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)

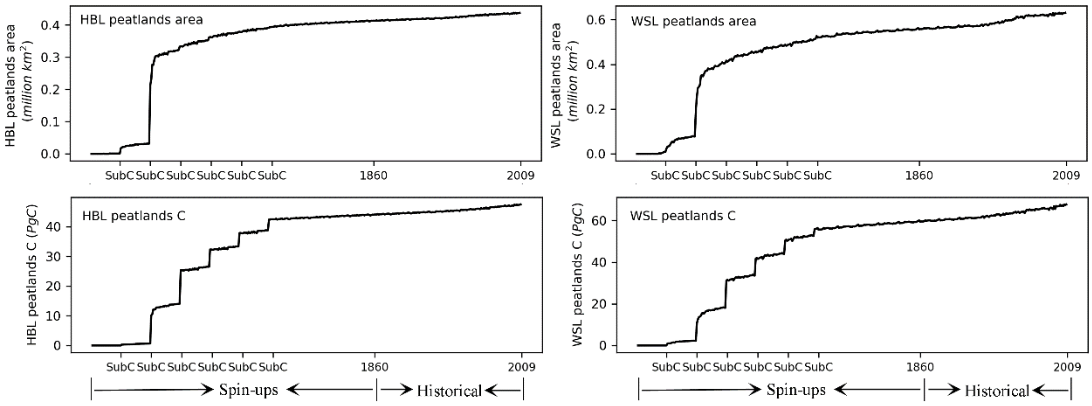
To note this issue, we add sentences on Line361: "……but contain more samples and cover larger areas. Note that as this study aims to reproduce development of northern peatlands since the Holocene, peat cores that are older than 12 ka are removed from the model evaluation. At last, 1521 out of 1685 observed 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.

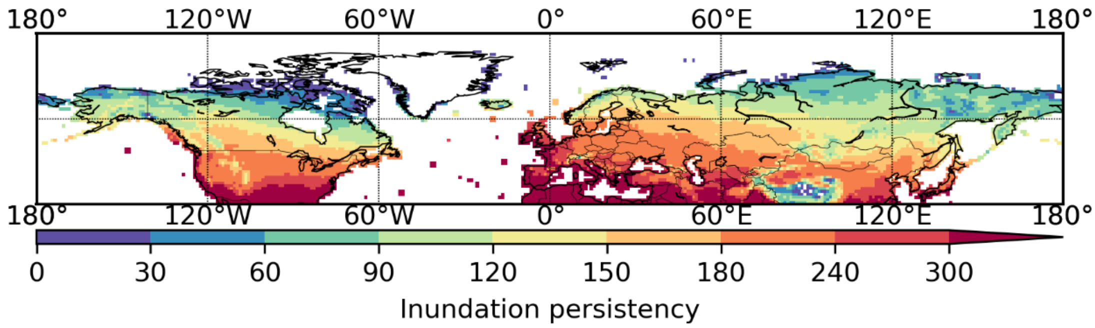
Corrected now in the text on Line476: "……From 1901 to 2009, both simulated net primary production (NPP) and simulated heterotrophic respiration (HR) show an increasing trend"

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.

