We thank all of the reviewers for their very useful comments.
We provide a version of the manuscript showing the proposed changes and updated figures at the end of this document

Typesetting:
TEXT: Original reviewer comments
TEXT: Author response
TEXT: Changes is manuscript
Page and line numbers are given in respect to the original manuscript.

Response to reviewer 1

In their manuscript, Müller and Joos explain the integration of peatland carbon cycle dynamics into the LPX DGVM and investigate how peatlands changed (in their model)over the time between the Last Glacial Maximum and today. They investigate the influence of climate forcing on the LGM peatland distribution, compare the present-daymodel results against observations, and describe the changes in peatland extent and carbon storage over time from the LGM to the present. Their manuscript makes fascinating reading, as the picture they draw on the temporal development of peatlands is much more detailed than the usual assumption of a more or less linear growth of peatlands.

The manuscript is very well written and is a major advance on the previous state. I recommend publication with minor changes.

I only have one major issue with the manuscript by Müller and Joos, and that is the fact that I didn't write it. I wish I had written such a comprehensive description of peatland development since the LGM. However, this rather obviously is not the author's fault, but my own.

There are, however, a few minor things that might improve the manuscript, and I very much hope that the authors will agree to that.

We thank the reviewer for the kind and supportive words and the helpful comments! We responded point by point below:

1) The TraCE21k forcing data is rather unusual in that it is what one might call a "guided" climate model experiment, in the sense that the modelling team at various points in the climate evolution performed perturbation and/or sensitivity experiments in order to make the climate model conform more closely to the observational record. This makes the data set especially valuable as a forcing data set, but it is quite different from the usual experiment setup, where one sets initial and boundary conditions, and then gets some climate evolution which may – or may not – be similar to what can be reconstructed. A few explanatory

sentences in section two would lessen the need of unintiated readers to refer to the original papers.
We added a sentence and corresponding citation to section 2.2 to explain the unique nature of this experiment:
"*The TraCE21k experiment constitutes a unique climate forcing, not only because it is to date the only published transient simulation over the deglaciation using a fully coupled general circulation model (GCM), but also because the meltwater forcing in TraCE21k was chosen, using sensitivity experiments, to best reproduce the abrupt climate events such as the Bolling-Allerod (BA) and the Younger Dryas (YD) (He 2011).*"

2) Personally I prefer SI units, so I would use PgC instead of GtC. Also, I may have overlooked it, but I did not see an explanation of Mkm2 – a definition would clarify things for readers unfamiliar with this unit.
The choice between PgC and GtC comes very much down to preference. As we feel GtC is more widely used in the community, we chose this over the other. For Mkm2 we added an explanation at the first occurrence (Abstract)

3) Page 4, line 19: ...with a rate of 0.01 per year. Is this a fraction of the grid cell, or a fraction of the difference between potential and actual area? Please clarify.
Meant is the fraction of existing peatland fraction. Expansion in the model is thus proportional to peatland fraction. The sentence was reworded to increase clarity:
"*Peatlands expand or shrink towards a changing f_pot with a rate of 1% of current f_peat per year.*"

4) Section 2.3, also 3.1.1 – PEATMAP is partially based on Gumbricht, if I remember correctly (unfortunately the original manuscripts and data sets are on a disk in my office, which I haven't been able to visit since March). I also seem to recall that South America is more or less exclusively based on Gumbricht. However, the manuscript seems to say that extent in South America is similar to Gumbricht, but larger than Peatmap? Please clarify in the manuscript, where PEATMAP and Gumbricht are identical, and where they differ.
We added at p6, l26: PEATMAP is partly based on the "Tropical and Subtropical Wetland Distribution" (https://doi.org/10.17528/CIFOR/DATA.00028) (REF to Gumbricht, 2012, 2015). We also compare model results to the updated version ("Tropical and Subtropical Wetland Distribution version 2" (https://doi.org/10.17528/CIFOR/DATA.00058) of Gumbricht et al., 2017.

5) Section 2.2 (Page 6, lines 7-14) please list the models considered in sensitivity experiments, otherwise readers need to refer to original PMIP papers.
A list of the models used, was added.

6) Figure 1 – I am wondering whether it is better to show PEATMAP on the 0.5◦resolution, or whether it might be better to show it on the LPX model grid. Please check.

We recognize that a regridding of PEATMAP to model resolution would ease comparison from cell to cell, but we believe for the reader it is better and more interesting to show PEATMAP on a 0.5° resolution. For one, the reader might not be familiar with the real distribution and thus might be interested in the local features only visible at high resolution. Additionally, Figure 1 aims to compare the real world with the model world, and the contrast of the resolutions highlights the limits of the model at hand to simulate smaller-scale features at high resolution. A conservative regridding of PEATMAP would also show peat in cells that lie outside of the land mask of LPX. For all these reasons, we continue to show the 0.5o version of PEATMAP:

7) Figure 5, bottom-left corner: What's G-IG supposed to mean? Either clarify or remove.
Label was removed.

8) Figures 6, 7, 8 – Figure caption refers to letter a,b,c, but subfigures not labelled accordingly.
Labeling was added. Also some size and other adjustments were made.

9) Page 21, line 2: "with an inconsistent temporal evolution" Inconsistent how? Please clarify.
We split the sentence and extended the second half sentence to give more context:
„The simulated temporal evolution, however, is different, with a rapid uptake in the early Holocene in the reconstruction, compared to a delayed uptake in the mid to late Holocene in the simulation."

10) Figures A1 & A2 (d): Please correct spelling of "Afrika" from German to English spelling (Africa). Similarly, I seem to recall that it's the "Congo", not "Kongo", as on page 7, line 19.
Spelling was corrected both on the figures and in the text.

11) Figures 7, 8, A1, A2: Background colour coding unclear from caption – I suggest to insert reference to Fig. 4, where it is explained.
Added "*Background coloring indicates different time periods, same as in Fig. 4*" to the respective captions.

12) Figure 2, caption: Explanation of (b) could be clearer ("...how many timeslice simulations with climate forcing from different models show...")
Sentenced changed to: *"... agreement (as number of models simulating peat in a given grid cell) between LGM time slice simulations run with LPX and forced with different climates anomalies from six PMIP3 models as well as the TraCE21k anomaly"*

13) What happens to shelf C after shelf flooding? Did I miss that or is it missing in the model description?
This was described in the model description, although may be too vaguely. Also taking comments by reviewer 2 into account the sentence on P4L25-26 was changed to: "*Given the evidence of coastal peat carbon deposits (Kreuzburg*

2018, Treat 2019), we assume that most of the carbon is buried within sediments rather than released to the atmosphere during flooding. In case of flooding in the model, carbon from all land use classes in the respective cell is combined into a single "flooded" land use class, where it slowly decays with a constant rate afterwards."

I am also adding an annotated version of the authors' original pdf with some wording /spelling suggestions.

All suggestions were adopted. The sentence on P2L15 was reworded to "Although research on tropical peatlands has increased in recent years [..], our understanding about tropical peatlands, their dynamics and life cycles is still limited."

Response to reviewer 2

This manuscript presents a new study using a revised/improved LPX-Bern model to simulate peatland distributions and carbon accumulation dynamics during and since the Last Glacial Maximum. This is an important study that makes significant contributions to understanding peatland dynamics and their critical roles in land biosphere carbon balance and global carbon cycle.

There are several novel aspects of the study. For example, the detailed sensitivity and uncertainty analysis of peatlands during the LGM using PMIP3 models as well as TraCE21k climate simulations is the most extensive analysis yet on LGM peatland accumulation. The conclusion that model-specific simulated climates are important for peatland extent and carbon stocks would be very much useful for future peatland-climate analysis on the basis of climate simulation results. Another novel aspect is the explicit considerations and analysis of "old/disappeared/buried" peatlands on land and under ocean in flooded continental shelves, which contributes to a more complete acounting and understanding of global peatland dynamics. The results also show very dynamic nature of peatland coming and going throughout the last 22,000 years, which make great ecological sense but has not been demonstrated previously! The attribution analysis is also novel, which provides insights into changing controls of peatlands distributions and accumulation through time in different regions of the world.

We thank the reviewer for their positive words and constructive and helpful comments! We respond point by point below:

The manuscript is rich with data and ideas. There are many new and significant results from this study. For example, peatlands initiated much earlier in Northern Asia than the available data show, and there is much larger simulated tropical peat carbon storage than the observations, etc. There are possibilities that the authors plan to explore some of these ideas further with more complete explanations in separate manuscripts. But I point out some of these, so authors may want to discuss a little further in this manuscript. I think it would be useful even if the authors point out these and then indicate that we don't really know what is going on (See also below).

Early peatland initiation in Northern Asia: As pointed out in the manuscript, the simulated major increase in peatland initiation is about 3000 years earlier at the beginning of BA than the basal peat age compilation. In particular, the West Siberia Lowland has relatively abundant basal age information. I wonder if the author could explore further about the discrepancy between simulations and observations. Is it simply because that available observations have missed the oldest peats, say in the WSL? Or the model overestimates peats, perhaps due to the criteria used to form peat, even though the TraCE21k simulated climates are not biased? Also, I wonder if the fact that Northern Asia, including the WSL, was not glaciated during the last glaciation has played a role in modulating surface topography and hydrology (through TOPMODEL). Addressing this difference could advance our understanding peatland formation process and its history.

We believe that at least the WSL is sampled thoroughly enough so that the reconstructions of peat initiation are rather robust. In other regions of northern Asia this however might not be the case. Concerning the topography: it does currently only effect the potential wetland size but has no influence on the peat initiation. Although such a connection could be conceivable and might be considered in the future, for the case of the WSL this would not change the timing of initiation, as the WSL is flat and constitutes optimal conditions for peat initiation. We believe that the most likely sources of data model mismatches lie in the climate forcing and the model itself. Although TraCE21k is designed to capture the abrupt climate events during the deglaciation, it is probably still subject to large regional and temporal biases. Our model, although it captures many broad scale temporal and spatial features, is very generalized and thus by design not able to capture all regional features. One drawback of the model could be its weak condition on moisture balance (see also "**Additional Changes**" in this document). Future investigation might bring us closer to learn more about the source of the model data mismatch reported in this study and enable us to reduce it further.

The above discussed points were integrated into section 3.3.4 of the manuscript as follows:

"*Although the freshwater change of TraCE21k was designed to capture the rapid climate events during the glaciation, the magnitude and timing of regional or even hemispheric changes may still have biases.*"

"*Another source of the model-data mismatch could lie in the simple representation of peatlands in the model [...]. One example could be the relative weakness of the initiation criteria on the moisture balance (precipitation over evapotranspiration > 1), which is almost always weaker than the indirectly mediated condition on inundation persistence. This might pose a problem especially in the WSL where moisture balance might have been the driving* *factor for peat initiation (Morris et al. 2018). Lastly, although the WSL is relatively densely sampled and reconstructions of peat initiation robust, other areas of northern Asia are vastly under sampled and reconstructions less reliable.*"

Also, I wonder what cause the sharp decrease in peat area and C stock in North America in the middle of the deglacial major warming event BA (Fig. A1b). Why? According to Fig. A2b, it appears that warm climate, especially shortly after 14 kyrBP, is responsible for negative change in peat area/C storage – dramatic increase in respiration/decomposition, with or without peat drying? It would be interesting to see the underlying data and some further analysis and discussion.
This is indeed an interesting feature. The extensive peatlands that exist in the model in North America during the LGM are very abruptly lost before only slowly new peatlands establish further north. This is due to drying both driven by warming and a precipitation decrease. However, the speed of this development is most certainly overestimated. The abrupt change in climate in this region is triggered probably due to boundary condition changes in the TraCE21k simulation at the year 13870 BP, where ice shield configuration and fresh water forcing are adjusted. Especially the change in ice shield can have pronounced effects on the atmospheric circulation and thus an immediate impact on the regional climate. We added this explanation to section 3.3.2 with the following sentences:
"The loss of old peat is especially abrupt in North America (see Fig. A1 (b)). Here precipitation decreases and temperature increases abruptly over the south west of North America at 13870 BP. Both changes decrease the water balance given by P-E which leads to a decrease in potential peat area and thus the loss of the previous extensive peat complexes. As this abrupt climate change occurs at a discontinuity of the TraCE21k boundary conditions (changes in ice shield configuration and freshwater forcing), the speed of this change is probably substantially overestimated."

Likely there are no satisfactory explanations to some of these issues/questions, which is understandable. However, I think it would be useful if the authors can point out these and suggest possible future research opportunities and directions in observational data collections and model improvements. The last paragraph of the manuscript touches on future directions, but it would be useful to the data and model researchers if the authors can expand the last paragraph a bit further – in order to benefit the rich data and ideas generated from this study.
We expanded the last paragraph with specifying statements and two sentences about possible model improvements. The revised paragraph now reads:
"*[…] New timeslice and transient climate model simulations under PMIP4 (Ivanovic 2016, Kageyama 2017) together with an increased effort of the peat community to fill in gaps in sample coverage both for today's peatlands and buried peat layers, especially in North America, Northern Asia, and the tropics, might help to constrain past peat dynamics further and to test the robustness of*

the results presented here. At the same time there is potential for improvements to the LPX-Bern which could decrease model data mismatches especially on the regional scale. Future improvements could include refining the moisture balance criteria on peat initiation, improving hydrology and boundary conditions on continental shelves, and finding key processes that might benefit from a more complex representation, such as a multi layer peat profile and distinctions between different peatland types."

The manuscript is mostly written clearly, but with many minor issues throughout that I have pointed out some of these in the specific comments below. I recommend publication after minor revisions.

I do have a suggestion about the reorganization of a subsection: Subsection 3.2 Peatland during the Last Glacial Maximum 3.2.1 Peatland distribution and carbon storage 3.2.2 Uncertainties and sensitivity to simulated climate input data (I think this would work and look better, as otherwise there is only one sub-subsection 3.2.1 in this sub-section: awkward).
The suggestion was adopted

Specific comments: Title: change to "....a process-based global model investigation"or "Global peatland area and carbon.... a process-based model investigation". Also, considering the efforts using PMIP3 climate simulations to explore LGM peat change, I'd suggest to emphasize LGM in the title. A suggestion: "Global peatland distribution and carbon dynamics during and since the Last Glacial Maximum: a process-based model investigation"
We changed the title to take the comments raised into account. It now reads: "*Global peatland area and carbon dynamics from the Last Glacial Maximum to the present – a process based model investigation*"

Page 1
Line 3: 22,000 years but in the title 21,000 years. Be consistent?
The title was changed and thus this problem was alleviated.
L9: unclear about "non-linear interactions"."Non-linear responses of peatland area/carbon to changes in climate (T and P) and CO2"?
Sentence was reworded to "In the tropics, peatlands are partly lost due to flooding of continental shelves and regained through non-linear responses to the combined changes in temperature, precipitation, and CO2."

