Interactive comment on “ORCHIDEE-PEAT (revision 4596), a model for northern peatland CO2, water and energy fluxes on daily to annual scales” by Chunjing Qiu et al.

We thank the two anonymous referees very much for their constructive comments. In the following, please find our response to the comments. Our responses are in bold, modifications done in the revised manuscript are in blue. All figure and table numbers, line numbers and pages refer to the initial manuscript version.

Referee #1

This manuscript describes a new peatland model implemented in the ORCHIDEE land model. The model was evaluated by comparing modeled water table, LE, GPP, and NEE to measured eddy covariance fluxes from several peatland field sites. The paper is generally well written and the key processes of the model are clearly described. The introduction section includes a useful review of recent peatland models that does a good job of setting the stage for this model. The paper generally does a good job of identifying uncertainties and potential weaknesses in the model that could be addressed in future work, although I think there is some room for improvement in describing some of these issues in more depth.

I think there are a couple of general areas in which the manuscript could be improved:
1. The key peatland-specific changes to the model are focused on peat carbon pools and hydrology, including a new architecture for simulating peat decomposition using acrotelm and catotelm layers. The modifications to plant processes are less dramatic. In my understanding the model uses an existing C3 grass plant functional type and does not introduce any new peatland-specific vegetation processes. Given the focus of model process changes on decomposition rather than plant processes, it seems strange that the evaluation is so focused on GPP. Why not show and evaluate modeled ecosystem respiration instead of or in addition to GPP? Analyzing respiration fluxes would allow a much better evaluation of the key new model features that are specific to peatland processes. Without an evaluation specific to these new processes, it feels like there is a big piece missing.
While our initial focus was on peatland productivity and carbon intake, of course GPP and ER are linked. So we followed the reviewer’s suggestion to incorporate an analysis of ecosystem respiration. To do so, we added analyses and discussion of simulated vs. measured ecosystem respiration. In the first set of simulation (S1) in which the modeled water table were used in the carbon module, with the site-specific V_{cmax}, the model showed good performance in capturing both spatial and temporal variations in ER, with r^2 of 0.78, 0.89, 0.86 for daily variations, across-sites annual variations and seasonal variations, respectively, and MEF of 0.75, 0.79, and 0.86, respectively. These results were compared with simulations using a fixed V_{cmax} (the mean of the optimized V_{cmax}, 40 μmol m^{-2} s^{-1}), as suggested by the review in the second comment. We conclude that by

taking site-to-site variations in V_{cmax} into consideration, model performances for carbon fluxes (GPP, ER and NEE) were improved. Table4 and Figure4 have been updated to include results of ER and results with the mean of the optimized V_{cmax}, and the description of the results from Line474 to Line487 was rephrased as: "For the 22 sites where NEE and ER measurements were available, the errors in the three carbon fluxes—GPP, ER, NEE were significantly reduced by optimizing V_{cmax} at each site (Table 4, Fig. 4, Fig. S4). With site-specific V_{cmax} values (Site-by-site model performances are shown in Fig. S5 to S10 in Supplementary Materials), the overall (all the daily data from all the 22 sites) performance of the model was good for GPP ($r^2 = 0.76$, MEF = 0.76), ER ($r^2 = 0.78$, MEF = 0.75), and acceptable for NEE ($r^2 = 0.38$, MEF = 0.26) (Fig. 4, Table 4). Seasonal variations in carbon fluxes were well captured by the model ($r^2 = 0.61$ to 0.86). The spatial across-sites gradients of annual mean GPP and ER were generally good, with r^2 of 0.93 and 0.89, and lower for NEE ($r^2 = 0.27$). Compared to simulations with a fixed V_{cmax} (the mean of the optimized values of 40 μmol m^{-2} s^{-1}), there were large improvements in capturing spatial gradients of carbon fluxes (r^2 increased from 0.20 to 0.93, from 0.27 to 0.89 and from 0.16 to 0.27 for GPP, ER and NEE, respectively, while the RMSD reduced by 63%, 48%, and 9%). This result indicates that model-data disagreement can be largely reduced by using site-specific V_{cmax} instead of a fixed (mean) value. In future regional simulations, spatial variations in V_{cmax} should be taken into account. There was, however, no significant improvement in LE, H and WT by using site-specific V_{cmax} values (Table4).**". We also compared simulated ER of S1 with the second set of simulation (S2, in which the measured water table was used) with the ER observations: the model showed only a small improvement in reproducing ER when WT_{obs} was used (Table 5 was added to show the results). Fig.S6 was added to show simulated vs. measured ER at each site.**

Table 5. Model performance measures of ER simulations for the site-by-site comparison, the comparison across sites, mean seasonal cycle and anomalies, using modeled (S1) and observed (S2) water table (WT). SDSD and LCS are two signals discriminated from the mean squared deviation, see Sect. 3.4.

	Modeled WT used (S1)					Observed WT used (S2)				
Site	RMSD	SDSD	LCS	r^2	MEF	RMSD	SDSD	LCS	r^2	MEF
CZ-Wet	1.45	0.86	0.87	0.81	0.68	1.51	1.05	0.79	0.81	0.66
DE-Bou	0.78	0.03	0.50	0.69	0.64	0.77	0.03	0.50	0.69	0.65
DE-Sfn	0.96	0.10	0.79	0.61	0.59	0.97	0.09	0.82	0.60	0.58
FI-Lom	0.46	0.00	0.19	0.85	0.84	0.45	0.02	0.18	0.85	0.84
IE-Kil	0.44	0.01	0.01	0.09	0.51	0.42	0.01	0.01	0.13	0.48
SE-Deg	0.69	0.26	0.19	0.75	0.62	0.64	0.16	0.23	0.75	0.68
SE-Faj	0.58	0.07	0.08	0.87	0.60	0.59	0.08	0.07	0.88	0.59
US-Los	0.63	0.01	0.39	0.85	0.85	0.60	0.00	0.35	0.87	0.87
Overall	0.79	0.09	0.51	0.78	0.76	0.79	0.09	0.51	0.78	0.76
Across sites	0.31	0.01	0.06	0.82	0.76	0.32	0.01	0.06	0.82	0.74
Seasonal	0.45	0.06	0.15	0.91	0.89	0.44	0.07	0.13	0.92	0.89

Anomalies	0.62	0.07	0.31	0.21	0.19	0.63	0.08	0.31	0.20	0.17

2. The approach to optimizing Vcmax is problematic. The optimized site-specific values are compared to a default value that is well outside the range of values that seem to be appropriate for these sites (within the model at least). Figure S3 demonstrates this very clearly for GPP and NEE: the model using the default Vcmax is not even close to reproducing the observed magnitude of photosynthesis at these sites. As a result, the comparison between optimized and default Vcmax simulations is not very informative. It would be more useful if that comparison used the mean or median of the optimized Vcmax values (which is actually used for a different analysis later in the paper). In that case, it would be possible to evaluate whether site-to-site variations in Vcmax were necessary for improving model fidelity. It's not very informative to show that optimized Vcmax is better than a Vcmax that is much too low for every site.

The fact that the default Vcmax based on observations does not work within the model raises further questions. The paper addresses this very briefly (lines 249-251) but I think a more detailed discussion of why the model Vcmax needs to be so much higher than observations would be useful. Were the other photosynthesis-related parameters (LAI, light absorption, etc) in the model consistent with site measurements? Site-specific optimization of Vcmax could mask other issues with the model, for example underestimates of plant biomass or LAI. I think it would be really helpful to show how modeled LAI compares to measurements, especially among different sites, and whether errors in modeled LAI can explain the latitude/temperature relationship in optimized site Vcmax.

The reviewer raises a fair point that a comparison between the optimized and the default V_{cmax} value (16 μmol m^{-2} s^{-1}) is not as informative as it could be in this study. The default value applied by Largeron et al. (2017, Geosci. Model Dev. Discuss.) was derived for three low productivity sites. When this value was applied at our dataset, GPP and NEE were underestimated. Thus, to make a more apples-to-apples test, we added a comparison between optimized and the mean of the optimized V_{cmax} values (40 μmol m^{-2} s^{-1}), as suggested by the reviewer. The comparison to the default V_{cmax} is removed from the manuscript. The description of the results from Line474 to Line487 was rephrased, as it is mentioned in our response to the first comment of the reviewer.

Our use of site optimized V_{cmax} is one way to account for large variance in a key ecosystem parameter. There is a large reported variation of V_{cmax} in observations. For instance, V_{cmax} value for Sphagnum at the Old Black Spruce site in Canada were 5, 14 and 6 μmol m^{-2} s^{-1} during spring, summer and autumn respectively, while that for Pleurozium were 7, 5, and 7 μmol m^{-2} s^{-1} (Williams and Flanagan, 1998, PCE); Bubier et al. (2011, Oecologia) reported that V_{cmax} for three ericaceous shrubs (*Vaccinium myrtilloides, Ledum groenlandicum* and *Chamaedaphne calyculata*) at Mer Bleue bog in Canada ranged from 67 to 137 μmol m^{-2} s^{-1} among the control and four nutrient addition treatments (measured V_{cmax} for the three shrubs in the control plots are 84.6 ± 13.5 μmol m^{-2} s^{-1}, 78.1 ± 13.4 μmol m^{-2} s^{-1}, and 132.1 ± 31.2 μmol m^{-2} s^{-1}, respectively); The V_{cmax} value applied by the McGill wetland model for evergreen shrubs is 17 μmol m^{-2} s^{-1}, which is the median value of over 50 measurements for *Chamaedaphne calyculata* and *Ledum groenlandicum* (St-Hilaire et al., 2010, Biogeosciences). Wu et al. (2016,

Geosci. Model Dev.) used values of 60, 50, 40μmol m^{-2} s^{-1} for evergreen shrubs, deciduous shrubs and sedges respectively. The optimized model V$_{cmax}$ values in our study ranged from 19 to 89 μmol m^{-2} s^{-1} (the mean value is 40 μmol m^{-2} s^{-1}), considering that the model optimized value represents an average for the ecosystem, we argue that the model value is not substantially above observations or values used in other land surface models.

We agree with the reviewer that site-specific optimization of V$_{cmax}$ could compensate for biases in LAI, plant biomass, etc. Unfortunately, at most of the sites, LAI was measured or estimated (by optical in-situ methods, annual litter collection, or from remote sensing) only once during the periods in question. We have an available time-series of measured LAI at IE-Kil – see Fig.S1(a), LAI was overestimated by the model at IE-Kil. Fig.S1 (b) showed that LAI was overestimated at sites with low reported (measured or estimated) LAI and underestimated at sites with higher reported values. As for aboveground biomass, there was no systematic error among sites. We emphasized the bias in LAI in the text, on Page16, Line463: “……, with a mean value of 40 μmol m^{-2} s^{-1}. The calibration of V$_{cmax}$ may compensate for biases in other model parameters. A brief comparison between simulated and reported (measured/estimated) LAI and aboveground biomass showed that there are no systematic errors (Fig. S1).**”.**

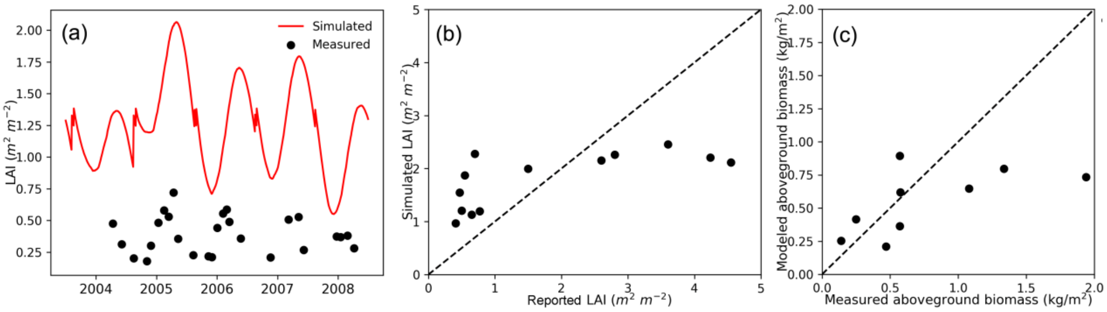


Fig. S1. (a) Simulated vs. measured leaf area index (LAI) at the blanket bog IE-Kil, Ireland. (b) Simulated vs. reported (measured/estimated) LAI across peatland sites, dashed line is a hypothetical 1:1 regression line. Note that in (b), the reported LAI was estimated at some sites. (c) Simulated vs. measured aboveground biomass, assuming that the carbon content of dry biomass is 50%.

Specific comments:

Lines 173-176: I’m not sure it’s that novel that this model is built into a land surface scheme that conserved water, carbon, and energy. Doesn’t the LPJ-GUESS model described above have a similar purpose? In any case, if there is not already a peatland submodel built into ORCHIDEE then I wouldn’t be that concerned about justifying the purpose of this effort. I think it’s clearly valuable to build and evaluate a working peatland submodel within ORCHIDEE.

The reviewer is right, the LPJ-GUESS does describe a similar development, however, there is no water input from surrounding areas (Chaudhary et al., 2016, Biogeosciences), so conservation is scale-dependent. We rephrased the sentences on Page6, Line173 as follows : “This new peat model is incorporated consistently into the land surface scheme in order to conserve water, carbon and energy at scales going from local sites to grid-based large-scale applications in an Earth System Modeling context.**”**

Line 232: Not all peatlands are grassy. Does this assumption cause issues when applying the model to shrubby or forested peatlands (such as the Old Black Spruce site mentioned a few lines after this)? Were all the peatland sites used for evaluation grassy peatlands?

The sites used for evaluation include grassy, shrubby, and forested peatlands (Table 2). We note the possible discrepancies between model output and observations in the text as suggested by Reviewer#2. Please refer to our response to the third comment of Reviewer#2 (Lines 231-232).

Line 249-251: It’s great that the paper brings up this issue of compensating errors, but it would be better if there were some evaluation of whether the model has systematic errors in LAI, etc.

As shown in Fig. S1b, LAI was overestimated at sites with low reported LAI and underestimated at sites with high reported values, there was no systematic error in LAI.

Line 257: “drainage flux reduced to zero”: So there is no water flow out of the peatland unless it is flooded? This seems inconsistent with a lot of real peatland systems.

We would like to note that although we considered deep drainage from peatland as negligible due to the low permeability of the catotelm (Ingram et al., 1978, EJSS; Rezanezhad et al., 2016, Chem. Geol.), the waterflow out of the peatland (as runoff) occurs not only when the peatland is flooded. In ORCHIDEE, the partitioning between water infiltration and surface runoff is computed through a time-splitting procedure (d'Orgeval, 2006, PhD thesis), with the maximum infiltration rates described as an exponential probability density distribution. The infiltration-excess water creates runoff. Thus in the model, the infiltration excess water will first fills the above-surface water reservoir, and then leaves the grid cell as runoff.

To clarify this, we added these sentences in the text, Page9, Line259: “……an above surface water reservoir with a maximum height of 10 cm was added (Fig. 1b). In the model, the partitioning between water infiltration and surface runoff is computed through a time-splitting procedure, with the maximum infiltration rates described as an exponential probability density distribution (d'Orgeval, 2006, Diss. Paris). The infiltration-excess water of peatland first fills the above-surface water reservoir, then leaves the grid cell as runoff. Water in this above-surface reservoir re-infiltrates into the peat soil on the next time step (Largeron et al., 2017).**”.**

Line 299-301 and Fig. S1: The difference between the soil carbon dynamics and the peat carbon dynamics is confusing. Do the peat pools contain the Active/Slow/Passive soil carbon pools, or do they replace them? Fig. S1 suggests that all of these pools are present in the peatland (metabolic litter, structural litter, acrotelm, catotelm, active, slow, passive) but this doesn’t seem consistent with the description in the text. If the peat layers are actually replacing the active/slow/passive pools, then Fig. S1 and the text should make that clearer.

The reviewer is right, the description of the carbon module is not clear enough. We

improved the description in the text on Page10, Line295 to "……Decomposed litter carbon from these two pools is then distributed into three soil carbon pools: the active, slow and passive pool, similar to the CENTURY model (Parton et al., 1988). Both temperature and moisture functions are used to control soil carbon decomposition rates (Text S1). In ORCHIDEE-PEAT, these standard processes are kept the same as in Krinner et al. (2005) for non-peatland vegetation (Fig. S2, black dashed box). For the peatland vegetation, we added a peat carbon module, in which the three soil carbon pools (active, slow, passive) are replaced by two pools forming distinct layers, following Kleinen et al. (2012) (Fig. S2, red dashed box).**" and we modified Fig. S2 as follows:**

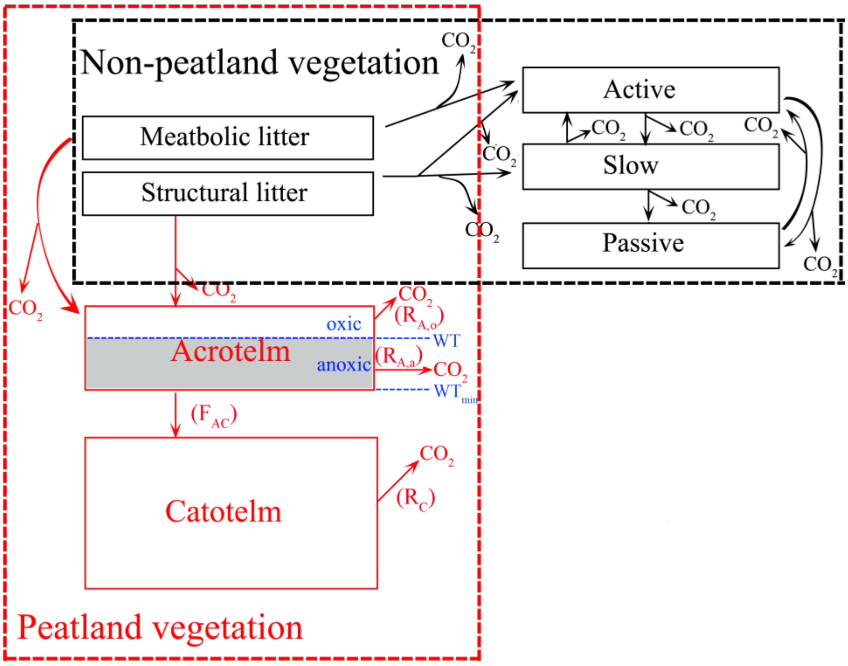


Fig. S2. Schematic overview of litter and soil carbon dynamics in ORCHIDEE-PEAT. For non-peatland vegetation (the black dashed box), decompositions of carbon in the two litter pools and three soil pools, and carbon flows between them are adapted from the CENTURY model (Parton et al., 1988); for peatland vegetation (the red dashed box), the active, slow and passive soil carbon pools are replaced by a two-layered model, following Kleinen et al. (2012).

Line 308-310: Did this use the observed or simulated water table? How would this be handled in larger-scale or global simulations?