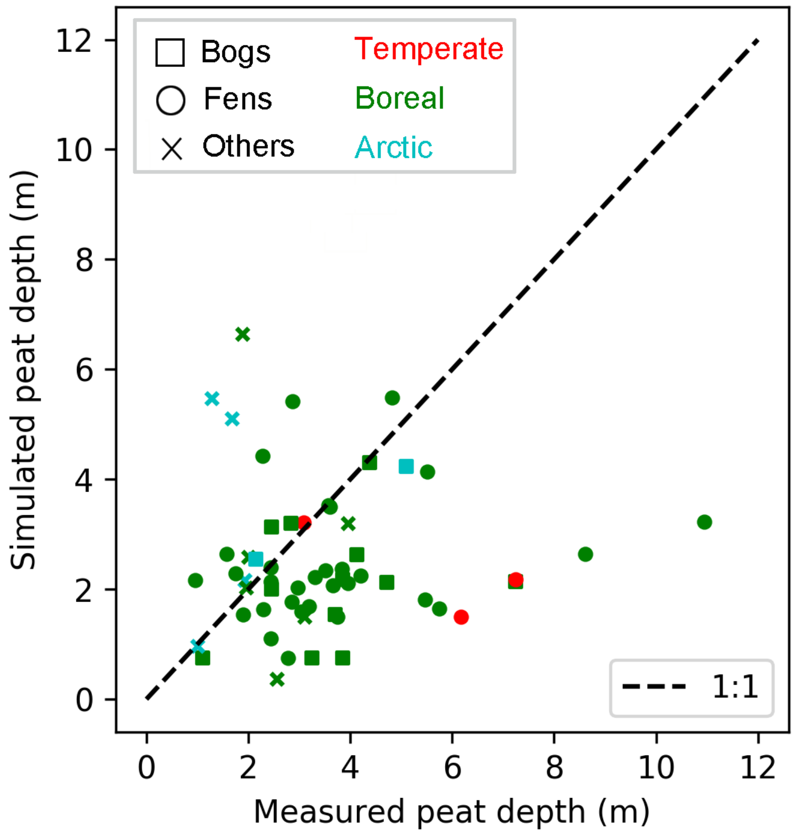


Fig. 1. Measured and simulated peat depth at 60 peatlands sites (Table S1). Shapes of markers indicate peatland types (bogs, fens, others), colors of markers imply climatic zones (temperate, boreal, arctic) of sites’ location.

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.