L13: change "through peatlands" to "by peatlands"? change "includes" to "considers"?
L14: unclear about "peatland area shifts": "shifts in peatlands distributions"?
L21: change "forrested" to "forested"
Suggestions were adopted.

Page 2
L5: “the last 12,000 years”; change from “ice shields” to “ice sheet”
Suggestions were adopted.

L9: I’m not sure to emphasize “global warming” from land-use change. I agree it is on that direction, but I’m not sure about the magnitude to global warming due to land use of tropical peatlands. It is different magnitude compared to C accumulation in northern peatlands (500 GtC) in the previous sentence. Rewording.
The sentence was reworded to put the relation to global warming into a clearer context. It now read: “Drainage and conversion of existing peatlands to plantations or other forms of land use leads to release of peat carbon into the atmosphere adding to the ongoing global warming trend.”
L13: change “peat” to “peatlands” here, to focus on ecosystems, rather than just a component of it, that is, soil.
Changed
L15: change to “picked up”
This sentence was reworded in response to Reviewer 1. It now reads: “*Although research on tropical peatlands has increased in recent years [..], our understanding about tropical peatlands, their dynamics and life cycles is still limited.*”

L18: change to “Congo Basin”
L26: add a comma “,” before “and knowledge of the amount....”
L34: spell out “DGVM” in the first use. Also, correct the typo “DGMV”.
Changed

Page 3:
L1: change to “spatial”
L21: change “and the current interglacial” to “as well as the current interglacial (Holocene)”?
Changed

L25: it would be good to state the age for the LMG here.
The sentence now reads: “*[…] since the Last Glacial Maximum (LGM) 21,000 years before present (BP).*”
L26: change “runs” to “simulations”?
Changed

Page 4
L2: delete “,” after “and peatlands”
Sentence was reworded to improve readability:
“*The implementation of permafrost and peatlands as long-term carbon stores are based on the LPJ-WHyMe model [...]*”

L6: change “Sphagnum” to italic
L10: change “Acro-“ to “Acrotelm” – change this throughout the manuscript. Also, change to “Carbon flux from the acrotelm to catotelm...”
Changed

L10: It is unclear how bulk density is used (along with mass balance) to determine acrotelm-to-catotelm carbon flux. Elaborate here. Also, this is the first time “bulk density” is mentioned, so how it is determined in the model.
We mistakenly used bulk density, where we mean C density. We reworded this section to improve clarity about what is happening in the model. The lines now read:
“*For the determination of the carbon flux between acrotelm and catotelm a fixed average acrotelm C density (18.7 kg C m-3) is used. The difference between this target acrotelm density and the actual average acrotelm density, determined by carbon influx from the litter pools and heterotrophic respiration within the acrotelm, is used to determine the size and sign of the daily flux between acrotelm and catotelm (Spahni 2013).*”
L11: change to: “acrotelm mass balance, the latter determined by carbon influx...”
See above comment
L12: If this is described elsewhere, please cite reference. Otherwise, present formulations here?
This is described in Wania2009a. Citation was added.
L20-21: change to “treated in the same way as the mineral soils...”
Changed

Page 5:
L1: change to “”seed”” (with quotation marks)?
L3: change to “precipitation over evapotranspiration ratio > 1”
L4: it is unclear what “precipitation-interception” stands for? Change to “precipitation minus interception”, if this is the case. Also, change “tree peat PFTs” to “peatland tree PFTs”
This part was rewritten (see comments in “**Changes not related to reviews**” section of this document). Suggestions were adopted where still applicable.

L9: change to “For a peat C stock change from 50 .. to about 45 kg m-2, fpot is reduced...”
Adapted except for the addition of ‘change’ after C stock because there could be confusions between C stock and C stock changes i.e. fluxes.

L12: on line 9, you can kg/m2 “C stock”, but here “C pool”. Be consistent. I think soil scientists call this metric as “Soil C density”.
Changed to “C stock” to be consistent with previous naming.
L14: “fpeat” is not defined. Do you mean “fpot”?

“fpeat” is defined earlier in the method section (beginning of second Paragraph). It is the gridcell fraction covered by peat.
L25: delete “them”
Changed
L27: LGM should be defined earlier, as well as its timing. See comments above. Also, change “runs” to “simulations”, so you don’t have to use the awkward sentence like “LPX runs...are run”.
Changed

L28: specify the latitude and longitude in the grid resolution, such as “2.5 latitude x 3.75 longitude”
Changed
L31: change “from 1960-1990” to “for the period 1960-1990” or “from 1960 to 1990”
Changed to “from 1960 to 1990”

Page 6:
L8: spell out PMIP3 here (you did in the Conclusions section)
Changed to “*[...] available LGM simulations from phase 3 of the Paleomodel Intercomparison Project (PMIP3) [...]*”

L11: change “dismissed” to “not used”, and to “because of THEIR poor performance”
L19: change to “from 0.37 to 1.7 Mkm2”
Changed

Page 7:
L2: change to “between 3 and 5 kyr BP”
L14-15: The sentence is unclear. Change to “These differences are due to new modifications/additions/features as described in Sect. 2.1 in the updated model version, LpX v1.4.” Not sure how “after data assimilation (Lienert and Joos, 2018)” fits here. Are these revisions based on data assimilation? If not, how does data assimilation contribute to the revision of LPX?
The data assimilation (which brings the LPX to version v1.4) is independent of the model revisions described in the manuscript. However as a result of the data assimilation, key parameters of the LPX are changed, which leads to different results in all coupled sub modules, including the peat module. This together with the changes described in the manuscript lead to different results compared to previous studies. The sentence was reworded to make this distinction clearer: *“Differences are due to a new model version after data assimilation, LPX v1.4, (Lienert and Joos, 2018) and the additional model changes described in Sect. 2.1.”*

L16: change “area” to “peatland area”
L21-22: change to “LPX simulates more peat in Alaska and Quebec and less in West-ern Canada than PEATMAP.”

Changed

Page 8:
L6: change “Northern” to “northern”, “from 270-604” to “from 270 to 604”
Changed

Page 9:
Table 1: change “Afrika” to “Africa”
Changed

Page 10:
L17: change to “Sphagnum” (italic) and “East North America”
L32: change to “these gaps; however, climate anomalies...”
Changed

Page 11:
Figure 2 caption: -“agreement (as number of models simulated peat in given gridcell) from LGM timeslice simulations from LPX that were forced with different climate anomalies from six PMIP3 model as well as TraCE21k simulations”
Partially adapted. Changed to: *“agreement (as number of models simulating peat in given grid cell) between LGM time slice simulations run with LPX and forced with different climates anomalies from six PMIP3 models as well as the TraCE21k anomaly”*
-change to “Dots in (a) and (b) show buried and still active peat deposits...”
Changed

Page 12:
L10: “from TraCE21k”?
Changed
L29: change “in some models” to “in simulated climates of some models”?
Changed to *“in some of the model climates”*

Page 13:
Figure 3: -caption: change to “...peatland carbon during the LGM (21 kyr BP) timeslice forced with climate anomalies simulated from seven different climate models”
Changed
Figure 3 -legend: maybe move legend between the 2nd and 3rd panel, so peat Cstock would be close to its Y-axis on the right side. -change “Trace21k” to “TraCE21k”throughout?
The suggestion regarding the legend was adopted. Also some size adjustments were made. In the figure and throughout the text it should now consistently say “*TraCE21k*”. Colors were changed to a colorblind color palette.

Page 14:
Figure 4 caption: also define PB as Preboreal, or better yet spell out “Holocene” on the figure itself!

It now says Holocene on the figure, which is indeed much clearer.

Page 15:
L4: add “and” before “(iii)”
L5: change “South-East” to “Southeast”, to be consistent. Delete “the beginning of”
Changed

Page 17:
Figure 6: add panel labels a, b, and c on the figure
Labeling was added.

Page 18:
L12: change “seized” to “ceased”
Changed

Page 19:
L12: “between 8 and 4 kyr BP”
L20: “during the recent millennia”, “warrants”
Changed
L21: “Southeast Asia”, be consistent. There are at least three ways for this in the manuscript: Southeast, South-East, and South East. Perhaps just use “Southeast Asia” throughout.
Changed throughout the manuscript. It should now be “Southeast Asia” throughout.
L32: change to “The so-called old peat carbon pools presented here...” or delete“so-called”
Deleted “so-called”
L32: When analyzing peat C impact on the global C cycle/budget, you assume that old carbon stored on flooded continental shelves were transferred and buried in marine sediments, rather than released into the atmosphere during flooding with rising sea level. Maybe state this assumption. It would be interesting to quantify the proportion of this C pool that has been buried under ocean or released to the atmosphere.
This assumption is based on the existence of coastal peat deposits. It was indeed almost an unstated assumption, which is why we reworded part of the model description where we talk about flooded peat (P4L25-26). This part now reads: *“Given the evidence of coastal peat carbon deposits (Kreuzburg 2018, Treat 2019), we assume that most of the carbon is buried within sediments rather than released to the atmosphere during flooding. In case of flooding in the model, carbon from all land use classes in the respective cell is combined into a single "flooded" land use class, where it slowly decays with a mean lifetime of 15 kyr.”*
The magnitude of the flooded shelf C pool is depicted in Figure 8 and PI values are stated in section 3.3.5

L34: “their respective pools”
Changed

Page 20:
Figure 7: add panel labels a, b, c and d on the figure
Labeling was added. Also some size and other adjustments were made.

Page 21:
Figure 8: add panel labels a, b, and c on the figure
Labeling was added. Also some size and other adjustments were made.
L4: change to “in-depth”
Changed

Response to reviewer 3

We thank also reviewer 3 for their comments, which were provided to us by the editor after the closure of the open discussion.

Müller and Joos use a process-based model (LPX-Bern) to simulate the expansion and contraction of peatlands around the world since the Last Glacial Maximum (LGM). They simulate both the gains and losses of peatland area and of carbon storage, including peatlands that are buried under mineral soils or by rising the oceans. Whilst peat core stratigraphy in other smaller scale studies (e.g. Tipping, 1995) has suggested the loss of older peat deposits and the accumulation of new peat, the explicit inclusion and treatment of these older peatlands in this study is new. The authors also assess the uncertainties of their results associated with climate forcing by using seven different climate models to drive their simulations. And they usefully compare their results to those of reconstructions of carbon accumulation histories based on peat cores and suggest reasons for discrepancies between them.

Overall this is a nicely written and very interesting paper. It is an important contribution to the subject area and should be published. Below I make some suggestions for (quite) minor changes.

P1, line 2. The title states 21,000 years line 2 says 22,000 years. Presumably these should be the same?
The title was changed. See also response to reviewer 2.
P2, line 15. ‘Research into tropical peatlands has since picked up’ – suggest ‘has grown’ or ‘has increased’.
The sentence was changed and now reads:
“*Although research on tropical peatlands has increased in recent years[...]*”

P2, line 18. Change Kongo to Congo.
Changed

P3, line 19. ‘Peatlands are slow reacting ...’ But many peatlands around the world have been degraded by land use and in these circumstances, loss of peat can be rapid and affect the future development of the peatlands. The authors make it clear that their model does not include land use (P4, line 5), but it would be useful to qualify this statement and perhaps include a brief comment on the magnitude of this change in light of the time scales of their simulations.
We added a qualifier to the sentence to remind the reader of the possibilities of fast changes under anthropogenic disturbance: “[…]*peatlands are, in absence of abrupt anthropogenic disturbance, slowly reacting systems [...]*”
To give context about the potential impact of this disturbance not considered in our model we added some sentences in the model description (P4, line 5) that provide literature estimates about the loss in the industrial period:
“*In this study, anthropogenic land use and land use change and corresponding land classes are not considered. Estimates about peat carbon loss through landuse only exist for the industrial period. Leifeld et al. (2019) estimate that between 1850 and 2015 about 22±5 GtC of peat carbon was lost globally. Houghton and Nassikas (2017) used results from Randerson et al. (2015) and Hooijer et al. (2010) to estimate carbon loss from draining and burning of peatlands for oil palm plantations in Southeast Asia. Losses are negligible before 1980 and amount to about 6GtCfor the period from 1980 to 2015. These estimates of the loss of peat carbon through land use, although substantial, are still small compared to the total pool sizes.*”

P8, line 9. Dargie et al. (2017) estimate that with the inclusion the Congo Basin peatlands, tropical peatland C is likely to be 69.6 – 129.8 Pg, which is closer to the estimate of LPX (135 Pg C).
We thank the reviewer for pointing this out. We added a sentence that addresses the estimate by Dargie et al.:
“*Including estimates for the newly discovered peat in the Congo Basin, Dargie et al. (2017) estimate a tropical peat inventory of 69.6-129.8GtC, closer to the LPX results.*”

Figure 4. I found panel c) a little bit difficult to interpret because the some of the colours are very similar. It would also be helpful to label the four time periods shown by the vertical shading – perhaps the shading colours could then be removed to simplify the plot.
The colors of the bars are chosen from a colorblind color palette and therefore already are optimized towards best discrimination ability for the general reader. The time periods are labeled in panel a) and described in the caption. We believe that indicating them with a background shading increases readability compared to the alternative of lines + labels.
Due to the above points we choose to leave this figure unchanged, and hope the reviewer agrees.
A discription of the backg

Figure 5. State what is G-IG.
Label was removed.

P15, line 10. (Rasmussen et al., 2014), - full stop not comma.
Changed

P19, line 5. Mismatch not 'miss match'.
Changed

P19, line 20. warrants not 'warrant's'.
Changed

Figure 7. The panels aren't labelled in line with the caption. What does the green bar represent in panel a)? Is it where LPX and Loisel17 coincide? There is no description in the caption or the figure of the four coloured time periods (see comment about Figure 4).
Labeling was added.
In panel a) what looks like green bars are the blue bars visible through the transparent orange of the second histogram. We added a clarification to the caption that hopefully helps in reading the figure: "*Peatland initiation frequency (two overlapping histograms) (a), [...]*"
Description of the time periods was added to the caption: "*Background coloring indicates different time periods, same as in Fig. 4*"

Although this study focuses on the past development of peatlands and their C stores, it would be interesting to hear more from the authors about using their model for future predictions under different climate change scenarios.
Indeed we are already working on future projections using the results of this study as a starting point. In th conclusion we added the following sentence to state this perspective: "*In a next step, the results presented here can serve as a starting point for projections of future peat dynamics under different scenarios.*"

Dargie, G. C., Lewis, S. L., Lawson, I. T., Mitchard, E. T. A., Page, S. E., Bocko, Y. E., & Ifo, S. A. (2017). Age, extent and carbon storage of the central Congo Basin peatland complex. Nature, advance online publication. https://doi.org/10.1038/nature21048

Tipping, R. (1995). Holocene evolution of a lowland Scottish landscape: Kirkpatrick Fleming. Part I, peat and pollen-stratigraphic evidence for raised moss development and climatic change. The Holocene, 5(1), 69–81. https://doi.org/10.1177/095968369500500108
We thank the reviewer for making us aware of this study. We added a citation in the introduction.