The simulated mean summer minimum water table position (WT_{min}) over the observational period is used here. WT_{min} was derived from a 'preparation run (S0)'. Specifically, we first ran the model at each site using the same simulation protocol as described in Sect. 3.3, but with peat carbon module deactivated. Then WT_{min} can be diagnosed from the output of this simulation (S0) and be fed into the model in S1 and S2.

We explained this procedure in the text on Page10, Line308 to: "……we used the average of simulated minimum summer water table position (WT_{min}) over the observational period to demarcate the boundary between the acrotelm and the catotelm at each site to take into account local site conditions. We conducted a “preparation run (S0)”, in which the model was run at each site using the same protocol (Sect. 3.3), but with the peat carbon module deactivated. WT_{min} was diagnosed from the output of S0 before feeding into the peat carbon module in S1 and S2 (Sect. 3.3). Soil carbon exerts no feedback effects on the soil temperature and hydraulics in the structure of our model, thus S0 and S1 produce the same simulated water table.**”. In large-scale or global simulations, we can either conduct the same “preparation run” or set WT_{min} to a constant value, for example, Wania et al. (2009, Global Biogeochem. Cycles) and Spahni et al. (2013, Clim. Past.) used 0.3 m as the interface between the acrotelm and the catotelm.**

Line 315-316: It would help to show the equation for beta instead of just describing it. Equations for acrotelm height and catotelm depth should also be included. Is the depth of catotelm and total peat depth calculated? What does the model do if water table goes below the bottom of the peat layer? Can it represent a situation with no catotelm layer? Is there mineral soil beneath the bottom of the peat layers?

We added equations of beta (Eq. 9) and acrotelm depth (Eq.10) on Page11, Line325:

$$\beta = \begin{cases} \beta = 1, & WT_{min} - WT \leq 0 \\ \beta = \dfrac{H_A - (WT_{min} - WT)}{H_A}, & 0 < WT_{min} - WT < H_A \\ \beta = 0, & WT_{min} - WT \geq H_A \end{cases}, \qquad \textbf{(9)}$$

$$H_A = \frac{C_A}{\rho_A \cdot C_{f,A}}, \qquad \textbf{(10)}$$

The depth of catotelm can be calculated using carbon fraction in the catotelm and the catotelm density, as in Kleinen et al. (2012, Biogeosciences). However, since the initiation and climate history of each site are unknown, we assumed that all sites initiated 10100 years ago, with a constant present-day climate condition since their initiation and the peatland area hasn’t changed, thus the simulated peat depth can’t be compared to the measured depth.

The model was started with no catotelm layer, the carbon started to accumulate in the acrotelm layer, and as soon as carbon occurred in the acrotelm layer, a prescribed fraction of the acrotelm carbon was moved to the catotelm. When simulated water table (WT) drops below the acrotelm (WT_{min}), the whole acrotelm layer is supposed to decompose aerobically, as shown by Eq. 9, while the whole catotelm layer is still decomposing anaerobically. In the hydrology module, the total soil depth is 2m, we assumed that all layers in the peat soil profile hold peat-specific hydraulic properties, and there is no mineral soil beneath the peat soil. While the soil thermodynamics in the soil thermal module has 32 layers (38m), in which the top first 11 layers are identical to layers in hydrology, soil profiles in one grid cell are treated as mineral soil, and the dominant texture is used to define soil thermal properties.

Line 331-332: k_A and k_C are defined as fixed parameters, but line 319 says that they have a temperature dependence that is not shown in equations 5-8. These equations should show the complete calculation, including temperature dependence etc.

We revised the equations on Page11, Line 318: “……Decomposition of peat carbon is controlled by temperature (f_T) and parameterized as an exponential function: $f_T = Q_{10}\exp((T-T_{ref})/10\,℃)$ with $Q_{10} = 2.0$ and $T_{ref} = 30\ ℃$ (Text S1). Soil carbon fluxes are given by:

$$F_{AC} = k_p f_T C_A \,, \tag{5}$$

$$R_{A,o} = \beta k_A f_T C_A \,, \tag{6}$$

$$R_{A,a} = (1-\beta) v k_A f_T C_A \,, \tag{7}$$

$$R_C = k_C f_T C_C \,, \tag{8}$$

Line 493-496: If this were the correct explanation, I would expect WT to be more accurately simulated in fens than in bogs. Was that the case?

We can’t conclude that WT should be more accurately simulated in fens than bogs because we don’t know the real amount of water input from non-peatland areas to peatland at fen sites. In this study, we routed all runoff from non-peatland soils into peatland. Considering that water table is relatively sensitive to the peatland area fraction in the grid cell (Fig. S11), it’s hard to quantify if this water input setup caused greater errors in bogs than fens or not. The Taylor diagram (Fig. 3f) showed that there is no significant evidence for concluding that WT of fens are better simulated than bogs. We added a sentence on Page17, Line496 to point out the possible cause of this result: “……an extra water source for bogs than only rainfall. However, the model did not perform better for fens (Fig. 3f), possibly because the amount of water that was routed into the fen was in error.**”.**

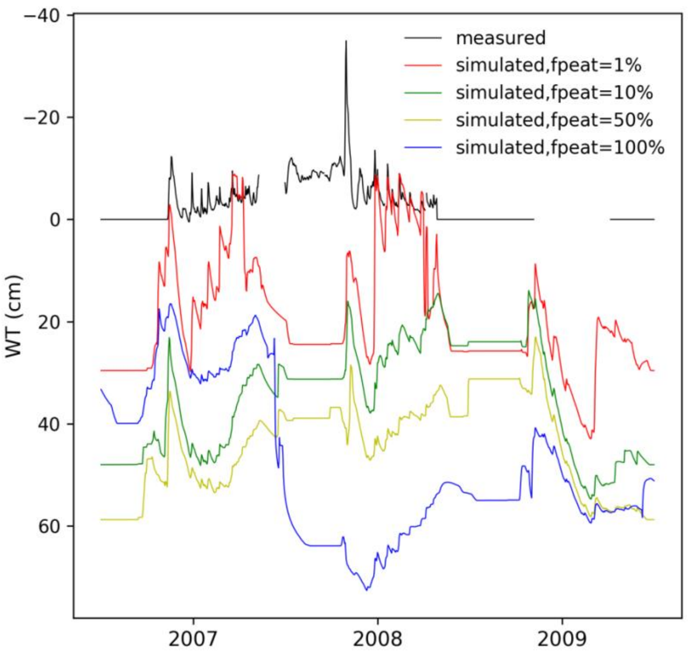


Fig. S11. Sensitivity test of simulated water table to peatland area fraction in the grid cell, performed at the fen site FI-Lom.

Line 496-499: This seems like a very likely explanation to me, and something that could be tested by using a range of source-area/peatland-area ratios. Watershed analyses for the sites in question could provide some suggestions of realistic ratios.

We agree with the reviewer that watershed analyses could be helpful, but we feel that it's out the scope of this study. It could be considered for further developments of the model. Here, we performed a sensitivity test of simulated water table to peatland area fraction in the grid cell at one fen site (FI-Lom) to show the dependence of simulated water table on peatland area fraction (Fig. S11). We point out the dependence in the text, Page17, Line496: "……3) WT depends on water input from surrounding non-peatland areas: the greater the peatland fraction in the grid cell, the smaller runoff input from other soils to the peatland, hence resulting in a deeper water table in the peatland (Fig. S11). **".**

Line 515-516: This really highlights how the main peatland-related processes in the model are related to decomposition and respiration, not plant growth. Since that's the case, why is the evaluation so focused on photosynthesis? I think analysis of respiration fluxes would be much more informative, particularly in this case where WT would be expected to have an effect.

As NEE is the small residual of GPP and ER, wrong values of GPP could be one of major sources for errors in simulated NEE, especially when we only have one PFT to represents peatland vegetations. We agree with the reviewers that respiration fluxes are informative, thus we added analyses of ecosystem respiration. Please refer to our response to the first comment of the reviewer.

Line 531: Water use efficiency doesn't really fit with these other variables. It's a biological parameter, not a climate forcing variable like the other ones.

Water use efficiency and water balance were included because we would like to find a

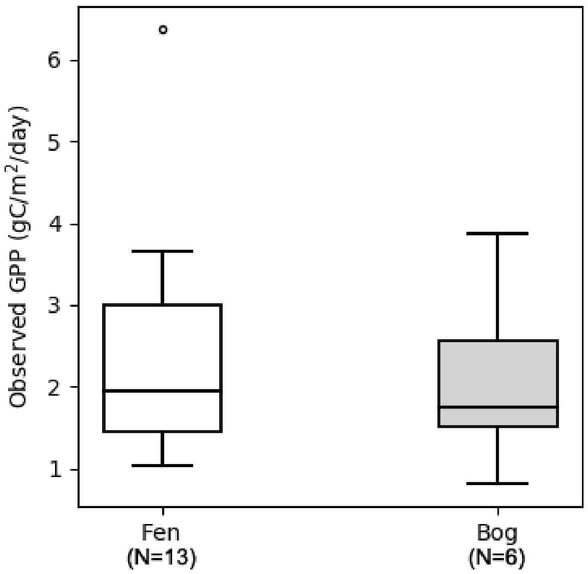
variable / parameter that is possibly related to the optimized V_{cmax}, and may be used in the future to prescribe the spatial pattern of V_{cmax} in larger scale simulations in the future. So here we included not only climate forcing variables, but also these two biological parameters. We rephrased the name of Fig.S5 as: "Fig. S15. Relationship between optimized V_{cmax} and meteorological variables and biological parameters, as well as latitude of the sites location"

Line 536-537: It's surprising that there is no difference in Vcmax between fens and bogs, since those have very different vegetation types and productivities.

We recognize that bogs are precipitation-fed and nutrient-poor while fens are fed by precipitation and groundwater and can be either oligotrophic or eutrophic. However, previous studies have shown that along a bog-rich fen gradient in Alberta, Canada, the total above-ground net primary production exhibited a pattern of bog < poor fen < wooded moderate-rich fen> extreme rich fen> sedge fen (Szumigalski and Bayley, 1996, Wetlands), the productivity of the bog was not significantly lower than the poor fen and was even higher than the sedge and the extreme-rich fen. Also in Alberta, Thormann and Bayley (1997, Ecoscience) compared total aboveground plant production along a bog-fen-marsh gradient in Alberta, Canada, and found that the bog and the three fens (a lacustrine sedge fen, a riverine sedge fen and a floating sedge fen) had a similar NPP, the lacustrine sedge fen was even significantly less productive than the bog. The sites used in our study include wooded fens, wooded bogs, grassy fens and grassy bogs. Among them, we can't see a significant difference in dominant vegetation types between fens and bogs (we don't know relative abundances of grasses vs. shrubs vs. trees at each site though). We compared measured GPP of fens with that of bogs, there is no significant difference between them (P=0.63), as shown in the figure below.

Site	Type	Aboveground biomass (kg/m2)	Dominant vegetation type
DE-Bou	bog	grass dominated: 0.577; heather and moss dominated: 0.517; mixed: 0.303	grasses, mosses
SE-Faj	bog	shrubs: 0.153; graminoids: 0.077; moses: 0.192	shrubs,grasses,mosses
CA-Mer	bog	vascular: 0.356; mosses: 0.144	shrubs,mosses
NO-And	bog		shrubs, grasses,mosses
DE-Sfn	bog		trees,shrubs,grasses,mosses
US-Bog	bog		trees,mosses
SE-Deg	fen	vascular:0.049; mosses:0.065	shrubs,grasses,mosses
CA-Wp3	fen	0.157	grasses,mosses
CA-Wp2	fen	0.231	shrubs,grasses,mosses
DK-Zaf	fen	0.471	grasses,mosses
CZ-Wet	fen	0.57	grasses
NO-Adv	fen	0.85	shrubs, grasses,mosses
CA-Wp1	fen	1.08	trees,shrubs,mosses

US-Los	fen	1.336	trees,shrubs,grasses
DE-Spw	fen		trees
PL-Kpt	fen		grasses,reeds and ferns
DE-Zrk	fen		grasses
DK-NuF	fen		grasses,mosses
US-Fen	fen		grasses,forbs
FI-Sii	fen		shrubs,grasses,mosses
FI-Lom	fen		shrubs,grasses,mosses



Line 540-541: This really seems like it could be compensating for some other error related to vegetation biomass, LAI, or productivity. I would expect higher biomass and LAI in warmer areas, which would drive exactly this type of relationship. I think this should be investigated since the optimization of Vcmax could be masking other important model issues.

The measured LAI indeed is larger in warmer areas, but we would like to mention that there is no systematic bias in LAI or biomass, as shown in Fig.S1. Verheije et al. (2013, Biogeosciences) demonstrated that Earth system models could be improved by taking plant traits variations within PFTs into account, and proposed relationships between trait parameters and the climate, which can be used to define the parameter values for each grid cell. Considering that there is no available observational-based trait-climate relationships that can be used for peatland vegetations, we optimized V_{cmax} at each site and built the relationship between the optimized V_{cmax} and the latitude (temperature), which showed better performance than using a mean value. The peat PFT in our study represents an average of the ecosystem, not a specific plant type. A broad decrease of V_{cmax} with latitude in the northern hemisphere has also been documented by Walker et al. (2017, New Phytologist), assuming that V_{cmax} was constrained by the rate of N uptake, with the rate of N uptake calculated as a function of soil C, N and mean annual air temperature. We note this in the text on Page20, Line587: “……relationship with the latitude of chosen peatland sites location. A decrease of V_{cmax} with latitude in the northern hemisphere, like the one inferred from optimized sites values, has also been documented by Walker et al. (2017), who assumed that V_{cmax} was constrained by the rate of N uptake, with the rate of N uptake calculated as a function of soil C, N and mean annual air temperature. We speculate the dependence of optimized V_{cmax} on latitude found in Sect. 4.2 can be attributed to……**".**

Line 549: Why not use this mean value of 40 in the previous comparison, instead of the default value of 16?

The mean value of 40μmol m^{-2} s^{-1} is used in the revised manuscript. Please refer to our responses to the second comment.

Line 560-561: Why are only these two sites discussed and shown in the figure? Was the relevant data not available for other sites, or are these just being used as illustrative examples?

We have data for other sites. The underestimation of soil temperature in winter and overestimation in summer occurred at most of these sites. DK-Nuf and CA-Wp1 are just used as illustrative examples. We corrected the text on Page19, Line560: "……soil temperature was underestimated in winter and overestimated in summer by our model (Fig. 7 and 8, results from sites DK-Nuf and CA-Wp1 are shown as illustrative examples).**"**

Line 564-566: The suggestion that the issues are due to errors in snow density implies that the snow mass was correct in the model. Is that true?

We didn't validate the simulated snow mass because of lack of available data. We rephrased the text on Page19, Line564: "……can be caused by the bias in snow processes of the model, such as underestimation of snow mass, and/or overestimation of snow density and…**".**

Line 582-585: Even if optimized Vcmax is an average for the ecosystem rather than a species-specific value, it should be comparable with the observed range among different species that exist in these systems. Other peatland models should definitely be comparable, because any peatland model would be representing an average plant type. I don't think this is a satisfying explanation for not comparing the optimized estimates with measurements. It's just as likely that the model underestimates LAI and needed to tune Vcmax higher to compensate. I don't find any of the three explaination below particularly convincing, and I think bias in LAI or plant biomass is a likely explanation that should be tested.

The reviewer is right, the optimized V_{cmax} should be compared with the observed range among different species. Therefore we added these sentences on Page20, Line582: "……The V_{cmax} values estimated in this study ranged from 19 to 89 μmol m^{-2} s^{-1}, with a mean value of 40 μmol m^{-2} s^{-1}. These values were not fully comparable with values reported for a specific vegetation type, as they are averages for all plants growing in the peatland ecosystem. As stated in Sect. 2.2, observed V_{cmax} varies strongly among different species and sites. V_{cmax} of mosses at the Old Black Spruce site (Canada) varied from 5 to 14 μmol m^{-2} s^{-1} (Williams and Flanagan, 1998), In a nutrient addition experiments conducted by Bubier et al. (2011), V_{cmax} for ericaceous shrubs in a temperate bog ranged from 67 to 137μmol m^{-2} s^{-1}, with V_{cmax} for *Vaccinium myrtilloides*, *Ledum groenlandicum* and *Chamaedaphne calyculata* valued at

84.6 ± 13.5 μmol m^{-2} s^{-1}, 78.1 ± 13.4 μmol m^{-2} s^{-1}, and 132.1 ± 31.2 μmol m^{-2} s^{-1} in the plots with no nutrient addition. The optimized model V_{cmax} in our study was within the range of these observations. Meanwhile, the values we inferred from sites to match peak GPP are comparable to those used in other land surface models: the McGill wetland model used a value of 17 μmol m^{-2} s^{-1} for evergreen shrubs (St-Hilaire et al., 2010); the CLASS-CTEM model (Wu et al., 2016) used 60, 50, 40 μmol m^{-2} s^{-1} for evergreen shrubs, deciduous shrubs and sedges, respectively; the values for mosses in these two models were adapted from the study of Williams and Flanagan (1998). **".**

Line 591-592: Does ORCHIDEE not already take the influence of temperature on photosynthesis into account?

ORCHIDEE does take the influence of temperature on photosynthesis into account by parameterizing the temperature dependences of Michaelis-Menten constants, CO_2 compensation point following Medlyn et al. (2002, Plant, cell & environment). And temperature acclimation of photosynthesis rates constants is included in ORCHIDEE following Yin et al. (2009, NJAS-Wageningen J. Life Sci.). We thus removed the following sentences on Page20, line 591-592: "……2) with an adequate water supply, leaves open their stomata in response to warm environments, leading to a higher photosynthetic efficiency (Chapin III et al., 2011);".

Line 593: If the issue were nutrient availability, I would expect strong contrasts in Vcmax between fen and bog ecosystems, which did not appear to be the case in this study.

As we mentioned above, the sites used in this study include wooded fens, wooded bogs, grassy fens and grassy bogs, among them, there is no significant difference in dominant vegetation types between fens and bogs. Meanwhile, there is neither significant difference in measured biomass between fens and bogs (P=0.097) nor significant difference in measured GPP (P=0.63).

Line 603-632: This is a nice review of observed drought effects on peatlands, but the paper doesn't demonstrate whether the model can reproduce any of these effects. Such a demonstration would be very informative.

We added these sentences to demonstrate results of the model on Page22, Line628: "……and growth of peatland vegetation was not constrained by water table depth in the model. Therefore, the sensitivity of GPP to WT fluctuations in observations was not included in the model. As a consequence, the model neither captured the reported decrease of photosynthesis due to drought at CA-Wp3 (Adkinson et al., 2011) and SE-Faj (Lund et al., 2012), nor the increase of photosynthesis as a result of lower water table at CA-Wp1 (Flanagan and Syed, 2011). However, the model can reproduce the pattern that above a critical level (acrotelm depth), peat respiration decreases with increasing WT (Fig.5, Fig.S13), as reported at site CA-Mer and US-Los (Lafleur et al., 2005; Sulman et al., 2009). **".**

Line 630-632: It would be better to show that the model reproduces this pattern (in a figure) rather than just asserting that it can.

