8.

4. line 282 - Why is the old peat treated as mineral soils? That strikes me as strange. The soils would continue to have high C contents for quite a while if drained so treating as a mineral soil seems unreasonable. Please expand on this logic.

We would like first to note that when simulated peatland area contracts, peat C is still there, not released immediately. But the hydrology of the old peat and the decomposition of C of the old peat is treated as mineral soils. It is noteworthy that draining of peatland may cause decrease of porosity and saturated moisture content. Changes of physical (and chemical) properties of peat soil due to drainage/drought depend on peat type, drainage intensity (Oleszczuk & Truba, 2013; Mustamo, 2017) and duration of drought period. In this study, parameterizations and parameters for old peat and mineral soils are identical, following the study of Stocker et al. (2014). To have a more realistic representation of "old peat soils", the model structure needs to be improved by adding a new sub-grid hydrological soil unit (HSU) which would take hydrological properties of drained peat soils. Substantial original work is needed to change the model structure and to tackle the issue of representation of drained peat soils, thus couldn't be resolved in this study.

We add these sentences on Line282 to acknowledge this issue: "……During the simulation, the contracted area and C are allocated to an 'old peat' pool and are kept track of by the model. It should be noted that drainage (drought) may cause decrease of porosity and saturated moisture content of peat soils (Oleszczuk & Truba, 2013) and, changes in peatland vegetation compositions (Benavides, 2014). But the current model structure doesn't allow us to take these potential changes in peatland into consideration. Therefore, parameterizations of the "old peat" pool is identical to mineral soils, following the study of Stocker et al. (2014). When peatland expansion happens, the peatland will first expand into this 'old peat' area and inherit its stored C (Stocker et al., 2014)."

5. line 400 - Didn't understand the last sentence there.

We meant to say that in grid cell G1 and grid cell G3, observed C fraction of peat cores are much larger than median values (obtained from 39 peat cores) we used to calculate empirical amount of C that each model layer can hold in Sect. 2.1.2. Therefore, we can see that in these two gridcells (Fig.3), simulated C concentration along the peat profile are smaller than observations, but peat depth are still overestimated by the model. This happens with grid cell Lake 785 and Lake 396 (Fig.2) and has been described on Line385-394. To clarify, we rephrase the sentence on Line400 as: "……Observed C fraction at grid cell G1 and G3 are much greater than the median value of all peat core samples (Sect. 2.1.2), thus simulated C concentration along the peat profile are smaller than observations, but peat depth are still overestimated by the model. As it is the case with Lake 785 and Lake 396."

6. line 447 - How many cores were simulated as non-peat out of the total?

Please see data in the table below: There are in total 1685 and 130 observed peat cores, respectively, in NA and WSL, respectively, from Gorham et al. (2007, 2012) and Kremenetski et al. (2003). Because our study aimed to reproduce development of northern peatlands since Holocene, observed peat cores that are older than 12 ka are removed from the evaluation. Then, 1202 out of 1521 peat cores in NA, and 109 out of 127 peat cores in WSL are captured by the model. In other words, out of 596 gridcells (1° × 1°) that contain observed peat cores in NA, the model simulate peatland in 429 gridcells; and, out of 60 gridcells that contain observed peat cores in WSL, the model simulate peatland in 54 gridcellls.

	North Amercia (NA)	West Siberian Lowland (WSL)
Sources of measured peat cores	Gorham et al. (2007, 2012)	Kremenetski et al. (2003)

Total number of observed peat cores	1685	130
Number of observed cores that are younger than 12 ka (Holocene)	1521	127
Number of grid cells (1° × 1°) occupied by observed peat cores (cores that are younger than 12 ka)	596	60
Number of grid cells occupied by simulated peat	429 (Note: there are 1202 observed peat cores in these grid cells)	54 (Note: there are 109 observed peat cores in these grid cells)

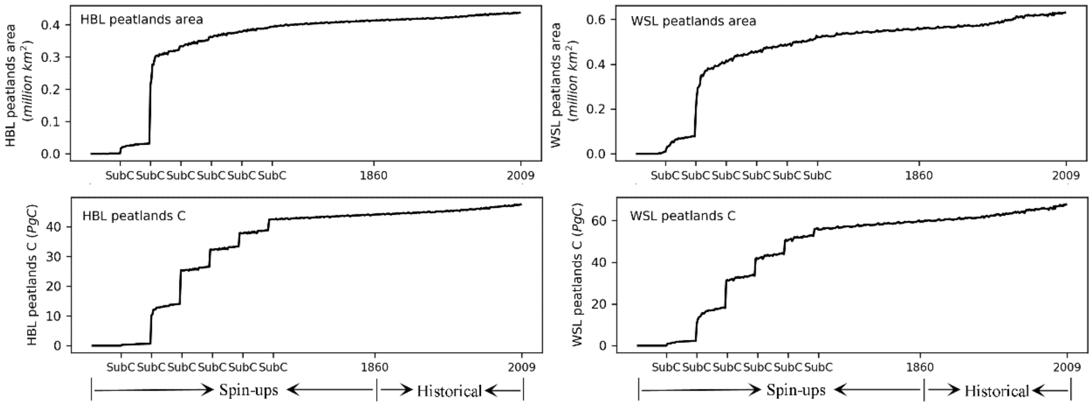
To note this issue, we add sentences on Line361: "……but contain more samples and cover larger areas. Note that as this study aims to reproduce development of northern peatlands since the Holocene, peat cores that are older than 12 ka are removed from the model evaluation. At last, 1521 out of 1685 observed peat cores in NA, 127 out of 130 observed peat cores in WSL, are used in model evaluation (Sect. 4.2: Peat depth)." And add sentences on Line445: "……dependent on local conditions, i.e. retreat of glaciers, topography, drainage, vegetation succession (Carrara et al., 1991; Madole, 1976). As a large-scale LSM, the model can't capture every single peatland: 429 out of 596 grid cells that contain observed peat cores in NA are captured by the model, while the model simulates peatlands in 54 out of 60 observed grid cells in WSL. Cores that are not captured by the model are removed from further analysis (319 out of 1521 peat cores in NA, 18 out of 127 peat cores in WSL, are removed)."

7. around line 476 - please specify 'simulated'. It gets a bit confusing that these are all just model quantities.

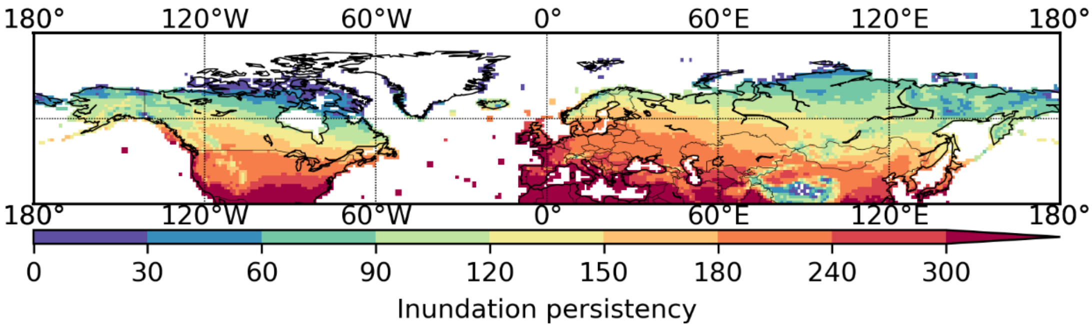
Corrected now in the text on Line476: "……From 1901 to 2009, both simulated net primary production (NPP) and simulated heterotrophic respiration (HR) show an increasing trend"

8. line 626 - This is where I find the technique a bit confusing. 'We notice a large interannual variability in peatland area'. In reality this is unlikely to be possible given that peat soils are slow to develop and slow to leave. The water-logging is the dynamic aspect. This sort of ties into my main comment #1 above. Please tighten up how this is all defined and referred to.

We agree with the reviewer that peat soils are slow to develop and slow to leave in reality. Although we set no limitation on peatland expanding/shrinking rate in the model parameterization, intra- and inter-annual changes in simulated peatland area were actually constrained by the “inundation persistency” criterion (*Num*, Sect 2.2.2) and the long-term C balance criterion (C_{lim}, Sect 2.2.2). Short-term dry/wet climate couldn’t cause significant change of peatland area. As shown in the figure below, simulated historical changes in peatland area and C stocks at the Hudson Bay lowlands (HBL) and the West Siberian lowland (WSL) are indeed gradual and small.



Simulated peatland area at the southeastern US, however, showed a large interannual variability. This is because for an area fraction to be diagnosed as peatland at the southeastern US, it needs to be inundated for more than 240 months in the preceding 30 years (*Num* = 240 months), making simulated peatland area sensitive to short-term variations in climate. The figure below shows the “inundation persistency” parameter (*Num*) for each grid cell, averaged over 1860-2009. The reviewer is right that the large inter-annual variability of peatland area at the southeastern US is related to the water-logging aspect, we remove the confusing sentence from the manuscript.



9. Fig 1 - Strange figure. I couldn’t figure out the green fade, nor understand how it was giving information. So is the above the green the >100% RMSE? Why a fade? Please rethink this one.

The same question has been raised by Referee1, we follow his suggestion by replacing Fig 1 with a scatterplot which splits temperate/boreal/arctic and bog/fen.

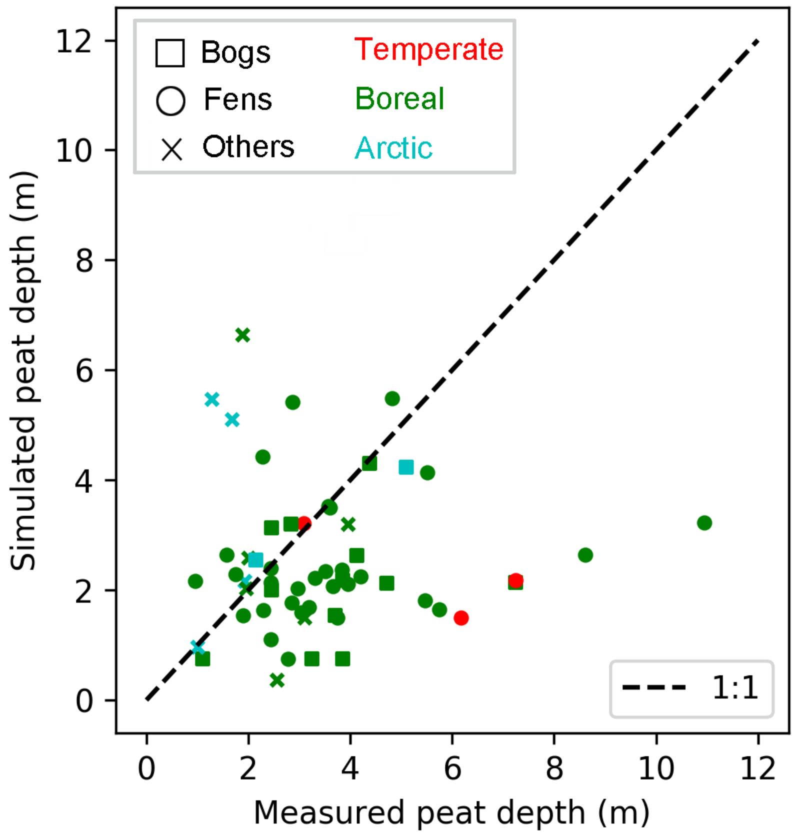


Fig. 1. Measured and simulated peat depth at 60 peatlands sites (Table S1). Shapes of markers indicate peatland types (bogs, fens, others), colors of markers imply climatic zones (temperate, boreal, arctic) of sites' location.

10. If Fig 6 is plotted as a simple scatterplot, what does it look like? I understand that Fig 7 is a more detailed look but I wonder if a simple scatter plot could be instructive for any bias.

We enrich Fig 6 by adding scatter plot of measured VS simulated peat depth.

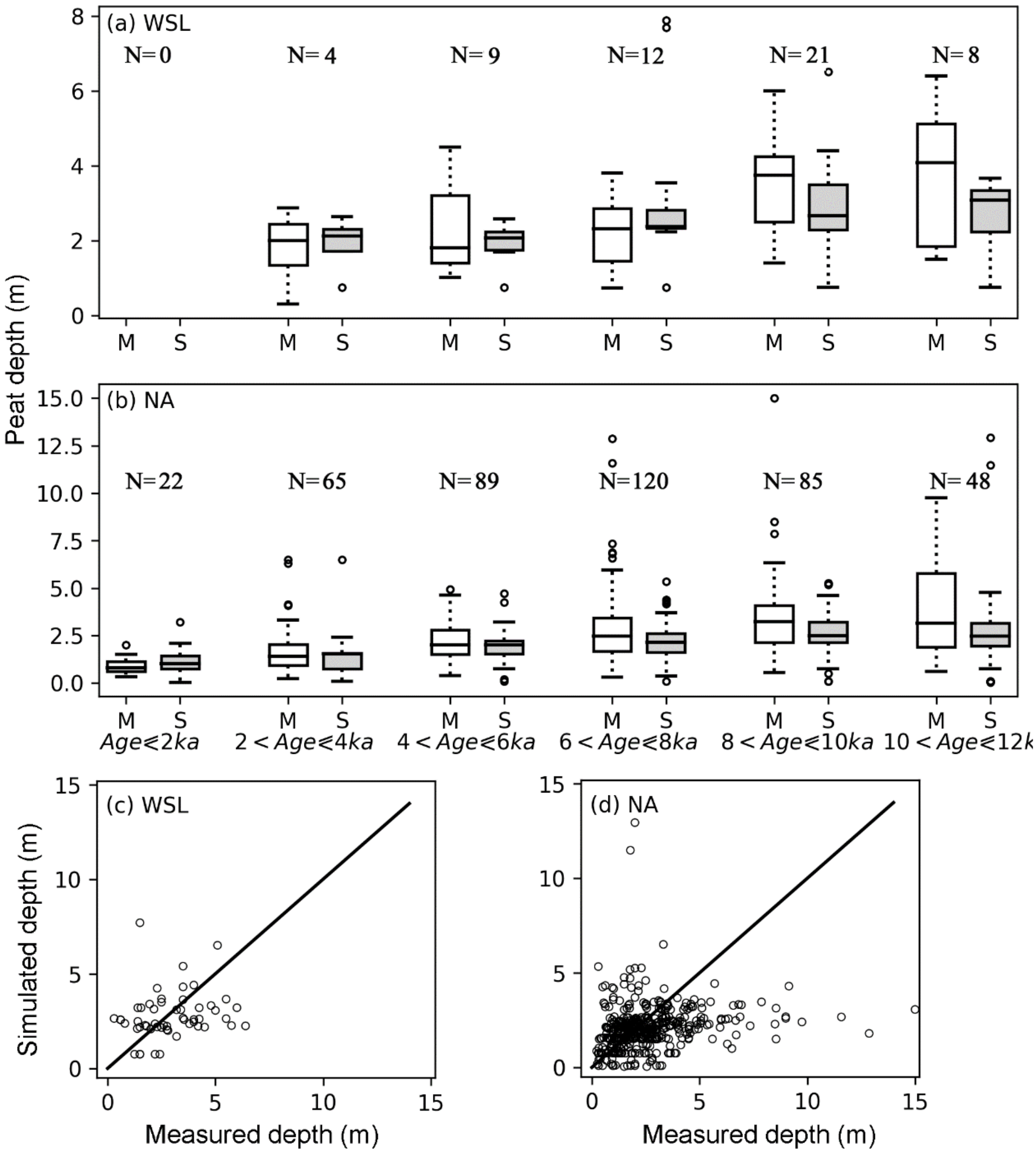


Fig. 6. (a, b) Measured (M) and simulated (S) mean peat depth at the West Siberian lowlands (a) and North America (b), grouped according to the mean age of peat cores. Measured peat cores are from Gorham et al. (2012) and Kremenetski et al. (2003). The horizontal box lines: the upper line - the 75th percentile, the central line - the median (50th percentile), the lower line - the 25th percentile. The dashed lines represent 1.5 times the IQR. The circles are outliers. Number of included grid cells in each age group is indicated by N. (c, d) The scatter plot of measured and simulated peat depth for the West Siberian lowlands (c) and North America (d). For a grid cell that has multiple measured peat cores, the median depth of all measurements is plotted against the simulated depth in the scatter plot.

11. Fig 10 - please split into 3 separate bars per time period. I couldn't figure this out. What is the light blue? What is the line midway through 8-10 Age bar meaning?