Additional changes

We repeated all simulations as we detected a (minor) inconsistency in the model code. Differences in results between the updated and originally presented simulations are insignificant (area: ~ 0.001-0.01 Mkm2; C inventory: ~ 0.1-1 GtC). We updated all numbers, figures, and tables in the main manuscript and the supplementary material with the results from the updated simulations.

The inconsistency is related to the change in the water balance criteria (precipitation over evapotranspiration) for the peat initiation described in the original manuscript on page 5 line 1-5. We reverted this change and use the same criteria as described in Stocker et al. 2014 and used in earlier LPX simulations. As noted above, this change does hardly affect results, because the water balance criteria has a very weak influence in our model.

We rewrote the respective section (P5L1-5) in the model description. It now reads: "*Peatland existence, beyond a small peatland "seed" (f_peat=10^-5) in every grid cell, is further limited by criteria on its carbon (C) and water balance. In this study, the evapotranspiration for peatland tree PFTs is now calculated analogously to non-peatland tree PFTs using demand and supply functions (Sitch 2003). The determination of the criterion of a positive water balance (precipitation over evapotranspiration ratio in peat > 1) however, was kept functionally unchanged to Stocker et al. 2014.*
The C criteria were slightly improved in this study. The peat establishment [...]"

We checked all figures and found a typo on P18L28. The amount of peat carbon accumulation on northern peatlands is 313 GtC and not 343 GtC as originally stated. This is a noticeable change, but does not affect our conclusions.

~~Peatland~~ Global peatland area and carbon ~~over~~ dynamics from the ~~past 21,000 years~~ Last Glacial Maximum to the present – a ~~global~~ process based model investigation

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Abstract.

Peatlands are an essential part of the terrestrial carbon cycle and the climate system. Understanding their history is key to ~~understand~~ understanding future and past land-atmosphere carbon fluxes. We performed transient simulations over the ~~past~~ last 22,000 years with a dynamic global peat and vegetation model forced by Earth System Model climate output, thereby complementing data-based reconstructions for peatlands. Our novel results demonstrate a highly dynamic evolution with concomitant gains and losses of active peatland areas. Modelled gross area changes exceed net changes several fold, while net peat area increases by 60 % over the deglaciation. Peatlands expand to higher northern latitudes in response to warmer and wetter conditions and retreating ice sheets and are partly lost in mid-latitude regions. In the tropics, peatlands are partly lost due to flooding of continental shelves and regained ~~by~~ through non-linear ~~interactions between~~ responses to the combined changes in temperature, precipitation, and CO_2. Large north-south shifts of tropical peatlands are driven by shifts in the position of the Inter Tropical Convergence Zone associated with the abrupt climate events of the glacial termination. Time slice simulations for the Last Glacial Maximum (LGM) demonstrate large uncertainties in modelled peatland extent (global range: 1.5 to 3.4 million square kilometers (Mkm^2)) stemming from uncertainties in climate forcing. Net uptake of atmospheric CO_2 ~~through~~ by peatlands, modelled at ~~350~~ 351 GtC since the LGM, ~~includes~~ considers decay from former peatlands. Carbon uptake would be misestimated, in particular during periods of rapid climate change and subsequent ~~peatland area shifts~~ shifts in peatland distribution, when considering only changes in the area of currently active peatlands. Our study highlights the dynamic nature of peatland distribution and calls for an improved understanding of former peatlands to better constrain peat carbon sources and sinks.

1 Introduction

Peatlands are a wetland landscape type that is characterized by permanently waterlogged conditions, resulting in accumulation of dead plant material as peat (Gorham, 1957; Moore, 1989; Blodau, 2002). Peatlands are globally distributed and can take multiple forms from minerotrophic fens to ombrotrophic bogs and ~~forrested~~ forested tropical peat swamps (Rydin and Jeglum, 2013; Page and Baird, 2016; Lindsay, 2018). Peatlands cover less than 3% of the global land area (Xu et al., 2018), but store a share of the total global soil organic carbon that is up to ~~a~~ an order of magnitude higher (Page et al., 2011; Yu, 2012). They are at the same time a significant carbon sink (e.g. Gorham et al., 2012; Lähteenoja et al., 2012; Leifeld et al., 2019) and a large natural source of methane (e.g. Frolking and Roulet, 2007; LAI, 2009; Korhola et al., 2010; Yu et al., 2013; Packalen et al., 2014), and thus an integral part of the terrestrial carbon cycle (Gorham, 1991; Yu, 2011; Page et al., 2011). Most of todays peatlands, formed over the past 12~~thousand~~ ,000 years, as a result of deglacial climate change and ice ~~shield~~ sheet retreat (e.g. Halsey et al., 2000; Gajewski et al., 2001; MacDonald et al., 2006; Gorham et al., 2007; Yu et al., 2010; Ruppel et al., 2013; Morris et al., 2018b; Treat et al., 2019). Since then northern peatlands alone sequestered about 500 ~~GtC~~ GtC (Yu et al., 2010; Yu, 2012) resulting in a net cooling effect on the climate (Frolking and Roulet, 2007). Drainage and conversion of existing peatlands to plantations or other forms of land use leads to ~~a carbon loss and contributes to global warming (Dommain et al., 2018)~~release of peat carbon into the atmosphere adding to the ongoing global warming trend (Dommain et al., 2018; Leifeld et al., 2019). Additionally, global warming will likely diminish the net carbon sink of remaining global peatlands (Spahni et al., 2013; Gallego-Sala et al., 2018; Wang et al., 2018; Leifeld et al., 2019; Ferretto et al., 2019), despite a possible increase in the sink of some northern peatlands (Swindles et al., 2015; Chaudhary et al., 2017a).

Despite their global importance, peat research has long focused almost exclusively on northern high latitude ~~peat~~ peatlands with about 80% of dated peat cores taken in Europe and North America, which only covers about 40% of global peat area (Xu et al., 2018; Treat et al., 2019). ~~Research into tropical peat has since piked up (e.g. Page et al., 2011; Dommain et al., 2011, 2014; Lawson et~~ ~~but~~ Although research on tropical peatlands has increased in recent years (e.g. Page et al., 2011; Dommain et al., 2011, 2014; Lawson et al., our understanding about tropical peatlands, their dynamics and life cycles is still limited. This also entails ongoing new discoveries of previously unknown peatland complexes such as in the ~~Kongo~~ Congo Basin (Dargie et al., 2017). The tendency to search for the deepest core within a peatland (Loisel et al., 2017) and the acute lack of information about the fate of old and buried peat (Treat et al., 2019) represent additional sampling biases that contribute to our limited understanding of peatland evolution and its drivers. These gaps in our understanding are also reflected in the large ranges of literature estimates of ~~todays~~ today's peatland area (e.g. Yu et al., 2010; Page et al., 2011; Loisel et al., 2017; Xu et al., 2018) and peatland carbon (e.g. Tarnocai et al., 2009; Yu et al., 2010; Yu, 2012; Page et al., 2011; Gumbricht et al., 2017). Only recently, a highly contested study proposed a doubling of conventional northern high latitudes peat carbon stock estimates ~~(Nichols and Peteet, 2019)~~(Nichols and Peteet, 2019; Yu, 2019). Refining our understanding and estimates of peatland carbon dynamics is timely as the potential past and future effects of peatlands on the global carbon cycle are substantial, and knowledge of the amount, timing and speed of carbon removal and release is crucial to constrain them.

Results from process based models can offer an independent perspective on the transient evolution of global peatlands and peat carbon stocks, complementing data-based reconstructions of global peatland expansion and carbon accumulation (e.g. MacDonald et al., 2006; Gorham et al., 2007; Yu et al., 2010; Ruppel et al., 2013; Dommain et al., 2014; Loisel et al., 2017; Treat et al., 2019). Efforts to model peatlands and processes within them exist on site level (e.g. Frolking et al., 2010; Morris et al., 2011; Baird et al., 2012; Morris et al., 2012; Kurnianto et al., 2015; Cresto Aleina et al., 2015; Chaudhary et al., 2017b; Cobb and Harvey, 2019) as well as on regional to global scales (e.g. Wania et al., 2009a, b; Kleinen et al., 2012; Spahni et al., 2013; Gallego-Sala et al., 2016; Alexandrov et al., 2016; Chaudhary et al., 2017a; Stocker et al., 2017; Largeron et al., 2018; Qiu et al., 2018b; Swinnen et al., 2019). Although still small, the number of DGMVs Dynamic Global Vegetation Models (DVGMs) with integrated peatland modules and dynamic peatland area is increasing (Kleinen et al., 2012; Stocker et al., 2014; Largeron et al., 2018; Qiu et al., 2018a) enabling, for the first time, a hindcast of past and a prediction of future peatlands on large spacial spatial and temporal scales. Representations of peatlands were also developed for the inclusion in the land modules of complex Earth System Models (Lawrence and Slater, 2008; Schuldt et al., 2013). However, peatlands are in general still prominently missing from the newest generation of Earth System Models (ESM) taking part in the sixth phase of the Climate Model Intercomparison Project (CMIP6), which is the main source for future climate and carbon cycle projections used for the determination of international climate mitigation targets (Eyring et al., 2016). Rigorous testing and improvement of the existing peat modules has thus not only the potential to yield further insights into peatland dynamics, but can also pave the way for the integration of peat into the next generation of ESMs for improved climate projections.

Peatlands and their carbon stocks evolve dynamically through time and over glacial cycles. Peatlands may disintegrate or be buried by mineral sediments when climatic conditions become locally unfavorable for peat growth or local hydrologic conditions change (e.g. Talbot et al., 2010; Tchilinguirian et al., 2014; Campos et al., 2016; Lähteenoja et al., 2012)(e.g. Talbot et al., 2010; Tch Peatlands on exposed coastal shelves may be flooded during periods of rising sea level (Kreuzburg et al., 2018), and new peatlands may form in areas previously covered by continental ice sheets, or in areas that were previously too cold or too dry for peat establishment. Net changes in peat extent are, therefore, the difference of concomitant gains and losses in peatland area. Similarly, the net flux of CO_2 from the atmosphere to peat carbon is the sum of complex changes. Peat carbon accumulates on active and expanding peatlands. Dying peatlands may lose some of the accumulated carbon to the atmosphere through degradation while another part might be buried and thus conserved on long timescales. Estimating peat carbon stocks for today's still active peatlands is an important but not sufficient step to to fully constrain the influence of peat carbon changes on the atmospheric carbon balance. At the same time, peatlands areslow , in absence of abrupt anthropogenic disturbance, slowly reacting systems with process time scales ranging from years to millenia. The present distribution of peatland and peat carbon and their future fate thus depend on past peatland dynamics and legacy effects from the last glacial-interglacial climate transition and as well as the current interglacial (Holocene). However, model studies that thoroughly investigate the establishment as well as the disintegration of global peatlands constraining the total carbon balance transiently over the deglaciation are still lacking.

Here our goal is to present a rigorous model investigation of peatland area and carbon dynamics since the Last Glacial Maximum (LGM) 21,000 years before present (BP). We use a DGVM to simulate LGM peatland distribution and assess uncertainties stemming from the climate forcing. Transient model and factorial runs simulations from the LGM to the present are analyzed to learn about past peatland dynamics, underlying drivers and the net peatland carbon balance. Model results are compared to available data for present and LGM as well as to reconstructions of modern day peatland initiation and development.

2 Methods

2.1 Model description

The simulations presented here were performed with the Land surface Processes and eXchanges (LPX-Bern) dynamic global vegetation model (DGVM) version 1.4 (Lienert and Joos, 2018). It includes an interactive carbon, water and nitrogen cycle and simulates dynamic vegetation composition with plant functional types (PFTs), which compete for water, light and nutrients (Sitch et al., 2003; Xu-Ri et al., 2012; Spahni et al., 2013). Implementation of the long term terrestrial carbon stores , permafrost and peatlands, The implementation of permafrost and peatlands as long term carbon stores are based on the LPJ-WHyMe model (Wania et al., 2009a, b) and a module to simulate peat area dynamically (Stocker et al., 2014). Peatlands are represented as a separate land class within a grid cell. The area of each grid cell is split into a fraction covered by the land classes "peat", "mineral soils" and "old peat" (former formerly active peat now treated as mineral soils). In this study, anthropogenic land use and land use change and corresponding land classes are not considered. Peat Estimates about peat carbon loss through land use only exist for the industrial period. Leifeld et al. (2019) estimate that between 1850 and 2015 about 22 ± 5 GtC of peat carbon was lost globally. Houghton and Nassikas (2017) used results from Randerson et al. (2015) and Hooijer et al. (2010) to estimate carbon loss from draining and burning of peatlands for oil palm plantations in Southeast Asia. Losses are negligible before 1980 and amount to about 6 GtC for the period from 1980 to 2015. These estimates of the loss of peat carbon through land use, although substantial, are still small compared to the total pool sizes. Peatland vegetation is represented by five peat PFTs: Sphagnum *Sphagnum* and flood tolerant graminoids as indicative mostly for high latitude peatlands, and flood tolerant tropical evergreen and decidious tree PFTs as well as a flood tolerant version of the C4 grass PFT, as indicative mostly for tropical peatlands (Stocker et al., 2014). Carbon cycling in peat soils is based on the distinction between a lower, fully water saturated slow overturning pool (catotelm) and an upper fast overturning pool (acrotelm) with fluctuating water table position (WTP) (Spahni et al., 2013). Acro- to catotelm flux is determined by an average acrotelm bulk For the determination of the carbon flux between acrotelm and catotelm a fixed average acrotelm C density ($18.7\ \mathrm{kg\,C\,m^{-3}}$) is used. The difference between this target acrotelm density and the acrotelm mass balanceactual average acrotelm density, determined by organic carbon influx from the litter pools and heterotrophic respiration within the acrotelm, is used to determine the size and sign of the daily flux between acrotelm and catotelm (Spahni et al., 2013). Decay rates are modulated by temperature in the catotelm and by temperature and WTP in the acrotelm (Wania et al., 2009a).