The decrease of soil respiration with increasing WT (shallower) was shown in Fig.5 and

Fig. S13. We added this sentence on Page22, Line630: "…… The model can reproduce the pattern that above a critical level (acrotelm depth), peat respiration decreases with increasing WT (Fig.5, Fig.S13), as reported at site CA-Mer and US-Los (Lafleur et al., 2005; Sulman et al., 2009).**".**

Line 634-635: If GPP was captured well but NEE was not, then the difference must be due to simulated respiration. This is another case where more analysis of simulated respiration would be very helpful.

Ecosystem respiration was relatively well captured by the model. We added these sentences on Page22, Line634: "……variations in GPP (with r^2 = 0.75, 0.86, and 0.93, respectively) and ER (with r^2=0.78, 0.86, and 0.89, respectively), but were less able to reproduce variations in NEE (with r^2 = 0.38, 0.61, and 0.27, respectively)**.** Note that in the two-layer soil carbon scheme, the dependence of soil respiration on temperature was parameterized as an exponential function of the soil layers-weighted average temperature (Text S1). ……and values of Q_{10} coefficient depend on the soil depth (Lafleur et al., 2005; D'Angelo et al., 2016). Small-scale peatland surface heterogeneities are not included in the model,**"**

Line 666: This implies that water table is not an important feature of carbon cycling according to this model. This seems very inconsistent with the observational literature showing that peatland CO2 fluxes are quite responsive to water table fluctuations (much of which is cited in this manuscript). Some papers have demonstrated that compensating responses of GPP and respiration (e.g. both increasing under a drying trend) can cause NEE to be insensitive to water table fluctuations (e.g. Sulman et al. 2010), but the paper doesn't really demonstrate that the model is reproducing those compensating responses. Given the centrality of water table and hydrology in our understanding of peatland carbon cycling, I think this conclusion that water table isn't actually that important needs to be investigated in more detail, especially in how it affects peat decomposition and ecosystem respiration in the model.

The point we were trying to make here is that although water table was poorly simulated by the model, it was good enough to simulate ER (NEE) properly. With water table being forced to be equal to observed values in S2, there were no large improvements in simulated ER, NEE (Table5, Table6, Fig. S13). This is because the oxic decomposition in the acrotelm (β), which is the main component of soil respiration, was calculated by comparing the height of the acrotelm with the WT depth, though absolute values of water table depth in S1 and S2 were quite different (Fig. S8), β were not so different. We took Lompolojänkkäfen site (FI-Lom) as an example, in which WT was most severely underestimated. As shown by Fig. S12, difference between β of S1 and S2 only occurred during short periods and mainly in winter when decompositions were inhibited by the low temperature. We performed an additional simulation (S3), in which we assumed that water table was more severely underestimated by the model (water table used in S3 was consistently 20cm deeper than in S1), thus the acrotelm was more exposed to the air in S3 (Fig. S12). S3 showed much larger ecosystem respiration and hence smaller carbon sequestration than S1. We clarified this by added these sentences on Page18, Line524: "……an overestimation (more negative values) of NEE in the warm period (May-September). The influence of WT on respiration was parameterized as the separation of oxic (β in Eq. 6) vs. anoxic (1-β in Eq. 7) decomposition in the acrotelm. Although absolute values of simulated WT in S1 and WT$_{obs}$ in S2 were quite different (Fig. S8), the values of β were not very different (Fig.S12). Therefore the simulated WT was good enough to properly replicate ER (Fig.S13). An additional simulation (S3) performed at FI-Lom showed that if WT was more severely underestimated, e.g. WT in S3 was consistently 20 cm deeper than in S1, the acrotelm was exposed to oxygen for longer time, resulting in larger ER and hence smaller carbon sequestration in S3 (Fig.S12, Fig.S13).**”. We rephrased the sentences in abstract on Page3, Line105: “**……likely due to the uncertain water input to the peat from surrounding areas. However, the poor performance of WT did not greatly affect predictions of ER and NEE.**”, and the sentences in conclusion on Page23, Line665: “**……instead of calculated by the model, was small, indicating that the simulated WT was reliable to predict ER and NEE properly.**”**

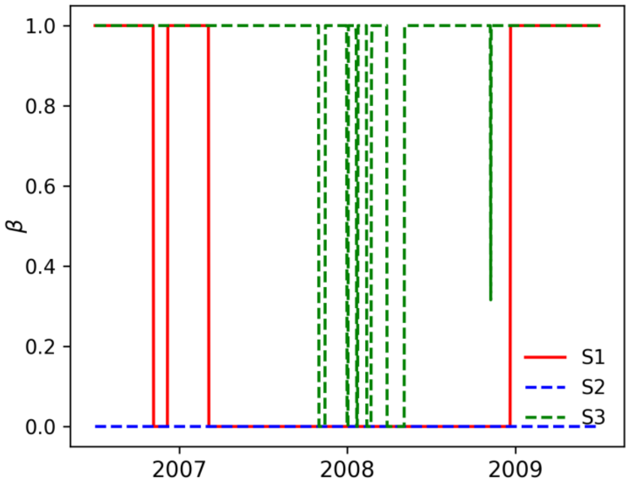


Fig. S12. The fraction of the acrotelm where carbon decomposes under oxic conditions (β) at Lompolojänkkä fen site (FI-Lom). S1: simulated water table (WT) were used in the carbon module; S2: observed water table (WT$_{obs}$) were used in the carbon module; S3: assumed that water table were 20cm deeper than simulated results, thus (WT−20cm) were used in the carbon module.

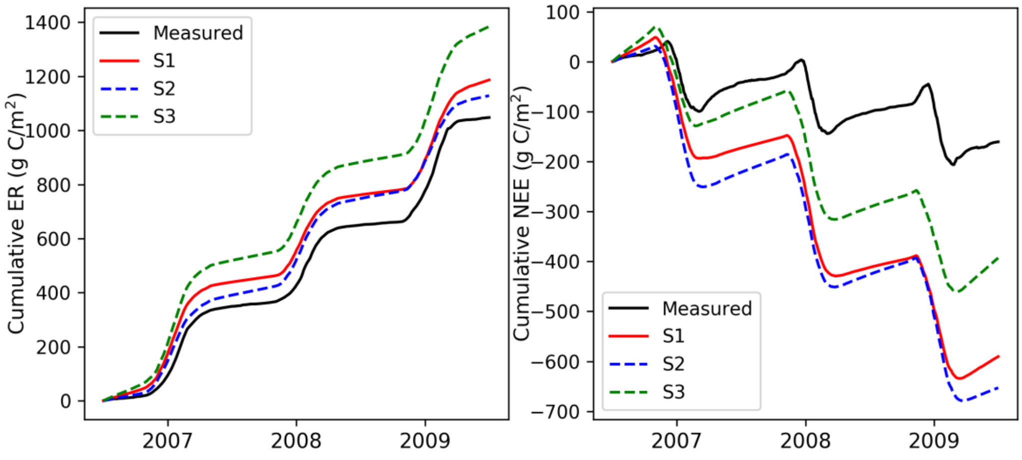


Fig. S13. Cumulative ER (left figure) and NEE (right figure) at Lompolojänkkä fen site (FI-Lom). S1: simulated water table (WT) were used in the carbon module; S2: observed water table (WT_{obs}) were used in the carbon module; S3: assumed that water table were 20cm deeper than simulated results, thus (WT−20cm) were used in the carbon module.

Line 670-671: The paper definitely did not establish that nitrogen availability was the explanation for the latitudinal dependence. It was one of several proposed explanations. In fact, I think it's unlikely to be the explanation because it did not vary consistently with fen/bog type, which is closely related to nitrogen availability.

Not all fens in this study are nutrient rich, for example, SE-Deg (Peichl et al., 2014, Environ. Res. Lett.), FI-Sii (Aurela et al., 2007, Tellus), CA-Wp2 (Adkinson et al., 2011, J. Geophys. Res. Biogeosciences) are oligotrophic fens, thus there is a large variation in V_{cmax} of fens. And there is no significant difference in biomass, GPP between fens and bogs. Meanwhile, Walker et al. (2017, New Phytologist) found that V_{cmax} values decreased with latitude in the northern hemisphere if the rate of nitrogen uptake was parameterized as a function of soil C, N, and mean annual air temperature. Thus, we can't rule out the possibility that the relationship was caused by nitrogen availability.

Table 2: In addition to bog/fen type, it would be informative to include something about the dominant vegetation type (grass, shrub, forested) and maybe aboveground biomass or LAI if available

We included the dominant vegetation type and LAI, and aboveground biomass in the Table2, detailed description of the sites can be found in the supplement material.

Referee #2

The authors present a new peatland model as part of the ORCHIDEE land-surface model. The manuscript is well written and does a nice job of describing recent advances in peatland modeling and identifying the need for the model developments reported here. Specifically, the model simulates water table by prescribing peat-specific hydraulic properties across the 11 soil-profile layers. Water table is then used to determine decomposition rates in in the near-surface acrotelm and deeper, saturated catotelm. The model is evaluated using eddy covariance measurements from 30 sites across northern hemisphere (bog, fen, and tundra). In general, I think the manuscript is in good shape, and I have a few relatively minor comments:

1. Would it be possible for the authors to evaluate model performance of heterotrophic respiration or ER vs. observed values?
We added comparisons of simulated vs. observed ER, please refer to our response to the first comment of Reviewer#1.

2. Line 132 – Should be permafrost “thaw”, not “melt
Corrected now in the text.

3. Lines 231-232 – While incorporating a peatland-specific PFT is a step in the right direction, I was surprised the authors did not develop a bryophyte or shrub PFT for application in this study, particularly given the range of peatlands used for model comparison. It seems like at the very least, the authors should acknowledge this as a cause of discrepancies between model output and observations.
Currently, ORCHIDEE (both the standard ORCHIDEE and ORCHIDEE-PEAT) lacks representation of mosses and shrubs. In the grid-based simulations, we do not know fractional coverage of the peatland vegetation at each site. Wania et al. (2009, Global Biogeochem. Cy.) parameterized flood-tolerant C3 graminoids and *Sphagnum* in LPJ-WHy to represent peatland-specific vegetations, with peatland extent defined from an organic soil map and the fractional cover of PFTs determined by bioclimatic conditions including temperature, water table depth, inundation stress etc. Stocker et al. (2014, Geosci. Model Dev.) applied a version of Wania et al's model but removed the upper temperature limitation of the peatland-specific PFTs and further included three additional PFTs — flood tolerance C4 grasses, tropical evergreen and tropical raingreen tree PFTs, with peatland extent diagnosed by TOPMODEL. Previous studies have shown that there was considerable overlap between the plant traits ranges among different plant functional types, while variations in plant traits within PFTs can be even greater than the difference in means among PFTs (Verheije et al., 2013, Biogeosciences; Wright et al., 2005, New Phytol; Laughlin et al., 2010, Funct. Ecol.). For simplicity, in this study, we applied only one PFT to represent an average of all vegetations growing in the peatland ecosystem. However, only one key photosynthetic parameter—V_{cmax} of the PFT has been tuned to match with observations at each studying sites, other processes and parameters of this PFT was inherited from a C3 grass, this simplification may cause

discrepancies between model outputs and observations.

Druel et al. (2017, Geosci. Model Dev. Discuss.) added non-vascular plants (bryophytes and lichens), boreal grasses, and shrubs into ORC-HL-VEGv1.0, biogeochemical and biophysical processes of these new PFTs were defined and evaluated in their study. Their work is in parallel with our model, after both ORCHIDEE-PEAT and ORC-HL-VEGv1.0 are incorporated into the main branch of ORCHIDEE in the future, it will then be possible to verify how many plant functional types are needed by the model to reliably simulate the peatlands at site-level and larger scales, though the vegetations implemented by Druel et al. are not peatland-specific. To acknowledge these, we added these sentences on Page8, Line 230: "……and extensive root systems (Boutin and Keddy, 1993; Iversen et al., 2015). Previous peatland models have incorporated more than one PFT to represent peatland plants and dynamically simulate fractional vegetation cover. For example Wania et al. (2009b) separated flood-tolerant C3 graminoids and *Sphagnum* moss in LPJ-WHy to represent peatland-specific vegetation, with peatland extent defined from an organic soil map and the fractional cover of PFTs determined by bioclimatic conditions including temperature, water table depth, inundation stress etc. Stocker et al. (2014) applied a version of this model but removed the upper temperature limitation of the peatland-specific PFTs and further included three additional PFTs — flood tolerant C4 grasses, tropical evergreen and tropical raingreen tree PFTs, with peatland extent diagnosed by the TOPMODEL scheme. At present, however, ORCHIDEE-PEAT lacks representation of dynamic moss and shrub covers, and we do not know the fractional coverage of different vegetation types at each site in grid-based simulations. Previous studies have shown that there was considerable overlap between the plant traits ranges among different plant functional types, while variations in plant traits within PFTs can be even greater than the difference in means among PFTs (Verheijen et al., 2013; Wright et al., 2005; Laughlin et al., 2010). Therefore, for simplicity, we applied the PFT of C3-grass with a shallower rooting depth to represent the average of vegetation growing in northern peatlands.

Only one key photosynthetic parameter—V_{cmax} of this PFT has been tuned to match with observations at each site. This simplification may cause discrepancies between model output and observations. Druel et al. (2017) added non-vascular plants (bryophytes and lichens), boreal grasses, and shrubs into ORC-HL-VEGv1.0. Their work is in parallel with our model and will be incorporated into the model in the future. It will then be possible to verify how many plant functional types are needed by the model to reliably simulate the peatlands at site-level and larger scale.**".**

4. Line 321-324 – Please clarify how the CENTURY-type model of the standard ORCHIDEE is incorporated in the new decomposition parameterizations for the peatland version. As is, it's not clear how the three-pool set-up relates to these equations.

We clarified the structure of the carbon module in ORCHIDEE-PEAT in the text and modified Fig.S1 to show the scheme of the model clearer, please refer to our response to Reviewer#1 (Specific comments, Line 299-301 and Fig. S1) for details.

5. Line 566-567 – The model does incorporate hydraulic properties of peat soils. It seems like it would have been relatively straightforward to also incorporate thermal properties of peats to

improve soil temperature performance and its effects on respiration.

ORCHIDEE-PEAT lacks parameterization of peat-specific thermal characteristics due to the original thermal scheme of the model. Within a gridcell, different soil columns are represented but only the charactericstic of the dominant are used to define the thermal properties (soil thermal conductivity and heat capacity) in the model. The model configuration doesn't allow us to assign different properties for each soil column in the same one grid cell. An ideal solution would be to change the structure of the model so that peat soil can have peat-specific thermal properties while non-peat soil columns keep using the dominant mineral soil texture. This is the approach we used for soil hydraulics. We would like to mention that a study by Guimberteau et al. (2017, Geosci. Model Dev.) conducted in parallel to our study added the feedback effects of soil organic carbon concentration on soil thermics into ORCHIDEE, specifically, soil physical properties of one grid cell is a weighted average of mineral soil and organic soil, with carbon content for organic soil derived from the soil organic carbon map from NCSCD. This approach takes thermal properties of peat (pure organic soil) into account in a simplified way. Guimberteau et al.'s development can be used by ORCHIDEE-PEAT after the model is merged into the main branch of ORCHIDEE in the near future.

6. The authors point toward possible causes of the poor model performance with respect to water table in the Discussion. It would be helpful if they could lay out some practical future steps to improve model performance, particularly given the importance of WT on below-ground C cycling parameters.

We added following senteneces to the discussion, Page22, Line641: "……depend on the soil depth (Lafleur et al., 2005; D'Angelo et al., 2016). Correct representation of peatland hydrology is a challenging problem in large-scale land surface models (Wania et al., 2009a; Wu et al., 2016). The simulated water table by ORCHIDEE-PEAT depends on water inflows from the surrounding non-peatland areas, and a water routing analysis on sub-grid scales can be included to improve the model performance for water table in the future (Ringeval et al., 2012; Stocker et al., 2014). Other studies have shown that microtopography exerts important influences on hydrological dynamics of peatlands, however, to capture the influence of microtopography on water table, high-resolution micro-topographic feature and vegetation information are needed (Gong et al., 2013; Shi et al., 2015). **" .**

ORCHIDEE-PEAT (revision 4596), a model for northern peatland CO$_2$, water and energy fluxes on daily to annual scales

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Abstract

Peatlands store substantial amounts of carbon~~,~~ and are vulnerable to climate change. ~~To predict the fate of carbon stored in peatlands, the complex interactions between water, peat and vegetations need more attention.~~ We present ~~This study describes~~ a modified version of the ORCHIDEE land surface model for simulating the hydrology, surface energy and CO_2 fluxes of peatlands on daily to annual time scales. The model~~, referred to as ORCHIDEE-PEAT,~~ includes a separate soil tile in each 0.5 ° grid-cell, defined from a global peatland map and identified with peat-specific soil hydraulic properties. Runoff from non-peat vegetation within a grid-cell containing a fraction of peat is routed to this peat soil tile, which maintains shallow water tables. The water table position separates oxic from anoxic decomposition. The model ~~is~~was evaluated against eddy-covariance (EC) observations from 30 northern peatland sites, with the maximum rate of carboxylation (V_{cmax}) being optimized at each site ~~to match the peak of growing season gross primary productivity (GPP), derived from direct EC measurements~~. Regarding short-term day-to-day variations ~~from day to day~~, the model performance was good for ~~the variations in~~ GPP (r^2 = 0.76, Nash-Sutcliff modeling efficiency, MEF = 0.76)~~,~~ and ecosystem respiration (ER, r^2 = 0.78, MEF = 0.75), with lesser accuracy for latent heat fluxes (LE, r^2 = 0.42, MEF = 0.14) and Net ~~ecosystem~~ Ecosystem CO_2 E~~e~~xchange (NEE, r^2 = 0.38, MEF = 0.26). Seasonal variations in GPP, ER, NEE and energy fluxes on monthly scales showed moderate to high r^2 values (~~ranging from~~ 0.57 – ~~to~~ 0.86). For spatial across-sites gradients of annual mean GPP, ER, NEE and LE, r^2 of 0.93, 0.89, 0.27, and 0.71~~, respectively,~~ were achieved, respectively. ~~The w~~Water table variation (WT) ~~s~~ ~~are~~was not well predicted (r^2 < 0.1), likely due to the uncertain water input to the peat from surrounding areas. However, the poor performance of WT simulation did not greatly affect predictions of ER and NEE. ~~when using the observed water table in the carbon module to define the fraction of oxic and anoxic decomposition instead of the modeled water table, ORCHIDEE-PEAT shows a small improvement in reproducing NEE. Moreover, we~~ We found a significant relationship between optimized V_{cmax} and

~~the~~ latitude (temperature), which ~~can~~ better reflects the spatial gradients of annual NEE than using an average V_{cmax} value. ~~In a future version of ORCHIDEE-PEAT, the influences of water table on photosynthesis and depth-dependent influences of soil temperature on respiration may be included~~.