Fig 10 was indeed misleading. The light blue, and the line through 8-10 Age bar was a result of color overlay. We split the fig into 3 separate bars, as suggested by the referee. Note that we changed the color of the figure.

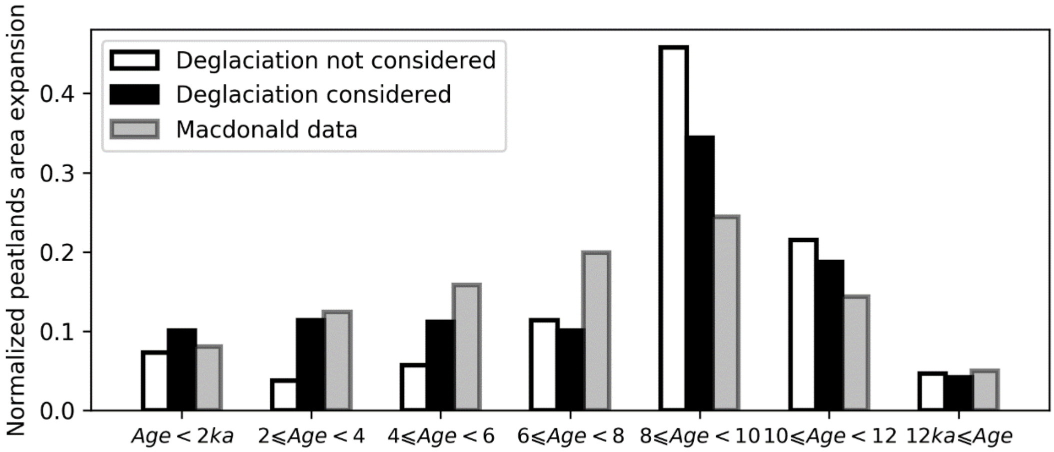


Fig. 10. (Grey bars) Percentage of observed peatland initiation in 2000-year bins. Peat basal dates of 1516 cores are from MacDonald et al. (2006), peat basal age frequency of each 2000-year bin is divided by the total peat basal age frequency. (White bars) Percentage of simulated peatlands area developed in each 2000-year bin, deglaciation of ice-sheets is not considered (the model was run with 6 times SubC, 2000 years each time). The peatlands area developed in each bin is divided by the simulated modern (the year 2009) peatlands area. (Black bars) Percentage of simulated peatlands area developed in each 2000-years bin, pattern and timing of deglaciation are read from maps in Fig. S5 and Fig. S6.

12. supplementary line 11 - So does all of the surface runoff from the grid cell get funnelled into the peatland HSU? Why only surface and not subsurface?

Yes, all surface runoff from the non-peatland HSUs of the grid cell are routed toward the peatland HSU, with the amount of water to be infiltrate into peat soils being calculated through a time-splitting procedure (d'Orgeval, 2006, Diss. Paris; Qiu et al., 2018, GMD). The referee is right that peatlands (fens) can receive both surface and subsurface water. However, the hydrology of the model splits the lateral fluxes into surface runoff and deep drainage. Subsurface runoff are not explicitly represented in the model and therefore not considered as a source of water funneling into the peatland.

p.s. Apologies for the slow review. There was some confusion between me and the editorial team if I was providing a review.

Modelling northern peatlands area and carbon dynamics since the Holocene with the ORCHIDEE-PEAT land surface model (SVN r5488)

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Abstract

The importance of northern peatlands in the global carbon cycle has ~~recently~~ been recognized, especially for long-term changes. Yet, the complex interactions between climate and peatland hydrology, carbon storage and area dynamics make it challenging to represent these systems in land surface models. This study describes how peatland are included as an independent sub-grid hydrological soil unit (HSU) into the ORCHIDEE-MICT land surface model. The peatland soil column in this tile is characterized by multi-layered vertical water and carbon transport, and peat-specific hydrological properties. The cost-efficient version of TOPMODEL and the scheme of peatland initiation and development from the DYPTOP model, are implemented and adjusted, to simulate spatial and temporal dynamics of peatland. ~~A cost-efficient TOPMODEL approach is implemented to simulate the dynamics of peatland area, calibrated by present-day wetland areas that are regularly inundated or subject to shallow water tables.~~ The model is tested across a range of northern peatland sites and for gridded simulations over the Northern Hemisphere (>30 °N). Simulated northern peatland area (3.9 million km^2), peat carbon stock (463 PgC) and peat depth are

generally consistent with observed estimates of peatland area (3.4 – 4.0 million km^2), peat carbon (270 – 540 PgC) and data compilations of peat core depths. Our results show that both net primary production (NPP) and heterotrophic respiration (HR) of northern peatlands increased over the past century in response to CO_2 and climate change. NPP increased more rapidly than HR, and thus net ecosystem production (NEP) exhibited a positive trend, contributing a cumulative carbon storage of 11.13 Pg C since 1901, most of it being realized after the 1950s.

1. Introduction

Northern peatlands carbon (C) stock is estimated between 270 and 540 PgC across an area of 3.4 – 4 million km^2 (Gorham, 1991; Turunen et al., 2002; Yu et al., 2010), amounting to approximately one-fourth of the global soil C pool (2000 – 2700 PgC) and one-half of the current atmospheric C pool (828 PgC) (Ciais et al., 2013; Jackson et al., 2017). Due to water-logged, acidic and low-temperature conditions, plant litter production exceeds decomposition in northern peatlands. More than half of northern peat ~~this~~ carbon was accumulated before 7000 years ago during the Holocene~~, in environments where plant litter production exceeds decay in water-logged, low-temperature conditions~~ (Yu, 2012). While ~~Despite~~ being one of the most effective ecosystems at sequestering CO_2 from the atmosphere over the long-term, northern peatlands are one of the largest natural sources of methane (CH_4), playing a pivotal role in the global greenhouse gas balance (MacDonald et al., 2006; Mikaloff Fletcher et al., 2004; Smith, 2004).

The carbon balance of peatlands is sensitive to climate variability and climate change (Chu et al., 2015; Lund et al., 2012; Yu et al., 2003a). Projected climate warming and precipitation changes press us to understand the mechanisms of peat growth and stability, and further to assess the fate of the substantial amount of carbon stored in peatlands and its potential feedbacks on the climate. Several Land Surface Models (LSMs) have included representations of the biogeochemical and physical processes of peatlands to simulate the observed past extent and carbon balance of peatlands and predict their responses to future climate change (Chaudhary et al., 2017a, 2017b;

Frolking et al., 2010; Kleinen et al., 2012; Spahni et al., 2013; Stocker et al., 2014; Wania et al., 2009a, 2009b; Wu et al., 2016). ~~The w~~Water table ~~depth (WTD)~~ is one of the most important factors controlling the accumulation of peat, because it~~s position in the soil column~~ limits ~~prevents~~ oxygen supply to the saturated zone and reduces decomposition rates of buried organic matter (Kleinen et al., 2012; Spahni et al., 2013). It is highlighted by observed and experimental findings, that variations in ecosystem respiration (ER) depend on water table depth ~~WTD~~ (Aurela et al., 2007; Flanagan and Syed, 2011). However, some studies showed that changes in soil water content could be very small while the water table was lowering~~below a critical level~~, the drawdown of the water table ~~did not lead to a significant decrease of soil moisture content, and~~ caused only small changes in soil air-filled porosity and hence exerted no significant effect on ER (Lafleur et al., 2005; Parmentier et al., 2009; Sulman et al., 2009). Therefore, while studying the interactions between peatland water and carbon balances, the dynamics of soil moisture deserves special attention.

The two-layered (acrotelm-catotelm) conceptual framework was chosen by many Earth System Models (ESMs) ~~groups~~ to describe peatland structures. The peat profile was divided into an upper layer with a fluctuating water table (acrotelm) and a lower, permanently saturated layer (catotelm) – using depth in relation to a drought water table or a constant value (a widely used depth is 0.3 m below the soil surface) as the discrete boundary of these two layers (Kleinen et al., 2012; Spahni et al., 2013; Wania et al., 2009a). This diplotelmic model assumes that all threshold changes in peatland soil ecological, hydrological and biogeochemical processes occur at the same depth, causing the lack of generality and flexibility in the model, and thus possibly hindering the representation of the horizontal and vertical heterogeneity of peatlands (Fan et al., 2014; Morris et al., 2011).

To our knowledge, only two models attempted to simulate peatland area dynamics for large-scale gridded applications (Kleinen et al., 2012; Stocker et al., 2014). Kleinen et al. (2012) modelled wetland extent and peat accumulation in boreal and arctic peatlands over the past 8000 years using the LPJ model. In their study, simulated summer mean, maximum and minimum wetland extent by TOPMODEL are used as surrogates for peatland area, from the assumption that peatland will only initiate and grow in frequently inundated areas. Stocker et al. (2014) extended the scope of Kleinen et al. (2012) in the ~~LPX~~ DYPTOP model. In their model, soil water storage and retention were enhanced and runoff was reduced by accounting for peatland-specific hydraulic properties. A positive feedback on the local water balance and on peatland expansion was therefore exerted by peatland water table and peatland area fraction within a grid cell. ~~, distinguishing areas~~ Areas that are suitable for peatland development were distinguished from wetland extent according to temporal persistency of inundation, ~~using~~ water balance and peatland C balance ~~criteria~~. While both studies made pioneering progresses in the modelling of peatland ecosystems, they adopted a simple bucket approach to model peatland hydrology and peatland C accumulation, and neither of them resolved the diel cycle of surface energy budget.

To tackle these above-mentioned discrepancies and estimate the C dynamic as well as the peat area, we used the ORCHIDEE-MICT land surface model incorporating peatland as a sub-grid hydrological soil unit (HSU). The vertical water fluxes and dynamic carbon profiles in peatlands are simulated with a multi-layer scheme instead of a bucket model or a diplotelmic model (Sect. 2.1). Peatlands extent are modelled following the approach of DYPTOP (Stocker et al., 2014) but with some adaptions and improvements (Sect. 2.2). ~~A cost-efficient TOPMODEL approach is applied to simulate the dynamics of peatland area extent.~~ The aim of this study is to model the spatial extent of northern peatlands since the Holocene and to reproduce peat carbon accumulation over the Holocene.

2. Model description

ORCHIDEE-MICT is an updated version of the ORCHIDEE land surface model with an improved and evaluated representation of high-latitude processes. Phase changes of soil water (freeze/thaw), three-layered snowpack and its insulating effects on soil temperature in winter, permafrost physics and its impacts on plant water availability and soil carbon profiles are all represented in this model (Guimberteau et al., 2018). Based on ORCHIDEE-MICT, ORCHIDEE-PEAT is specifically developed to dynamically simulate northern peatland extent and peat accumulation. ORCHIDEE-

PEAT version 1 was evaluated and calibrated against eddy-covariance measurements of CO_2 and energy fluxes, water table depth, as well as soil temperature from 30 northern peatland sites (Qiu et al., 2018). Parameterizations of peatland vegetation and water dynamics are unchanged from ORCHIDEE-PEAT version 1: Vegetations growing in peatlands are represented by one C3 ~~peatland~~ grass plant functional type (PFT) with shallow roots (see dedicated section 2.2.1 of Qiu et al. (2018) for additional discussion on peatland PFT);~~,~~ ~~lateral water flow from~~ S~~s~~urface runoff of non-peatland areas in the grid cell is routed into peatland;~~,~~ V~~v~~ertical water fluxes in peatland tile is modelled with peat-specific hydraulics (Text S1 in the Supplement). Here, we improve peatland C dynamics by replacing the diplotelmic peatland C model with a multi~~many~~-layered one. The 32-layered thermal and C models in the standard ORCHIDEE-MICT is used to simulate peatland C accumulation and decomposition (Sect. 2.1). With fine resolution in the soil surface (10 layers for the top 1m), this 32-layer model better represents the effects of soil temperature, soil freezing, and soil moisture on carbon decomposition continuously within the peat profile than a diplotelmic model. Furthermore, the ~~computationally efficient TOPMODEL~~ approach proposed by Stocker et al. (2014) is incorporated into the model to simulate dynamics of peatland area~~, calibrated with a new dataset of wetland areas excluding permanent lakes~~ (Sect. 2.2). This model simulating the dynamics of peatland extent and the vertical buildup of peat is hereinafter referred to as ORCHIDEE-PEAT v2.0. It is worth mentioning that Guimberteau et al. (2018) defined soil thermal properties of a specific grid cell as the weighted average of mineral soil and pure organic soil in that grid, with C content of the grid cell derived from the soil organic C map from NCSCD (Hugelius et al., 2013) and HWSD (FAO et al., 2012). This development makes it possible to include the impacts of peat carbon on the gridcell soil thermics, and is activated in this study.

2.1 Modeling peat accumulation and decomposition

The model has two litter C pools (metabolic and structural) and three soil C pools (active, slow and passive); all pools are vertically discretized into 32 layers, with exponentially coarser vertical resolution as depth increases and a total depth of 38 m. Decomposition of the C in each pool and the C fluxes between the pools are calculated at each layer, with each pool having a distinct residence time. A detailed description of the litter and soil C pools and carbon flows between them can be found in the Supplement Text S2.

2.1.1 Peat carbon decomposition

Decomposition of peat soil C is calculated at each layer, controlled by base decomposition rates of different pools modified by soil temperature, moisture and depth:

$$k_{i,l} = k_{0,i} \times f_{T,l} \times f_{M,l} \times f_{Z,l} \quad , \tag{1}$$

where $k_{i,l}$ is the decomposition rate of the pool i at layer l, $k_{0,i}$ is the base decomposition rate of pool i, $f_{T,l}$ is the temperature modifier at layer l, $f_{M,l}$ is the moisture modifier, $f_{Z,l}$ is a depth modifier that further reduces decomposition at depth. For unfrozen soils, the temperature modifier is an exponential function of soil temperature, while below 0°C when liquid water enabling decomposition disappears, respiration linearly drops to zero at −1°C (Koven et al., 2011). The soil moisture modifier is prescribed from the meta-analysis of soil volumetric water content ($m^3 m^{-3}$) - respiration relationship for organic soils conducted by Moyano et al. (2012). See Supplement Text S3 for a more detailed description of the temperature and moisture modifier.

Following Koven et al. (2013), we implement a depth modifier ($f_{Z,l}$) to represent unresolved depth controls (i.e. priming effects, sorption of organic molecules to mineral surfaces) on C decomposition. This depth modifier decreases exponentially with depth:

$$f_{Z,l} = \exp\left(-\frac{z_l}{z_0}\right) \quad , \tag{2}$$

where z_l (m) is the depth of the layer l, z_0 (m) is the e-folding depth of base decomposition rate.

2.1.2 Vertical buildup of peat

Water-logging and cold temperature in northern peatland regions prevent complete decomposition of dead plant material, causing an imbalance between litter production and decay (Parish et al., 2008). The un-decomposed plant residues accumulate as peat, and consequently, the peat surface shows an upward growth. Instead of modeling this upward accumulation of peat, we simulate a downward movement of C by adapting the method that Jafarov and Schaefer (2016) used to build up a dynamic surface organic layer.

From 102 peat cores from 73 sites (Lewis et al., 2012; Loisel et al., 2014; McCarter and Price, 2013; Price et al., 2005; Tfaily et al., 2014; Turunen et al., 2001; Zaccone et al., 2011), we compiled bulk density (BD) measurements into depth bins which correspond to the top 17 soil layers (~8.7 m) of the model (Fig. S1a). The median observed bulk density at each depth bin is assigned to the corresponding soil layer of the model (BD_l). For deeper soil layers of the model (18^{th} - 32^{th}), the value of the 17^{th} soil layer is used. The fraction of C (% weight) of each soil layer (α_{cl}) is derived from a regression with bulk density from 39 cores from 29 sites (Fig. S1b). With these data, we calculate the empirical amount of C that each soil layer can hold:

$$M_l = BD_l \times \alpha_{cl} \times \Delta Z_l \ , \qquad (3)$$

where BD_l ($\mathrm{kg\ m^{-3}}$) is the soil bulk density of layer *l*, α_{cl} is the mass fraction of carbon in the soil, and ΔZ_l (m) is the thickness of the layer.