The area fraction covered by peat (f_{peat}) in a given grid cell is determined dynamically with the DYPTOP module (Dynamical Peatland Model Based on TOPMODEL) (Stocker et al., 2014). The TOPMODEL approach (Beven and Kirkby, 1979) is used to predict the monthly inundated area fraction given sub grid sub-gridscale topographic information and mean grid cell

WTP. Here the WTP calculation of mineral soils has slightly changed with respect to Stocker et al. (2014), with drainage runoff excluded from the calculation. The area potentially available for peatlands (f_{pot}) is then determined by inundation persistency. Peatlands expand or shrink towards a changing f_{pot} with a rate of ~~0.01~~ 1% of current f_{peat} per year. The gridcell fraction lost during peatland retreat is treated as a separate ~~landuse~~ land use class named "old peat". It inherits the carbon stocks of the dying peat and is subsequently treated ~~the same~~ in the same way as the mineral soils regarding vegetation, hydrology and carbon cycling. Growing active peatlands first expand on eventual old peat inheriting the remaining carbon there.

As vegetation growth and carbon cycling continues normally on the old peat fraction, the carbon inherited by the former peatland, which would form distinct organic soil layers in the real world, can in the model not be distinguished from new carbon accumulated by new ~~non-peat vegetation. Similar~~ non-peatland vegetation. The same is true for gridcells that get flooded by rising sea level~~, in which~~. Given the evidence of coastal peat carbon deposits Kreuzburg et al. (2018); Treat et al. (2019), we assume that most of the carbon is buried within sediments rather than released to the atmosphere during flooding. In case of flooding in the model, carbon from all ~~landuse~~ land use classes in the respective cell is combined into a single "flooded" ~~landuse class. However~~land use class, where it slowly decays with a mean lifetime of 15 kyr. Despite this mixing of carbon from different sources, we can track peat carbon in post processing using the transient model output for peatland area changes, decay rates of slow pool carbon, and carbon input into the catotelm of the active peatlands. Area changes are used to transfer carbon between active, old and flooded peatlands. Transient decay rates are used to decay the carbon in the respective pools. Carbon is thus tracked from the entry into the catotelm of an active peatland until decay in either an active, old or peatland flooded by ocean. This approach can not take account of the acrotelm carbon. However acrotelm carbon constitutes only a small part of total peat carbon (5% at pre-industrial), and we can assume that this carbon at the peat surface is quickly respired after peatland transformation. The "old peat carbon" calculated this way represents the remaining peatland carbon after peatland death and is used in the calculation of the peatland carbon balance (see Sect. 3.3.5).

Peatland existance, beyond a small peatland ~~seed~~ "seed" ($f_{peat} = 10^{-5}$) in every grid cell, is further limited by criteria on its carbon (C) and water balance. In this study~~these C and water balance criteria were slightly improved with respect to Stocker et al. (2014). The criterion of a positive water balance (precipitation over evapotranspiration > 1) now includes interception loss by tree peat PFTs (precipitation-interception) over evapotranspiration > 1). Further~~, the evapotranspiration for ~~tree peat~~ peatland tree PFTs is now calculated ~~analogues to non-peat~~ analogously to non-peatland tree PFTs using demand and supply functions (Sitch et al., 2003). The determination of the criterion of a positive water balance (precipitation over evapotranspiration ratio in peat > 1) however, was kept functionally unchanged to Stocker et al. (2014). The C criteria were slightly improved in this study. The peat establishment and persistence criterion on the C balance during the spinup is a positive net ecosystem production (NEP) and an ~~acro-~~ acrotelm to catotelm flux higher than 10 $\mathrm{g\,m^{-2}yr^{-1}}$, or C stocks of the peat seed exeeding 50 $\mathrm{kg\,m^{-2}}$ as in Stocker et al. (2014). During the transient run this criterion is changed so that peat establishment depends on the ~~acro-~~ acrotelm to catotelm flux alone. For peat persistance, the sharp C ~~pool~~ stock threshold is softened. ~~From~~

For a peat C stock of from 50 $\mathrm{kg\,m^{-2}}$ to about 45 $\mathrm{kg\,m^{-2}}$ f_{pot}, is reduced to an actual potential peatland fraction (f_{apot}) according to a sigmaoid sigmoid function:

$$f_{apot} = f_{pot} \times \frac{1}{1 + 20\, e^{-2.4\,(C_{peat} - 46)}} \quad |\, if\ C_{peat} < 50\,\mathrm{kgm^{-2}} \tag{1}$$

with C_{peat} representing the peatland soil carbon pool in $\mathrm{kg\,m^{-2}}$. This avoids peatland collapse due to a sharp threshold. Peatlands can now endure short periods of carbon loss even with C pools falling bellow the threshold of 50 $\mathrm{kg\,m^{-2}}$, but have to suffer area losses as a consequence, as f_{peat} now approaches f_{apot}.

The above described representation of peatlands in the LPX is a simplification in many respects. The absence of local processes and information like lateral water flow, the influence of sea level variations on the water balance, local soil features, or influence of animals by grazing and river damming can limit the ability of the TOPMODEL approach to predict peatlands on a regional to local scale. Further, direct human-caused influences such as land use, drainage, or peat mining are not considered. The lack of a distinction and transition between different peatland types like fens, bogs, blanket bogs, or marshes neglects possible differences in the constraints on their formation and evolution. The treatment of acrotelm and catotelm as single carbon pools, and the absence of strong disturbances such as peat fires, constitute limits on the comparability of the model results to peat core carbon profiles. This simplified representation however has been shown to reproduce peatland area and carbon accumulation well within the observational constraints (Wania et al., 2009a; Spahni et al., 2013; Stocker et al., 2014, 2017) while using a minimal set of free paramtersparameters. Our efficient representation allows for long transient paleo simulations and sensitivity studies as we present them here.

2.2 Simulation setup

The transient LPX runs simulations from the Last Glacial Maximum (LGM), 22 kyr before present (BP), till present are run with a model resolution of 2.5° latitude × 3.75° longitude and were forced with CO_2 (Joos and Spahni, 2008), temperature and precipitation fields, and transient evolving orbital parameters influencing available photosynthetic active radiation. Temperature and precipitation anomalies are taken from the transient CCSM3 run TraCE21k (Liu et al., 2009). The TraCE21k experiment constitutes a unique climate forcing, not only because it is to date the only published transient simulation over the deglaciation using a fully coupled general circulation model (GCM), but also because the meltwater forcing in TraCE21k was chosen, using sensitivity experiments, to best reproduce the abrupt climate events such as the Bølling-Allerød (BA) and the Younger Dryas (YD) (He, 2011). The TraCE21k anomalies are imposed on the CRU TS 3.1 (Mitchell and Jones, 2005) base climate from 1960-1990. 1960 to 1990. Inter annual variability thus is adopted from TraCE21k. The land-sea-ice mask is changing every 1 kyr according to Peltier (2004) and is interpolated in between. The model is spun up under LGM conditions for 2.5 kyr before starting the transient simulations.

Additional In addition to the standard LPX transient simulation, five transient factorial simulations were performed using the same setup but for each keeping one of the five transient forcings (land-sea-ice mask, orbital, CO_2, precipitation, and temperature) constant at LGM levels. These were used to identify the dominant drivers and driver contributions through time, by comparing the factorial and standard runs. (see Sect. 3.3)

To investigate the uncertainty stemming from the choice of climate forcing, seven additional LGM timeslice simulations were performed. Mean LGM climate anomalies from six different PMIP3 models (Braconnot et al., 2012), CCSM4, COSMOS-ASO, IPSL-CM5A-LR, MIROC-ESM, MPI-ESM-P, and MRI-CGCM3, and the mean LGM anomaly of the TraCE21k simulation were imposed on the CRU 3.1 climatology from 1901-1931. Inter annual variability thus is adopted from CRU. CO_2, ice-sea-land mask and orbital parameters are set to LGM levels (in this case 21 kyr BP). Two of the eight available ~~PMIP3 LGM simulations were dismissed~~ LGM simulations from phase 3 of the Paleomodel Intercomparison Project (PMIP3) were not used (FGOALS-g2 and CNRM-CM5), because of ~~the~~ their poor performance compared to observational data, especially in the variables of temperature and precipitation (Harrison et al., 2014). Simulations are spun up for 2.5 kyr and run an additional 2 kyr under unchanged conditions. In the analysis the temporal mean over the last 2 kyr is used.

2.3 Validation data

Even estimates for the current global peatland area are still subject to large uncertainties as peatlands often lie in remote, inaccessible or understudied regions, such as the tropical forests or the Arctic tundra. Even estimates for the relatively well studied northern high-latitude peatlands have a range ~~of~~ from 2.4 ~~-~~ to 4.0 Mkm^2 (see Loisel et al. (2017) for a review). Total area of tropical peatlands is even less well defined and estimates range from 0.37-1.7 Mkm^2 (Yu et al., 2010; Page et al., 2011; Gumbricht et al., 2017). The upper end of this range is given by an estimate that uses an expert system method, combining hydrological modelling, satellite imaging, and topographic data and thus tries to also account for still undiscovered peatlands (Gumbricht et al., 2017). The to date most extensive and comprehensive compilation of known peatlands is the recent PEATMAP by Xu et al. (2018). PEATMAP shows a distribution shifted more towards the tropics, than previous literature estimates. For example Yu et al. (2010) estimates the area of northern peatlands to 4 Mkm^2 and of tropical peatlands to 0.37 Mkm^2, whereas PEATMAP gives 3.18 Mkm^2 and 0.99 Mkm^2, respectively. In Fig. 1, Table 1, and Sect. 3.1 LPX present day peatland extent and global distribution are compared against a $0.5° \times 0.5°$ gridded version of PEATMAP.

Measured peat core basal dates have long been used to estimate northern peat initiation and lateral expansion through time. Yu et al. (2013) compiled a dataset containing 2808 basal dates combining published datasets from MacDonald et al. (2006), Gorham et al. (2007) and Korhola et al. (2010). Loisel et al. (2017) used this dataset (MGK13) to produce a version with only the oldest date per 1°x1° gridcell (MGK13G), as a proxy for peatland initiation. The MGK13G dataset is used in this study to compare to simulated northern peat initiation (see Sect. 3.3.4). Multiple local basal dates are needed to disentangle lateral expansion from initiation. Loisel et al. (2017) compiled a reconstruction based on the gridded MGK13 dataset, but only gridcells with three or more peat cores were considered (MGK13S). Expansion curves were built regionally and then stacked to compensate for regional sampling bias. Korhola et al. (2010) used a similar approach using 954 basal dates from 138 sites, with at least 3 dated cores per site. Their expansion reconstruction (KOR10) shows delayed expansion compared to Loisel et al. (2017) and fastest expansion between ~~3-5~~ 3 and 5 kyr BP. Both MGK13S and KOR10 are compared to the expansion simulated by LPX for currently existing northern peatlands (see Sect. 3.3.4), thereby not including area changes of previously existing, but by now disappeared peatlands.

3 Results and discussion

3.1 Distribution and carbon inventories of present day peatlands

3.1.1 Peatland area

Modern peatland distribution simulated by LPX-Bern (standard run) compares well to the distribution given by PEATMAP (see Fig. 1 and Table 1). LPX and PEATMAP yield, with ~~4.36~~ 4.37 Mkm^2 and 4.23 Mkm^2 respectively, a very similar global peatland area. The same is true for the latitudinal distribution. LPX simulates 3.2 Mkm^2 in the high latitudes (>30° N) and 1.15 Mkm^2 in the tropics (30° S - 30° N), whereas PEATMAP gives 3.18 Mkm^2 and 0.99 Mkm^2 respectively. This broad scale agreement between LPX and PEATMAP notably emerges without any tuning of the LPX against PEATMAP. These results are similar to previous results using the LPX (Stocker et al., 2014) with slightly larger tropical peatland coverage in the current study. Differences are due to a new model version after data assimilation, LPX v1.4, ~~after data assimilation (Lienert and Joos, 2018) and~~ (Lienert and Joos, 2018) and the additional model changes described in Sect. 2.1.

Minor and major differences in peatland area between LPX and PEATMAP are seen on the local to regional scale (Fig. 1 and Table 1). In the tropics, LPX simulates more peat in South America and Southeast Asia than PEATMAP indicates. Compared to the estimate of Gumbricht et al. (2017), LPX peatland extent is similar for South America and a factor two smaller for Southeast Asia. The vast peatland complex in the ~~Kongo~~ Congo Basin is almost absent in LPX. In the northern mid to high latitudes, LPX seems to underestimates European peatland area by a factor of two and slightly overestimates peatland area in northern Asia, mostly west and east of the Western Siberian Lowland (WSL) peat complex. In North America, LPX ~~shows~~ simulates more peat in Alaska and Quebec ~~than PEATMAP~~ and less in Western Canada than PEATMAP.

Other modeling studies present results from prognostic simulations of Northern hemisphere peatlands. Kleinen et al. (2012) simulated peatland dynamics and carbon accumulation over the past 8000 years using the coupled climate carbon cycle model CLIMBER2-LPJ. However, no quantitative results in terms of peatland area were reported. Qiu et al. (2018b) used the ORCHIDEE-PEAT DGVM Qiu et al. (2018a) to simulate northern (>30° N) peat expansion over the Holocene. Their simulated northern present day peatland area is with 3.9 Mkm^2 slightly larger than in LPX. They find similar regional discrepancies between simulated and observation-based peat area in North America, northern Europe and Asia, as described above for LPX. Peat area dynamics in ORCHIDEE-PEAT are also using the TOPMODEL approach following Stocker et al. (2014), with some different expansion criteria. This might indicate that these discrepancies could have their source in the TOPMODEL approach and its limitations. Another major source of uncertainties is in the climate data used to force LPX (see also Sect. 3.2.2). In particular precipitation data show large discrepancies between available observational products (Sun et al., 2018).