1. Introduction

Peatlands cover only 3 – 5 % of the Earth's land area, but store large amounts of soil organic carbon (SOC). This carbon is primarily located in the boreal and sub-arctic regions (75 – 80 %), while about 15 % ~~is~~ are located in ~~the~~ tropical regions (Frolking et al., 2011; Page et al., 2011). Current estimates of the northern peatland ~~carbon stocks~~SOC vary from 270 to 450 Pg C (Gorham, 1991; Turunen et al., 2002; Yu et al., 2010). Northern peat accumulation occurred mainly during the Holocene, originating from plant litter production that exceeds~~ing~~ decomposition in water-logged soil conditions, with low pH and low temperatures (Parish et al., 2008). The future of the carbon stored in these peatlands under ~~the~~ a warmer environment and altered hydrological regimes is very uncertain. Logically, higher CO_2 concentrations and elevated temperatures will stimulate higher carbon uptake ~~due to~~because of longer growing seasons and higher photosynthetic rates (Aurela et al., 2004; Adkinson et al., 2011). However, the accumulation is also coupled with a high evaporative demand that will lower the ground water table, resulting in increased heterotrophic respiration rates (i.e., carbon loss) (Mertens et al., 2001; Sulman et al., 2009; Adkinson et al., 2011). In addition to these ~~above~~ potential climatic influences, other natural and anthropogenic disturbances (permafrost ~~melt~~thaw, drainage, fires, etc.) further~~can also~~ play a role in determining the future carbon balance of these vulnerable ecosystems (Turetsky et al., 2002; Parish et al., 2008). Drainage and fires have particularly important impacts on the carbon balance of the tropical peatlands (Page et al., 2002; Hooijer et al., 2010).

A number of peat carbon models have been reported in the literature. For example, Frolking et al. (2010) ~~created~~ developed the Holocene Peat Model (HPM), which includes feedbacks between plant communities, water table, peat properties, and peat decomposition. This model was applied at Mer Bleue bog in southern Canada and validated with data from peat-core observations. HPM is a long-term peat accumulation model that works at an annual time step but cannot simulate seasonal variations of key water processes in peatlands. Wania et al. (2009a, 2009b) integrated peatlands and permafrost into the Lund-Potsdam-Jena model (LPJ-WHy), ~~in their model,~~where the upper 0.3 m of peatland soils (the acrotelm) experiences a fluctuating water table and the underlying layer (the catotelm) is permanently inundated ~~permanently~~. A constant soil moisture modifier (0.35) was used to reduce acrotelm decomposition. Spahni et al. (2013) adopted and improved LPJ-Why ~~to take into account~~by considering the effects of varying water table depth on acrotelm decomposition rates, using a weighted average of the aerobic and anaerobic respiration modifier, and ~~implemented~~ implementation of a dynamic nitrogen cycle. In the dynamic global vegetation model (DGVM) CLIMBER2-LPJ, Kleinen et al. (2012) quantified~~determined~~ the fraction of oxic decomposition in the acrotelm by comparing the water table position and the acrotelm height. Chaudhary et al. (2016, 2017) included a dynamic multi-layer peat accumulation functionality in a customized Arctic version of the Lund-Potsdam-Jena General Ecosystem Simulator (LPJ-GUESS). In their approach, new layers of litter were added at the top of the soil every year, and the remaining litter mass, after decomposition, was treated as a new individual peat layer from the first day of the following year. The decomposition rate of peat, modulated by temperature and moisture, declined over time. In these four peatland models, the water table depth ~~is~~ was calculated from a bucket model. In the context of Earth System Modeling, the land surface processes are better ~~is tend to be~~ represented by ~~several~~ multi-layer schemes, such as multi-layer plant canopy and root, multi-layer snow, multi-level soil carbon and energy budgets (Best et al., 2011; Mcgrath et al., 2016; Zhu et al., 2016). To model peatlands consistently in land surface models, a multi-layer soil hydrology scheme is needed. Meanwhile, a more physically~~s~~-based multi-layer scheme can provide more prognostic power in predicting peatland water table dynamics.

In this study, we present~~ed~~ the ~~results of the~~ development of a multi-layer peat hydrology and carbon model in the ORCHIDEE land surface scheme, with a focus~~ing~~ on the water table dynamics and its effects on the energy budgets, and on carbon decomposition occurring within the oxic and the water-saturated part of the peat profile. CH_4 fluxes and DOC loss through runoff are important components of the carbon balance of a peatland (Chu et al., 2014; Olefeldt et al., 2012), but are not included in this study. ~~The originality of t~~This new peat model is ~~that it is~~ incorporated consistently into the land surface scheme in order to conserve water, carbon and energy at scales ~~going~~ from local sites to grid-based large-scale applications in an Earth System Modeling context.~~ The model structure and equations are described in Sect. 2, and its evaluation against water table depth, energy and CO_2 fluxes measured in 30 northern peat sites is presented in Sect. 3.~~

2. Model description

2.1 General structure of the model

The ORCHIDEE land surface model simulates biophysical processes of rainfall interception, soil water transport, latent (LE) and sensible (H) heat fluxes, heat diffusion in the soil, and photosynthesis on a 30-min time step (Ducoudré et al., 1993). Carbon cycle processes (e.g., ~~such as~~ carbon allocation, respiration, mortality, litter and soil carbon dynamics)~~,~~ are simulated on a daily time step (Krinner et al., 2005).

ORCHIDEE discretizes the vegetation into plant functional types (PFT): eight for trees, two for natural C3 and C4 grasses, two for C3 and C4 crops, and one ~~as~~ for bare-soil type. Across the PFTs, plants are described with the same equations but different parameter values, except for leaf onset and senescence that follow PFT-specific equations (Botta et al., 2000). In grid-based simulations, PFTs are grouped into three soil tiles: one with bare soil, one with all tree PFTs, and one with all short vegetation. The water budget of each soil tile is calculated independently. The version of ORCHIDEE implemented in this study uses the same (dominant) soil texture for all the soil tiles of a grid cell to define the reference saturated hydraulic conductivity ($K_{s\text{-}ref}$), and the saturated and residual volumetric water contents (θ_s, θ_r). Dominant soil textural classes are taken from the Zobler's soil texture map (Zobler, 1986) at 1° resolution. The original five soil textures (fine, medium-fine, medium, medium-coarse, coarse) in Zobler's map are reduced to three (fine, medium, coarse), by grouping the medium-fine, medium, and medium-coarse into a single~~one~~ class. Hydrological parameters of the three dominant soil textures are taken from Carsel and Parrish (1988) (Table 1).

Each soil tile in ORCHIDEE has eleven vertical layers (up to ~~with a total depth of~~ 2.0 m) with exponentially coarser vertical resolution (Fig. 1). The Fokker-Planck equation is used to describe the vertical diffusion of water in the soil. The Mualem (1976) - Van Genuchten (1980) model (Eq. 1 and 2) is used to define the hydraulic conductivity (K, m s^{-1}) and diffusivity (D, m^2 s^{-1}) as a function of volumetric water content (θ, m^3m^{-3}):

$$K(\theta) = K_s\sqrt{\theta_f}(1-(1-\theta_f^{1/m})^m)^2, \tag{1}$$

$$D(\theta) = \frac{(1-m)K(\theta)}{\alpha m}\frac{1}{\theta-\theta_r}\theta_f^{-\frac{1}{m}}(\theta_f^{-\frac{1}{m}}-1)^{-m}, \tag{2}$$

where θ is the volumetric water content (m^3 m^{-3}), θ_s is the saturated water content (m^3 m^{-3}), θ_r is the residual water content (m^3 m^{-3}), θ_f is the relative water content and is calculated as $\theta_f = \frac{\theta-\theta_r}{\theta_s-\theta_r}$, K_s is the saturated hydraulic conductivity (m s^{-1}), α is the inverse of the air entry suction (m^{-1}), and *m* is a dimensionless parameter.

Following Orgeval (2006) and Orgeval et al. (2008), K_s exponentially decreases with soil depth (z) below z_{lim} = 30 cm ($F_d(z)$), while a root-fracturing factor increases K_s where roots are denser ($F_{root}(z)$):

$$K_s(z) = K_{s-ref} * F_d(z) * F_{root}(z), \tag{3}$$

with $F_d(z) = \min(\max(\exp(-f(z-z_{lim})),0.1),1)$,

$F_{root}(z) = \prod_{j\epsilon c}\max(1,\left(\frac{K_s^{max}}{K_{s-ref}}\right)^{\frac{1-\alpha_j z}{2}})^{f_j}$, where $K_{s\text{-}ref}$ is the reference top-soil saturated hydraulic conductivity determined by soil texture (m s^{-1}), K_s^{max} is the value of the coarser (sandy) texture and equals 8.25 × 10^{-5} m s^{-1}, α_j is a root profile decay factor for PFT *j* with a coverage fraction f_j, and *c* is the soil tile to which PFT *j* was assigned ~~to~~.

2.2 Modifications in ORCHIDEE-PEAT

To simulate peat, we: 1) modified the parameters of plants growing on peat, 2) added a new peat soil tile with specific peat soil hydraulic properties, and 3) changed the decomposition of peat carbon as being controlled by saturated conditions, through the modeled water table (WT).

Modified peat plant parameters~~.~~:

As a response to the unique stress conditions in peatlands (i.e., oxygen deficit, nutrient limitation), peatland vegetation has shallow and extensive root systems (Boutin and Keddy, 1993; Iversen et al., 2015). ~~In this study, a C3 grass peatland PFT with a rooting depth of 30 cm implemented by Largeron et al. (2017) was used.~~ Previous peatland models have incorporated more than one PFT to represent peatland plants and dynamically simulate fractional vegetation cover. For example, Wania et al. (2009b) separated flood-tolerant C3 graminoids and *Sphagnum* moss in LPJ-WHy to represent peatland-specific vegetation, with peatland extent defined from an organic soil map and the fractional cover of PFTs determined by bioclimatic conditions including temperature, water table depth, inundation stress etc.. Stocker et al. (2014) applied a version of this model but removed the upper temperature limitation of the peatland-specific PFTs and further included three additional PFTs — flood tolerant C4 grasses, tropical evergreen and tropical raingreen tree PFTs, with peatland extent diagnosed by the TOPMODEL scheme. At present, however, ORCHIDEE-PEAT lacks representation of dynamic moss and shrub covers, and we do not know the fractional coverage of different vegetation types at each site in grid-based simulations. Previous studies have shown that there are considerable overlaps between the plant traits ranges among different plant functional types, while variations in plant traits within a PFT can be larger than the differences in means of different PFTs (Verheijen et al., 2013; Wright et al., 2005; Laughlin et al., 2010). Therefore, for simplicity, we applied only the PFT of C3-grass with a shallower rooting depth to represent the average of vegetation growing in northern peatlands.

Only one key photosynthetic parameter—V_{cmax} of this PFT has been tuned to match with observations at each site. This simplification may cause discrepancies between model output and observations. Druel et al. (2017) added non-vascular plants (bryophytes and lichens), boreal grasses, and shrubs into ORC-HL-VEGv1.0. Their work is in parallel with our model and will be incorporated into the model in the future. It will then be possible to verify how many plant functional types are needed by the model to reliably simulate the peatlands at site-level and larger scale. The maximum rate of carboxylation (V_{cmax}) typically varies across peat sites (Rennermalm et al., 2005; Bubier et al., 2011)~~,~~ and further varies with leaf nitrogen, phosphorus content, and specific leaf area (Wright et al., 2004; Walker et al., 2014). For instance, V_{cmax} ~~value~~ for *Sphagnum* at the Old Black Spruce site (53.985 °N, 105.12 °W) in Canada ~~were~~ was 5, 14 and 6 µmol m^{-2} s^{-1} during spring, summer and autumn, respectively, while V_{cmax}~~that~~ for *Pleurozium* ~~were~~ was 7, 5, and 7 µmol m^{-2} s^{-1} during the three seasons (Williams and Flanagan, 1998). Bui (2013) conducted a fertilization experiment at the Mer Bleue ~~Bog~~ bog (Canada, 45.41 °N, 75.52 °W) on the dominant ericaceous shrub and reported that V_{cmax} values ranged between 6 and 179 µmol m^{-2} s^{-1}, with significantly higher V_{cmax} values after addition of nitrogen (6.4 g N m^{-2} $year^{-1}$) at 20 times the growing season ambient wet N deposition rate with or without phosphorus (P) and potassium (K). In this study~~, we used a default V_{cmax} value of 16 µmol m^{-2} s^{-1} for peat PFT, following a literature survey by Largeron et al. (2017). Later~~ (Sect. 4.1), we calibrated V_{cmax} at each site so that modeled peak gross primary production (GPP) matched peak values derived from direct EC measurements, and then regressed this adjusted V_{cmax} value with environmental and climate variables. We note that this adjustment of V_{cmax} may over- or under-compensate for biases in other model parameters that impact maximum GPP, such as leaf area index (LAI), specific leaf area (SLA), canopy light absorption parameters, water and temperature stresses (Fig. S1).

Peat-specific soils hydraulics~~.~~:

Peatlands generally occur in flat areas that are poorly drained and/or receive runoff and sub-surface water from the surrounding landscape (Graniero and Price, 1999).

The low permeability catotelm peat layer is permanently saturated. In ORCHIDEE-PEAT, the new soil tile added in a grid cell to represent peatland as a landscape element was assumed to receive surface runoff from the other three soil tiles (bare soil, trees, grasses) and has a drainage flux reduced to zero (Largeron et al., 2017). Further, considering that the water table of a peatland can rise above the ground surface, an above surface water reservoir with a maximum height of 10 cm was added (Fig. 1b). In the model, the partitioning between water infiltration and surface runoff is computed through a time-splitting procedure, with the maximum infiltration rates described as an exponential probability density distribution (d'Orgeval, 2006). The infiltration-excess water of peatland first fills the above-surface water reservoir, then leaves the grid cell as runoff. Water in this ~~This~~ above-surface reservoir ~~loses water to rivers when filled, and~~ re-infiltrates into the peat soil on the next time step (Largeron et al., 2017). We verified that the measured standing water remained below 10 cm above the soil surface at 16 out of 20 northern peat sites where water table depth was recorded in this study (Table S1). The four exceptions were Winous Point North Marsh (US-WPT), Himmelmoor (DE-Hmm), an Alaska fen (US-Fen) and an Alaska bog (US-Bog), where observed water tables reached up to 77 cm, 39 cm, 46 cm and 34 cm above the soil surface, respectively.

Peat soils cannot be described with any of the mineral soil textures used for other tiles (Table 1) because the low bulk density and high porosity increase the downward water percolation (Rezanezhad et al., 2016). ~~There is a large variability of observed~~ Observed peat saturated hydraulic conductivity (K) and diffusivity (D) strongly vary in space, depth and time. This is partly related to the degree of decomposition and compression of organic matter (Gnatowski et al., 2010). Morris et al. (2015) reported near-surface saturated hydraulic conductivities (K) of 2.69×10^{-2} m s^{-1} to 7.16×10^{-6} m s^{-1} in bogs. Gnatowski et al. (2010) measured values of 5×10^{-6} m s^{-1} in a moss-covered peat, which ~~is~~ was two orders of magnitude larger than for~~in~~ a woody peat (5.56×10^{-8} m s^{-1}). Peat hydraulic parameters values used in this study were applied after ~~(~~Largeron et al., (2017), based on Letts et al. (2000) and Dawson (2006) (Table 1). The peat saturated hydraulic conductivity value of 2.45 × 10^{-5} m s^{-1} is comparable to the harmonic mean value (6 × 10^{-5} m s^{-1}) of Morris et al. (2015). The values of the other Van Genuchten parameters for peat (Table 1) are similar to those employed in other peatland models (Wania et al., 2009a; Wu et al., 2016).

The peatland water table depth (WT, cm) is diagnosed by summing water heights in the eleven soil layers, calculated from the relative water content (Largeron et al., 2017):

$$\mathrm{WT} = \mathrm{H_{tot}} - \sum_{i=1}^{11}\left(\theta_{fi} * \mathrm{dz_i}\right) - \mathrm{H_{ab}}, \text{with } \theta_{fi} = \frac{\theta_i - \theta_r}{\theta_s - \theta_r}, \quad (4)$$

where θ_{fi} is the relative volumetric water content of the i^{th} soil layer, θ_s is the saturated water content (m^3 m^{-3}), θ_r is the residual water content (m^3 m^{-3}), dz_i is the distance between node *i-1* and node *i* (Fig. 1, m), H_{tot} is the total soil column height being fixed to 2.0 m, and H_{ab} is the height of the water reservoir above soil surface (m). Thus, when the water table is above the surface, the modeled WT takes negative values.