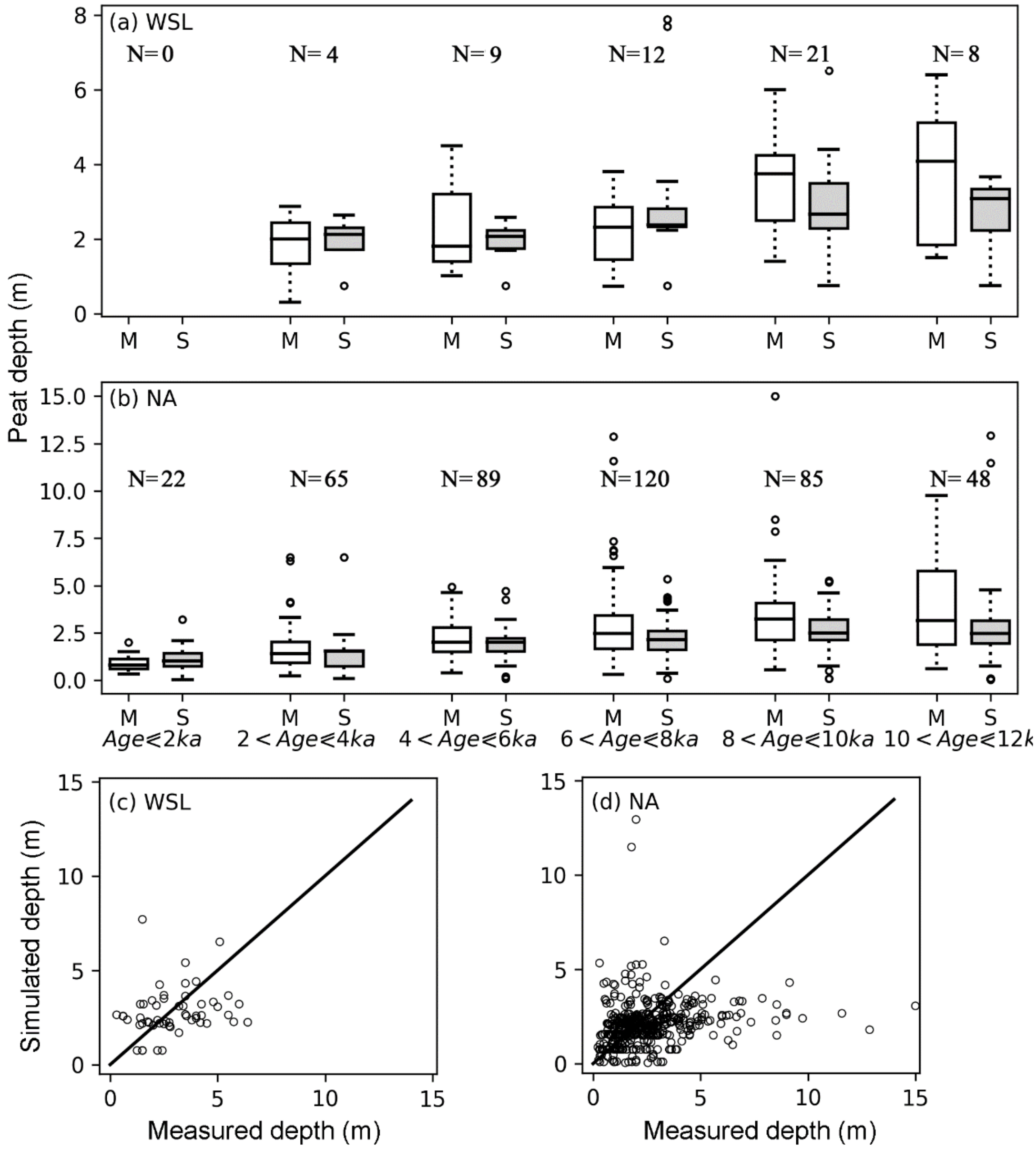


Fig. 6. (a, b) Measured (M) and simulated (S) mean peat depth at the West Siberian lowlands (a) and North America (b), grouped according to the mean age of peat cores. Measured peat cores are from Gorham et al. (2012) and Kremenetski et al. (2003). The horizontal box lines: the upper line - the 75th 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.

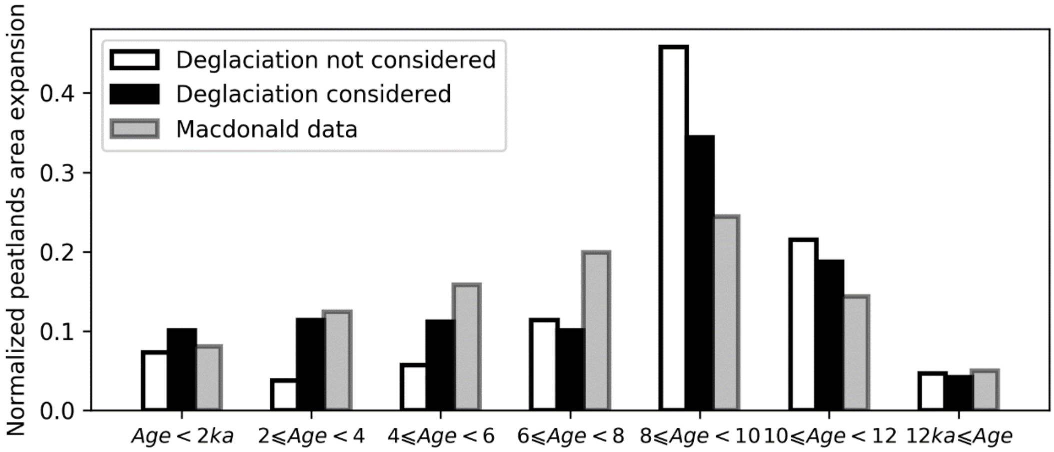


Fig. 10. (Grey bars) Percentage of observed peatland initiation in 2000-year bins. Peat basal dates of 1516 cores are from MacDonald et al. (2006), peat basal age frequency of each 2000-year bin is divided by the total peat basal age frequency. (White bars) Percentage of simulated peatlands area developed 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.