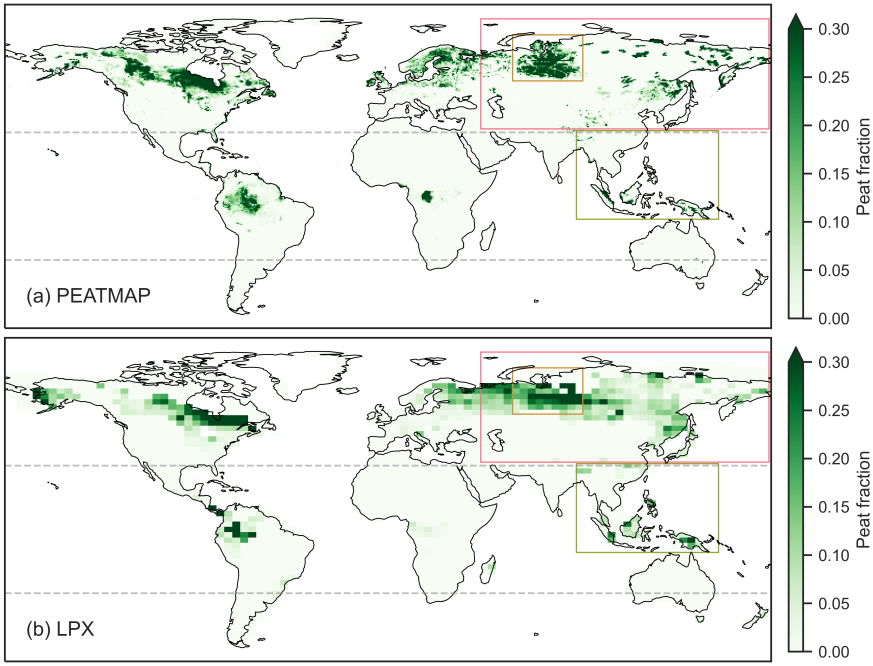

Figure 1. Global present day peatland distribution according to PEATMAP (Xu et al., 2018) in a 0.5° × 0.5° gridded version (a) and simulated by LPX-Bern after the transient 'standard' setup simulation from 22 kyr BP to present (b). Colored rectangulars show three of the regions listed in Table 1: Northern Asia (red), Western Siberian lowlands (orange), and Southeast Asia (green)

3.1.2 Peatland carbon

Total peat carbon estimates are closely linked to the estimates for area and thus inherit their uncertainties. Additional assumptions on bulk density and peat depth introduce additional uncertainties. The range of carbon estimates therefore is similarly large as for area (Gorham, 1991; Turunen et al., 2002; Yu et al., 2010). The research bias allows for more constrained estimates in well studied regions such as Europe and North America and less constrained in the tropics and Northern Asia. Estimates for ~~Northern~~ northern peatlands range from ~~270-604~~ 270 to 604 GtC, obtained with various methods and area estimates (see Yu (2012) and Yu et al. (2014) for a review). The modern carbon inventory of northern peatlands simulated by LPX at the end of the transient standard run from the LGM till present is with 361 GtC well within this observational range. In the tropics, LPX simulates a peat carbon inventory of ~~135~~ 136 GtC which is substantially larger than classical literature estimates that range from 50-87 GtC (Yu et al., 2010; Page et al., 2011). These, however, also assume a substantially smaller tropical peatland area than LPX or PEATMAP suggest (see Sect. 3.1.1). Including estimates for the newly discovered peat in the Congo Basin, Dargie et al. (2017) estimate a tropical peat inventory of 69.6-129.8 GtC, closer to the LPX results. Gumbricht et al. (2017)

Table 1. Peatland area for different regions and latitudinal bands as given by PEATMAP (Xu et al., 2018) for today and peatland area and their carbon stocks as simulated by LPX-Bern for the preindustrial period (PI) and the Last Glacial Maximum (LGM) in the transient 'standard' setup simulation from 22 kyr BP to present. The extent of the regions Northern Asia, Western Siberian (WS) Lowlands, and Southeast Asia are shown in Fig. 1.

Region	PEATMAP	LPX (PI)		LPX (LGM)	
	Mkm^2	Mkm^2	GtC	Mkm^2	GtC
Global	**4.232**	**~~4.364~~4.366**	**~~499.0~~499.3**	**~~2.686~~2.687**	**275.6**
Northern (> 30°N)	**3.168**	**~~3.203~~3.202**	**~~361.3~~361.4**	**~~1.431~~1.430**	**142.1**
Tropics (30°S to 30°N)	**0.976**	**~~1.149~~1.151**	**~~135.5~~135.7**	**~~1.235~~1.236**	**131.6**
North America	1.330	~~1.291~~ 1.294	~~98.9~~ 99.2	0.823	86.4
South America	0.489	0.744	94.9	~~0.633~~ 0.634	62.7
Europe	0.414	~~0.232~~ 0.231	19.6	0.331	30.8
Northern Asia	1.467	~~1.686~~ 1.685	243.4	0.301	27.0
WS Lowlands	0.624	0.691	108.9	~~0.031~~ 0.030	~~2.6~~ 2.5
~~Afrika~~ Africa	0.189	0.050	~~3.8~~ 3.9	~~0.114~~ 0.115	~~6.9~~ 7.0
SE Asia	0.273	0.349	36.1	0.471	60.4

calculate an even larger area than LPX and combining their area estimate with the peat properties assumed by Page et al. (2011) would result in a tropical peat inventory of 350 GtC.

Previous studies with LPX-Bern reported somewhat different carbon inventories than given here. Stocker et al. (2014) reported 460 GtC and 88 GtC for northern and tropical peatlands respectively. Differences stem from an updated model version, also resulting in different areas as mentioned in the previous section. Additionally, their carbon stocks were the results of an accelerated spinup scheme, whereas in this study the pools are filled over a transient run. Spahni et al. (2013) also reports northern peatland carbon stocks after a transient LPX run from the LGM, however with prescribed not prognostic peatland area. Their simulation resulted in 365 GtC stored in northern peatlands.

Other model studies with dynamic peatland area reported 317 GtC after an 8 kyr Holocene run (Kleinen et al., 2012) and 463 GtC after a 12 kyr Holocene run (Qiu et al., 2018b) in northern peatlands.

3.2 ~~Area distribution and carbon inventories of peatlands~~ Peatlands during the Last Glacial Maximum

3.2.1 Peatland distribution and carbon storage

Under LGM conditions global simlulated peatland area and carbon inventories are reduced compared to preindustrial (Table 1). Globally, simulated peatland area and peat C inventory are 38% and 45% smaller at LGM than PI respectively. This reduction is dominated by the northern extratropics, where peat extent and C inventory are by almost 60% smaller at LGM than PI. In contrast, peat C inventory in the tropics is only about 3% smaller and tropical peat area is even 7% larger at LGM than PI.

This difference in the tropics is mostly linked to large peatlands simulated on flat exposed continental shelves in Southeast Asia at the LGM, which were subsequently flooded during the deglaciation. Another modeling study by Kaplan (2002) also suggests extensive wetlands on the flat Sunda Shelf, but reconstructions of Indonesian peatlands suggest that vast peat presence in Indonesia during the LGM is unlikely (Dommain et al., 2014). Establishment of now existing inland peatlands seems to be connected to rising sea level (Dommain et al., 2011). In sediment cores from the now submerged Sunda Shelf, there is little evidence of peatlands during the LGM (Hanebuth et al., 2011). Dommain et al. (2014) suggest that the shelf, although with a small topographic gradient, had an effective drainage system with deeply incised river valleys, preventing the formation of large wetlands. Both, the hydrological feedback of rising sea level and deep river systems, are not represented in LPX and thus might limit the models ability to reproduce peat and wetland dynamics in this region correctly.

Simulated peatland coverage in northern mid and high-latitudes is smaller and shifted southwards at LGM compared to PI. ~~Ice-shields~~ Ice sheets covered large parts of Europe and North America during the LGM preventing vegetation and peat ~~to grow~~from growing. But also in Northern Asia and the WSL, peat is mostly absent due to the substantially colder and dryer conditions compared to today. On the other hand, large peatland complexes are simulated along the southern ~~ice-shield~~ ice sheet margins in North America and in Europe (Fig. 2), in regions where modelled peatlands are mostly absent under current conditions. This even leads to a simulated net increase of peatland area in Europe (+43%) compared to present. ~~Veriyfing~~ Verifying the existence of these extensive LGM peatlands that do not exist under present conditions (compare Fig. 1) is difficult, as existing compilations of peat core dates focus almost exclusively on today's existing peatlands (MacDonald et al., 2006; Gorham et al., 2007; Yu et al., 2010; Loisel et al., 2017). In a recent study Treat et al. (2019) presented a compilation of dated buried peat deposits together with simulated peatland area and carbon stocks. Their simulation also suggests large mid latitude peatlands in North America in agreement with our results. Their peat deposits data for the LGM (Fig. 2; dots), together with pollen analyses suggesting the presence of at least some ~~sphagnum in East North-America~~ *Sphagnum* in East North America (Halsey et al., 2000; Gajewski et al., 2001), provide plausible evidence for the existence of mid-latitude LGM peatlands in North America and Europe. Their extent however is probably overestimated in our simulation. Comparisons between the North-American LGM hydroclimate in TraCE21k and proxy reconstructions have resulted in a poor skill score especially in eastern North-America (Lora and Ibarra, 2019). Bad performance in this region is shared with all PMIP3 models (Lora and Lora, 2018).

3.2.2 Uncertainties from climate forcing

The peat distribution as simulated by LPX-Bern for the LGM and the past 20,000 years is subject to many uncertainties. Uncertainties arise from model parameterisations, not only in the peat module, but through all components of the model, and are often hard to quantify. Data assimilation, as done recently for the LPX in Lienert and Joos (2018) to constrain model parameters, is an approach to improve model performance in the light of uncertain key parameters. Another source of uncertainty stems from uncertainties in the prescribed forcings. Orbital parameters, atmospheric CO_2 mixing ratio, and land-sea-ice mask for the LGM and their deglacial evolution are all well constrained for the purpose of peat modelling in contrast to the climate anomalies. Although there are paleoclimate reconstructions for the LGM (Bartlein et al., 2011; Schmittner et al., 2011; Annan

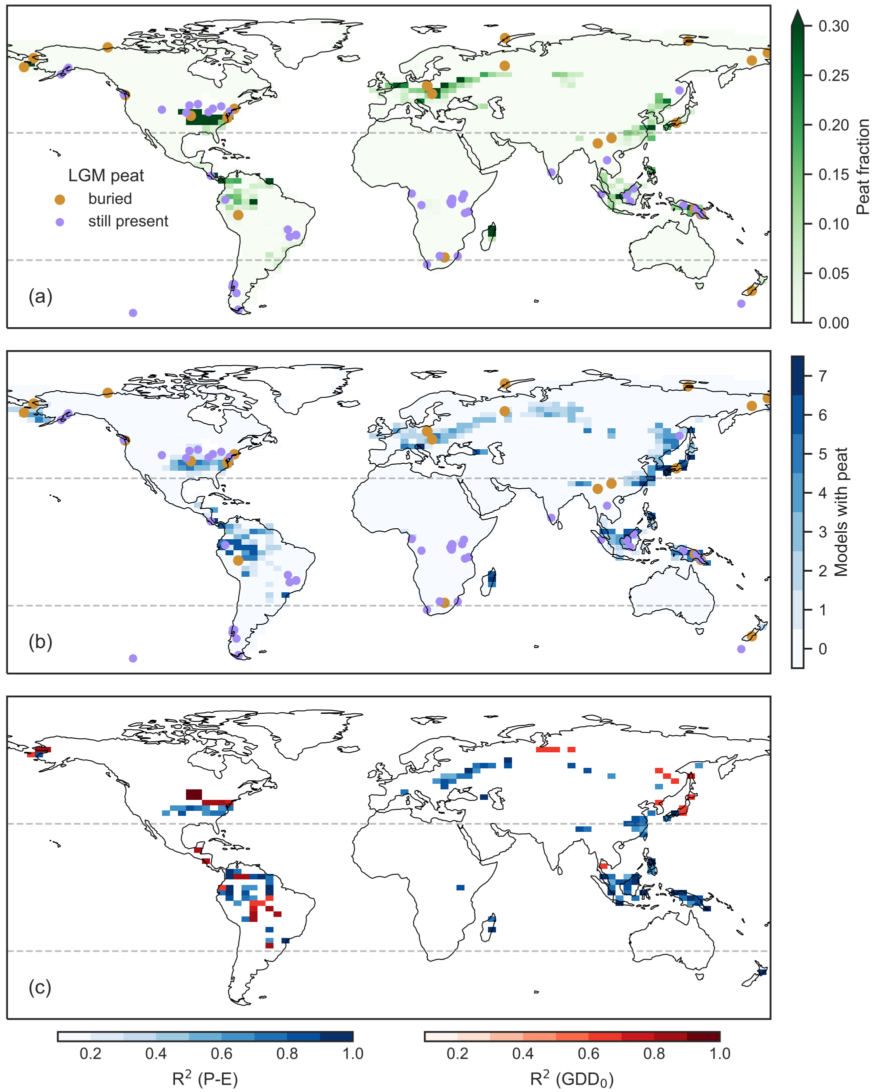

Figure 2. Peatland distribution at the Last Glacial Maximum (LGM) as simulated by LPX-Bern in the standard setup (a), agreement (as number of models simulating peat in given gridcell) between ~~LPX~~ LGM timeslice simulations ~~,~~ run with LPX and forced with different climates anomalies from six PMIP3 models ~~and~~ as well as the TraCE21k anomaly (b), and squared correlation coefficient for a linear regression between physical properties of the different timeslice simulations (precipitation minus evapotranspiration (P-E) and growing degree days above 0 °C) and peat fraction in the respective cells. Plotted are only cells with significant correlation ($p > 0.05$). Color shading in (b) indicates how many timeslice simulations show a peat fraction of > 0.05 in the respective cell. Color code in (c) denotes the dominant predictor in the respective cell. Dots in (a) and (b) show buried and still active peat deposits that indicate active peat accumulation during the LGM (24.5-17.5 kyr BP). Peat core data are from Treat et al. (2019).

and Hargreaves, 2013), 6k (Bartlein et al., 2011) and the last millennium (Hakim et al., 2016; Tardif et al., 2019), they lack the temporal resolution and/or spatial coverage needed for a global transient simulation from the LGM to present. Climate models can fill these gaps, ; however climate anomalies are model dependent and model performance differs between variables, regions, and simulated time period (Harrison et al., 2014). These differences in climate models have been shown to propagate large uncertainties into carbon cycle projections (Stocker et al., 2013; Ahlström et al., 2017).

We assess the uncertainty in peatland area and peat carbon stemming from climate forcing uncertainties. Climate anomalies from seven different models are used to force the LPX into seven different LGM states (see Sect. 2.2). This yields a very wide range for global mean inundated area (2.6-3.6 Mkm^2), peat area (1.5-3.4 Mkm^2) and peat carbon (144-343 147-347 GtC). Interestingly, simulated wetland and peatland area and peat C inventory for the 21 kyrBP period are also substantially different between the standard transient simulation using temporally evolving climate anomalies from the Trace21k TraCE21k simulation compared to the timeslice simulation forced with Trace21k TraCE21k anomalies (Fig. 3; red star versus magenta grey star versus grey dot). This highlights both the influence of different methods of input preparation, with slightly different treatment of anomalies and an inter annual variability taken form from TraCE21k in the transient simulation and from CRU 3.1 for the timeslice, as well as the importance of memory effects for a slowly reacting system such as peatlands.