Decomposition of peat carbon controlled by water saturation~~.~~:

In the standard version of ORCHIDEE, plant litter carbon is added to two litter pools: the metabolic and the structural pool. Decomposed litter carbon from these two pools is then distributed into three soil carbon pools: the active, slow and passive pool ~~(Fig. S1)~~, similar to the CENTURY model (Parton et al., 1988). Both temperature and moisture functions are used to control soil carbon decomposition rates (Text S1). In ORCHIDEE-PEAT, these standard processes are kept the same as in Krinner et al. (2005) for non-peatland vegetation (Fig. S2, black dashed box). For the peatland vegetation, we added a peat carbon module, in which the three soil carbon pools (active, slow, passive) are replaced by two pools forming distinct layers, following ~~The original decomposition equations are combined with a new module to account for peat decomposition being controlled by water saturation, after~~ Kleinen et al. (2012)

(Fig. ~~S1~~S2, red dashed box). Specifically, carbon from decomposed litter pools is added to the acrotelm carbon pool where it is ~~then~~ decomposed aerobically above the simulated water table, and anaerobically below it. The permanently saturated deep catotelm carbon pool receives a prescribed fraction ~~(1.91% per year, Kleinen et al., 2012)~~ of the acrotelm carbon, and is decomposed only anaerobically at a very slow rate ~~(3.35 × 10^{-5} yr^{-1}, Kleinen et al., 2012)~~. ~~Whereas~~ While the acrotelm depth ~~was~~ is fixed to 30 cm in some ~~two-layer~~ peat decomposition models (Yurova et al., 2007; Wania et al., 2009a; Spahni et al., 2013), we used the average of simulated minimum summer water table position (WT_{min}) over the observational period to demarcate the boundary between the acrotelm and the catotelm at each site to take into account local site conditions. We conducted a “preparation run (S0)”, in which the model was run at each site using the same protocol (Sect. 3.3), but with the peat carbon module deactivated. WT_{min} was diagnosed from the output of S0 before feeding into the peat carbon module in S1 and S2 (Sect. 3.3). Soil carbon exerts no feedback effects on the soil temperature and hydraulic in the structure of our model, thus S0 and S1 produce the same simulated water table. WT_{min} values were estimated based on current climate due to the lack of knowledge of initiation histories of these sites. For the long-term carbon accumulation estimations, the Holocene climate may be a better proxy since northern peatlands show peak initiation in the early Holocene (Yu et al., 2010). By comparing the height of the acrotelm (Fig. ~~S1~~S2, Eq. 9) with the WT depth, we derived the fraction of the acrotelm where carbon decomposes under oxic (β) vs. anoxic conditions (1-β). Acrotelm height (H_A, Eq.10) was calculated from acrotelm carbon stock (C_A in Eq. 5-7), acrotelm carbon fraction ($C_{f,A}$) and acrotelm bulk density (ρ_A). Decomposition of peat carbon is controlled by ~~temperaturev~~temperature (f_T) and parameterized as an exponential function: $f_T = Q_{10}\exp((T-T_{ref})/10\ ℃)$ with $Q_{10} = 2.0$ and $T_{ref} = 30\ ℃$ (Text S1). Soil carbon fluxes are given by:

$$F_{AC} = k_p f_T C_A, \qquad (5)$$

$$R_{A,o} = \beta k_A f_T C_A, \qquad (6)$$

$$R_{A,a} = (1-\beta) v k_A f_T C_A, \qquad (7)$$

$$R_C = k_C f_T C_C, \qquad (8)$$

$$\beta = \begin{cases} \beta = 1, & WT_{min} - WT \leq 0 \\ \beta = \frac{H_A - (WT_{min} - WT)}{H_A}, & 0 < WT_{min} - WT < H_A \\ \beta = 0, & WT_{min} - WT \geq H_A \end{cases}, \qquad (9)$$

$$H_A = \frac{C_A}{\rho_A \cdot C_{f,A}}, \qquad (10)$$

where F_{AC} is the carbon flux from acrotelm to catotelm; $R_{A,o}$ is aerobically decomposed acrotelm carbon; $R_{A,a}$ is anaerobically decomposed acrotelm carbon; R_C is decomposed carbon in catotelm; C_A is carbon stored in the acrotelm; C_C is carbon stored in the catotelm; and β is the fraction of acrotelm under oxic conditions. A 10,100 years' spin-up was conducted to initialize peat depth at each site (Sect. 3.3). Following the study of Kleinen et al. (2012), the catotelm formation rate $k_p = 1.91 \times 10^{-2}$ yr^{-1}, the acrotelm decomposition rate $k_A = 0.067$ yr^{-1}, the catotelm decomposition rate $k_C = 3.35 \times 10^{-5}$ yr^{-1}, the ratio of anaerobic to aerobic CO_2 production $\mu = 0.35$, carbon fraction in the acrotelm peat $C_{f,A} = 0.50$, the acrotelm density ρ_A = 35.0 kg m^{-3}~~3.5×10^4 g m^{-3}~~, carbon fraction in the catotelm peat $C_{f,C} = 0.52$, and the catotelm density ρ_C = 91.0 kg m^{-3}~~9.1×10^4 g m^{-3}~~.

~~In the following analysis, carbon fluxes are defined positive if upwards. Thus, ecosystem respiration is positive, GPP is negative, and a negative NEE signifies the uptake of CO_2 by the ecosystem.~~

3. Validation of ORCHIDEE-PEAT at northern hemisphere peatland eddy-covariance sites

3.1 Sites description

To evaluate the performance of ORCHIDEE-PEAT in simulating CO_2, water and energy fluxes on daily to annual time scales~~ among the peatlands~~, we compiled data from 30 northern peatland sites where eddy-covariance data and physical variables (water table, snow depth, soil temperature) were collected (Fig. 2, Table 2). These sites are spread between the temperate to the arctic climate zones, and include nine bogs and 18 fens. A marsh and two wet tundra sites (note that these two wet tundra sites are neither a fen nor a bog, hereafter they are referred to as ‘tundra’) with a ~30–50 cm thick organic layer are also included in this study. Among them, six sites are underlain by permafrost and one site is in a thermokarst area. The peatland fractional cover in the 0.5 ° grid cell containing each site is from the Yu et al. (2010) map (Fig. 2, Table 2). A short description of all sites can be found in Supplementary Materials.

3.2 Meteorological forcing data

We ran the model for 30 different 0.5 ° grid cells corresponding to each peatland site (US-Fen and US-Bog are in the same grid cell, but their local meteorological data was different). Peatland fraction in each grid cell was prescribed from Yu et al. (2010), adapted by Largeron et al. (2017) to be matched with a high-resolution land cover map. For the 16 out of 30 cells ~~(15 out of 29)~~ without peatland (Fig. 2, Table 2) in the large-scale map from Yu et al. (2010), a mean peatland fraction of 22 % was assigned.

Time series of half-hourly air temperature, wind speed, wind direction, long-wave incoming radiation, short-wave incoming radiation, specific humidity, atmospheric pressure, and precipitation were used to drive ORCHIDEE-PEAT. All ~~mentioned~~ variables were from measurements made at each flux tower where CO_2 and energy (latent heat (LE) and sensible heat (H)) fluxes, water table position, soil temperature, and snow depth were recorded on a half-hourly time step. The linearly interpolated 6-hourly CRU-NCEP 0.5 ° global climate forcing dataset was used to fill the gaps in the driving variables. A linear correction was applied to meteorological forcing variables (except precipitation) in the CRU-NCEP dataset to match observations before gap-filling. For precipitation, no correction was applied. At CA-Wp2 and CA-Wp3, meteorological forcing data were measured only during the growing season, so CRU-NCEP data were linearly corrected using relationships derived from the available data. For some sites, several meteorological ~~data~~ variables were not measured, such as long-wave incoming radiation at NO-And, atmospheric pressure, short-wave incoming radiation, and long-wave incoming radiation at CZ-Wet. In these cases, uncorrected CRU-NCEP data were used~~ to fill the gaps without correction~~.

3.3 Model setup

ORCHIDEE-PEAT was first spun-up for 10,100 years, forced by the preindustrial atmospheric CO_2 concentration of 285 ppm, with repeated site-specific observational meteorological fields, and present-day vegetation fractions for each site. In reality, the climate changed through the Holocene, but since the initiation and climate history of each site are unknown, we assumed a constant present-day climate condition and peatland area. Thus, this model is only suitable for simulating water, energy and CO_2 fluxes from peat on time scales ranging from days to decades. To accelerate the spin-up, ORCHIDEE-PEAT was first run for 100 years to reach the equilibrium for hydrology and soil thermal conditions, fast carbon pools and soil carbon input from dead plants. Then, a sub-model simulating only soil carbon dynamics (with fixed daily litter input from the previous simulation) was run for 10,000 years to accumulate soil carbon. Peatlands can reach equilibrium only when the addition of carbon equals carbon lost, which is attained on time scales of 10^4 years (Clymo, 1984; Wania et al., 2009b). The catotelm carbon pool in this study was still not fully equilibrated even after 10,100 years due to the low carbon decomposition rate in this reservoir (3.35×10^{-5} yr^{-1}, Kleinen et al., 2012). The modeled peat carbon pool thus depends on the time length of spin-up, which was fixed at 10,100 years~~.~~, w~~W~~hile in the real world, peat age at some sites can be younger. For example, the sample from the second last 10 cm peat segment at CA-Wp1 has an un-calibrated radiocarbon date of ~2200 years (Flanagan and Syed, 2011). Since we focus on carbon and water fluxes on daily to annual scales in this study, rather than on the simulation of peat carbon stocks, we conducted a sensitivity analysis of modeled heterotrophic respiration to the length of the spin-up, which shows only a slight increase of catotelm respiration with increasing simulation time (Fig. ~~S2~~S3). After the spin-up, transient simulations were conducted for each site, forced by repeated site-specific climates and rising atmospheric CO_2 concentration during the period 1901-2015. Finally, the model outputs corresponding to the respective measurement periods (all during 1999-2015) were compared to observed time series for each site.

Two sets of simulations were conducted. In the first one (S1), soil water content and water table position (WT) were modeled by ORCHIDEE-PEAT, and the WT was used in the carbon module to define the fraction of oxic and anoxic decomposition in the acrotelm. S1 was performed for all the 30 sites. In the second set (S2) of simulations, we prescribed water table in the model to equal to observed values (WT_{obs}). That is, soil moisture at layers below the measured water table was prescribed as saturated ($\theta(z > WT_{obs}) = \theta_s$), while soil moisture above WT_{obs} was simulated. WT_{obs} was further used in the carbon module in S2. S2 was performed only for a subset of eight sites where at least two years of water table measurements were available and where there were sufficient observations to gap-fill the WT_{obs} time series (Table 2). For these sites, the gaps of WT_{obs} were filled with the mean value of the same period from other years of measurement (Table S2). The simulation S2 was designed to check if the model performance will improve (or deteriorate) when prescribing WT exactly to its observed value, since WT is known to be a critical variable impacting peat water, ~~and~~ CO_2 and CH4 fluxes ~~exchange, and CH_4 emissions~~ (Dušek et al., 2009; Parmentier et al., 2011; Strack et al., 2006). Fixing the simulated water table to WT_{obs} in S2 violated the water mass conservation of the model, but allowed us to evaluate the carbon module independently from the hydrological module biases.

3.4 Measures for evaluating model performance

Following Jung et al. (2011) and Tramontana et al. (2016), we used site-specific daily means, annual means, seasonal variations and daily anomalies to evaluate the model performance. For each site, seasonal variations are calculated by removing the annual mean value from the mean seasonal cycle (averaged value for each month across all available years~~), ~~). A~~a~~nomalies are calculated as the deviation of a daily flux value from the corresponding mean seasonal cycle.

A series of measures were used to assess the model performance (Kobayashi and Salam, 2000; Jung et al., 2011; Tramontana et al., 2016).

The root mean square deviation (RMSD) reports the model accuracy by measuring the differences between simulation and observation.

$$\mathrm{RMSD} = \sqrt{\frac{1}{n}\sum_{\mathrm{i}=1}^{n}(x_i - y_i)^2},$$ (11~~9~~)

where x_i is simulated variable, y_i is measured variable, and n is the number of observations.

Two signals (SDSD and LCS) are discriminated from the mean squared deviation (Kobayashi and Salam, 2000). The squared difference (SDSD) between the standard deviation of the simulation ($\mathrm{SD_s}$) and the measurement ($\mathrm{SD_m}$) shows if the model can reproduce the magnitude of fluctuation among the n measurements.

$$\mathrm{SDSD} = (\mathrm{SD_s} - \mathrm{SD_m})^2\text{; with } \mathrm{SD_s} = \sqrt{\frac{1}{n}\sum_{\mathrm{i}=1}^{n}(x_i - \bar{x})^2},\ \mathrm{SD_m} = \sqrt{\frac{1}{n}\sum_{\mathrm{i}=1}^{n}(y_i - \bar{y})^2},$$ (~~10~~12)

where $\bar{x}$ is simulated mean value, $\bar{y}$ is measured mean value.

The lack of correlation weighted by the standard deviations (LCS) is a measure to examine if the model reproduces the observed phase of variability.

$$\mathrm{LCS} = 2\mathrm{SD_s}\mathrm{SD_m}(1 - r)\text{;with } r = \left[\frac{1}{n}\sum_{\mathrm{i}=1}^{n}(x_i - \bar{x})(y_i - \bar{y})\right]/(\mathrm{SD_s}\mathrm{SD_m}),$$ (13~~11~~)

where r is the Pearson's correlation coefficient.

The Nash-Sutcliff modeling efficiency (MEF) is used to indicate the predictive accuracy of the model. MEF varies between negative infinity (–inf) and 1, an efficiency of 1 indicates a perfect fit between simulations and observations; an efficiency of 0 indicates the simulations are as accurate as the mean value of observations; a negative MEF indicates that mean value of observations has greater predictive power than the model. The modeling efficiency is defined as:

$$\mathrm{MEF} = 1 - \frac{\sum_{\mathrm{i}=1}^{n}(x_i - y_i)^2}{\sum_{\mathrm{i}=1}^{n}(y_i - \bar{y})^2},$$ (~~12~~14)

4. Results

4.1 Site-specific V_{cmax} reduces errors in carbon flux simulations

Out of the 30 sites, 22 sites provided observed daily GPP (~~separated from~~based on measured NEE). The values of optimized V_{cmax} at each site were listed in Table 3. The optimized V_{cmax} varied from 19 to 89 μmol m^{-2} s^{-1} (Table 3), with a mean value of 40 μmol m^{-2} s^{-1}~~, which was higher than the default value (16 μmol m^{-2} s^{-1}) fixed by (Largeron et al., 2017)~~. The calibration of V_{cmax} may compensate for biases in other model parameters. A brief comparison between simulated and reported (measured/estimated) LAI and aboveground biomass showed that there are no systematic errors (Fig. S1).

Taylor diagrams were used to evaluate model results at these 22 sites (Fig. 3). The model had the best performance for GPP, with the correlation coefficient between simulated and observed GPP varied between 0.66 and 0.93 and all data points fell within the 0.9 root mean square difference circle. Simulated water table depth had a larger spread in correlation (0.16–0.82) and root mean square difference (0.4–4.0). We found no significant patterns of model-data misfits among different peatland types (fen, bog, others) or climate zones (temperate, boreal and arctic)~~, as shown by different shapes or colors of markers in~~ (Fig. 3).

For the 22 sites where ~~GPP~~NEE and ER ~~observations~~ measurements were available, the~~ modeled GPP~~ errors in the three carbon fluxes GPP, ER, NEE were significantly reduced by optimizing V_{cmax} at each site~~–~~ (Table 4, Fig. 4, Fig. S4). ~~When a fixed V_{cmax} value (16 μmol m^{-2} s^{-1}) was used, GPP was generally underestimated and across-sites differences were not reproduced (Fig. S3, Table 4). Unsurprisingly, neither the spatial nor the temporal variations of NEE were captured by the model when using the fixed V_{cmax} value (Fig. S3, Table 4).~~ With site-specific V_{cmax} values (~~Site~~site-by-site model performances are shown in Fig. ~~S6~~ S5 to ~~S10~~ S10 in Supplementary Materials), the overall (all the daily data from all the 22 sites) performance of the model was ~~improved~~ high for GPP (r^2 = 0.76, MEF = 0.76), ~~LE~~ ER (r^2 = 0.~~42~~78, MEF = 0.~~14~~75), and lower for NEE (r^2 = 0.38, MEF = 0.26)~~ and~~

~~sensible heat ($r^2 = 0.24$, MEF = −0.50)~~ (Fig. 4, Table 4). Seasonal variations in carbon ~~and energy~~ fluxes were ~~generally~~ well captured by the model (r^2 = 0.~~57~~61 to 0.86). The spatial across-sites gradients of annual mean GPP~~,~~ and ER~~NEE and LE~~ were generally good, with r^2 of 0.93~~,~~ and 0.89~~0.27,~~ and lower for NEE (r^2 = 0.27). ~~and RMSDs of 0.41 g C m^{-2} day^{-1}, 0.60 g C m^{-2} day^{-1} and 9.85 W m^{-2}, respectively.~~ Compared to simulations with a fixed V_{cmax} (the mean of the optimized values of 40 μmol m^{-2} s^{-1}), there were large improvements in capturing spatial gradients of carbon fluxes with a site-specific V_{cmax} (e.g. r^2 increased from 0.20 to 0.93, from 0.27 to 0.89 and from 0.16 to 0.27 for GPP, ER and NEE, respectively, while the RMSD reduced by 63%, 48%, and 9%). This result indicates that model-data disagreement can be largely reduced by using site-specific V_{cmax} instead of a fixed (mean) value. In future regional simulations, spatial variations in V_{cmax} should be taken into account. There was, however, no significant improvement in LE, H and WT by using site-specific V_{cmax} values (Table4). The model performance was poor for predicting daily anomalies of all fluxes, with $r^2 < 0.20$. For both temporal and spatial variation, the MEF of the WT were negative, and r^2 smaller than 0.10, indicating that the model had a low ~~the lowest~~ predictive capability for the WT. Possible reasons for this could be: 1) ~~peat~~ Peat ~~management~~ disturbance was not parameterized; i.e., the removal of beaver dams resulted in a decline of water level at US-Los; water level at US-WPT, CZ-Wet and RU-Che were manipulated~~;~~. 2) ~~the~~ The model diagnosed all peatland sites as fens by routing runoff from non-peatland areas into the peatland soil tile, whereas in reality ~~the real world~~, bogs receive water and nutrients only through precipitation ~~are only fed by precipitation~~. In other words, we included an extra water source for bogs other than ~~only~~ rainfall.~~;~~ However, the model did not perform better for fens (Fig. 3f), possibly because the amount of water that was routed into the fen was in error. ~~and~~ 3) WT depends on water input from surrounding non-peatland areas~~,~~: the greater the peatland fraction in the grid cell, the smaller runoff input from other soils to the peatland, hence resulting in a deeper water table in the peatland (Fig. S11). ~~and t~~The peatland area fraction derived from the map of Yu et al. (2010) can~~could~~ not represent

~~the~~ local area providing water for fens~~; ~~. 4) ~~for~~ For global applications, the effects of micro-relief ~~cannot~~ were not~~be~~ represented in the model, ~~which has been~~although they have been shown~~ proven~~ to be an important regulator of the local hydrology cycle (Gong et al., 2012; Shi et al., 2015).

To better understand the influence of the water table dynamics on ER and NEE in the model, we compared the second set of simulations (S2, ~~the~~ with observed water table ~~was~~ used in the carbon module to define the fraction of oxic and anoxic decomposition in the acrotelm) with the first set (S1, ~~the~~ water table ~~dynamics was~~ calculated by the model). ORCHIDEE-PEAT showed only a small improvement in reproducing ER and NEE when WT_{obs} was used (Table 5 and 6). To illustrate this effect, we took the Lompolojänkkä (FI-Lom) fen site as an example, in which WT was most severely ~~seriously~~ underestimated among the 22 sites where NEE and ER measurements were available (Fig. S8). While modeled WT varied between 5 and 54 cm below the surface, WT_{obs} was always above the soil surface. Fig. 5a showed that in comparison to S1, there was no aerobic respiration and larger anaerobic respiration in the acrotelm in S2. Due to the smaller acrotelm respiration (aerobic + anaerobic) in S2, ~~there was larger~~ carbon input from acrotelm to catotelm was larger and consequently, ~~there was~~ more carbon accumulated in the catotelm in S2. Thus, the catotelm respiration in S2 was ~~greater~~ higher than that in S1 (Fig. 5c), even though the catotelm respiration rate was very small. Because the growth of the peatland vegetation was not constrained by water in the model, the simulated GPP values were similar between S1 and S2 (Fig. 5a). With similar GPP but smaller soil respiration (sum of the acrotelm ~~+~~ and the catotelm respiration), S2 simulations thus resulted in more negative NEE values than S1 (higher net CO_2 uptake). Simulated leaf onset occurred earlier than observed at Lompolojänkkä site, causing the ecosystem to switch~~ed~~ from ~~a~~ carbon source to ~~a~~ carbon sink in May, while ~~in observations~~ the start of the carbon uptake was observed to occur later (Fig. 5b). Although the modeled ~~reproduced a similar amplitude of the observed~~ NEE was similar in amplitude to the observations, the day-to-day variations of this flux were not captured (Fig. 6), causing an overestimation (more negative values) of NEE in the warm period (May-September).