We then model the vertical downward movement of C between soil layers to mimic the aggradation of carbon in the peat as follows: If carbon in layer l (C_l) exceeds a maximum amount ($\mathrm{M}_{th,l}$), a prescribed fraction (f) of the carbon is moved to the layer below (*l+1*). Here, the carbon flux from layer *l* to the layer below (*l+1*) is calculated as:

$$flux_{l \to l+1} = \begin{cases} 0, & C_l < M_{th,l} \\ f \times C_l & C_l \geq M_{th,l} \end{cases} , \qquad (4)$$

where C_l ($\mathrm{kg\ m^{-2}}$) is the carbon content of layer *l*. The threshold amount of carbon in layer *l* ($\mathrm{M}_{th,l}$) is a prescribed fraction (f_{th}) of the empirically determined M_l:

$$M_{th,l} = f_{th} \times M_l \ , \qquad (5)$$

The values of model parameters f and f_{th} do not change with soil depth.

Finally, the total peat depth is defined as the depth that carbon can be transferred to:

$$H = \frac{C_k}{M_k} \times \Delta Z_k + \sum_{i=1}^{k-1} \Delta Z_i \ , \qquad (6)$$

where *k* is the deepest soil layer where carbon content is greater than 0, C_k ($\mathrm{kg\ m^{-2}}$) is the carbon content of layer k, M_k ($\mathrm{kg\ m^{-2}}$) is empirical amount of carbon that layer

k can hold, and ΔZ_k (m) is the thickness of layer k.

2.2 Simulating dynamic peatland area extent

In grid-based simulations, each grid cell is characterized by fractional coverages of PFTs. The dynamic coverage of each non-peatland PFT is determined by the DGVM equations as functions of bioclimatic limitations, sapling establishment, light competition and natural plant mortality (Krinner et al., 2005; Zhu et al., 2015). Here, ~~dynamics of peatland area is calculated by~~ a cost-efficient TOPMODEL from the DYPTOP model (Stocker et al., 2014) is incorporated, and calibrated for each grid cell by present-day wetland area that are regularly inundated or subject to shallow water tables, to simulate wetland extent (Sect. 2.2.1). Then, the criteria for peatland expansion is adapted from DYPTOP to distinguish peatland from wetland (Sect. 2.2.2). ~~(Stocker et al. 2014).~~

2.2.1 The cost-efficient TOPMODEL

Concepts of TOPMODEL (Beven and Kirkby, 1979) have been proven to be effective at outlining wetland areas in current state-of-the-art LSMs (Kleinen et al., 2012; Ringeval et al., 2012; Stocker et al., 2014; Zhang et al., 2016). Based on TOPMODEL, sub-grid-scale topography information and soil properties of a given watershed / grid cell are used to redistribute the mean water table depth to delineate the extent of sub-grid area at maximum soil water content. The empirical relationship between the flooded fraction of a grid cell and the grid cell mean water table position ($\overline{WT}$) can be established (Fig. ~~S2a~~1a) and approximated by an asymmetric sigmoid function, which is more computationally efficient than determining water table depth for each sub-grid pixel (Stocker et al., 2014). Here, we adopted the cost-efficient TOPMODEL from Stocker et al. (2014) and calibrated TOPMODEL parameters for each grid cell to match the spatial distribution of northern wetlands (see more details in Text S4). Tootchi et al. (201~~9~~8) reconciled multiple current wetland datasets and generated several high-resolution composite wetland (CW) maps. The one used here (CW-WTD) was derived by combining regularly flooded wetlands (RFW), which is obtained by overlapping three open-water and inundation datasets (ESA-CCI (Herold et al. 2015), GIEMS-D15 (Fluet-Chouinard et al., 2015), and JRC (Fluet-Chouinard et al., 2015)), with areas that have shallow (WT ≤ 20cm) water tables from groundwater modeling of (Fan et al., (2013). CW-WTD wetlands are static and aim at representing the climatological maximum extent of active wetlands and inundation. We therefore compare simulated maximum monthly mean monthly maximum wetland extent over 1980−2015 with CW-WTD to calibrate TOPMODEL parameters. Note that lakes from the HydroLAKES database have been excluded from the CW-WTD map because of their distinct hydrology and ecology compared with wetlands– (Tootchi et al., 2019)(Tootchi et al., 2018).

2.2.2 Peatland development criteria

The criteria used to constrain peatland area development are greatly inspired by Stocker et al. (2014)DYPTOP (Stocker et al., 2014), but with some adaptions.

The initiation of peatland only depends on moisture conditions of the grid cell (Fig. 1b S2b③ – ⑦): First, only the sub grid cell area fraction that is frequently inundated has the potential to become peatland (f_{pot}). Stocker et al. (2014) determined introduced a 'flooding persistency' parameter (*N* in Eq.12, Eq.13 in Stocker et al. (2014)) for the DYPTOP model– to represents the temporal frequency of inundationby comparing simulated peatland area fraction and total C storage with observations. *N* is a globally uniform parameter in DYPTOP, being set to 18 months during the preceding 31 years. However, the formation of peat is a function of local climate, and thus suitable formation conditions for peatland vary between geographic regions. To be specific, the accumulation of peat in arctic and northern latitudes is due both to high water table and to low temperature, while it is mainly a result of water-logging conditions in sub-tropical and tropical latitudes (Parish et al., 2008). Therefore, it is essential to apply different values for the 'flooding persistency' parameter for different regions, according to local climate conditions. We re-defined the requirement of persistent flooding for peatland formation as: the area fraction that has the potential to become peatland needs to be flooded at least *Num* months during the preceding 30 years, with *Num* being the total number of growing season months (monthly air temperature > 5 °C) in 30 years (Fig. S2b1b ⑤). In this case, with the help of relatively low air temperature making shorter growing seasons, arctic and boreal latitudes need shorter inundation periods than sub-tropical and tropical regions to form peatland. Furthermore, as *Sphagnum*-dominated peatlands are sensitive to summer moisture conditions (Alexandrov et al., 2016; Gignac et al., 2000), the summer water balance of the grid cell needs to pass a specific threshold (*SWB*) to form peat and to achieve the potential peatland area (Fig. ~~S2b~~1b ⑦). The summer water balance is calculated as the difference between total precipitation (P) and total potential evapotranspiration (PET) of May-September. We consider *SWB* as a tunable parameter in the model and run simulations with *SWB* = − 6 cm, 0 cm, 3 cm, and 6 cm. *SWB* = 6 cm is selected so that the model captures the southern frontier of peatland in Eurasia and western North America (Text S5). Note that the definition of summer (May-September) and *SWB* are not applicable for tropical regions and the Southern Hemisphere.

After the initiation, the development of peatland area is controlled by both moisture conditions of the grid cell and the long-term carbon balance of the peatland HSU (Fig. ~~S2c~~1c ⑨ – ⑰). If the climate becomes drier and the calculated potential peatland area is smaller than the current peatland area, the peatland HSU area will contract to the new potential peatland area fraction (Fig. ~~S2c~~1c ⑫). Otherwise (Fig. ~~S2c~~1c ⑬), the peatland has the possibility to expand when the summer water balance threshold is passed. If these above criteria are satisfied, the final decision depends on the carbon density of the peatland (C_{peat}): the peatland can expand only when long-term input exceeds decay and a certain amount of C (C_{lim}) has accumulated (Fig. ~~S2c~~1c ⑰). C_{lim} is defined here as long-term peatland C balance condition, it's a product of a mean measured peat depth (1.07 m) from 40 peat cores (with peat age greater than 1.8 ka but smaller than 2.2 ka) from North American peatland (Gorham et al., 2007, 2012) and from the West Siberian lowlands (Kremenetski et al., 2003), a dry bulk density assumption of 100.0 kg m^{-3} and a mean C fraction of 47% in total peat (Loisel et al., 2014). Our estimation for C_{lim} is 50.3 kg C m^{-2}, matches well with the C density criterion (50 kg C m^{-2}) chosen by Stocker et al. (2014) to represent typical peatland soil.

The moisture conditions are evaluated every month throughout the simulation, while C_{peat} is checked only in the first month after the S~~s~~ubC in Spin-up1 and is checked every month in Spin-up2 and the transient simulation (see Sect. 3.2). The peatland area fraction (f_{peat}) is updated every month. During the simulation, the contracted area and C are allocated to an ‘old peat’ pool and are kept track of by the model. It should be noted that drainage (drought) may cause decrease of porosity and saturated moisture content of peat soils (Oleszczuk and Truba, 2013) and, changes in peatland vegetation compositions (Benavides, 2014). But the current model structure doesn’t allow us to take these potential changes in peatland into consideration. Therefore, p~~P~~arameterizations of ~~this~~ the “old peat” pool ~~are~~is identical to mineral soils, following the study of Stocker et al. (2014). When peatland expansion happens, the peatland will first expand into this ‘old peat’ area and inherit its stored C (Stocker et al., 2014).

The difference between our model and the DYPTOP model in simulating peatland area dynamics can be summarized as follows: (1) TOPMODEL calibration: TOPMODEL parameters are globally uniform in the DYPTOP model, but grid cell-specific in ORCHIDEE-PEAT v2.0. (2) Criteria for peatland expansion: In the DYPTOP, the “flooding persistency” parameter is globally uniform, being 18 months in the preceding 31 years. And the ecosystem water balance is expressed as annual precipitation-over-actual-evapotranspiration (POAET). In ORCHIDEE-PEAT v2.0, the flooding persistency parameter is grid cell-specific, being the total number of growing season months in the preceding 30 years. And peatland expansion is limited only by summer water balance. The relative areal change of peatland is limited to 1% per year in DYPTOP, but not limited in our model. (3) Peatland initiation: DYPTOP prescribes a very small peatland area fraction (0.001%) in each grid cell to simulate peatland C balance condition. Peatland can expand from this “seed” once water and carbon balance criteria are met. In ORCHIDEE-PEAT v2.0, no “seed” is needed because only the flooding persistency and summer water balance criteria need to be met for the first initiation of peatland (Fig. 1b), carbon balance is only checked after initiation (Fig.1c).

~~4.~~3.Simulation setup and evaluation datasets

3.1 Critical Model parameters

The base decomposition rates of active, slow and passive peat soil carbon pools in the model are 1.0 a^{-1}, 0.027 a^{-1} and 0.0006 a^{-1} at reference temperature of 30 °C, respectively (Table 1, Sect. 5: Choice of model parameters). The e-folding depth of the depth modifier (z_0, Eq. 2) determines the general shape of increases of soil C turnover time with depth; the prescribed threshold to allow downward C transfer between soil layers (f_{th}, Eq. 5) and the prescribed fraction of C to be transferred (f, Eq. 4) determine movement and subsequent distribution of soil C along the soil profile. We compare simulated C vertical profiles with observed C profiles at 15 northern peatland sites (Table S1) (Loisel et al., 2014) using different combinations of parameters ($z_0 = (0.5, 1.0, 1.5, 2.0)$, $f_{th} = (0.5, 0.7, 0.9)$ and $f = (0.1, 0.2, 0.3)$) and eventually selected $z_0 = 1.5\ m$, $f_{th} = 0.7$ and $f = 0.1$ based on visual examinations to match the observed C content. Model sensitivity to the selection will be discussed in Sect. 5.

3.2 Simulation protocol

We conduct both site-level and regional simulations with ORCHIDEE-PEAT v2.0 at 1° × 1° spatial resolution. Regional simulations are performed for the Northern Hemisphere (>30° N), while site-level simulations are performed for 60 grid cells containing at least one peat core (Table S1, Fig. ~~S3~~S2). Peat cores used in site-level simulations are from the Holocene Perspective on Peatland Biogeochemistry database (HPPB) (Loisel et al., 2014). Both site-level and regional simulations are forced by the 6-hourly meteorological forcing from the CRUNCEP v8 dataset, which is a combination of the CRU TS monthly climate dataset and NCEP reanalysis (https://vesg.ipsl.upmc.fr/thredds/catalog/store/p529viov/cruncep/V7_1901_2015/catalog.html).

All simulations start with a two-step spin-up followed by a transient simulation after the pre-industrial period (Fig. ~~S4~~S3). The first spin-up (Spin-up1) includes *N* cycles of a peat carbon accumulation acceleration procedure consisting of 1) 30 years with the full ORCHIDEE-PEAT (FullO) run on 30 min time step followed by 2) a stand-alone soil carbon sub-model (SubC) run to simulates the soil carbon dynamics in a cost effectively way on monthly steps (fixed monthly litter input, soil water and soil thermal conditions from the preceding FullO simulation). Repeated 1961−1990 climate forcing is used in Spin-up1 to approximate the higher Holocene temperatures relative to the preindustrial period (Marcott et al., 2013). The atmospheric CO_2 concentration is fixed at the preindustrial level (286 ppm). Each time we run the SubC for 2000 years (2 ka) in the first $N-1$ sets of acceleration procedures while, the value of N and the time length of the last set of acceleration procedure (X) are defined according to the age of the peat core in site-level simulations, and are defined according to the reconstructed glacial retreat in regional simulations (Fig. ~~S5~~S4, ~~S6~~S5). The reconstructed glacial retreat used in this study are from Dyke (2004) for North America and are from Hughes et al. (2016) for Eurasia (Text S6).

In the second spin-up step (Spin-up2), the full ORCHIDEE-PEAT model was run for 100 years, forced by looped 1901−1920 climate forcing and preindustrial atmospheric CO_2 concentration so that physical and carbon fluxes can approach to the preindustrial equilibrium. After the two spin-ups, a transient simulation is run, forced by historical climate forcing from CRUNCEP and rising atmospheric CO_2 concentration. For site-level simulations, the transient period starts from 1860 and ends at the year of coring (Table S1). For regional simulations, the transient period starts from 1860 and ends at 2009.

3.3 Evaluation datasets

3.3.1 Evaluation datasets for site-level simulations

All peatland sites used in this study are from the HPPB database (Loisel et al., 2014). All the peat cores measured peat ages and depths (60 sites, Table S1), hence are used to evaluate simulated peat depth, with sites being grouped into different peatland types, climate zones and ages. For peat cores where peat ages, depths, fraction of C and bulk density were recorded (15 sites marked in red in Table S1), we construct vertical C profiles with this measured information to compare with our simulated C profiles.

3.3.2 Northern peatland evaluation datasets for regional simulations

Area

Simulated peatlands area in 2009 is evaluated against: 1. World Inventory of Soil Emission potentials (WISE) database (Batjes, 2016); 2. An improved global peatland map (PEATMAP) by reviewing a wide variety of global, regional and local scale peatland distribution information (Xu et al., 2018); 3. International Mire Conservation Group Global Peatland Database (IMCG-GPD) (Joosten, 2010); 4. Peatland distribution map by Yu et al. (2010).

Soil organic carbon stocks

Simulated peatlands SOC is evaluated against: 1. The WISE database (Batjes, 2016); 2. The IMCG-GPD (Joosten, 2010).

All the above-mentioned datasets used to evaluate ORCHIDEE-PEAT v2.0 at regional scale are described in the Supplement Text S7.

Peat depth

Gorham et al. (2007, 2012) and Kremenetski et al. (2003) collected depth and age of 1685 and 130 peat cores, respectively, from literature data on peatlands in North America (NA) and in the West Siberian lowlands (WSL). These compilations make it possible for us to validate peat depths simulated by ORCHIDEE-PEAT v2.0 at regional scales, in addition to the detailed site-runs in Sect. 3.3.1. Compared to the HPPB database, these datasets lack detailed peat properties (i.e. C content, peatland type…), but contain more samples and cover larger areas. Note that as this study aims to reproduce development of northern peatlands since the Holocene, peat cores that are older than 12 ka are removed from the model evaluation. At last, 1521 out of 1685 observed peat cores in NA, 127 out of 130 observed peat cores in WSL, are used in model evaluation (Sect. 4.2: Peat depth).

~~5.~~4. Results

~~5.1~~4.1 Site simulation

We first evaluate the performance of ORCHIDEE-PEAT v2.0 in reproducing peat depths and vertical C profiles at the 60 sites from HPPB (Table S1). Out of the 60 grid cells (each grid cell corresponding to one peat core), ORCHIDEE-PEAT v2.0 produces peatlands in 57 of them. The establishment of peatlands at Zoige, Altay and IN-BG-1 (Table S1) is prevented in the model by the ~~unmet~~ summer water balance criterion~~a~~ of these grid cells. ~~Simulated peat~~Peat depths are underestimated for most sites (Fig. 2). Simulated depth of these 57 sites ranges from 0.37 m to 6.64 m and shows a median depth of 2.18 m ~~(Table 1)~~, while measured peat depth ~~shallower than observations~~ ~~(~~ranges from 0.96 to 10.95 m, with the ~~observed~~ measured median depth being 3.10 m (Table 2)~~)~~. The root mean square error (RMSE) between observations and simulations is 2.45 m.