Agreement on simulated peat extent among the seven simulations differs among regions (Fig. 2 (b)). It tends to be higher in the tropics and East Asia, and lower in North America, Europe and West Siberia. Differences in temperature and precipitation anomalies propagate into differences in the water balance and productivity, partly limited by growing season length, and thus into differences in peat abundance and extent.

A statistical analysis of the differences in climatic drivers and simulated peat area reveals regionally different mechanisms (Fig. 2 (c)). Temperature, precipitation, precipitation minus evapotranspiration (P-E), and growing degree days over 0 °C (GDD_0) are considered as climatic predictor variables for the peat fraction within a gridcell. We correlated, for each grid cell, the seven climatological mean values of a selected predictor with the modelled peat fraction from each of the seven time slice simulations. P-E and GDD_0 show significant correlations ($p<0.05$) in more gridcells than precipitation and temperature, respectively. Both moisture balance and GDD_0 have been shown to be among the most important predictors of northern peat initiation and carbon accumulation in the past (Morris et al., 2018a; Charman et al., 2013). In LPX the water balance, influenced by P-E, and the carbon balance, influenced by temperature and growing season length, define thresholds on peatland existence and size. In eastern Europe, differences in peat extent between the seven LGM time slice simulations are mostly driven by differences in local precipitation anomalies driving P-E. Similar The same is true in the tropics, with MRI-CGCM3 and IPSL-CM5A-LR being the driest models with the least tropical peatlands and TraCE21k and COSMOS-ASO being the wettest with the most largest tropical peatlands. In parts of central South America however, temperature is the dominant predictor signaling a fragile carbon balance, where peat presence in some models of the model climates is possible because of cooler conditions and thus reduced respiration. In the south of North America, moisture balance, with contributions of both P and E, is the dominant determinant of the inter model differences. The timeslice forced with TraCE21k climate shows the peatland

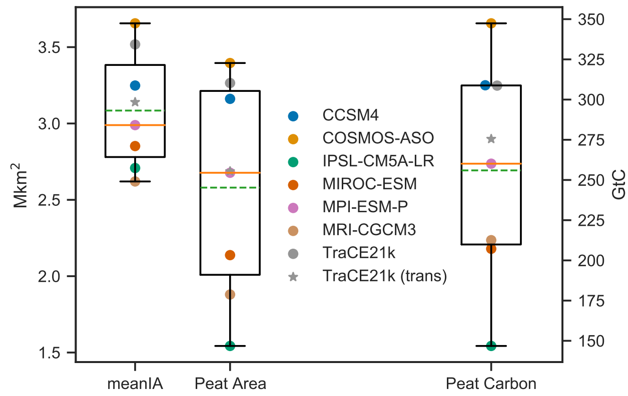

Figure 3. Spread of global annual mean inundated area (meanIA), peatland area, and peatland carbon ~~over~~ during the ~~seven~~ LGM (21 kyr BP) in timeslices forced with climate anomalies from seven different climate models (see Sect. 2.2). The box, the solid line, and the dashed line indicate the interquartile range, the median and the mean from the seven simulations. The star indicates the values of the transient simulation for the same time period using climate anomalies from ~~Trace21k~~TraCE21k.

distribution in North America more shifted to the east compared to most other PIMP3 forcings alongside warmer and wetter conditions (see also Lora and Lora (2018)). Peatland extent in the north of North America is sensitive to temperature differences with longer growing season allowing for increased productivity and therefore peat formation. In the MRI-CGCM3 timeslice temperature anomalies with respect to preindustrial are lowest and peat is subsequently shifted northwards compared to other time slices. Similar is true for Northern and East Asia where lower temperature anomalies allow for more peatlands. Large areas in central Europe, East Asia and South America show differences in peatland extent induced by differences in climate forcings, but no significant correlations between peat fraction and predictor variables are found. This might be the result of non linear interactions and threshold behaviours not captured by our linear regression approach. Taken together these findings demonstrate a strong sensitivity of simulated peat extent and C inventory to the prescribed climate fields and a strong dependence of the results on the choice of climate model output used to force LPX . In other words, caution is warranted In other words, caution is warranted when interpreting model results for times and regions in which proxy records or observations are sparse and have limited power to constrain the actual climate conditions. This holds not only in the context of this study, but for global peat and carbon cycle model studies in general.

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3.3 Transient peat evolution

Figure 4 (a) shows the peatland evolution in the transient model run. The model simulates the establishment and expansion of peatlands under favorable conditions, but also the decay and disappearance of peatlands under unfavorable conditions. Both processes can happen simultaneously on a global as well as a regional scale (Fig. A1). To treat carbon storage in a consistent manner, we distinguish between the active peatlands, which are treated as peatlands in the LPX, and old peatlands, which are treated as mineral soils. Old peatlands inherit the carbon stocks of the peatlands that are shrinking or vanishing. Similarly, growing active peatlands first expand onto the area of old peatlands inheriting the remaining carbon stored there (see also Sect. 3.3.5). In the analysis, we decompose the net changes of peatland area into gross positive and negative changes. This allows for a deeper insight into the underlying temporal dynamics (Fig. 4 (b)). Transient factorial runs, performed over the same time period as the standard setup (see Sect. 2.2), allow us to attribute driver contributions to the simulated changes (Fig. 4 (c) and 5).

3.3.1 22 kyr BP - 17.43 kyr BP

Global changes in peatland area and carbon before the onset of the Heinrich Stadial 1 (HS1) are small, due to the relatively small changes in the main drivers. There is initial carbon loss in some regions of the tropics, due to some gridcells still approaching equilibrium after the spinup (Fig A1). North America sees an accelerating carbon accumulation with unchanging area already before the HS1, driven mostly by increasing temperature. Carbon and area also increase in Europe with large temperature driven fluctuations

3.3.2 17.43 kyr BP - 11.65 kyr BP

Three main features characterize the peat area evolution over the last glacial termination: (i) a northward shift in the distribution of northern extratropical peatlands, including peat expansion in northern Asia, (ii) dipole-like north-south shifts in tropical South America, associated with north-south shifts of the rain belts of the Inter Tropical Convergence Zone (ITCZ), and (iii) flooding of peatlands on continental shelves, mostly in ~~South-East~~ Southeast Asia, due to ~~the beginning of~~ rising sea levels.

The last termination represents the transition of the climate system from the last glacial to the current interglacial, accompanied by large warming, ocean circulation changes, and an increase in atmospheric CO_2 (Monnin et al., 2001; Shakun and Carlson, 2010; Ritz et al., 2013). The termination is divided into the HS1 (17.43 - 14.63 kyr BP) northern hemisphere (NH) cold period, the Bølling-Allerød (BA, 14.63 - 12.85 kyr BP) NH warm period, and the Younger Dryas (YD, 12.85 - 11.65 kyr BP) NH cold period (Rasmussen et al., 2014)~~,~~. These NH cold-warm swings are associated with a large-scale reorganization of ocean circulation, thought to have been provoked by freshwater release from ice sheet melting leading to changes in the ocean heat transport (Stocker and Johnsen, 2003). With changing low- to high-latitude temperature gradients the ITCZ shifted and with it the high precipitation zones in the tropics (McGee et al., 2014; Shi and Yan, 2019; Cao et al., 2019). These climate dynamics are well captured by the transient TraCE21k simulation (Liu et al., 2009).

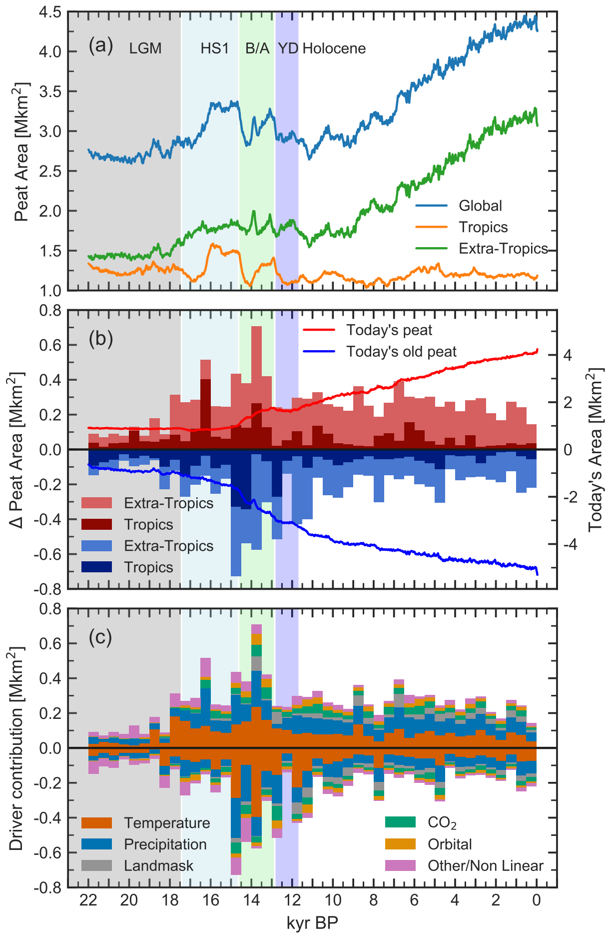

Figure 4. Simulated peatland area over time (a), gross positive and negative peatland area changes in 0.5 kyr bins, as well as evolution of today's simulated peatland area and old peat area (b), and driver contributions to the same changes (c), calculated using factorial simulations (see Sect. 2.2). Contributions by regions (b) and by drivers (c) are plotted cumulatively. Vertical bars indicate the Last Glacial Maximum (LGM) period, the Heinrich Stadial 1 (HS1) Northern Hemisphere cold phase, the Bølling-Allerød (BA) Northern Hemisphere warm phase, and the Younger Dryas (YD) Northern Hemisphere cold phase.

The responses of peatlands in LPX to these climatic changes are drastic. Large shifts in peatland area start to set in at the onset of the HS1 and increase into the BA. During the BA, peatlands show the fastest gross positive and negative area changes throughout the simulation (see Fig. 4 (b)). In the northern mid and high latitudes, peatlands shift north and eastward (see Fig. 6 and Fig. A2). Peatlands disappear in mid latitude North America and Europe and new peatlands emerge at higher latitudes and in cold continental regions of Asia. These new peatlands include the large peat complex in the Western Siberian Lowlands (WSL). Some of the peatlands established in northern Europe during HS1 vanish again during the BA. ~~These~~ The described changes are driven by the ~~Trace21k~~ TraCE21k climate which shows a substantial warming and wettening of the Northern

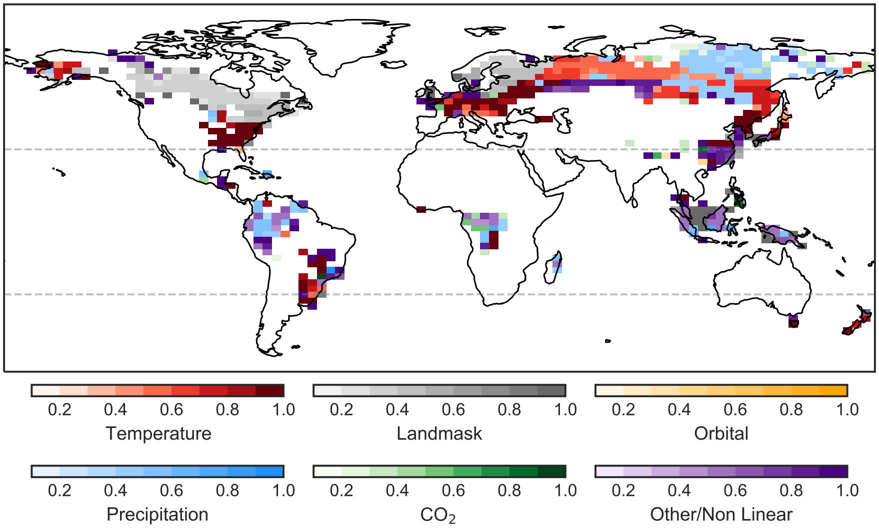

Figure 5. Drivers of the change in peatland area from LGM to present. Colors indicate the most important driver, and color shade the contribution of the respective driver on a scale from 0 (no contribution) to 1 (only contributor).

Hemisphere already starting during the HS1. Temperature is the dominant driver for peat loss and expansion in Europe and North America. The loss of old peat is especially abrupt in North America (see Fig. A1 (b)). Here precipitation decreases and temperature increases abruptly over the south west of North America at 13870 BP. Both changes decrease the water balance given by P-E which leads to a decrease in potential peat area and thus loss of the previous extensive peat complexes. As this abrupt climate change occurs at a discontinuity of the trace boundary conditions (changes in ice sheet configuration and freshwater forcing), the speed of this change is probably drastically overestimated. In Northern Asia both temperature and precipitation drive the peatland expansion. This expansion sees a pronounced halt during the YD where northern hemisphere climate is briefly returning to more glacial conditions (see Fig. A2 (e)).

In the tropics, the area and carbon changes are mostly driven by precipitation changes. Largest changes are simulated in South America, where precipitation patterns respond to changes in ITCZ position (see Fig. 6). During the HS1 and the YD where the Atlantic meridional overturning circulation (AMOC) is in a reduced state, peatland area shifts to the south following the southward shift of the ITCZ. During the BA the AMOC is strong and precipitation and peatland area shift back north. In Africa half the peatland area is lost during the BA mostly driven by drying. In South East Asia peatlands are lost over the whole termination due to precipitation changes and the onset of sea level rise, which starts to flood the large continental shelves at about 16 kyr BP.