The influence of WT on respiration was parameterized as the separation of oxic (β in Eq. 6) vs. anoxic (1-β in Eq. 7) decomposition in the acrotelm. Although absolute values of simulated WT in S1 and WT_{obs} in S2 were quite different (Fig. S8), the values of β were not very different (Fig.S12). Therefore, the simulated WT was good enough to properly replicate ER (Fig.S13). An additional simulation (S3) performed at FI-Lom showed that if WT was more severely underestimated, e.g. WT in S3 was consistently 20 cm deeper than in S1, the acrotelm was exposed to oxygen for longer time, resulting in larger ER and hence smaller carbon sequestration in S3 (Fig.S12, Fig.S13).

4.2 Relationship between optimized V_{cmax} and meteorological variables

Several uni-variate ANOVA models were used to explain the spatial gradient of optimized V_{cmax}, explanatory variables including air temperature (T), precipitation (P), net radiation (NET_RAD), water use efficiency (WUE), water balance (WB) and ~~the~~ latitude (LAT). All explanatory variables were calculated as daily mean values during the growing season. Water use efficiency (g C m^{-2} mm^{-1} H_2O) was calculated as the ratio of GPP and evapotranspiration (ET). Water balance (mm~~/~~ day^{-1}) was calculated as the difference between precipitation and ~~evapotranspiration~~ET.

There was no significant difference between optimized V_{cmax} among peatland types (fen vs bog, p = 0.16), climate zones (temperate vs boreal vs arctic, p = 0.17), or dominant vegetation types (grasses and/or mosses dominated vs shrubs and/or trees dominated, p = 0.67) (Fig. ~~S4~~S14). However, we found a significant positive relationship between V_{cmax} and the growing season mean air temperature (Fig. ~~S5~~S15, Table 6, V_{cmax} = 2.78T +8.74, with $r^2 = 0.19$, $p < 0.05$) and a significant negative relationship between V_{cmax} and the latitude ~~of the sites location~~ (Fig. ~~S5~~S15, Table 6, V_{cmax} = -0.92LAT +93.56, with $r^2 = 0.23$, $p < 0.05$).

To verify the applicability of the empirical relationship found across sites between optimized V_{cmax} and the latitude (Fig. ~~S5~~S15~~, slope = -0.92, intercept = 93.56, r^2 =~~

~~0.23, $p < 0.05$~~), we used the seven sites where there were no GPP observations available (US-Bes, DE-Hmm, US-Ics, PL-wet, SE-Sto, CA-Wp2 and CA-Wp3) as cross-validated sites. We compared model performance in simulating NEE, with V_{cmax} being calculated according to the empirical relationship, and with V_{cmax} being fixed to its mean value of all 22 sites from Table 3 (40 μmol m^{-2} s^{-1}). The model performance in reproducing spatial gradients of NEE was improved when the V_{cmax} values derived from the empirical relationship were used (Fig. ~~S11b~~S16b, with RMSD reduced by 11%, r^2 increased from 0.20 to 0.38, and MEF increased from -0.04 to 0.17). This implies that, compared to a fixed V_{cmax}, the usage of V_{cmax} value from the empirical relationship can better capture spatial gradients of NEE. It is worth mentioning that the empirical relationship was built on climate conditions from the last two decades (1999-2015), and thus may change in the future when the climate changes.

4.3 Soil temperature and a snow depth underestimation in the model

For most of the sites, soil temperature was underestimated in winter and overestimated in summer by our model (Figs. 7 and 8, results from sites DK-Nuf and CA-Wp1 are shown as illustrative examples). One possible reason for the underestimation of soil temperature in winter is the underestimation of ~~a~~ snow depth (Fig. 9), since snow insulates the soil changing thermal conditions in comparison to a snow-free surface. The underestimation of the snow depth can be caused by the bias in snow processes of the model, such as underestimation of snow mass, and/or overestimation of ~~a~~ snow density and subsequently overestimation of snow compaction, and/or overestimation of ~~its~~ sublimation. The insulation effect~~s~~ of the moss layer and the top organic layer are not included in this study, which may explain why soil temperature was overestimated in summer but underestimated in winter. ORCHIDEE-PEAT calculates one energy budget for the vegetation and soil columns in one grid cell. Key parameters used for solving the heat diffusion equations in the soil, such as soil heat capacity and thermal conductivity, were prescribed by the dominant soil texture in the grid cell (Gouttevin et al., 2012). Nevertheless, similarly to the case of the hydrology module, the three default (coarse, medium, fine) soil textures cannot represent thermal properties of a peat soil (Paavilainen and Päivänen, 1995; Abu-Hamdeh and Reeder, 2000).

5. Discussion

ORCHIDEE-PEAT ~~grouped~~ groups various peatland vegetation~~s~~ into one plant functional type (PFT). This PFT cannot represent the true range in vegetation composition (shrubs, sedges, mosses etc.) of peatlands. However, by optimizing the value of V_{cmax} at each site, ~~we matched~~ simulated GPP well represented ~~with~~ observations and yielded ~~so that we had~~ reasonable ~~good~~soil –carbon input ~~to the soil~~. The V_{cmax} values estimated in this study ranged from 19 to 89 μmol m^{-2} s^{-1}, with a mean value of 40 μmol m^{-2} s^{-1}. T~~t~~hese values were not fully comparable with values ~~those~~ reported for a specific vegetation type, ~~in field studies, or values which were used in other peatland models~~ ~~because~~ as they are ~~it is more like a representation of an~~ averages ~~of~~ for all plants growing in ~~peatland~~the peatland ecosystem. As stated in Sect. 2.2, observed V_{cmax} varies strongly among different species and sites. V_{cmax} of mosses at the Old Black Spruce site (Canada) ranged from 5 to 14 μmol m^{-2} s^{-1} (Williams and Flanagan, 1998). In a nutrient addition experiments conducted by Bubier et al. (2011), V_{cmax} for ericaceous shrubs in a temperate bog ranged from 67 to 137μmol m^{-2} s^{-1}, with V_{cmax} for *Vaccinium myrtilloides*, *Ledum groenlandicum* and *Chamaedaphne calyculata* valued at 84.6 ± 13.5 μmol m^{-2} s^{-1}, 78.1 ± 13.4 μmol m^{-2} s^{-1}, and 132.1 ± 31.2 μmol m^{-2} s^{-1} in the plots with no nutrient addition. The optimized model V_{cmax} in our study was within the range of these observations. Meanwhile, the values we inferred from sites to match peak GPP are comparable to those used in other land surface models: the McGill wetland model used a value of 17 μmol m^{-2} s^{-1} for evergreen shrubs (St-Hilaire et al., 2010); the CLASS-CTEM model (Wu et al., 2016) used 60, 50, 40 μmol m^{-2} s^{-1} for evergreen shrubs, deciduous shrubs and sedges, respectively; the values for mosses in these two models were adapted from the study of Williams and Flanagan (1998). Here w~~W~~e found that optimized V_{cmax} ~~had~~ has a significant positive relationship with temperature, and a significant negative relationship with ~~the~~ latitude of chosen peatland sites ~~location~~. A decrease of V_{cmax} with latitude in the northern hemisphere, like the one inferred from optimized sites values, has also been documented by Walker et al. (2017), who assumed that V_{cmax} was constrained by the rate of N uptake, with the rate of N uptake calculated as a function of soil C, N and mean annual air temperature. We speculate~~d~~ that the dependence of optimized V_{cmax} on latitude ~~this~~ found in Sect. 4.2 can be attributed to two effects. First, there is an increase of the ~~1)~~ length of the growing season increases as latitude decreases~~, –~~. Simultaneously, ~~and~~ temperature and incoming solar ~~radiation,~~radiation, increases. Longer growing season may enhance vegetation productivity (Fang et al., 2003; Nemani et al., 2003; Piao et al., 2007).~~; 2) with an adequate water supply, leaves open their stomata in response to warm environments, leading to a higher photosynthetic efficiency (Chapin III et al., 2011); 3)~~ Second, temperature influences the~~the influence of temperature on~~ nutrient availability for plants. The decomposition of plant litter and the release of nitrogen can be enhanced by high temperature, although litter decomposition is also driven by soil moisture, vegetation composition, litter quality and their interactions with temperature (Aerts, 2006; Cornelissen et al., 2007; Gogo et al., 2016). Because nitrogen (N) is one key element in proteins that are involved in photosynthesis process, photosynthesis capacity is highly correlated to ~~nitrogen~~ N availability (Evans, 1989; Takashima et al., 2004; Walker et al., 2014). Since the ~~nitrogen~~ N cycle is not explicitly included in the ORCHIDEE-PEAT, the relationship between V_{cmax} and the latitude (and temperature) possibly reflected the impact of ~~nitrogen~~ N on photosynthesis rates.

Previous studies have shown that peatlands ~~functioning may~~can have contrasting responses to variations in water table depth. ~~Among~~ Concerning sites analyzed ~~incorporated~~ in our study, Aurela et al. (2007) reported that at the nutrient-poor fen FI-Sii site, drought increased respiration and thus diminished ~~NEE~~carbon uptake; Adkinson et al. (2011) reported that reduced water availability ~~in 2006~~ constrained photosynthesis capacity at the rich fen CA-Wp3 and consequently suppressed NEE, while the poor fen CA-Wp2 did not show a significant response to the lower water table~~; ~~. A~~a~~t the moderately rich treed fen CA-Wp1 site, Flanagan and Syed (2011) reported that both photosynthesis and respiration increased in response to the warmer and drier conditions; Hurkuck et al. (2016) stated that temperature and light played a more important role than water table depth in controlling respiration and photosynthesis at the DE-Bou ~~site~~bog. ~~In ~~Based on the field observations, the timing, duration and intensity of drought have a major impact on the responses of peatland ecosystems. Lund et al. (2012) demonstrated that at the raised bog SE-Faj~~ site~~, a relatively short but severe drought that occurred in the middle of growing season of 2006 amplified respiration while a long-lasting drought that occurred at the beginning of growing season of 2008 reduced GPP. Lafleur et al. (2005) and Sulman et al. (2009) concluded from their studies at CA-Mer bog and US-Los fen that wetter peatlands would show stronger relationship between respiration and water table than drier peatlands because in a narrow range of the upper soils, small increases in WT (shallower WT) can result in a large increase in ~~a ~~soil water content and therefore respiration decrease, while below a critical level, soil water content shows only small increase with increasing WT and respiration changes are not so pronounced. Sulman et al. (2010) found that wetter conditions decreased respiration at fens but increased respiration at bogs, mainly due to different vegetation composition at these two types of peatland: the fen sites had more shrubs and sedges while the bog sites had more mosses. In this study, we did n~~'~~ot distinguish between fens and bogs, and growth of peatland vegetation was not constrained by ~~soil ~~water table depth in the model.~~,~~ ~~thus~~ Therefore, the sensitivity of GPP to WT fluctuations in observations was not included in the model. As a consequence, the model neither captured the reported decrease of photosynthesis due to drought at CA-Wp3 (Adkinson et al., 2011) and SE-Faj (Lund et al., 2012), nor the increase of photosynthesis as a result of lower water table at CA-Wp1 (Flanagan and Syed, 2011). However, the model can reproduce the pattern that above a critical level (acrotelm depth), peat respiration decreases with increasing WT (Fig.5, Fig.S13), as reported at site CA-Mer and US-Los (Lafleur et al., 2005;

Sulman et al., 2009).

ORCHIDEE-PEAT adequately captured the daily, seasonal and across-sites annual variations in GPP (with r^2 = 0.75, 0.86, and 0.93, respectively) and ER (with r^2=0.78, 0.86, and 0.89, respectively), but did not perform as well in reproducing NEE variations ~~were less able to reproduce variations in NEE~~ (with r^2 = 0.38, 0.61, and 0.27, respectively). Note ~~One possible cause is~~ that in the two-layer soil carbon scheme, the dependence of soil respiration on temperature was parameterized as an exponential function of the soil layers-weighted average temperature (Text S1), the vertical temperature gradient in the soil profile was ignored by the model. ~~While~~ However, field studies have shown that soil temperature is one of the most important predictors of respiration and values of Q_{10} coefficient depend on the soil depth (Lafleur et al., 2005; D'Angelo et al., 2016).

Correct representation of peatland hydrology is a challenging problem in large-scale land surface models (Wania et al., 2009a; Wu et al., 2016). The simulated water table by ORCHIDEE-PEAT depends on water inflows from the surrounding non-peatland areas, and a water routing analysis on sub-grid scales can be included to improve the model performance for water table in the future (Ringeval et al., 2012; Stocker et al., 2014). Other studies have shown that microtopography exerts important influences on hydrological dynamics of peatlands, however, to capture the influence of microtopography on water table, high-resolution micro-topographic feature and vegetation information are needed (Gong et al., 2013; Shi et al., 2015).~~Another possible cause is that small-scale peatland surface heterogeneities are not included in the model, which may exert important influences on water and carbon cycles but has been a challenge for global land surface models (Gong et al., 2013; Cresto Aleina et al., 2016).~~

~~For sites where latent and sensible heat were measured, about half of them used closed/enclosed path, which may cause an underestimation of LE and H (Twine et al., 2000). We also need to note that~~ The poor correspondence between simulated and observed energy fluxes was not completely unexpected, since ORCHIDEE-PEAT only calculates one energy budget ~~diagnose energy fluxes on one~~for the whole grid-cell and not for each soil tile/PFT present in the same grid cell. A site-varied and/or time-varied correction of LE and H measurements to force energy balance closure, and parameterizations of an independent energy budget at peatland ~~may~~ would be helpful for better comparison of simulated and observed energy fluxes at peatland.

6. Conclusions

We developed ORCHIDEE-PEAT to simulate soil hydrology and carbon dynamics in peatlands. The model was evaluated at 30 northern peatland sites (Europe, USA, Canada, Russia). The optimization of V_{cmax} reduced the errors in the simulated carbon ~~simulations~~budget~~, generally,~~. T~~t~~he model, generally, reproduced the spatial gradient and temporal variations in GPP, ER, and NEE well. Water table depth was poorly simulated, possibly due to uncertainties in water input from non-peatland areas in the grid cell, and to a lack of representation of micro-relief, as well as the lack of consideration of peat disturbance~~the human impacts~~. A significant relationship between V_{cmax} and latitude was found~~,~~. ~~which~~ This may be attributed to the influence of temperature on growing season length and nutrient availability. For ER and NEE ~~fluxes~~, the improvement brought by forcing the carbon module to use observed WT values (WT_{obs}), instead of calculated by the model, ~~is~~ was small, indicating that ~~the influence of poorly~~ the simulated WT~~ on NEE is small~~ was reliable to predict ER and NEE properly.

Our study shows that in order to reproduce spatial gradients of NEE for northern peatlands, an average V_{cmax} value is not sufficient. To represent a spatial gradient of carbon fluxes in large-scale simulations of northern peatlands, incorporating the peatland nitrogen cycle ~~in peatlands~~ ~~could~~ would be helpful~~,~~. Alternatively~~or,~~ an empirical relationship between V_{cmax} and the latitude (temperature) may be used as a proxy of nitrogen availability. Effects of water table variations on soil carbon decomposition are modeled as the partitioning of the acrotelm layer into oxic and anoxic zones, but effects of water table changes on GPP ~~are~~ were not modeled in this study. ~~The model needs further improvement in case to include~~ Future priorities for improving ORCHIDEE-PEAT include better representing the influence~~s~~ of water table on photosynthesis and depth-dependent influence~~s~~ of soil temperature on soil respiration, as well as including an independent sub-grid energy budget for peatland areas ~~in a future model version~~.

Competing interests

The authors declare that they have no conflict of interest.

Code availability

~~The code of ORCHIDEE-PEAT will be available upon request. The SVN version of the code branch is svn://forge.ipsl.jussieu.fr/orchidee/perso/chunjing.qiu/ORCHIDEE, revision 4596. Please contact the corresponding author to obtain the model.~~

The access of the source code is available online via the following address: (http://forge.ipsl.jussieu.fr/orchidee/browser/perso/chunjing.qiu/ORCHIDEE), but its access is restricted. Readers interested in running the model should follow the instructions at http://orchidee.ipsl.fr/index.php/you-orchidee, and contact the corresponding author for a username and password.

Data availability

Measured Eddy Covariance fluxes and related meteorological data can be obtained from the FLUXNET database (http://fluxnet.ornl.gov/), the Ameriflux database (http://ameriflux.lbl.gov/), and from investigators upon request. Model outputs are available at: https://files.lsce.ipsl.fr/public.php?service=files&t=c12c831ef46cd2bf6d1f61b6e65f8c98.