The measured and simulated median peat depths for the 14 fen sites are 3.78 m and 2.16 m, compared to 3.30 m and 2.18 m, respectively for the 33 bog sites (Table ~~1~~2). The model shows slightly higher accuracy for fens than for bogs, with RMSE for fens being 2.08 m and 2.59 m for bogs~~ (Fig. 1a)~~. RMSE for peat depths of sites that are older than 8 ka are greater than that of younger sites, but are smaller than the measured mean depth (3.5 m) of all peat cores~~ (Fig. 1b)~~. Simulated median ~~peat~~depth of the 6 arctic sitess are ~~deeper ~~larger than observations~~ at the 6 arctic sites~~, but that of the 47 boreal sites and the 4 temperate sites are ~~shallower ~~smaller than observations ~~at the 47 boreal sites and at the 4 temperate sites ~~(Table ~~1~~2). The RMSE for temperate sites is larger than that for arctic or boreal sites~~rises above the measured mean depth of all cores (Fig. 1c)~~.

The simulated and observed vertical profiles of soil C for the 15 sites are shown in Fig. ~~2~~3, simulated C concentrations are generally within the range of measurements at most of the sites, but are underestimated at Sidney bog, Usnsk Mire 1, Lake 785 and Lake 396. In the model, the buildup of peat is parameterized by downward movement of C between soil layers, with the maximum amount of C that each layer can hold being calculated from median observed bulk density and C fraction of peat core samples (Sect. 2.1.2). High C concentration of cores that have significantly larger bulk density and / or C fraction than the median of the measurements thus cannot be reproduced. This is the case of Lake 785 and Lake 396 (Table S1), where C concentrations are underestimated and depths are overestimated (Fig. 2), while simulated total C content is close to observations (for Lake 785, measured and simulated C content is 86.14 $\mathrm{kgC\ m^{-2}}$ and 96.13 $\mathrm{kgC\ m^{-2}}$, respectively, while values for Lake 396 are 57.2 and 70.2 $\mathrm{kgC\ m^{-2}}$).

As shown in Fig. ~~3~~4, there is considerable variability in depth and C concentration profiles among peat cores within a grid cell, even though these cores have a similar age. We rerun the model at the 5 grid cells where more than one peat core has been sampled, with time length of the simulation being defined as the mean age of cores in the same one grid cell. The simulated peat depth and C concentration profiles at G2, G4, and G5 are generally within the range of peat core measurements (Fig. ~~3~~4). ~~G1 and G3 is the same case as Lake 785 and Lake 396.~~ Observed C fraction at grid cell G1 and G3 are much greater than the median value of all peat core samples (Sect. 2.1.2), thus simulated C concentration along the peat profile are smaller than observations, but peat depth are still overestimated by the model. As it is the case with Lake 785 and Lake 396.

~~5.2~~4.2 Regional simulation

Northern peatlands area and C stock

Simulated maximum inundated area of the Northern Hemisphere is 9.1 million km^2, smaller than the wetland areas in CW-WTD (~13.2 million km^2 after excluding lakes). TOPMODEL gives an area fraction at maximum soil water content while CW-WTD includes both areas seasonally to permanently flooded and areas that are persistently saturated or near-saturated (the maximum water table shallower than 20 cm) soil-surface. Therefore, an exact match between CW-WTD and the model prediction is not expected. The model generally captures the spatial pattern of wetland areas represented by CW-WTD (Fig. ~~S7~~5). The multi-sensor satellite-based GIEMS dataset (Prigent et al., 2007, 2012) which provides observed monthly inundation extent over the period of 1993 − 2007 is used to evaluate simulated seasonality of inundation. Fig. 6 shows that the seasonality of inundation is generally well captured by the model, although simulated seasonal maximum of inundation extent occurs earlier than observations (except in WSL) and simulated duration of inundation is longer than observations.

While our model predicts the natural extent of peatlands under suitable climate conditions, soil formation processes and soil erosion are not included in the model. We mask grid cells that are dominated by Leptosols, which are shallow or stony soils over hard rock, or highly calcareous material (Nachtergaele, 2010) (Fig. ~~S8~~S6, Fig. ~~S9~~S7). Peatlands have been extensively used for agriculture after drainage and / or partial extraction worldwide (Carlson et al., 2016; Joosten, 2010; Leifeld and Menichetti, 2018; Parish et al., 2008). Intensive cultivation practices might cause rapid loss of peat C and ensuing disappearance of peatland. Additionally, agricultural peatlands are often classified as cropland, not as organic soils (Joosten, 2010). Therefore, we masked agricultural peatland from the results by assuming that crops occupy peatland in proportion to the grid cell peatland area (Carlson et al., 2016). The distribution and area of cropland used here is from the MIRCA2000 data set (Portmann et al., 2010), which provides monthly crop areas for 26 crop classes around the year 2000 and includes multicropping explicitly (Fig. ~~S10~~S8). After masking Leptosols and agricultural peatlands from the simulated peatland areas and peatland C stocks, the simulated total northern peatlands area is 3.9 million km^2 ($f_{\mathrm{noLEP\text{-}CR}}$, Fig. ~~4d~~7d), holding 463 PgC ($C_{\mathrm{noLEP\text{-}CR}}$, Fig. ~~5b~~8b). These estimates fall well within estimated ranges of northern peatland area (3.4 – 4 million km^2) and carbon stock (270 – 540 PgC) (Gorham, 1991; Turunen et al., 2002; Yu et al., 2010). Simulated peatland area matches relatively well with PEATMAP data in Asian Russia but overestimates peat area in European Russia (Table ~~2~~3). The simulated total peatlands area of Canada is in relatively good agreement with the three evaluation data sets, though the world’s second largest peatland complex~~hotspot~~ at the Hudson Bay lowlands (HBL) is underestimated and a small part of the northwest Canada peatlands is missing. ~~(~~Packalen et al.~~,~~ (2014) stressed that initiation and development of HBL peatlands are driven by both climate and glacial isostatic adjustment (GIA), with initiation and expansion of HBL peatlands tightly coupled with land emergence from the Tyrrell Sea, following the deglaciation of the Laurentide ice sheet and under suitable climatic conditions. The pattern of peatlands at southern HBL was believed to be driven by the differential rates of GIA rather than climate (Glaser et al., 2004a, 2004b). More specifically, Glaser et al. (2004a, 2004b) suggested that the faster isostatic uplift rates on the lower reaches of the drainage basin reduce regional slope, impede drainage and shift river channels. Our model, however, can’t simulate the tectonic and hydrogeologic controls on peatland development. In addition, the development of permafrost at depth as peat grows in thickness over time acts to expand peat volume and uplift peat when liquid water filled pores at the bottom of the peat become ice filled pores (Seppälä, 2006). This process is not accounted for in the model and may explain why the HBL does not show up as a large flooded area today whereas peat developed in this region during the early development stages of the HBL complex. ~~In Alaska, T~~The simulated distribution of peatland area in Alaska agrees well with Yu et al. (2010) and WISE. There is a large overestimation of peatland area in southeastern US (Table ~~2~~3, Fig. ~~4d~~7d). The simulated peat C stock in Russia (both the Asian and the European part), and in US are overestimated compared to IMCG-GPD and WISE, but that of Canada is underestimated (Table ~~3~~4, Fig. ~~5b~~8b).

Peat depth

Fig. ~~6~~ 9 shows measured and simulated peat depth in NA and WSL. Some peat cores are sampled from the Canadian Arctic Archipelago, southwestern US and the northern tip of Quebec, where there is no peatland in peat inventories / the soil database. These sites support the notion that the formation and development of peatland are strongly dependent on local conditions, i.e. retreat of glaciers, topography, drainage, vegetation succession (Carrara et al., 1991; Madole, 1976). As a large-scale LSM, the model can't capture every single peatland: 429 out of 596 grid cells that contain observed peat cores in NA are captured by the model, while the model simulates peatlands in 54 out of 60 observed grid cells in WSL. ~~We do not expect the model to capture every single peatland because it is a large-scale LSM. Therefore, C~~Cores that are not captured by the model are removed from further analysis (319 out of 1521 peat cores in NA, 18 out of 127 peat cores in WSL, are removed).

As shown in Fig. ~~3~~4, within a grid cell, sampled peat cores can have very different depths and / or ages. We calculate the mean depth of cores in each of the grid cells and compare it against the simulated mean depth. The mean age of cores in each of the grid cells is used to determine which output of the model should be examined. For instance, the mean age of the four cores in grid cell (40.5 °N, 74.5 °W) is 2.5 ka, and accordingly, we pick out the simulated depth of this grid cell right after the first run of SubC (Fig. ~~S4~~S3) to compare with the mean depth of these cores. We acknowledge that this is still a crude comparison since the simulation protocol implies that we can only make the comparison at 2000-year intervals. Nonetheless, it is a compromise between running the model for 1815 peat cores independently and comparing the mean depth of measured points with grid-based simulated depth. As shown in Fig. ~~7~~10, for each age interval (of both the West Siberian lowlands and North America), the variation in simulated depth is smaller than that in the measurement. The two deepest simulated peat in WSL belong to the fourth age group (6 < Age ≤ 8 ka) and are the result of a shallow active layer; while C is moving downward to deeper and deeper layers, the decomposition is greatly limited by cold conditions at depth. At both WSL and NA, simulated median peat depths (2.07 – 2.36 m at WSL, 1.02 – 2.15 m at NA~~-~~) are in relatively good agreement with measurements (1.8 – 2.31 m at WSL, 0.8 – 2.46 m at NA) for cores younger than 8 ka (Fig. ~~7~~10). For the two oldest groups (peat age > 8 ka), the simulated median depths are about 0.70 m shallower than measurements at NA and about 1.04 m shallower at WSL.

Undisturbed northern peatland carbon balance in the past century

Simulated mean annual (averaged over 1901 – 2009) net ecosystem production (NEP) of northern peatlands varies from – 63 gC m^{-2} a^{-1} to 46 gC m^{-2} a^{-1} (Fig. ~~8~~11). The West Siberian lowlands, the Hudson Bay lowlands, Alaska, and the China-Russia border are significant hotspots of peatland C uptake. Simulated mean annual NEP of all northern peatlands over 1901 – 2009 is 0.1 PgC a^{-1}, consistent with the previous estimate of 0.076 PgC a^{-1} by Gorham (1991) and the estimate of 0.07 PgC a^{-1} by Clymo et al. (1998). From 1901 to 2009, both simulated net primary production (NPP) and simulated heterotrophic respiration (HR) show an increasing trend, but NPP rises faster than HR during the second half of the century (Fig. ~~9a~~12a). The increase of NPP is caused by atmospheric CO_2 concentration and increasing of air temperature (Fig. ~~9~~12, Fig. ~~S11~~S9). As air (soil) temperature increases, HR also increases but lags behind NPP (Fig. ~~9~~12, Fig. ~~S11~~S9). Simulated annual NEP ranges from –0.03 PgC a^{-1} to 0.23 PgC a^{-1}, with a significant positive trend over the second half of the century (Fig. ~~9b~~12b). NEP shows a significant positive relationship with air (soil) temperature and with atmospheric CO_2 concentration (Fig. ~~S11~~S9). CH_4 and dissolved organic carbon (DOC) are not yet included in the model, both of them are significant losses of C from peatland (Roulet et al., 2007).

~~6.~~5. Discussion

Peat depth

We found a general underestimation of peat depth (Fig. ~~1~~2, Fig. ~~7~~10), possibly due to the following ~~several~~ reasons. Firstly, there is a lack of specific local climatic and topographic conditions: The surfaces of peatlands are mosaics of microforms, with accumulation of peat occurring at each individual microsites of hummocks, lawns and hollows. Differences in vegetation communities, thickness of the unsaturated zone, local peat hydraulic conductivity and transmissivity between microforms result in considerable variation in peat formation rate and total C mass (Belyea and Clymo, 2001; Belyea and Malmer, 2004; Borren et al., 2004; Packalen et al., 2016). Cresto Aleina et al. (2015) found that the inclusion of microtopography in the Hummock-Hollow model delayed the simulated runoff and maintained wetter peat soil for a longer time at a peatland of Northwest Russia, thus contributed to enhanced anoxic conditions. Secondly, site-specific parameters are not included in gridded simulations: Parameters describing peat soil properties, i.e., soil bulk density and soil carbon fraction, determine the amount of C that can be stored across the vertical soil profile. Hydrological parameters, i.e., the hydraulic conductivity and diffusivity, and the saturated and residual water content, regulate vertical fluxes of water in the peatland soil and expansion/contraction of the peatland area, and hence influence the decomposition and accumulation of C at the sites considered. Plant trait parameters, i.e. the maximal rate of carboxylation (V_{cmax}), the light saturation rate of electron transport (J_{max}) determine the carbon budgets of the sites (Qiu et al., 2018). The depth modifier, which parameterizes depth dependence of decomposition, controls C decomposition at depth and is an important control on simulated total C and the vertical C profile. A third reason is sample selection bias: Ecologists and geochemists tend to take samples from the deepest part of a peatland complex to obtain the longest possible records (Gorham, 1991; Kuhry and Turunen, 2006). In contrast, the model is designed to model an average age and C stock of peatlands in a grid location and thus preferably, the simulated C concentrations of a grid cell should only be validated against grids represented by a number of observed cores. We do try to compare the model output with multiple peat cores (Fig. ~~3~~4, Fig. ~~7~~10), but we need to note that shallow peats are not sufficiently represented in field measurements. A fourth source of error is that simulated initiation time of peat development at some sites are too late compared to ages of measured cores: The model multiple spin-up strategy ~~is designed to~~ accounts for coarse-scale ice-sheet distribution at discrete Holocene intervals (Sect. 3.2, Fig. ~~S4~~S3), and if the modelled occurrence of peatland is too late, the accumulated soil C may be underestimated. For example, at the Patuanak site, where the core age is 9017 ~~k~~a, the model was run with 4 times' SubC (Table S1). However, there was no peatland before the first SubC, meaning that simulated peatland at this grid cell was 2000 years younger than the observation and that our simulation missed C accumulation during the first 2000 years at this site. This may be another source of bias associated with the model resolution, namely that local site conditions fulfilled the initiation of peatland at specific locations, but the average topographic and climatic conditions of the coarse model grid cell were not suitable for peatland initiation. Also, one has to keep in mind that a single / a few sample (s) from a large peat complex may not be enough to capture the lateral spread of peat area, which may be an important control on accumulation of C (Charmen, 1992; Gallego-Sala et al., 2016; Parish et al., 2008). The underestimation of peat depth can also come from biased climate input data: Spin-ups of the model are forced with repeated 1961−1990 climate, assuming that Holocene climate is equal to recent climate. While peatland carbon sequestration rates are sensitive to climatic fluctuations, centennial to millennial scale climate variability, i.e. cooling during the Younger Dryas period and the Little Ice Age period, warming during the Bølling-Allerød period are not included in the climate forcing data (Yu et al., 2003a, 2003b). An early Holocene carbon accumulation peak was found during the Holocene Thermal Maximum when the climate was warmer than present (Loisel et al., 2014; Yu et al., 2009). Finally, effects of landscape morphology on drainage as well as drainage of glacial lakes are not incorporated and can represent a source of uncertainty.

Vertical profiles of peatland soil organic carbon

We note that caution is needed in interpreting the comparison between simulated peat C profile and measured C profile from peat cores (Fig. 3, Fig. 4). In reality, peat grow both vertically and laterally since inception, with the peat deposit tend to be deeper and its basal age tend to be older at the original nucleation sites / center of the peatland complex (Bauer et al., 2003; Mathijssen et al., 2017). As mentioned earlier, field measurements tend to take samples from the deeper part of a peatland complex and shallow peat are underrepresented. The model, however, only simulates peat growth in the vertical dimension and lacks an explicit representation of the lateral development of a peatland in grid-based simulations, thus simulated peat C (per unit peatland area) is diluted when the simulated peatland area fraction in the grid cell increases. In addition, while a dated peat core tells us net burial of peat C during time intervals, the model can't provide a peat age-depth profile because it simulates peat C accumulation based on decomposition of soil C pools, rather than tracking peat C as cohorts over depth/time (Heinemeyer et al., 2010).