The shifts in peatland distribution result in a similar global peatland area at the beginning of the Holocene compared to the LGM and at the onset of the HS1. However, much less carbon is stored in active peatlands at the beginning of the Holocene

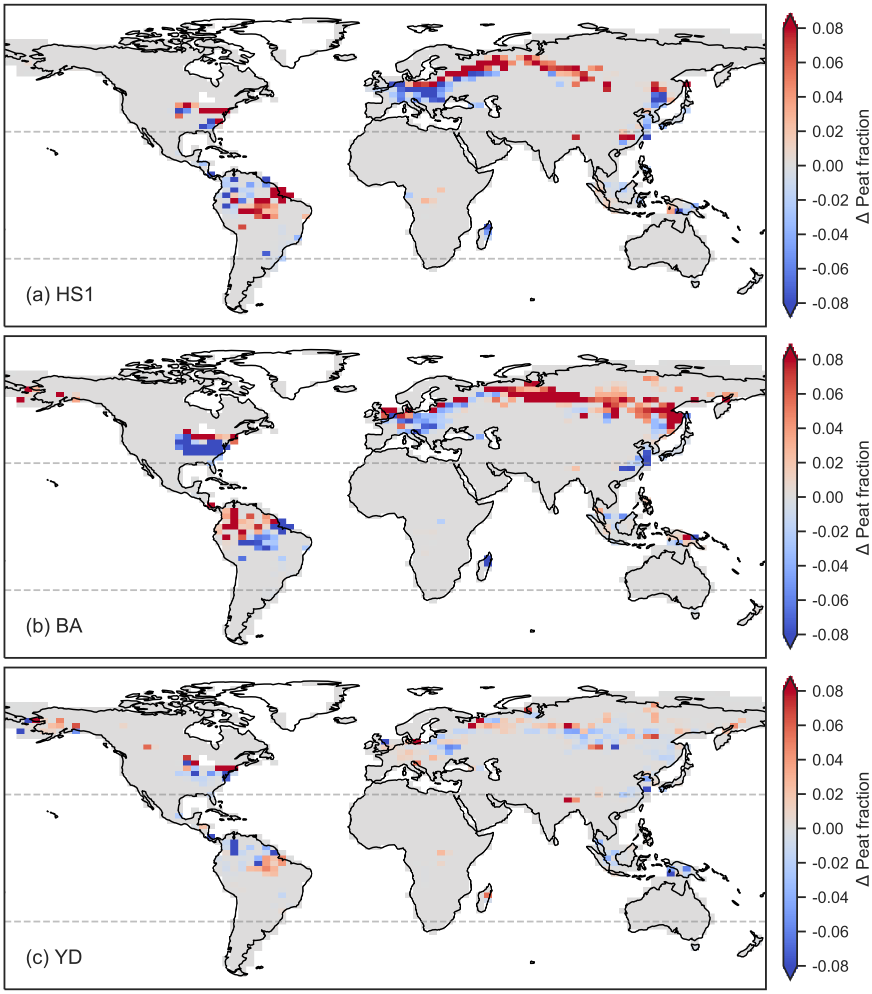

Figure 6. Maps showing the changes in peatland fraction during three periods of past substantial climate change: Heinrich Stadial 1 (HS1, 17.43 - 14.63 kyr BP) (a), the Bølling-Allerød northern hemisphere warm period (BA, 14.63 - 12.85 kyr BP) (b), and the Younger Dryas northern hemisphere cold period (YD, 12.85 - 11.65 kyr BP) (c)

than during the LGM and at the onset of the HS1. Thus, the carbon density per unit area is much lower for the newly established peatlands than for the lost LGM peatlands.

3.3.3 11.65 kyr BP - 0 kyr BP

Modelled peatlands in the Holocene show a continuous net expansion in the northern extratropics, with ~~new~~ newly forming peatlands more than balancing the loss of peatlands elsewhere. The Holocene experienced relative stability in climate and CO_2 levels compared to the termination. The early to mid Holocene was likely characterized by warmer summer temperatures than pre-industrial with a larger seasonality in the northern hemisphere (Marcott et al., 2013; Liu et al., 2014; Samartin et al., 2017). Ice sheet retreat and sea level rise lagged behind the deglacial temperature increase and was mostly completed at about 7 $\mathrm{kyr\,BP}$ (Peltier, 2004). Locally new land keeps emerging to this day due to isostatic rebound. This effect is especially pronounced in the Hudson Bay Lowlands, where new land emerges with a rate of up to 12 $\mathrm{mm\,yr^{-1}}$ (Henton et al., 2006).

For northern peatlands, positive area changes are consistently larger than negative changes throughout most of the Holocene (see Fig. 4 (a)). This leads to a large continuous area expansion. Old peatland area is also simulated to increase continuously during the Holocene (Fig. 4 (b)), showing that the parallel positive and negative changes are more than mere fluctuations of existing peat but that there is actual continuous peatland loss and growth. Net area increase picks up at about 9 $\mathrm{kyr\,BP}$, decreases in the late Holocene and turns into a net area reduction in the last millennium. This late Holocene slow down and reversal of net peatland area growth is most pronounced in Northern Asia where increasing negative changes start to balance and eventually offset the still large positive changes (Fig. A1 and A2). Both negative and positive dynamics here are driven by temperature and precipitation. The early fast expansion in Northern Asia is offset by a temperature driven net area loss in Europe which is recovered partly towards the late Holocene. Net area increase in North America is delayed by continued loss of mid latitude peat and the slow retreat of the Laurentide Ice Sheet, which limits the establishment of new peatlands. Today's peatlands in North America start to establish after about 9 $\mathrm{kyr\,BP}$ with most of today's peatlands forming between 7 and 2 $\mathrm{kyr\,BP}$. Carbon stocks follow these regional trends but with larger relative increases especially towards the late Holocene. As the timescale for building up carbon pools is generally much longer than the timescale of potential area changes, fluctuations in area, mostly by young peatlands, are smoothed in the carbon stocks (see e.g. Fig. A1 (b)).

The tropical peatland area is simulated to stay relatively stable throughout the Holocene, with positive changes balancing negative changes. ~~South East~~ Southeast Asia sees a reduction in area in the early Holocene due to continued sea level rise and a subsequent gradual recovery of integrated peat area driven by precipitation and non linear effects. Peat area in South America increases slightly over the Holocene with mostly precipitation driven fluctuations in between. On the other hand, fluctuations in region-integrated peat carbon stocks are largely absent in South America, as carbon, with changing area, is shifted between peat and old peat pools. Peat carbon stocks in South America show a large relative increase following a near linear path. Africa sees an increase in area at about 10 $\mathrm{kyr\,BP}$ driven by precipitation and enabled by high CO_2 concentrations. The new area gradually degrades again until 3 $\mathrm{kyr\,BP}$ with another peak at 0.5 $\mathrm{kyr\,BP}$.

3.3.4 Model versus reconstructions

The study of peatland initiation, life cycle, dynamics and responses to external forcing has been focused on today's existing and active peatlands. This work includes large compilations of peat core basal dates (MacDonald et al., 2006; Gorham et al., 2007; Yu et al., 2010) which are used to reconstruct initiation dates and lateral expansion (Yu et al., 2010; Korhola et al., 2010; Dommain et al., 2014; Loisel et al., 2017) of the sampled active peatlands. This approach, however, does not include earlier peatlands that dried out, were buried or flooded or otherwise ~~seized~~ ceased to be active accumulating peatlands. Treat et al. (2019) presented a first compilation of dated buried peat layers, but the small sample size make quantitative reconstructions difficult. We thus limit most of the model-data comparison of the transient behaviour to the today's existing peatlands. Figures

7 and 8 (c) show modeled initiation date frequency, area and carbon dynamics of northern peatlands that are still active at present.

Figure 7 (a) compares LPX results to a gridded 'oldest age' dataset compiled by Loisel et al. (2017) and Fig. 7 (b) and (c) to two different reconstructions for lateral expansion (Loisel et al., 2017; Korhola et al., 2010) based on similar methods but different underlying peat core datasets (see Sect. 2.3). The two reconstructions for peat expansion agree on a limited pre Holocene expansion, but disagree substantially on the timing of fastest expansion during the Holocene (7). Both simulated initiation and peat expansion have peaks about 4 kyr earlier than the reconstructions. The model simulates early initiation of today's northern peatlands, already beginning in HS1, and a large expansion during BA. The reconstructions on the other hand suggest lateral peat expansion picking up only with the transition into the Holocene. Agreement between model and reconstructions becomes good in the mid to late Holocene.

The early expansion in the model also propagates to the carbon balance for presently active peatlands. The model simulates earlier accumulation extending into the HS1 and slower accumulation during the early Holocene than suggested by net carbon balance (NCB) reconstructions by Yu (2011) (Fig. 7 (c)). The summed simulated carbon increase from LGM to PI in today's northern peatlands amounts to ~~343~~ 313 GtC (Fig. 8 (c)).

The early expansion of northern peatlands in the simulation is mostly dominated by peat establishment in Western Siberian Lowlands (WSL) and Northern Asia in general (see Sect. 3.3.2 and Fig. A1). The dominant drivers of this expansion are temperature and precipitation, which, according to TraCE21k, both increase substantially over Northern Asia during the HS1 and BA. A similar simulated early expansion into the WSL was reported by Treat et al. (2019), with the coupled CLIMBER2-LPJ setup. Morris et al. (2018b) investigated possible climatic drivers for peat initiation in a modelling study using the HadCM3 model. They suggest the WSL to have responded to an increase in effective precipitation at about 11.5 kyr BP, instead of the early warming. One source of the model data ~~miss match~~ missmatch could lie in the uncertainties in climate anomalies discussed in Sect. 3.2.2. Especially in high latitudes climate anomalies can vary greatly between climate models, and model performance at one point in time does not always correspond to performance at another point in time (Harrison et al., 2014). Although the freshwater change of TraCE21k was designed to capture the rapid climate events during the glaciation, the magnitude and timing of regional or even hemispheric changes can still have large biases. To date TraCE21k is the only available transient GCM simulation, but new simulations under the umbrella of PMIP4 might shed more light on the model dependence of the warming pattern in question (Ivanovic et al., 2016). Another source of the ~~miss match~~ missmatch could lie in the simple representation of peatlands in the model, which might be unsuitable to reproduce specific initiation and expansion pathways, like terrestrialization and fen-bog transition that might have been important controlling factors in that time and region (Kremenetski et al., 2003). One example could be the relative weakness of the initiation criteria on the moisture balance (precipitation over evapotranspiration > 1), which is almost always weaker than the indirectly mediated condition on inundation persistence. This might pose a problem especially in the WSL where moisture balance might have been the driving factor for peat initiation (Morris et al., 2018b)). Lastly, although the WSL is relatively densely sampled and reconstructions of peat initiation robust, other areas of northern Asia are vastly under sampled and reconstructions less reliable.

Throughout the tropics dated buried and active peat cores show peatland presence already during and preceding the LGM. But peatland extent or evolution towards the presence are not well constrained and are subject to large uncertainties. The small number of available dated tropical peat cores impedes a statistical approach. Applied nevertheless, it indicates a more or less continuous growth of today's peatlands since about 19 kyr BP with largest expansion rates between 8 ~~–~~ and 4 kyr BP (Yu et al., 2010). Dommain et al. (2014) reconstructed the evolution of Indonesian peatlands using a combination of dated cores and a transfer function between depth and age. They argue for a peat expansion much later than infered by basal ages alone, with 90% of todays peat establishing after 7 kyr BP and 60% after 3 kyr BP. In this study the dominant control on peatland area was found to be local sea level. Rising sea level during the termination and the early Holocene triggering the establishment of inland peatlands through alterations in moisture availability and the hydrological gradient, and stabilization of sea level and subsequent sea level regression after 4 kyr BP prompting the establishment of coastal peatlands. In contrast to these reconstructions, the transient simulation shows 60% of today's tropical peatland area already present in the LGM and only small expansion during the ~~last~~ recent millennia. The sparsity of the data ~~warrant's~~ warrants caution when comparing to model results. However, in ~~South East~~ Southeast Asia, this discrepancy could indicate the importance of the feedback of sea level on local hydrology, missing in LPX.

3.3.5 Transient carbon balance of peatland soils and the land biosphere as seen by the atmosphere

In this section, we address how carbon stored in soils of active peatlands and carbon stored in the remains of former peat soils changed over time. Thereby, we quantify the overall contribution of peatland soils and peat carbon to the changes in the global carbon inventory of the land biosphere.

When trying to quantify the net effect of peatlands on the atmosphere, looking only at carbon stored in today's active peatlands can be misleading. Former active peatlands have transformed into other landscapes. Organic rich peat layers may now be burried under mineral soils on land or in coastal ocean sediments (Treat et al., 2019; Kreuzburg et al., 2018). When analyzing the transient carbon balance of global peatlands such "old peat carbon" pools have to be considered.

Figure 8 (b) shows the temporal evolution of carbon stored in soils of active peatlands, old peat soil carbon remaining on former peatlands, and old peat carbon stored on flooded continental shelves. The here presented ~~so-called~~ old peat pools include exclusively the carbon from the organic rich layers of formerly active peatlands, remaining after accounting for decomposition over time (see 2.1). At PI 499 GtC, 139 GtC, and 22 GtC of peat carbon are stored in ~~the~~ their respective pools. The total simulated increase in peat carbon from LGM to PI within these three pools is ~~350~~ 351 GtC. This represents the simulated net carbon accumulation of global peat and thus the net amount of carbon sequestered from the atmosphere by peat. When only considering carbon stored in active peatlands we would underestimate the deglacial peat carbon change with ~~223~~ 224 GtC. On the other hand if we only consider the carbon stored in today's active peatlands, the inferred deglacial change amounts to 365 GtC (Figure 8 (c)), and we would overestimate the net peat accumulation since the LGM. While the latter difference in net peat carbon accumulation between the complete and incomplete accounting scheme appears small for the total deglacial change, the difference can be substantial and relevant for other periods. For example, a particular large difference is identified for the phase of high peatland expansion and loss rates as simulated from the Bølling/Allerød to the Preboreal in our model. Here the

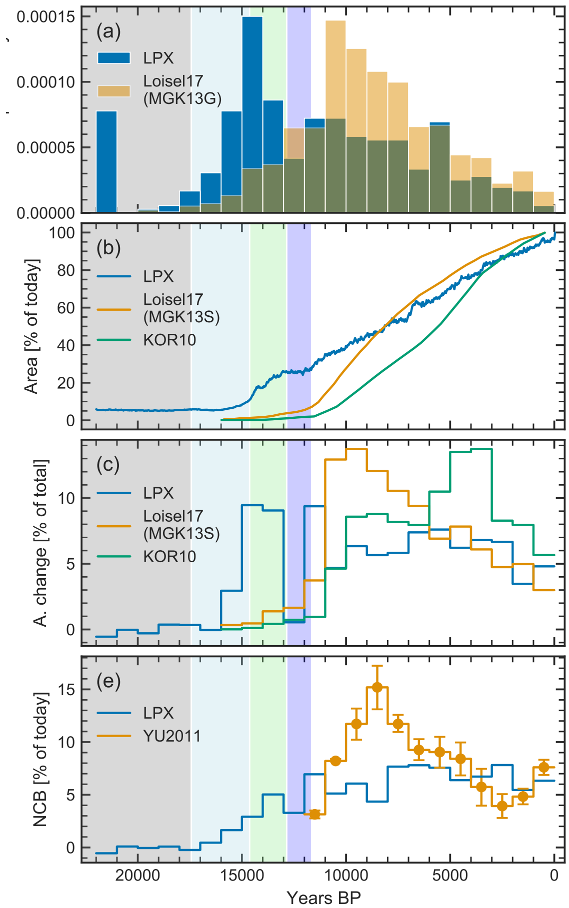

Figure 7. Simulated and reconstructed dynamics of today's existing northern peatlands: Peatland initiation frequency (two overlapping histograms) (a), peatland area expansion (b) and expansion rate (c), and net carbon balance (NCB) normalized by respective estimates of today's carbon pool (d). The reconstruction datasets are described in Sect. 2.3. Background coloring indicates different time periods, same as in Fig. 4

carbon balance is given by the complete accounting, including old peat, as 12 GtC versus 102 GtC when only looking at the carbon in today's active peat for the period from 14.6 to 10 kyr BP.