~~Primary data and scripts used in the analysis and other supplementary information can~~

~~be obtained from the corresponding author upon request.~~

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Figures and Tables

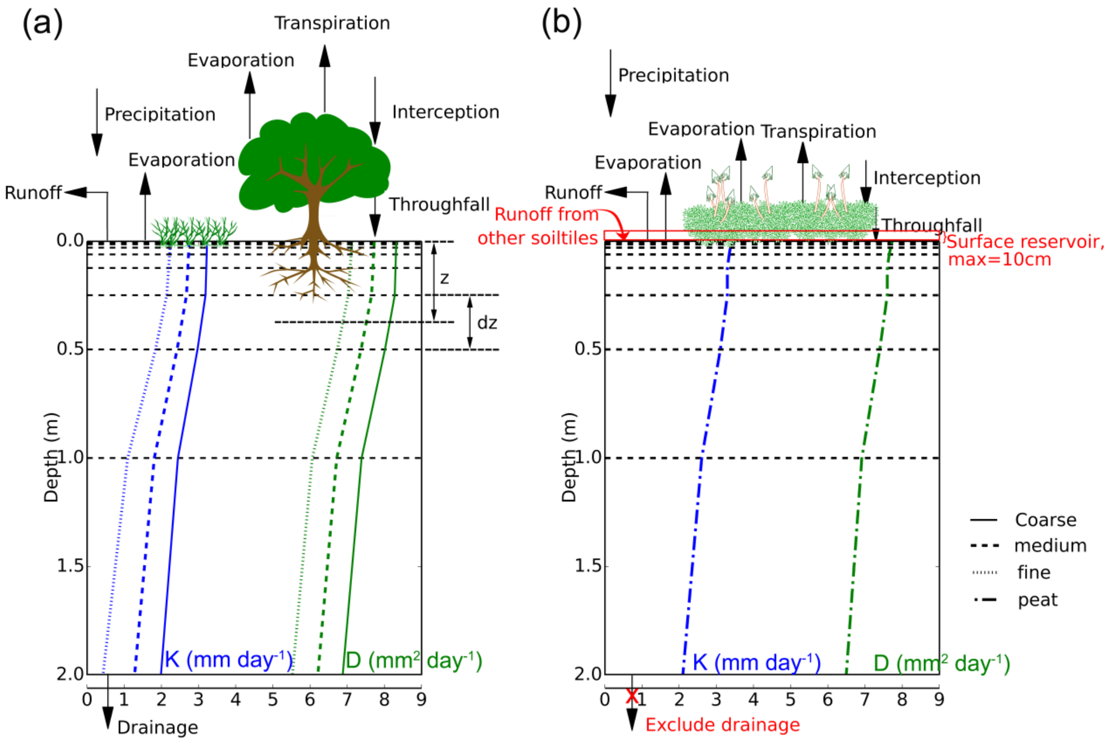

Fig. 1. Schematic of the hydrology module in ORCHIDEE. (a) water balance components in (a) a soil tile with either trees or grasses, (b) a peatland soil tile. Black dashed lines indicate the position of nodes in the eleven soil layers of the model. Blue lines: vertical profile of saturated hydraulic conductivity for different soil textures. Green lines: diffusivity for different soil textures. Vertical axis indicates soil depth, the horizontal axis indicates values of saturated hydraulic conductivity (K, mm day-1) and diffusivity (D, mm2 day-1), and scales are logarithmic based 10.

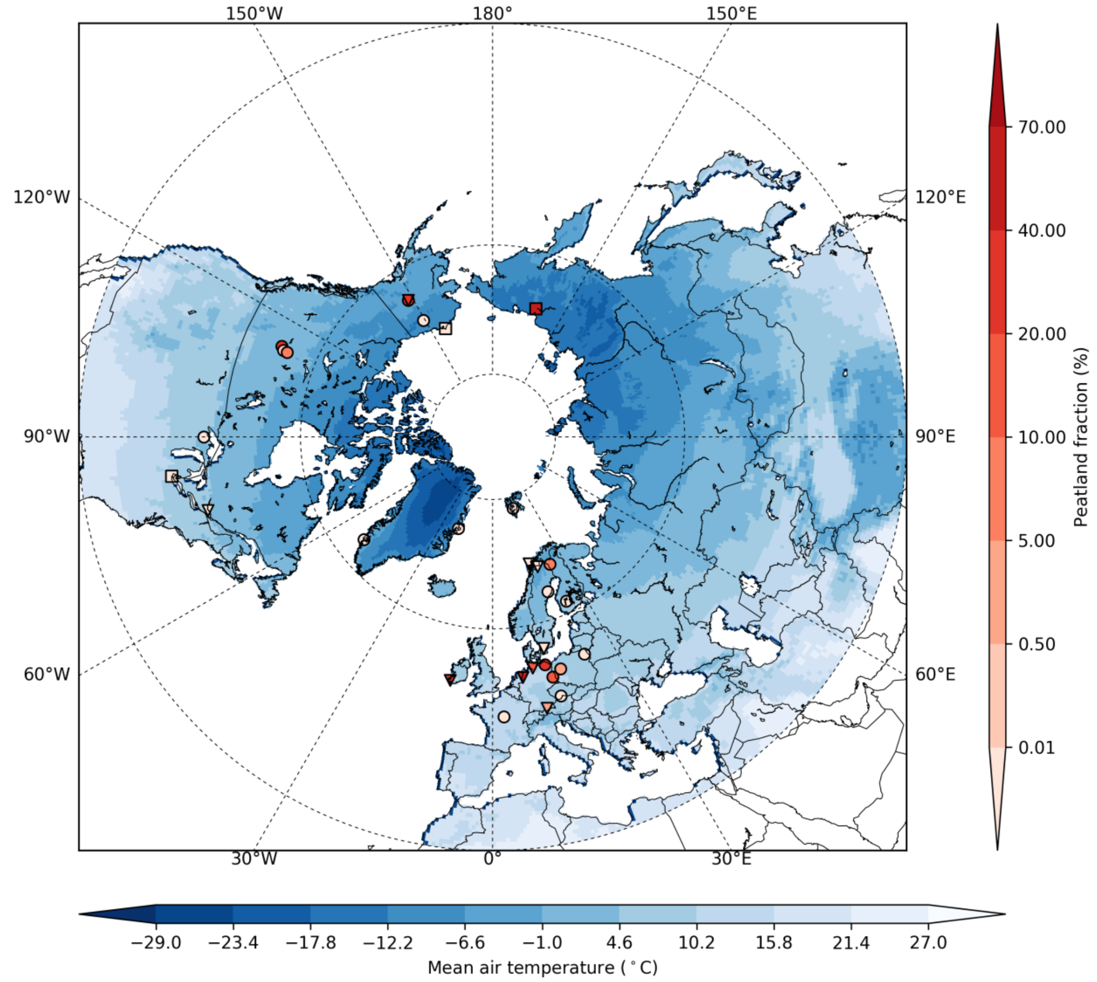

Fig. 2. The distribution of 30 peatland sites used in this study. Triangles are bogs; circles are fens; squares are tundra and marsh. Colors of the markers indicate peatland fractions in the 0.5 ° grid cell. Mean air temperatures is the annual mean from 1999 to 2015, based on the 6-hourly CRU-NCEP 0.5 °global database.

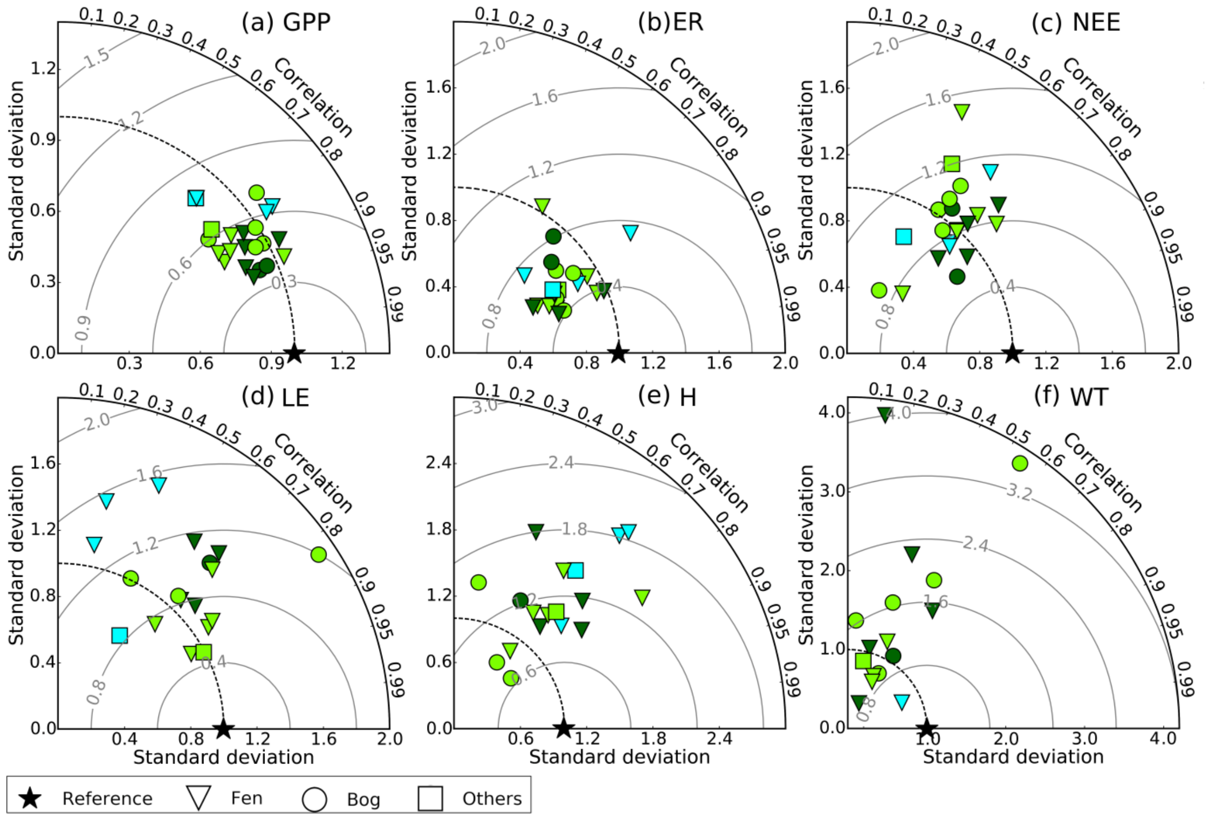

Fig. 3. Taylor diagrams of: (a) GPP (g C m-2 day-1); (b) ER (g C m-2 day-1); (c~~b~~) NEE (g C m-2 day-1); (~~c~~d) LE (W m-2); (~~d~~e) H (W m-2) and (~~e~~f) Water table depth (WT, cm). All statistics were calculated using daily averaged data. All points were normalized by dividing the standard deviation of model results by the standard deviation of the corresponding measurement, thus the reference point is 1.0. Light green markers represent temperate sites, dark green markers - boreal sites, blue markers - arctic sites.

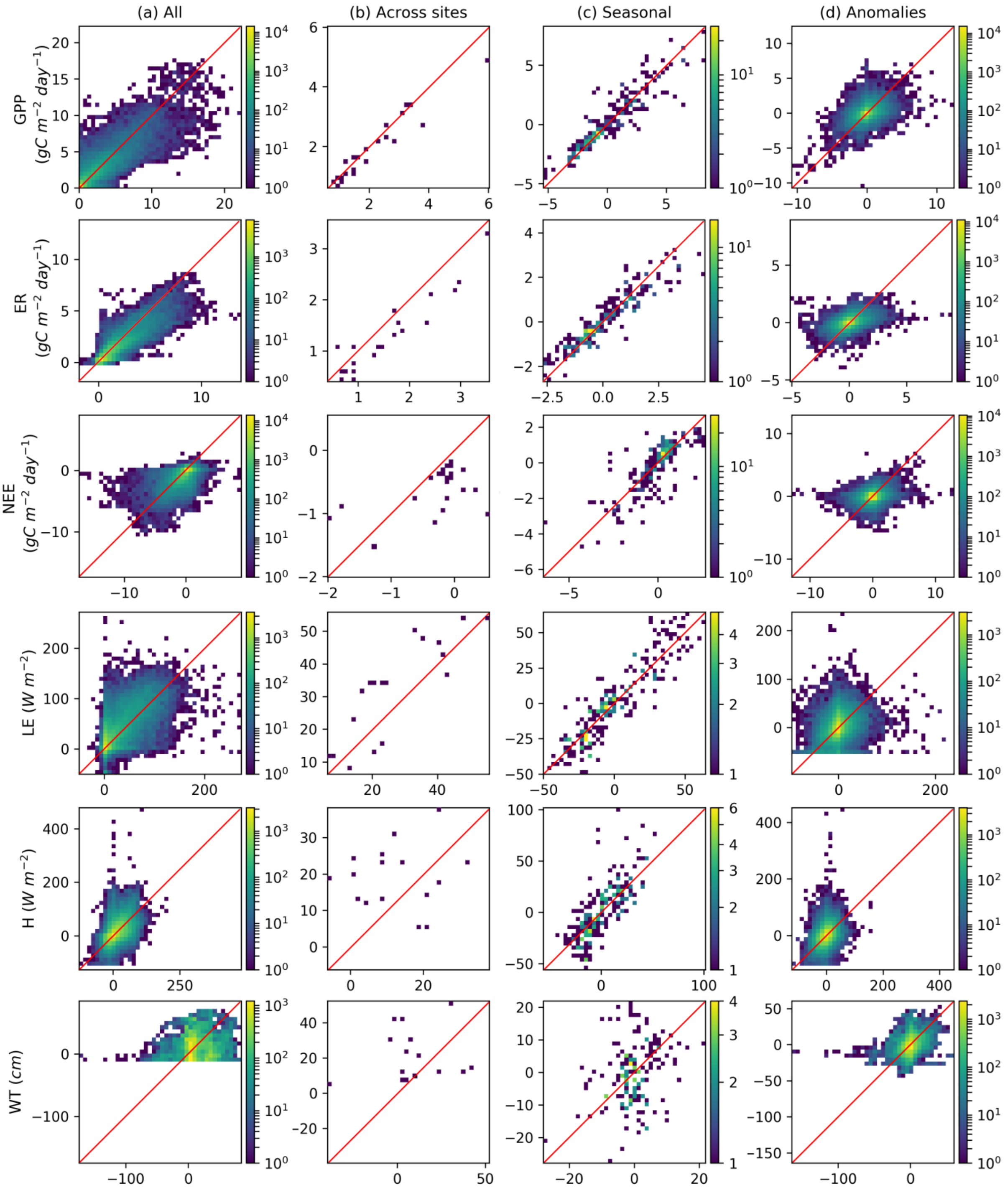

Fig. 4. Observed (x-axis) versus simulated (y-axis) fluxes (GPP, ER, NEE, LE, H, and WT) at the 22 sites where GPP derived from EC measurements were available. Fluxes were simulated using site-specific optimized Vcmax. The colors of points indicate the number of data in each bin, in panel (b) each data point represents one peatland site. The red line identifies the observations = the simulations.

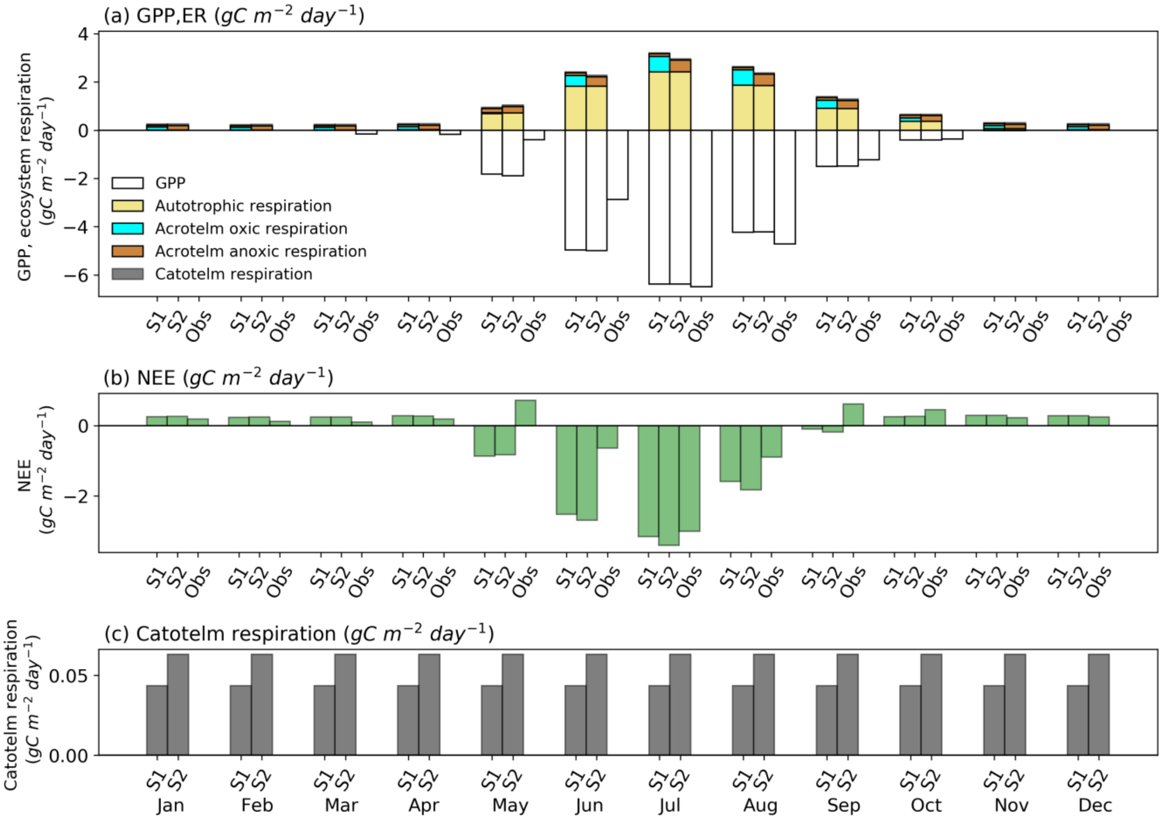

Fig. 5. Monthly mean (averaged over 2007–2009) of (a) GPP and ecosystem respiration(ER); (b) NEE; (c) catotelm respiration at Lompolojänkkä fen site (FI-Lom). S1: simulated water table (WT) was used in the carbon module; S2: observed WT values (WT_{obs}) was used; ob: measured NEE. The graph inserted shows catotelm respiration. By convention, a source of CO2 to the atmosphere is a positive number.

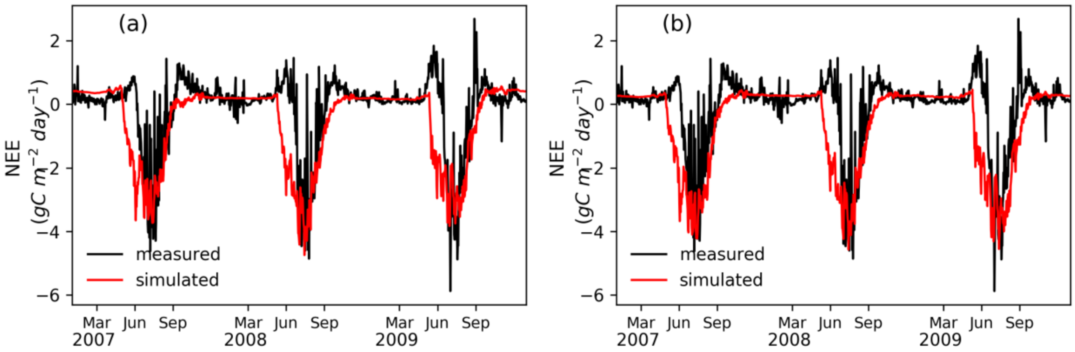

Fig. 6. Observed and simulated daily mean NEE at FI-Lom fen site in a) S1 (Simulated WT was used in the carbon module); (b) S2 (modeled water table was assimilated to observed values (WT_{obs}) and was used in the carbon module).