The above-noted discrepancies between the simulation and the observation highlight both the need for more peat core data collected with more rigorous sampling methodologies and the need to improve the model. In parallel with this study, ^{14}C dynamics in the soil has been incorporated into the ORCHIDEE-SOM model (Tifafi et al., 2018), which may give us an opportunity to compare simulated ^{14}C age-depth profiles with dated peat C profiles in the future after being merged with our model.

Simulated peatland area development

The initiation and development of peatlands in NA followed the retreat of the ice sheets, as a result of the continuing emergence of new land with the potential to become suitable for peatland formation (Gorham et al., 2007; Halsey et al., 2000). To take glacial extent into account for simulating the Holocene development of peatlands, we use ice sheet reconstructions in NA and Eurasia (Fig. ~~S5~~S4, ~~S6~~S5). Not surprisingly, when ice cover is considered, the area of peatlands that developed before 8 ka is significantly decreased, while the area that developed after 6 ka is increased (Fig. ~~10~~13). We use observed frequency distribution of peat basal age from MacDonald et al. (2006) as a proxy of peatland area change over time, following the assumption proposed by Yu (2011) that peatland area increases linearly with the rate of peat initiation. We grouped the data of MacDonald et al. (2006) into 2000-years bins to compare with simulated peatlands area dynamics (Fig. ~~10~~13). The inclusion of dynamic ice sheet coverage triggering peat inception clearly improved the model performance in replicating peatland area development during the Holocene, though the peatland area before 8 ka is still overestimated by the model in comparison with the observed frequency distribution of basal ages (Fig. ~~10~~13). In spite of the difference in peatlands area expansion dynamics between the simulation that considered dynamic ice sheets and the one that did not, the model estimates of present-day total peatland area and carbon stock are generally similar (Fig. ~~S12~~S10). Without dynamic ice sheet, the model would predict only 0.1 million km^2 more peatland area and 24 Pg more peat C over the Northern Hemisphere (>30 °N). We are aware of two studies that attempted to account for the presence of ice sheets during the Holocene (Kleinen et al., 2012) and the last Glacial Maximum (Spahni et al., 2013) while simulating peatland C dynamics. Kleinen et al. (2012) modelled C accumulation over the past 8000 years in the peatland areas north of 40 °N using the coupled climate carbon cycle model CLIMBER2-LPJ. A decrease of 10 PgC was found when ice sheet extent at 8 ka BP (from the ICE-5G model) was accounted for. Another peatland modelling study conducted by Spahni et al. (2013) with LPX also prescribed ice sheets and land area from the ICE-5G ice-sheet reconstruction (Peltier, 2004), but influences of ice sheet margin fluctuations on simulated peatland area and C accumulation were not explicitly assessed in their study.

The peatland carbon density criterion for peatland expansion (C_{lim}) is an important factor impacting the simulated Holocene trajectory of peatlands development. Without the limitation of C_{lim}, a larger expansion of northern peatlands would occur before 10 ka (Fig. ~~S13~~S11). Such a premature, ‘explosive’ increase of peatland area would result into the overestimation of C accumulated in the early Holocene in the model. In the meantime, peatland area in regions that only have small C input, i.e. Baffin Island, and northeast Russia, would be overestimated (Fig. ~~S14~~S12).

Choice of model parameters

For the active, slow and passive peat soil carbon pool, the base decomposition rates are 1.0 a^{-1}, 0.027 a^{-1} and 0.0006 a^{-1} at reference temperature of 30 °C, respectively, meaning that the residence times at 10 °C (no moisture and depth limitation) of these three pools are 4 years, 148 years and 6470 years. In equilibrium / near- equilibrium state, simulated C in the active pool takes up only a small fraction of the total peat C, while generally 40% − 80% of simulated peat C are in the slow C pool and about 20% − 60% are in the passive C pool. Assuming that in a peatland, the active, slow and passive pool account for 3%, 60%, and 37% (median values from the model output of the year 2009) of the total peat C, we can get a mean peat C residence time of 2500 years. If depth modifier is considered, the C residence time will vary from 2500 years at the soil surface to 13200 years at the 2.5 m depth. For the record, in previous published large-scale diplotelmic peatland models, at 10 °C, C residence time for the acrotelm (depth = 0.3 m) ranged from 10 to 33 years and ranged from 1000 to 30000 years for the catotelm (Kleinen et al., 2012; Spahni et al., 2013; Wania et al., 2009b). We performed sensitivity tests to show the sensitivity of the modelled peat C to model parameters at the 15 northern peatland sites where observed vertical C profiles can be constructed (Table S1). Tested parameters are the e-folding decreasing depth of the depth modifier (z_0, Eq. 2), the prescribed thresholds to start C transfer between soil layers (f_{th}, Eq. 5) and the prescribed fraction of C transferred vertically (f, Eq. 4). We found that changing f_{th} or f leads to only small effects on the vertical soil C profile (see e.g. Burnt Village peat site in Fig. ~~S15~~S13). The parameter z_0, by contrast, exerts a relatively strong control over C profiles. It is noteworthy that while our model resolves water diffusion between soil layers according to the Fokker–Planck equation (Qiu et al., 2018), simulated soil moisture does not necessarily increase with depth (Fig. S14~~4~~). z_0 is therefore an important parameter to constrain peat decomposition rates at depth. With smaller z_0, decomposition of C decreases rapidly with depth, resulting in deeper C profile (Fig. ~~S15~~S13). Regional scale tests verified these behaviors of the model: ~~w~~When $f_{th} = 0.9$ is used (instead of $f_{th} = 0.7$), changes in peatland area and peat C stock are negligible (Fig. ~~S16~~S15~~);~~). Without z_0, simulated northern peatlands area will not change (3.9 million km2), but northern peatlands C stock will be underestimated (only 300PgC). If $z_0 = 0.5$ m is applied (instead of $z_0 = 1.5$ m), the simulated total peat C would triple while the total peatland area would only increase by 0.2 million km^2 (Fig. ~~S17~~S16). ~~This illustrates the importance of constraining decomposition rates at depth in peatland models.~~

Uncertainties in peatland area and soil C estimations

There are large uncertainties in estimates of peatland distribution and C storage. Some studies prescribe peatlands from wetlands. However, in spite of the fact that there are extensive disagreements between wetland maps, it is a challenge to distinguish peatlands from non-peat forming wetlands (Gumbricht et al., 2017; Kleinen et al., 2012; Melton et al., 2013; Xu et al., 2018). Estimates based on peatland inventories are impeded by poor availability of data, non-uniform definitions of peatlands among regions and coarse resolutions (Joosten, 2010; Yu et al., 2010). In addition, as peatlands are normally defined as waterlogged ecosystems with a minimum peat depth of 30 cm or 40 cm, shallow peats are underrepresented. Another approach to estimate peatland area and peat C is to use a soil organic matter map to outline organic-rich areas, such as histosols and histels (Köchy et al., 2015; Spahni et al., 2013). This approach overlooks local hydrological conditions and vegetation composition (Wu et al., 2017). Our model estimates of peatland area and C stock generally fall well within the range of published estimates, except in southeastern US, where there is only 0.05 – 0.10 million km^2 of peatland in observations but 0.37 million km^2 in the model prediction (Fig. ~~4d~~7d, Table ~~2~~3). From early 1600's to 2009, ~ 50% of the original wetlands in the lower 48 states of US have been lost to agricultural, urban development and other development (Dahl, 2011; Tiner Jr, 1984). Although wetlands are not necessarily peatlands, the reported losses of wetlands in US indicating that a potentially large area of peatlands in US may have been lost to land use change. However, historical losses of peatlands due to land use change and the impact of agricultural drainage of peatlands haven't been taken into account by our model. ~~We notice a large interannual variability in peatland area and C predictions in southeastern US (Fig. S18), which suggests that some areas are not suitable for long-term development of peatlands.~~ Another factor that might have contributed to the overestimation is a limitation of TOPMODEL, namely that the 'floodability' of a pixel in the model is determined by its compound topographic index (CTI) value regardless of the pixel's location along the stream, and thus the floodability of an upstream pixel with a large CTI might be affected by downstream pixels that have small CTI. The model's inability to resolve small-scale streamflows might be another cause of the overestimation. ~~Fires, historical peat extraction and drainage posed great dangers to peatlands, but are not considered in this study (Hatala et al., 2012; Turetsky et al., 2004, 2015).~~

The simulated mean annual NPP, HR and NEP of northern peatlands increase from about 1950 onwards. We find positive relationships between NPP and temperature, NPP and atmospheric CO_2 concentration, as well as HR and temperature over the past century (Fig. S11S9). From a future perspective, it is unclear whether the increasing trend of NEP can be maintained. While photosynthetic sensitivity to CO_2 decreases with increasing atmospheric CO_2 concentration and photosynthesis may finally reach a saturation point in the future, decomposition is not limited by CO_2 concentration and may continue to increase with increasing temperature (Kirschbaum, 1994; Wania et al., 2009b).

Our model applies a multi-layer approach to simulate process-based vertical water fluxes and dynamic C profiles of northern peatlands, highlights the vertical heterogeneities in the peat profile in comparison to previous diplotelmic models (Kleinen et al., 2012; Spahni et al., 2013; Stocker et al., 2014; Wania et al., 2009b). While simulating peatland dynamics, large-scale models used a static peatland distribution map obtained from peat inventories / soil classification map (Largeron et al., 2018; Wania et al., 2009b, 2009a), or prescribed the trajectory of peatland area development over time (Spahni et al., 2013), or used wetland area dynamics as a proxy (Kleinen et al., 2012). We adapt the scheme of DYPTOP, to simulate spatial and temporal dynamics of northern peatland area however, predicted peatland area dynamics by combing simulated inundation and a set of peatland expansion criteria (Stocker et al., 2014).

As a large-scale LSM which is designed for large-scale gridded applications, ORCHIDEE-PEAT v2.0 cannot explicitly model the lateral development of a peatland. The model therefore aims to simulate average peat depth and C profile in a grid location rather than capturing peat inception time and age-depth profiles of peat cores. For tropical peatlands, the model needs to be improved to represent its tree dominance, oxidation of deeper peat due to pneumatophore (breather roots) of tropical trees, and the greater water table fluctuations as a result of the higher hydraulic conductivity of wood peats and tropical climates (Lawson et al., 2014). In addition, tropical peat is formed as riparian seasonally flooded wetlands with water coming from upstream river networks, whereas the TOPMODEL equations used here implicitly assume a peatland is formed in a grid cell only from rainfall water falling into that grid-cell. We add the scheme of DYPTOP into our model with some adaptions to simulate spatial and temporal dynamics of northern peatland area. Further work to improve this simulation framework is needed in areas such as an accurate representation of the Holocene climate, higher spatial resolution, distinguish bogs from fens to better parameterize water inflows into peatland. Including CH_4 emissions and leaching of DOC will be helpful to get a more complete picture of peatland C budget.

7. 6. Conclusions

Multi-layer schemes have been proven to be superior to simple box configurations in ESMs at realistic modeling of energy, water and carbon fluxes over multilayer ecosystems (De Rosnay et al., 2000; Jenkinson & K. Coleman, 2008; Best et al., 2011; Wu et al., 2016). We apply multi-layer approaches to model vertical profiles of water fluxes and vertical C profiles of northern peatlands. Besides representations of peatland hydrology, peat C decomposition and accumulation, a dynamic model of peatland extent is also included. The model shows good performance at simulating average peat depth and vertical C profile in grid-based simulations. Modern total northern peatlands area and C stock is simulated as 3.9 million km^2 and 463 PgC (Leptosols and agricultural peatlands have been marsked), respectively. While this study investigated the capability of ORCHIDEE-PEAT v2.0 to hindcast the past, in ongoing work, the model is being used to explore how peatlands area and C cycling may change under future climate scenarios.

Author contribution:

CQ implemented peatland water and carbon processes into ORCHIDEE-MICT, introduced the dynamic peatland area module and performed the simulation. DZ contributed to ensuring consistency between the peatland modules and various other processes and modules in the model. PC conceived the project. PC, BG, GK, DZ and CQ contributed to improving the research and interpreting results. SP assisted in implementing of the cost-efficient TOPMODEL. AT and AD provided the dataset of wetland areas. SP, AT, AD and AH contributed to the calibration of the TOPMODEL. All authors contributed to the manuscript.

Code availability:

The source code is available online via: https://forge.ipsl.jussieu.fr/orchidee/wiki/GroupActivities/CodeAvalaibilityPublication/ORCHIDEE_PEAT_V2.~~http://forge.ipsl.jussieu.fr/orchidee/browser/branches/publications/ORCHIDEE-PEAT_r5488,~~

Readers interested in running the model should follow the instructions at http://orchidee.ipsl.fr/index.php/you-orchidee.

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Table 1. Parameter values in peatland modules of ORCHIDEE-PEAT v2.0.

Parameter	Value	Description
$k_{0,i}$		the base decomposition rate of carbon pools, Eq. 1
$k_{0,i}$: i=*active*	1.0 a^{-1}	the base decomposition rate of the active pool at 30 °C, Eq. 1
$k_{0,i}$: i=*slow*	0.027 a^{-1}	the base decomposition rate of the slow pool at 30 °C, Eq. 1
$k_{0,i}$: i=*passive*	0.0006 a^{-1}	the base decomposition rate of the passive pool at 30 °C, Eq. 1
z_0	1.5m	The e-folding depth of base decomposition rate, Eq. 2
f	0.1	The fraction of carbon content in the model layer to be transported to the layer below, Eq. 4
f_{th}	0.7	The amount (fractional) of carbon content that the model layer need to hold before transporting carbon to the layer below, Eq. 5
m	gridcell specific	TOPMODEL parameter (the saturated hydraulic conductivity decay factor with depth), Fig.1, TextS4
CTI_{min}	gridcell specific	TOPMODEL parameter (the minimum CTI for floodability), Fig.1, TextS4
Num	gridcell specific	The total number of growing season months in the preceding 30 years, Fig.1, Sect. 2.2.2
SWB	6 cm	Minimum summer water balance, Fig.1, Sect. 2.2.2
C_{lim}	50.3 kg C m^{-2}	Minimum peat C density , Fig.1, Sect. 2.2.2

Table ~~1~~2. Measured and simulated minimum, maximum and median depth (m) of peat cores, grouped by peatland types, ages, and climatic regions. The root mean square errors between observations and simulations are also listed.