Peatlands contribute about 40% to the total land biosphere carbon increase of 892 893 GtC. The result for the total land carbon increase between LGM and PI is in good accordance with a recent estimate, integrating multiple proxy constraints (median: 850 GtC; 450 - 1250 GtC $\pm$ 1 standard deviation) (Jeltsch-Thömmes et al., 2019). The model also simulates the total change of the land biosphere carbon inventory between the beginning of the Holocene and preindustrial in reasonable agreement with the reconstruction by Elsig et al. (2009). The simulated temporal evolution, however, with an inconsistent

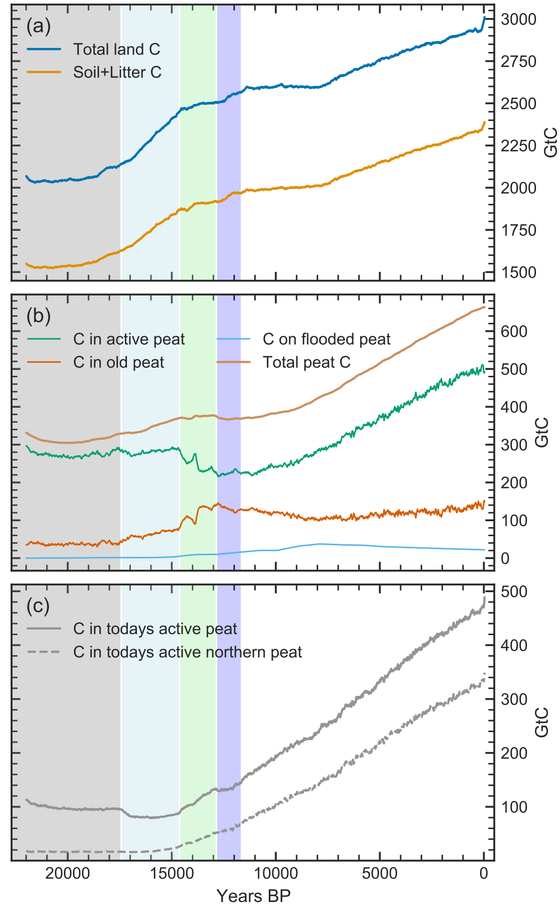

Figure 8. Carbon on global land (soil + litter + vegetation) (a), active peatland areas, old peatland areas, on flooded continental shelves (b), and in today's active peatlands (c). The brown line in (b) represents global carbon that originated from peatlands even if it is not part of an active peatland anymore. Background coloring indicates different time periods, same as in Fig. 4

~~simulated temporal evolution~~is different, with a rapid uptake in the early Holocene in the reconstruction, compared to a delayed uptake in the mid to late Holocene in the simulation.

4 Conclusions

We used the LPX-Bern dynamic global vegetation model to produce an in depth model analysis of transient area and carbon dynamics of global peatlands from the Last Glacial Maximum (LGM) to the present. For the LGM, peatland area, reduced to the tropics and northern mid latitudes, is predicted at ~~2.686~~ 2.687 Mkm^2 in the transient run, storing 275.6 GtC of carbon. Under LGM climatic conditions, LPX-Bern predicts peatlands in areas with low or no peat cover at present, or on now submerged continental shelves. Uncertainty from the climate forcing was assessed by using, in addition to the TraCE21k, climate anomalies from six different time slice simulations for the LGM from phase 3 of the Paleomodel Intercomparison Project PMIP3. This results in a peat area range of 1.5-3.4 Mkm^2 with a carbon storage of ~~144-343~~ 147-347 GtC. This large range illustrates the dependence of results on, uncertain, LGM climate conditions and the sensitivity of simulated peatlands to these differences. Sparse data on paleo peatlands, on their extent, and their carbon storage make it difficult to further constrain this range. At the same time there are, to date, only a few coupled climate simulations for the LGM and only one transient simulation with an atmosphere-ocean general circulation model available for the period LGM to present.

A driver attribution of the simulated transient evolution of peatlands using factorial simulations showed regional and temporal differences. Modelled changes in the tropics were dominated by shifts in the position of the Inter Tropical Convergence Zone and associated precipitation changes during the last glacial termination as well as by rising sea level. Changes in the northern high latitudes are mostly driven by temperature and precipitation increases. ~~Largest~~ The largest model mismatches to available area reconstructions can be seen in the onset and timing of the earliest expansion of today's northern peatlands. A strong warming in the climate forcing during Heinrich Stadial 1 and the Bølling/Allerød triggers a first expansion into Northern Asia, which according to reconstructions only starts during the Preboreal, about 4 kyr later.

The simulated transient evolution of peatlands is characterized by continuous and simultaneous increases and decreases of area and carbon, with fastest positive and negative changes happening during the termination (Heinrich Stadial 1 and Bølling/Allerød). This reveals a different perspective than the commonly assumed linear and continuous growth of global peatlands. Instead peatlands become a dynamic, growing, dying and shifting landscape. Carbon in soils of formerly active peatlands can be trapped in mineral soils or ocean sediments. When assessing the net carbon balance of global peatlands over time, accounting for paleo peatlands and their remains thus becomes essential. In our transient simulation the LGM to PI net peat carbon balance is predicted at ~~350~~ 351 GtC, with 499 GtC, 139 GtC, and 22 GtC stored at pre-industrial in soils of still active peatlands, in the remains of former peat soils on land, and in the remains on submerged shelves, respectively. For today's active northern peatlands, simulated peat area and carbon is in good accordance with the range of literature estimates, whereas predictions for the tropics are larger than most estimates. However, data constraints in the tropics are significantly weaker as ~~peat~~ peatland sciences has long focused on the northern high latitudes and only in the last decades is accelerating its effort in the tropics. Even fewer data is available to constrain old peat carbon that remains outside of today's active peatlands.

Taken together our study provides an ~~in depth~~ in-depth model analysis of peatland development, the associated drivers, and uncertainties on a global scale. It contributes to a foundation for a better understanding of past peat dynamics and emphasises the importance of treating and understanding peatlands as dynamic and evolving systems. In a next step, the results presented here can serve as a starting point for projections of future peat dynamics under different scenarios.

A growing database of buried peat and knowledge emerging from the growing literature on anthroprogenically drained peatlands might shed more light on the fate of old peat carbon and inform future modeling studies. New timeslice and transient climate model simulations under PMIP4 (Ivanovic et al., 2016; Kageyama et al., 2017) together with an increased effort of the peat community to fill in gaps in sample coverage both for today's peatlands and buried peat layers, especially in North America, Northern Asia, and the tropics, might help to constrain past peat dynamics further and to test the robustness of the results presented here. At the same time there is potential for improvements to the LPX-Bern which could decrease model data mismatches especially on the regional scale. Future improvements could include refining the moisture balance criteria on peat initiation, improving hydrology and boundary conditions on continental shelves, and finding key processes that might benefit from a more complex representation, such as a multi layer peat profile and distinctions between different peatland types.

Data availability. Data from main text figures are available as electronic supplementary material and further data is available on request

Appendix A: Supplementary Figures

Competing interests. The authors declare to have no competing interests

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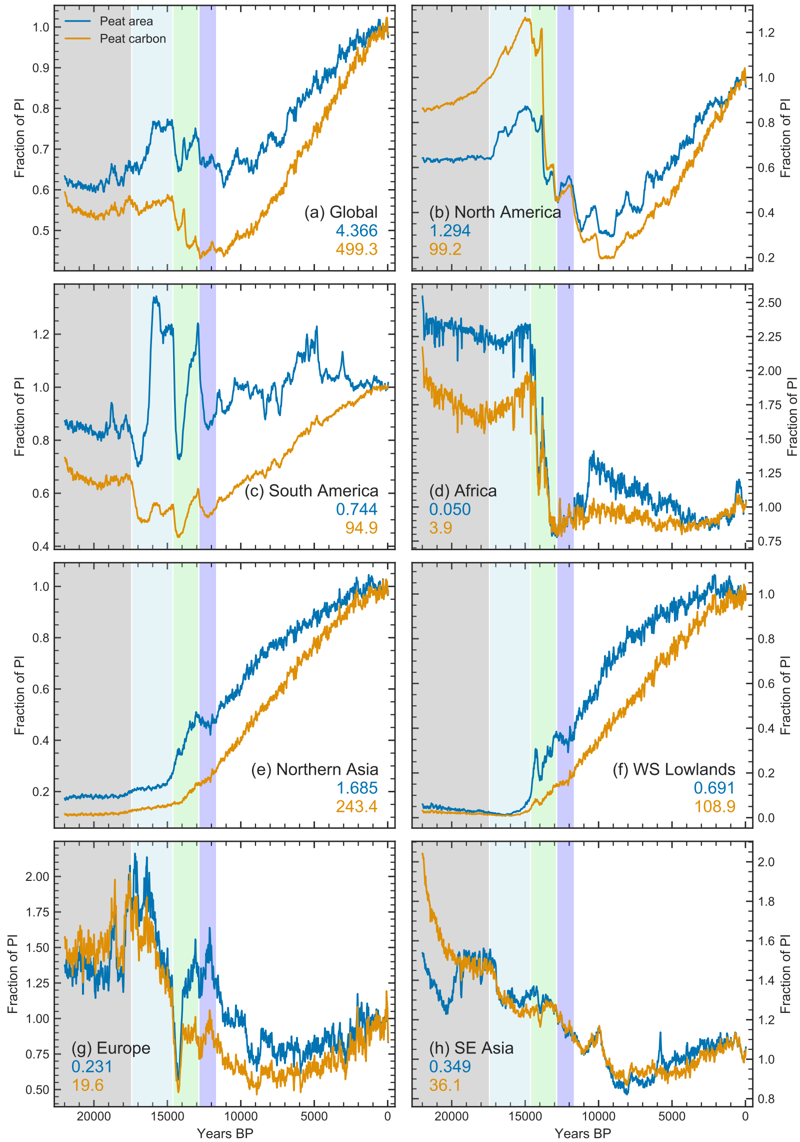

Figure A1. Simulated global and regional peatland area and carbon dynamics over time, relative to PI levels. PI levels are given in Mkm^2 for peat area and GtC for peat carbon. The extent of the regions Northern Asia, Western Siberian (WS) Lowlands, and Southeast Asia are shown in Fig. 1. Background coloring indicates different time periods, same as in Fig. 4

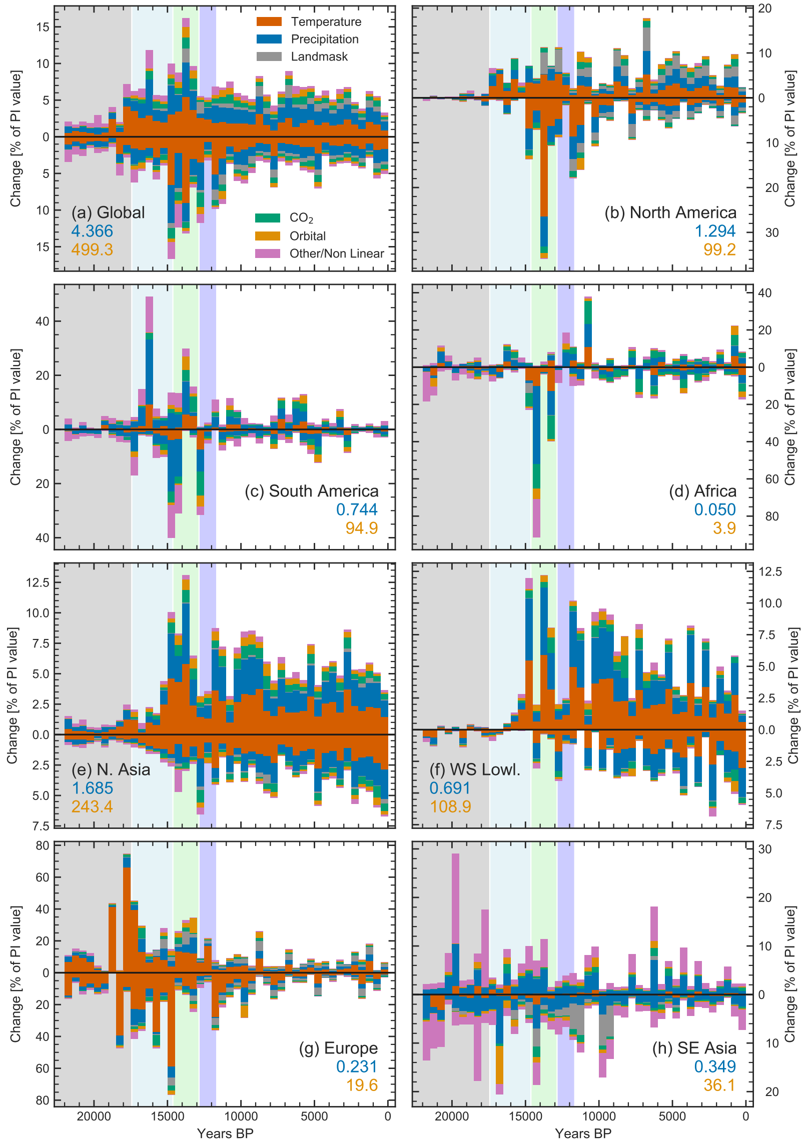

Figure A2. Simulated global and regional gross positive and negative changes in peatland area in 0.5 kyr bins, relative to PI levels. PI levels are given in Mkm^2 for peat area and GtC for peat carbon. Colors indicate driver contributions to changes attributed using factorial simulations. The extent of the regions Northern Asia, Western Siberian (WS) Lowlands, and Southeast Asia are shown in Fig. 1. Background coloring indicates different time periods, same as in Fig. 4

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