	Measured			Simulated			
	Minimum	Maximum	Median	Minimum	Maximum	Median	RMSE
Fens	1.10	7.25	3.78	0.75	4.30	2.16	2.08
Bogs	0.96	10.95	3.30	0.75	5.49	2.18	2.59
Others	1.00	3.95	1.94	0.37	6.64	2.38	2.46
12 ka ≤ Age	2.45	8.61	3.52	0.37	3.21	2.64	2.78
10 ≤ Age < 12 ka	1.28	7.24	3.60	1.50	5.40	3.20	2.72
8 ≤ Age < 10 ka	1.89	10.95	3.25	0.75	6.64	2.16	3.33
6 ≤ Age < 8 ka	0.96	4.82	3.00	0.75	5.49	2.15	1.54
4 ≤ Age < 6 ka	1.00	5.75	2.44	0.75	2.18	1.54	1.73
Arctic	1.00	5.10	1.80	0.97	5.48	3.39	2.25
Boreal	0.96	10.95	3.22	0.37	6.64	2.15	2.35
Temperate	3.09	7.24	6.17	1.50	3.20	2.18	3.98
All	0.96	10.95	3.10	0.37	6.64	2.18	2.45

Table ~~2~~3. Observed (estimates from peatland inventories and soil database) and simulated northern peatland area, countries are sorted in descending order according to the estimate of IMCG-GPD.

country/area	Peatland area (10^3 km^2)			
	IMCG-GPD	WISE	PEATMAP	Simulated $f_{noLEP\text{-}CR}$
>30°N	>3000	2823	3250	3896
Russia-Asian part	1176	852	1217	1336
Canada	1134	1031	1095	1009
Russia-European part	199	285	207	392
USA(Alaska)	132	167	72	168
USA(lower 48)	92	49	98	365
Finland	79	89	69	42
Sweden	66	65	58	35
Norway	30	19	14	29
Mongolia	26	13	13	6
Belarus	22	29	22	11
United Kingdom	17	21	17	42
Germany	17	14	13	33
Poland	12	18	16	8
Ireland	11	9	14	17

Table ~~3~~4. Observed and simulated northern peatland C, countries are sorted in descending order according to the estimate of IMCG-GPD.

country/area	Peat carbon stock (Pg C)		
	IMCG-GPD	WISE	Simulated $f_{noLEP-CR}$
>30°N		421	463
Canada	155	155	87
Russia-Asian part	118	114	174
Russia-European part	20	38	49
USA(Alaska)	16	28	32
USA(lower 48)	14	10	45
Finland	5	15	5
Sweden	5	10	4
Norway	2	3	3
Germany	2	3	5
United Kingdom	2	4	7
Belarus	1	4	1
Ireland	1	2	4

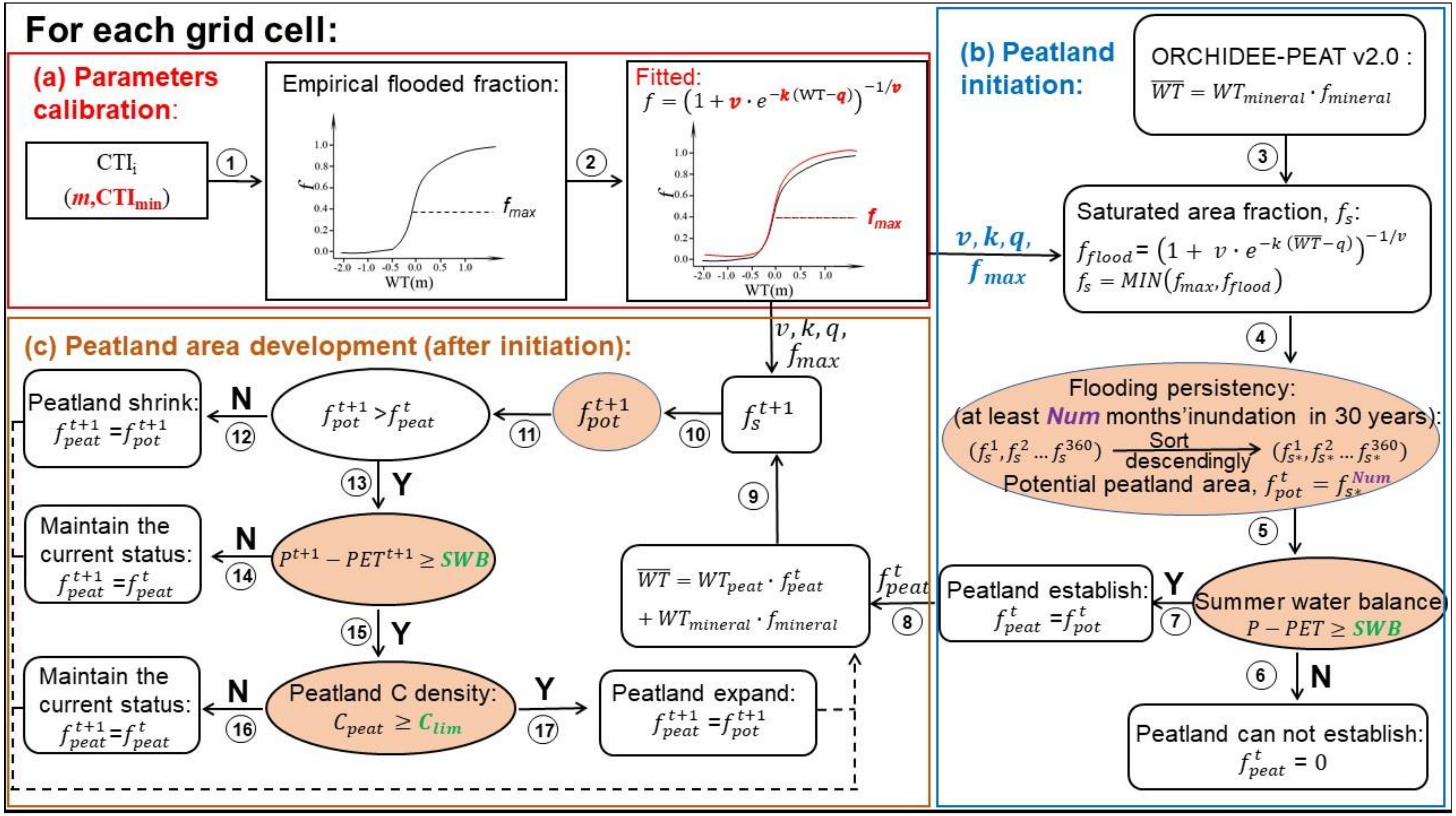


Fig. 1. Information flow of dynamic peatland area module in ORCHIDEE-PEAT v2.0. *Num* is a gridcell-specific parameter, *SWB* and C_{lim} are globally uniform parameters (Sect. 2.2)

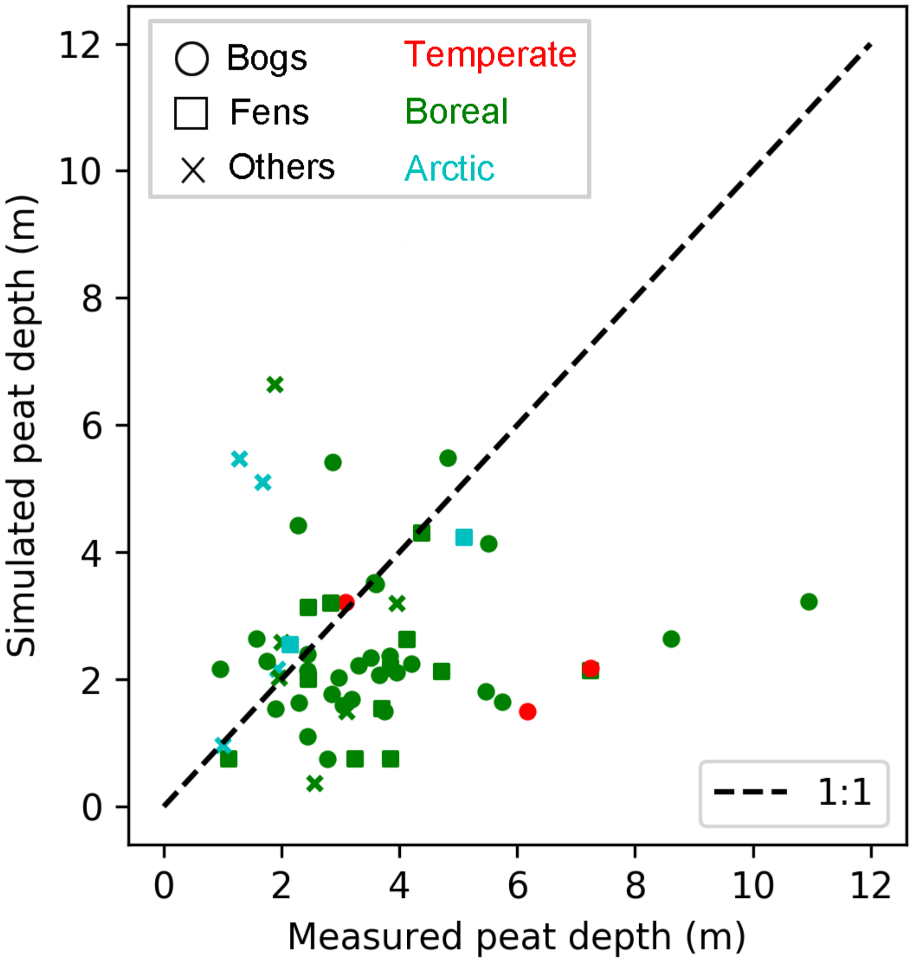
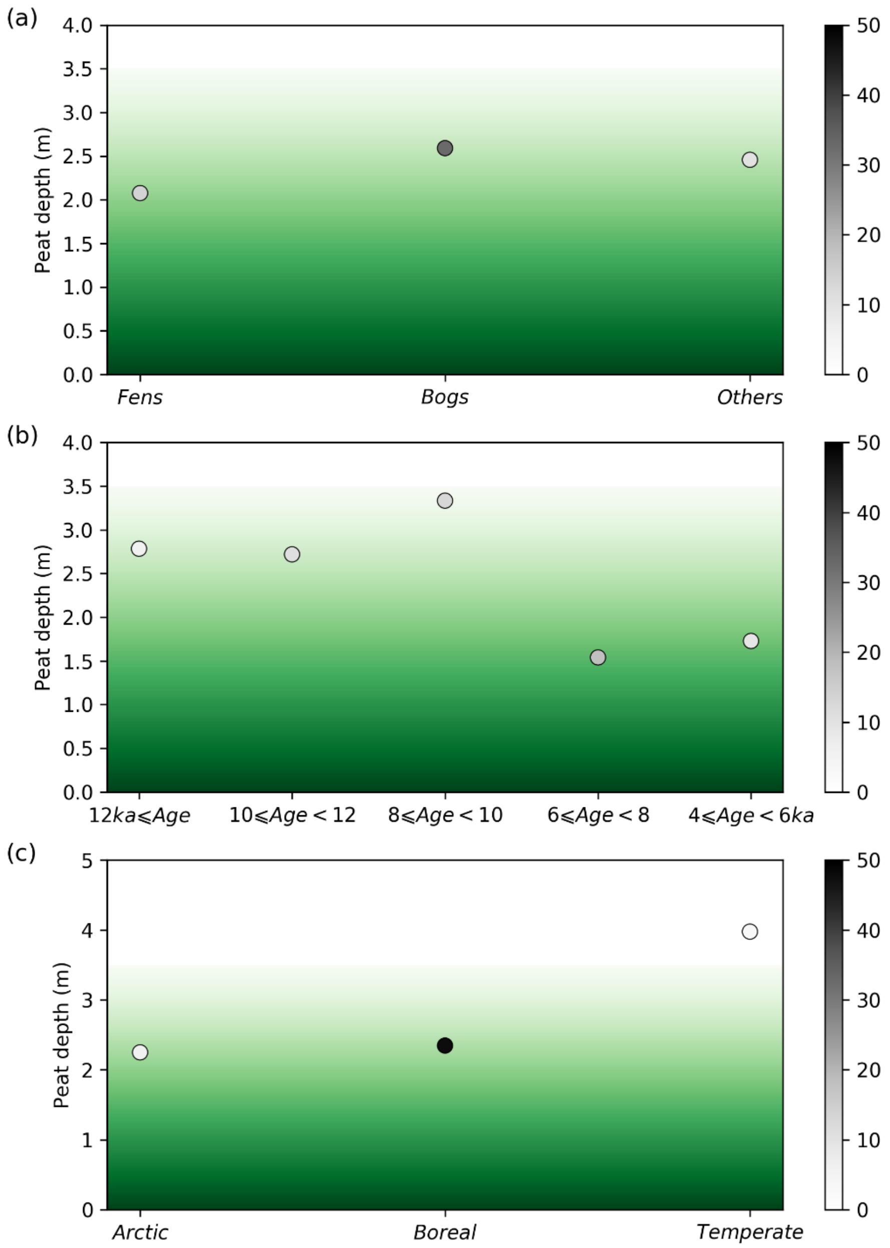


Fig. 2. Measured and simulated peat depth at 60 peatlands sites (Table S1). Shapes of markers indicate peatland types (bogs, fens, others), colors of markers imply climatic zones (temperate, boreal, arctic) of sites' location.



~~**Fig. 1.** Root mean square error (RMSE) of measured and simulated peat depth at 60 peatlands sites (Table S1), grouped by peatland types (a), ages (b), and climatic regions (c). The transition from green to white indicates an RMSE of 100 %. Number of sites included in the calculation is showed by colors of the symbols.~~

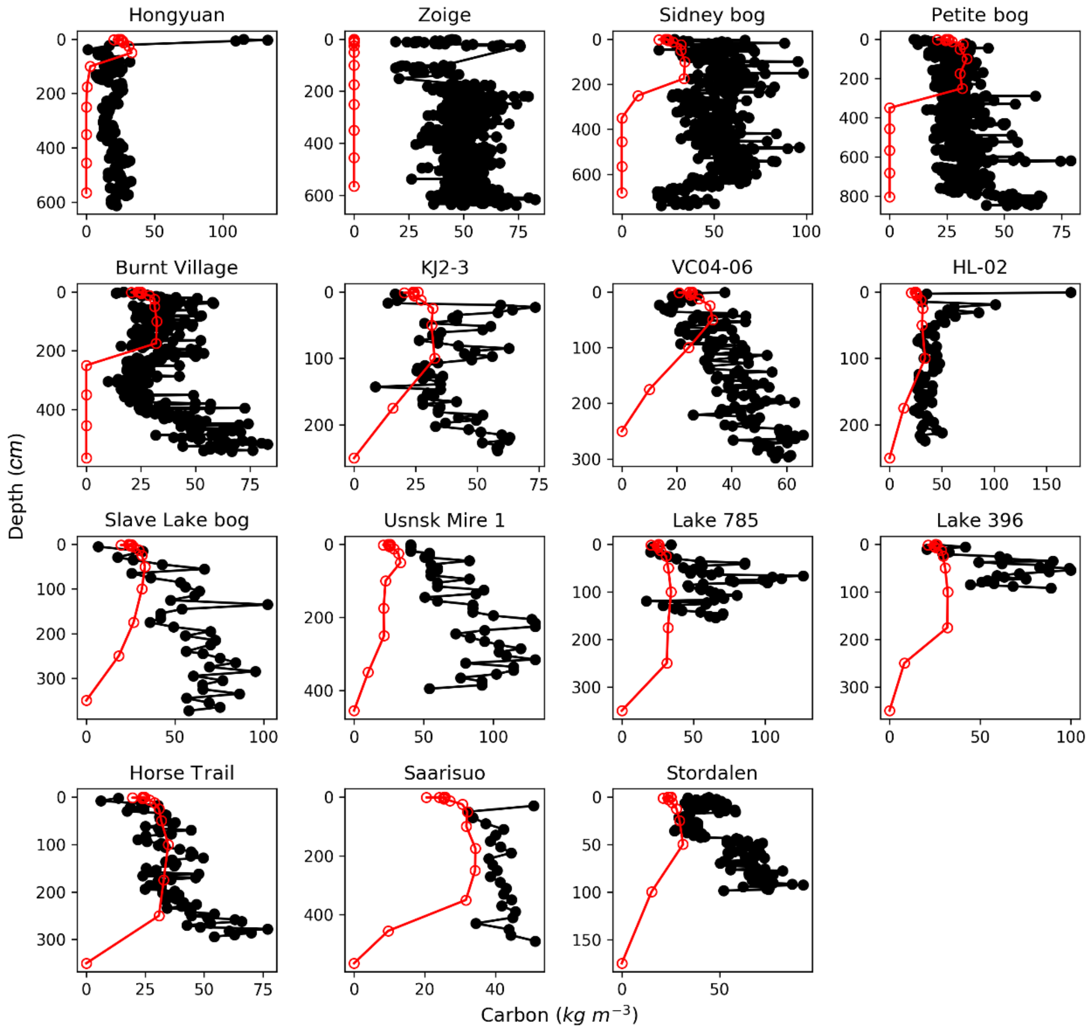


Fig. ~~2~~3. Observed (black) and simulated (red) vertical profiles of soil C, at the 15 sites where peat age, depth, bulk density and carbon fraction have been measured (Table S1). The black circles indicate depths of measurements, the red circles indicate the depth of each soil layer in the model.

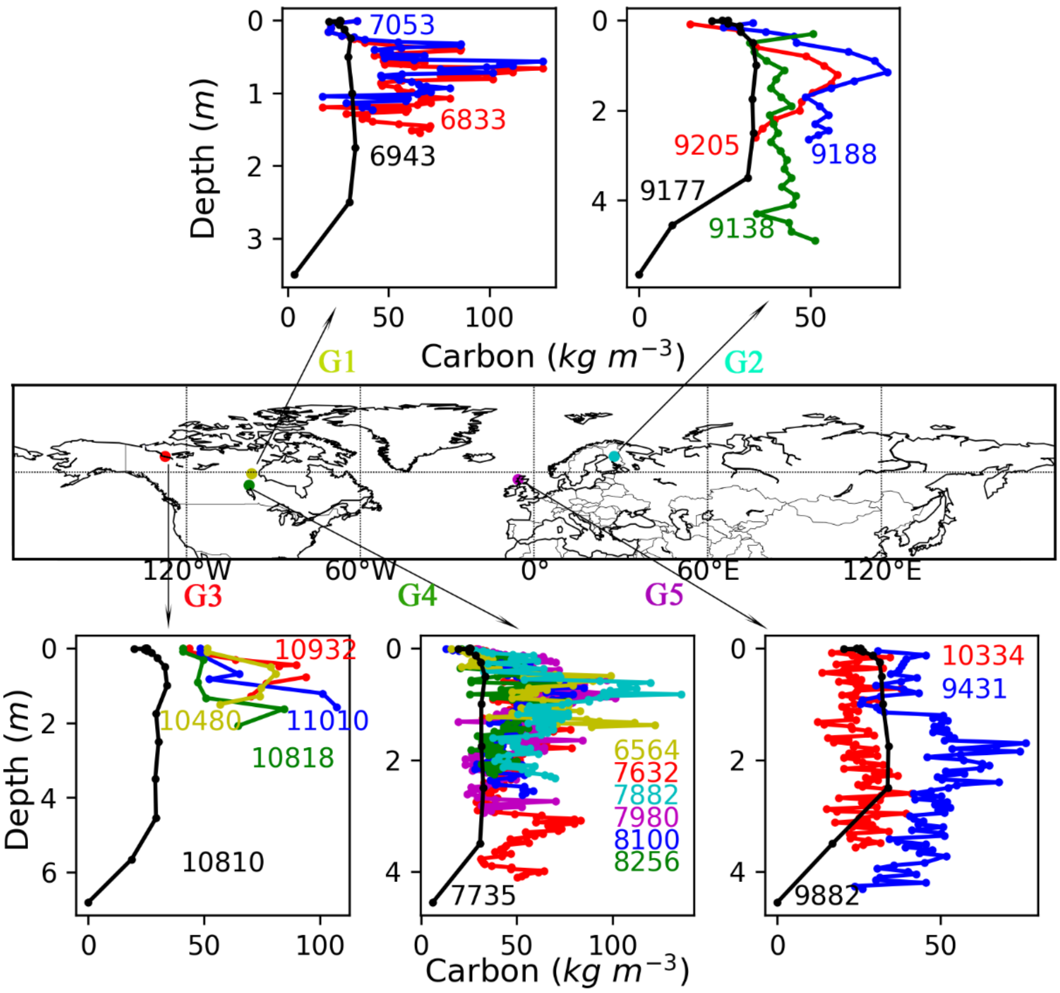


Fig. ~~3~~4. Observed (colored, with each colored line represent one peat core) and simulated (black) vertical C profiles of five grid cells where there is more than one core. The numbers in the figure indicate ages of sampled peat cores (colored) and time length of the simulation (black, is the mean age of all cores in the same grid cell).

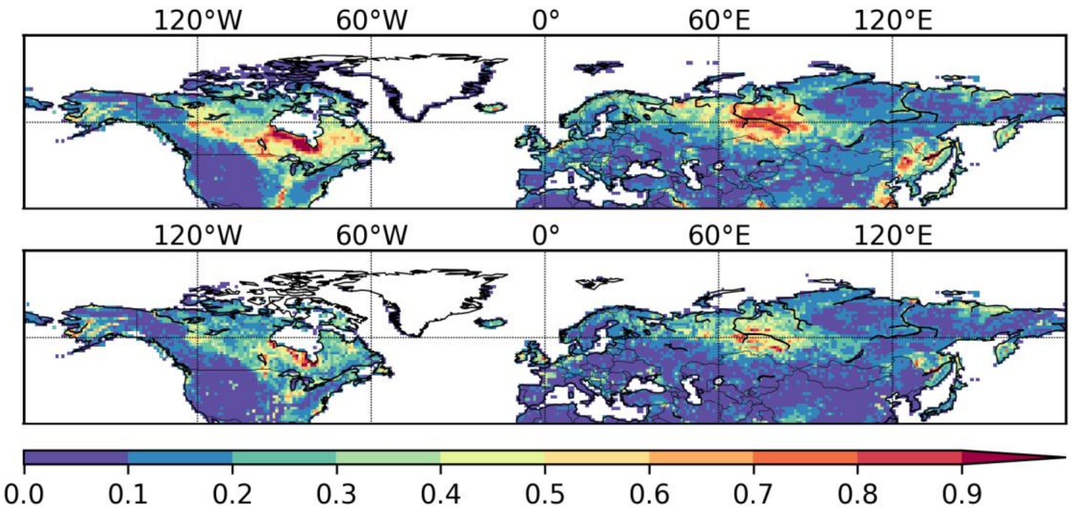


Fig. 5. Wetland area fraction from CW-WTD (upper panel), simulated maximum inundation areas (lower panel)

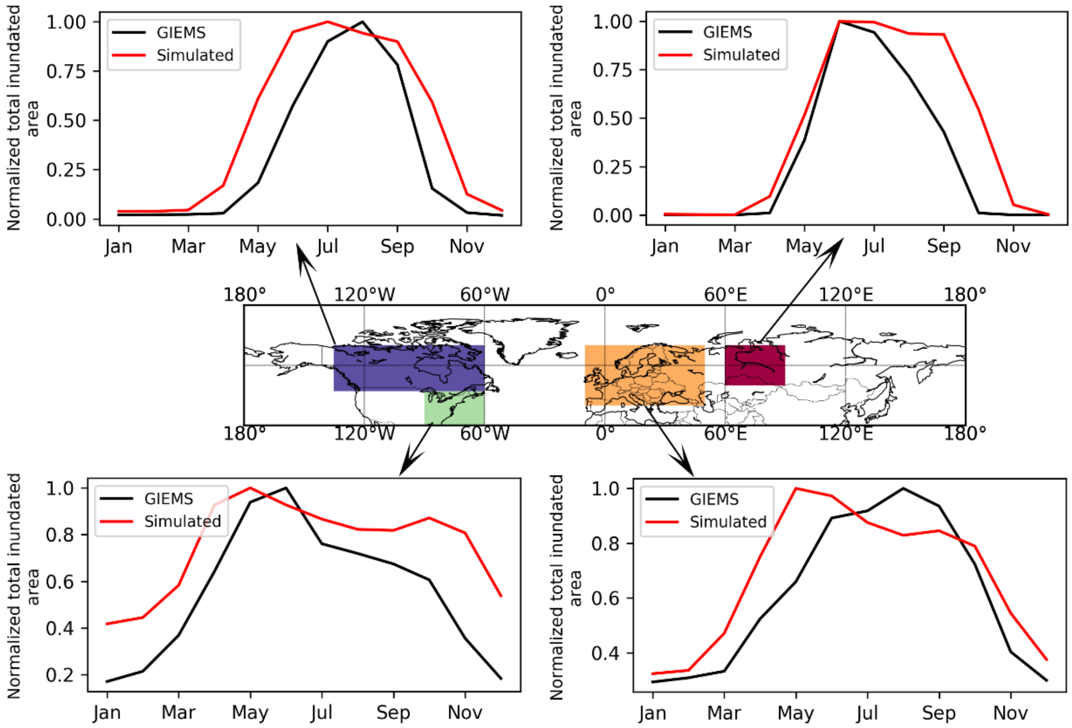


Fig. 6. Simulated and observed (GIEMS, (Prigent et al., 2007, 2012)) mean seasonality (averaged over 1993–2007) of total inundated area. Note that the simulated and observed total inundated area of each month is divided by the simulated and observed maximum monthly value, respectively, to highlight seasonality of inundation rather than comparing absolute values of inundated area.

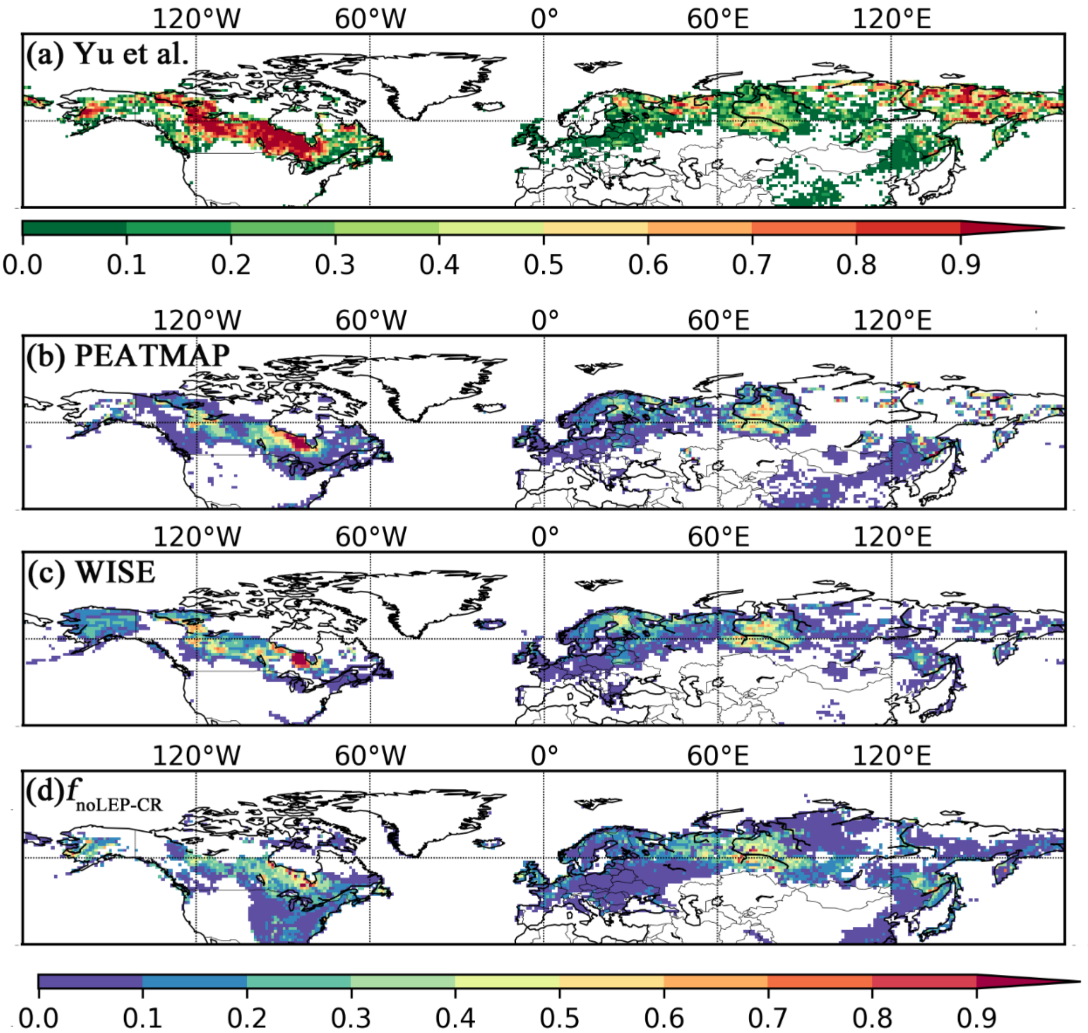


Fig. 47. Observed and simulated peatland area fraction. (a) Peatland fractions obtained from qualitative map of Yu et al. (2010). The original qualitative map only delineates areas with peatland coverage greater than 5%, the quantitively data here is derived by aggregating the interpolated 0.05° × 0.05° grid cells into 1° ×1° fractions, thus it's not directly comparable to the fractional peatland area of other datasets and the model output. We illustrate it with a distinct color key, (b) peatland area fraction derived from the PEATMAP, (c) histosol fractions from the WISE soil database, (d) simulated peatland area fraction ($f_{noLEP-CR}$), with pattern and timing of deglaciation has been considered. Areas dominated by Leptosols has been masked and areas occupied by crops has been excluded, under the assumption that cropland occupied peatland in proportion to grid cell peat fraction.

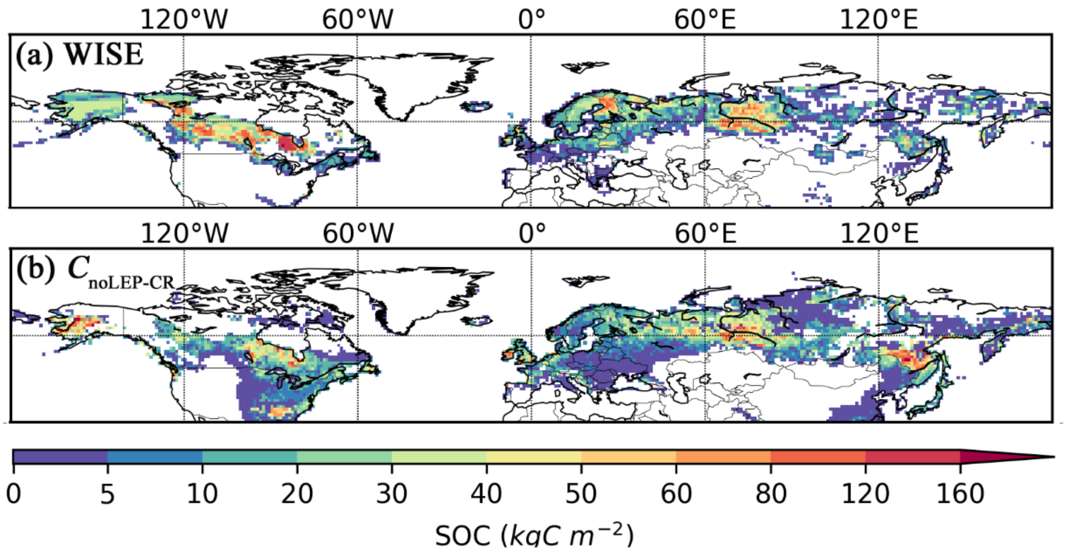


Fig. ~~5~~8. Observed and simulated peatland soil carbon density. (a) Peatland (Histosols) soil carbon density from the WISE soil database, (b) simulated peatland soil carbon density ($C_{\text{noLEP-CR}}$), with pattern and timing of deglaciation has been considered. Areas dominated by Leptosols has been masked and areas occupied by crops has been excluded, under the assumption that cropland occupied peatland in proportion to grid cell peat fraction.

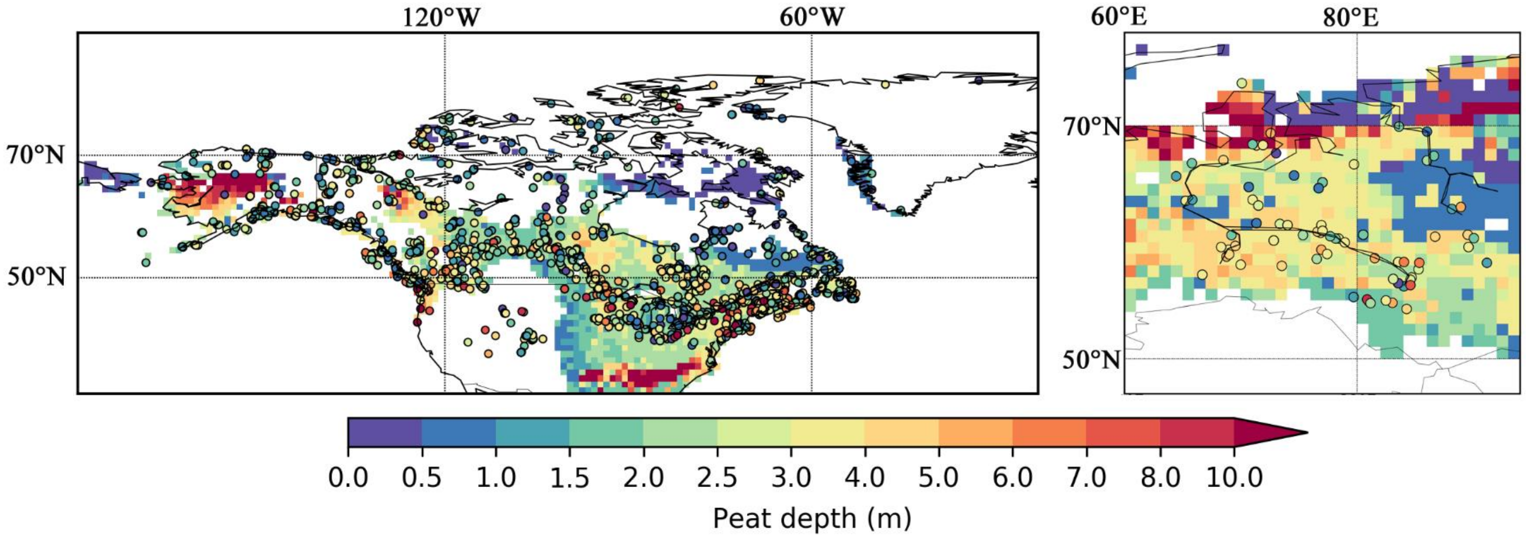
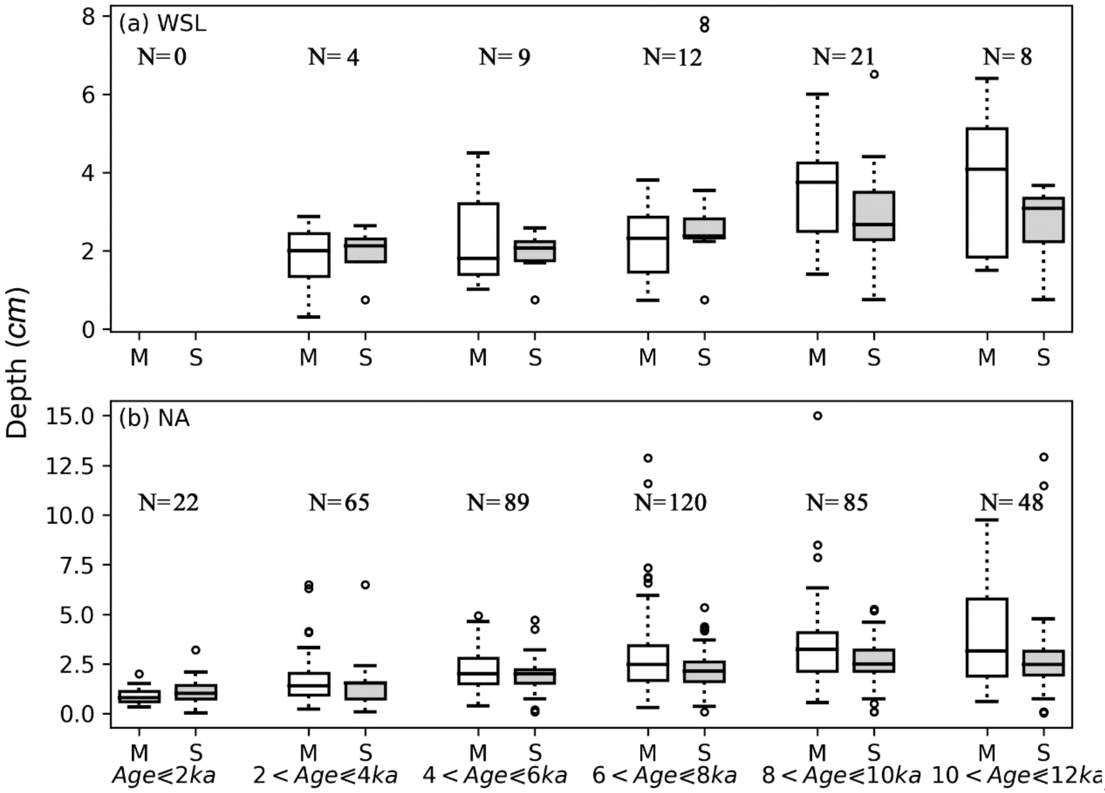


Fig. ~~6~~9. Measured (color filled circles, with colors indicating measured values) and simulated (background maps) peat depth in North America (left) and in the West Siberian lowlands (right). Measured peat cores from North America are from Gorham et al. (2012), while that from the West Siberian lowlands are from Kremenetski et al. (2003).


(a) WSL
N=0
N=4
N=9
N=12
N=21
N=8
(b) NA
N=22
N=65
N=89
N=120
N=85
N=48
Depth (cm)
M
S
Age⩽2ka
2 < Age⩽4ka
4 < Age⩽6ka
6 < Age⩽8ka
8 < Age⩽10ka
10 < Age⩽12ka

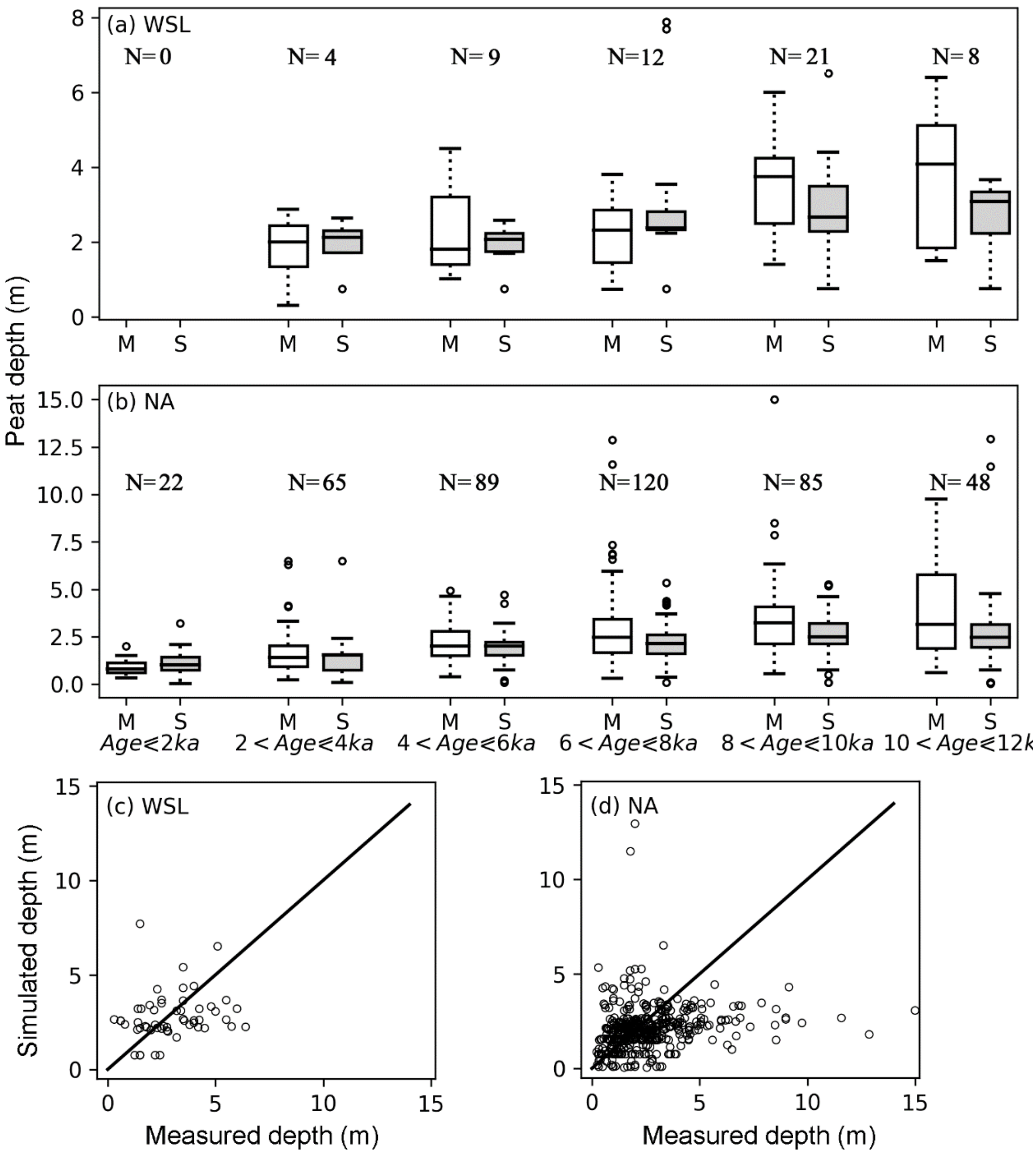


Fig. 710. (a, b) Measured (M) and simulated (S) mean peat depth at the West Siberian lowlands (a) and North America (b), grouped according to the mean age of peat cores. Measured peat cores are from Gorham et al. (2012) and Kremenetski et al. (2003). The horizontal box lines: the upper line - the 75th percentile, the central line - the median (50th percentile), the lower line - the 25th percentile. The dashed lines represent 1.5 times the IQR. The circles are outliers. Number of included grid cells in each age group is indicated by N. (c, d) The scatter plot of measured and simulated peat depth for the West Siberian lowlands (c) and North America (d). For a grid cell that has multiple measured peat cores, the median depth of all measurements is plotted against the simulated depth in the scatter plot.

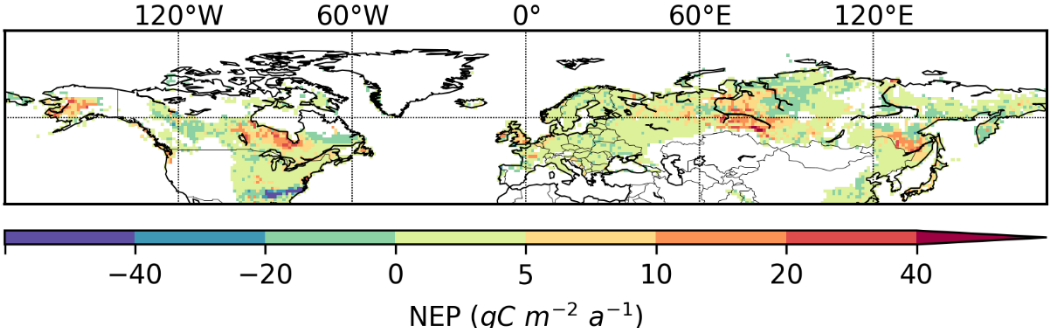


Fig. ~~8~~11. Simulated annual net ecosystem production (NEP), averaged over 1901 – 2009. Obtained by multiplying peatland NEP (gC m^{-2} peatland a^{-1}) with peatland fraction for each grid cell.

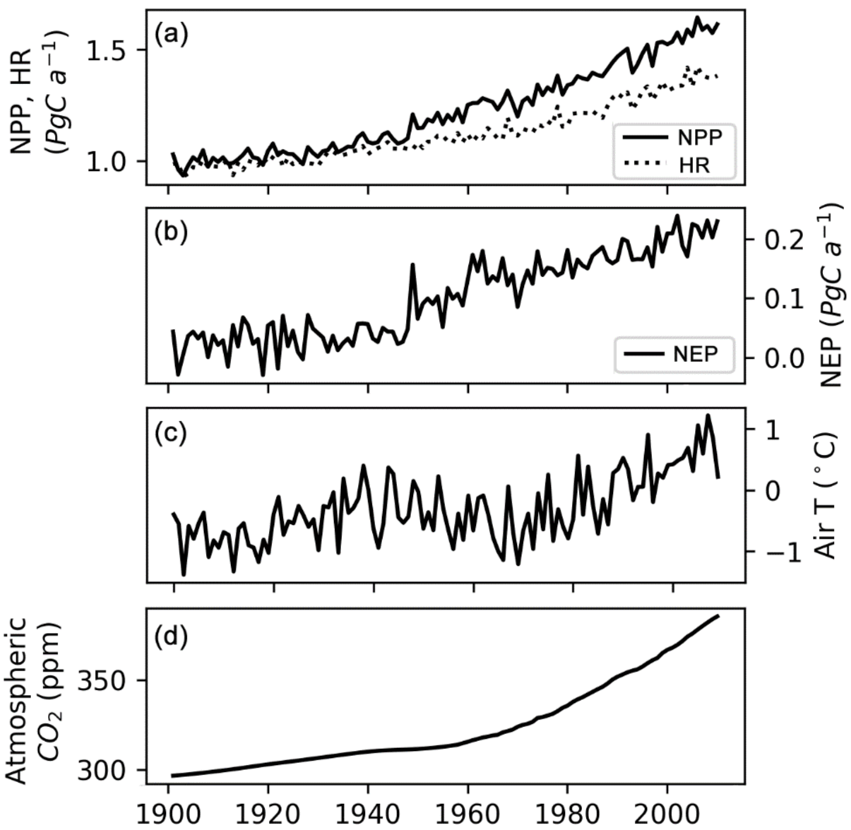


Fig. ~~9~~12. (a) Simulated annual net primary production (NPP), heterotrophic respiration (HR) of northern peatlands, (b) simulated net ecosystem production (NEP) of northern peatlands, (c) mean air temperature (T) of grid cells that have peatland, (d) atmospheric CO_2 concentration.

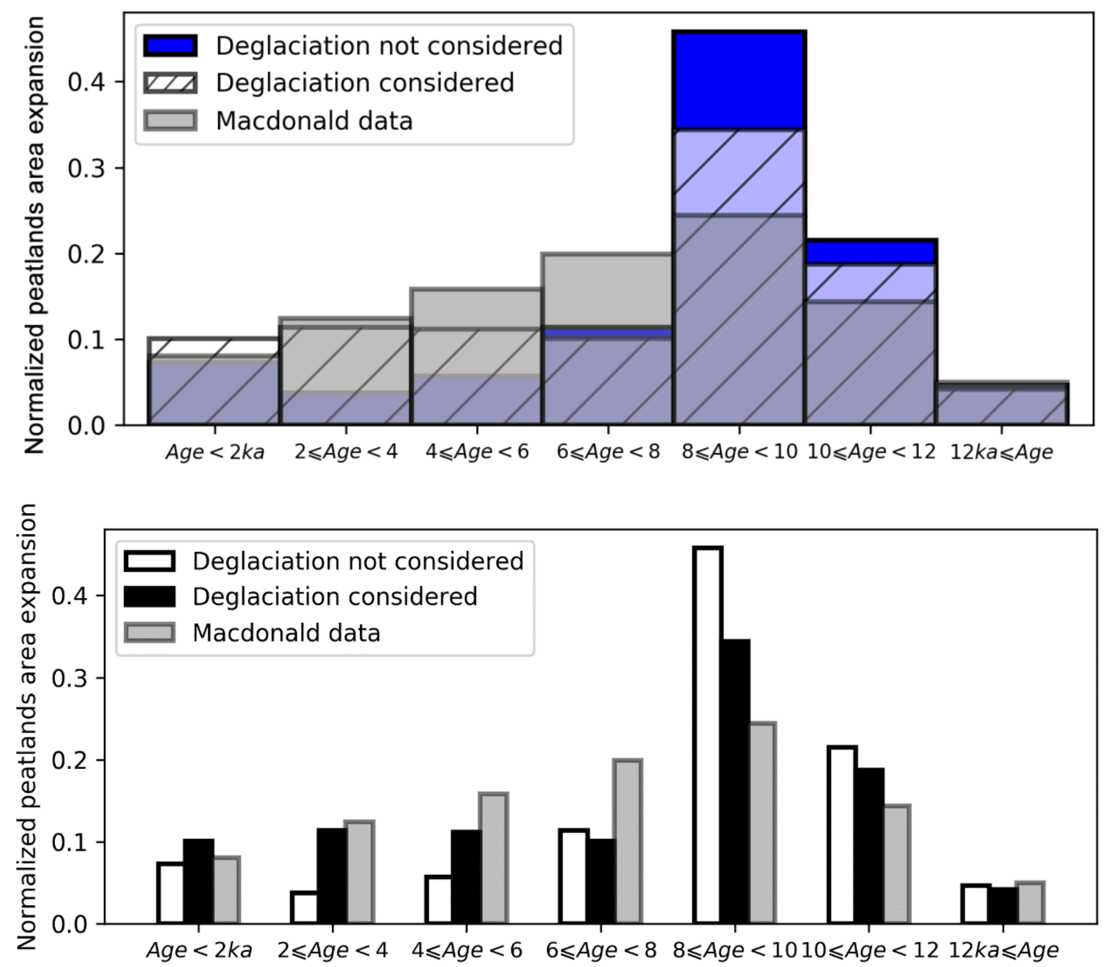


Fig. ~~10~~13. (Grey bars) Percentage of observed peatland initiation ~~(grey)~~ in 2000-year bins. Peat basal dates of 1516 cores are from MacDonald et al. (2006), peat basal age frequency of each 2000-year bin is divided by the total peat basal age frequency. (~~Blue~~ White bars) Percentage of simulated peatlands area developed in each 2000-year bin, deglaciation of ice-sheets is not considered (the model was run with 6 times SubC, 2000 years each time). The peatlands area developed in each bin is divided by the simulated modern (the year 2009) peatlands area. (~~White hatched~~Black bars) Percentage of simulated peatlands area developed in each 2000-years bin, pattern and timing of deglaciation are read from maps in Fig. S5 and Fig. S6.