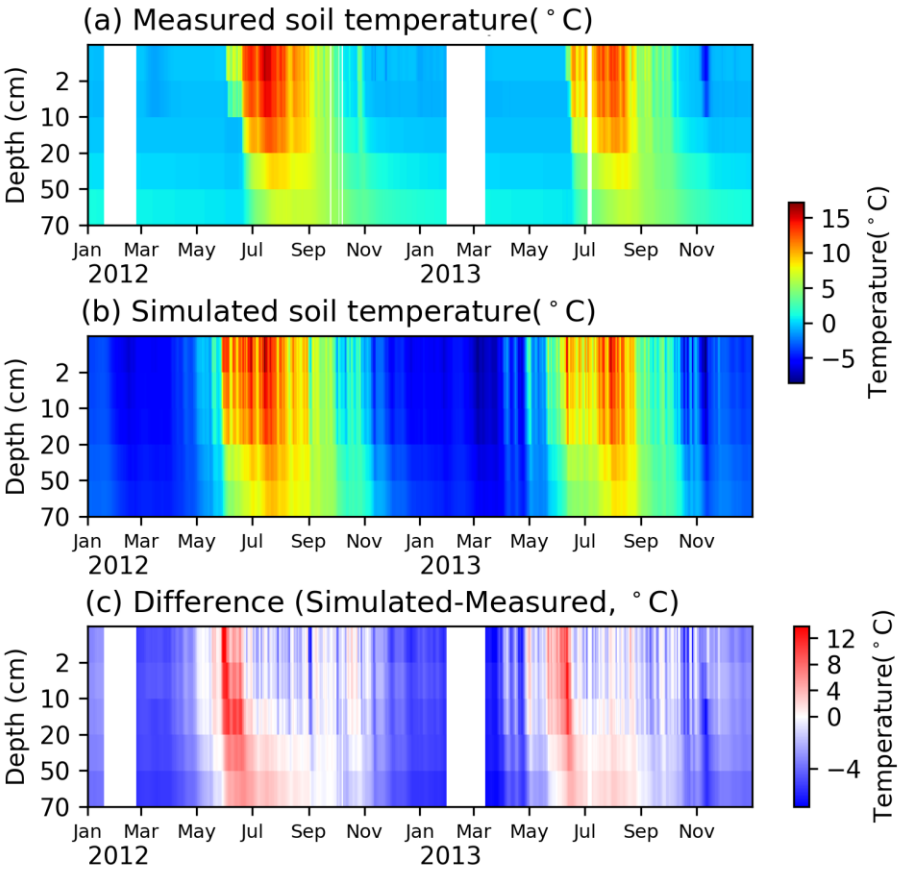

Fig. 7. Measured (a), simulated (b) soil temperature, and their difference (c) at DK-Nuf (64.13 °, -51.39 °) fen site. Soil temperature was measured at 2, 10, 20, 50 and 70 cm below soil surface. To compare simulated soil temperatures with the measurements, we linearly interpolated simulated soil temperature in different layers to the depths of the measurements.

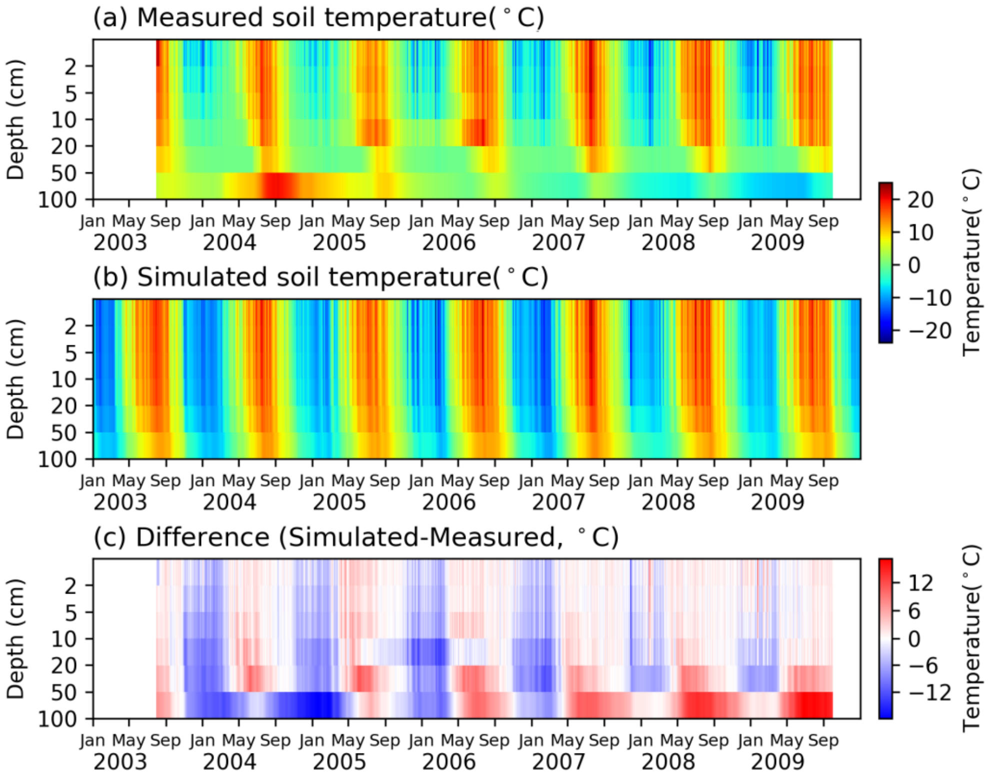

Fig. 8. Measured (a), simulated (b) soil temperature, and their difference (c) at CA-Wp1 (54.95 °, -112.47 °) fen site. The measured soil temperature (a) is the mean of a hummock and a hollow. Soil temperature was measured at 2, 10, 20, 50 and 100 cm below soil surface. To compare simulated soil temperatures with the measurements, we linearly interpolated simulated soil temperature in different layers to the depths of the measurements.

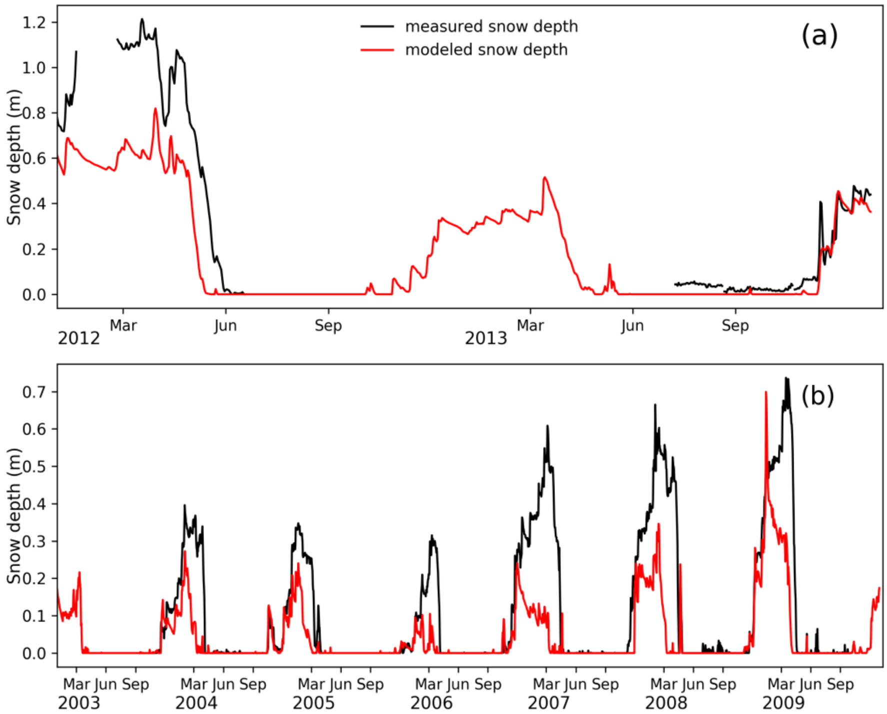

Fig. 9. Simulated versus measured snow depth (m) at (a) DK-Nuf fen and (b) CA-Wp1 fen.

Table 1. Van Genuchten parameters used for different soil texture classes for non-peat soils (coarse, medium, fine), and for peat. θ_s is the saturated water content (m^3 m^{-3}), θ_r is the residual water content (m^3 m^{-3}); $K_{s\text{-}ref}$ is the reference saturated hydraulic conductivity (m s^{-1}); α is the inverse of the air entry suction (m^{-1}); n is a dimensionless parameter. In Eq. 1 and Eq. 2, $m = 1\text{-}1/n$.

	$K_{s\text{-}ref}$ (m s^{-1})	n	α (m^{-1})	θ_s (m^3 m^{-3})	θ_r (m^3 m^{-3})
COARSE	1.23×10^{-5}	1.89	7.5	0.41	0.065
MEDIUM	2.89×10^{-6}	1.56	3.6	0.43	0.078
FINE	7.22×10^{-7}	1.31	1.9	0.41	0.095
PEAT	2.45×10^{-5}	1.38	5.07	0.90	0.15

Table 2. Sites Characteristics of the 30 peatlands (sites are sorted by latitude from south to north). The first column denotes if the site is used in the second set of simulation (S2, with water table prescribed in the model equal to observed values): y-YES, n-NO. Lat: latitude; Lon: longitude; MAT: long term mean annual air temperature; MAP: long term mean annual precipitation; Peatland fraction (%): fraction of peatland in the 0.5 ° grid cell which is read from the map of Yu et al. (2010), for cells where there is no peatland, mean fraction (22%) is used. Note that at US-Bog and US-Fen, the precipitation is growing season (from 16th May to 31th August) mean value, thus clarified as 'GS' in the table. Details of S2 and peatland fraction are provided in Sect. 3.3.

S2	Code	Lat	Lon	climatic zone	Type	MAP (mm)	MAT(℃)	Elevation(m a.s.l.)	Peatland fraction	Period	Dominant vegetation type	LAI (m^2 m^{-2})	Aboveground biomass (kg m^{-2})	Citation
n	US-WPT	41.5	-83.0	temperate	marsh	840	9.2	175	Mean	2011 -2013	grasses	area-average: 2.3; emergent vegettion: 3.3; open water: 1.0	area-average: 1.94; emergent vegetation area: 3.04; open water area: 0.44	Chu et al., 2014, 2015
n	CA-Mer	45.4	-75.5	temperate	bog	944	6	70	Mean	1999 -2012	shrubs, mosses	1.5	moss: 0.144 ± 0.03; vascular: 0.356 ±0.1	Lafleur et al., 2005
y	US-Los	46.1	-90.0	temperate	fen	666	3.8	470	Mean	2000 -2010	trees, shrubs, grasses	4.24	1.336	Sulman et al., 2009
n	LA-GUE	47.3	2.3	temperate	fen	880	11	145	Mean	2011 -2013	grasses			D'Angelo et al., 2016; Laggoun-Défarge et al., 2016

y	DE-Sfn	47.8	11.3	temperate	bog	1127	8.6	590	3.01%	2012 -2014	trees, shrubs, grasses,mosses			Hommeltenberg et al., 2014
y	CZ-Wet	49.0	14.8	temperate	fen	614	7.4	426.5	Mean	2007 -2013	grasses	2.45	0.57	Dušek et al., 2009
n	DE-Spw	51.9	14.0	temperate	fen	559	9.5	61	11.01%	2010 -2014	trees	3.6		Petrescu et al., 2015
y	IE-Kil	52.0	-9.9	temperate	blanket bog	2467	10.5	150	28.97%	2002 -2012	shrubs,grasses, mosses	from 0.4 to 0.6 in different years		Sottocornola et al., 2009; McVeigh et al., 2014
y	DE-Bou	52.7	7.2	temperate	bog	799	10	19	63.98%	2011 -2014	grasses,mosses	0.7	grass dominated: 0.577 ±0.029; heather and moss dominated: 0.517.0 ±0.026; mixed: 0.303 ± 0.015	Hurkuck et al., 2016
n	PL-Wet	52.5	16.2	temperate	fen	526	8.5	54	4.01%	2006 -2013	shrubs,grasses, mosses			Chojnicki et al., 2007; Barabach, 2012; Milecka et al., 2017
n	PL-Kpt	53.6	22.9	temperate	fen	600	7.1	109	Mean	2013 -2015	grasses, reeds and ferns	Sedges: 4.3; Reeds and Ferns: 4.8		Fortuniak et al., 2017
n	DE-Hmm	53.7	9.9	temperate	bog	838	9	12	15.99%	2012 -2014	90% bare peat, 10% vegetation			Vanselow-Algan et al., 2015

											cover: trees, grasses			
n	DE-Zrk	53.9	12.9	temperate	fen	584	8.7	<0.5	23.16%	2013-2014	grasses			Franz et al., 2016
n	CA-Wp3	54.5	-113.3	boreal	fen	504	2.1	670	29.77%	2004-2006	grasses,mosses	1.1	0.157	Adkinson et al., 2011
n	CA-Wp1	55.0	-112.5	boreal	fen	504	2.1	540	0.20%	2003-2009	trees, shrubs, mosses	2.6	1.08	Flanagan and Syed, 2011
n	CA-Wp2	55.5	-112.3	boreal	fen	504	2.1	730	8.07%	2004-2006	shrubs,grasses, mosses	1.5	0.231	Adkinson et al., 2011
y	SE-faj	56.3	13.6	temperate	bog	700	6.2	140	Mean	2005-2009	shrubs,grasses, mosses		dwarf shrub: 0.153;Sphagnum: 0.192; graminoid: 0.077	Lund et al., 2007, 2012
n	FI-Sii	61.8	24.2	boreal	fen	713	3.3	162	Mean	2005-2014	shrubs,grasses, mosses	0.55 (maximum value, occurs in June-July)		Aurela et al., 2007; Riutta et al., 2007
n	DK-NuF	64.1	-51.4	arctic	fen	750	-1.4	40	Mean	2008-2014	grasses,mosses	0.7		Westergaard-Nielsen et al., 2013
y	SE-Deg	64.2	19.6	boreal	fen	523	1.2	270	Mean	2001-2005	shrubs,grasses, mosses	0.47	moss: 0.065; vascular : 0.049	Sagerfors et al., 2008; Nilsson et al., 2008; Peichl et al., 2014
n	US-Bog	64.7	-148.3	boreal, thermokarst	bog	146 (GS)	-2.2	100	28.01%	2011-2015	trees, mosses			Euskirchen et al., 2014

n	US-Fen	64.7	-148.3	boreal	fen	146 (GS)	-2.2	100	28.01%	2011 -2015	grasses, forbs			Euskirchen et al., 2014
y	FI-Lom	68.0	24.2	boreal	fen	521	-1	269	5.08%	2007 -2009	shrubs,grasses, mosses	1.3		Aurela et al., 2009
n	SE-Sto	68.4	19.1	boreal, permafrost	bog	322	-0.14	360	Mean	2014 -2015	shrubs,grasses, mosses			Malmer et al., 2005; Olefeldt et al., 2012
n	US-Ics	68.6	-149.3	arctic, permafrost	fen	318	-7.4	920	Mean	2007 -2011	shrubs, grasses			Euskirchen et al., 2012, 2016
n	RU-Che	68.6	161.3	arctic, permafrost	tundra	200 -215	-12.5	4	64.09%	2002 -2005	shrubs, grasses	0.3 - 0.4		Corradi et al., 2005; Merbold et al., 2009
n	NO-And	69.1	16.0	boreal	bog	1060	3.6	17	Mean	2008 -2014	shrubs,grasses, mosses			Lund et al., 2015
n	US-Bes	71.3	-156.6	arctic, permafrost	tundra	173	-12	4	Mean	2005 -2008	grasses,mosses			Zona et al., 2009
n	DK-Zaf	74.5	-20.6	arctic, permafrost	fen	211	-9	35	Mean	2008 -2011	grasses,mosses	0.65	0.471	Stiegler et al., 2016
n	NO-Adv	78.2	15.9	arctic, permafrost	fen	190	-6.7	17	Mean	2011 -2014	shrubs,grasses, mosses	0.41 ±0.12	0.85 ±0.28	Pirk et al., 2017

*For most of the sites, NEE was partitioned into GPP and ecosystem respiration following the nighttime partitioning method of Reichstein et al. (2005), except that: NO-And used a light response curve approach following Lund et al. (2015); CA-Wp1 used the Fluxnet-Canada Research Network (FCRN) standard NEE partitioning procedure following Barr et al. (2004); and DE-Spw used the online gap filling and flux partitioning tool (http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/) which uses the method proposed by Lloyd and Taylor (1994). Note that the we grouped sedges, grasses, and herbaceous plants into one class — grasses in the table.

Table 3. Optimized V_{cmax} (μmol m^{-2} s^{-1}) at each site.

Site	V_{cmax}	Site	V_{cmax}
US-WPT	80	FI-Sii	19
CA-Mer	25	DK-NuF	31
US-Los	65	SE-Deg	23
DE-Sfn	45	US-Bog	42
CZ-Wet	54	US-Fen	56
DE-spw	89	FI-Lom	28
IE-Kil	28	RU-che	35
DE-Bou	34	NO-And	21
DE-Zrk	33	DK-Zaf	37
CA-Wp1	38	NO-Adv	28
SE-faj	21	PL-Kpt	52

Table 4. Model performance measures for GPP, ER, NEE, ~~WT, NEE,~~ LE, H and

~~H~~WT. The left-hand column shows results with site-specific optimized V_{cmax} at each site, the right-hand column shows results with the fixed V_{cmax} (~~16~~ 40 μmol m^{-2} s^{-1}) at all sites.

	Site-specific optimized V_{cmax}					Mean V_{cmax} (constant value,40 μmol m^{-2} s^{-1})				
Flux	RMSD	SDSD	LCS	r^2	MEF	RMSD	SDSD	LCS	r^2	MEF
	Overall (Daily variability)					Overall (Daily variability)				
GPP	1.39	0.11	1.80	0.76	0.76	2.17	0.06	4.60	0.47	0.41
ER	0.83	0.09	0.52	0.78	0.75	1.09	0.14	1.04	0.57	0.56
NEE	1.30	0.02	1.56	0.38	0.26	1.48	0.00	2.01	0.29	0.03
LE	31.67	21.65	932.76	0.42	0.14	31.67	21.19	933.95	0.42	0.14
H	35.40	96.59	1151.28	0.24	-0.50	35.40	97.21	1150.59	0.24	-0.50
WT	25.93	10.26	661.80	0.01	-0.56	26.14	7.63	675.51	0.01	-0.59
	Across sites variability					Across sites variability				
GPP	0.41	0.03	0.10	0.93	0.89	1.11	0.42	0.80	0.20	0.19
ER	0.38	0.01	0.06	0.89	0.79	0.72	0.16	0.33	0.27	0.23
NEE	0.60	0.06	0.20	0.27	-0.01	0.66	0.17	0.13	0.16	-0.21
LE	9.85	1.13	65.49	0.71	0.50	9.80	1.04	65.21	0.71	0.50
H	14.31	2.67	155.85	0.01	-1.04	14.28	2.83	154.38	0.01	-1.03
WT	24.40	15.20	444.83	0.02	-0.82	25.10	4.65	478.84	0.03	-0.92
	Mean seasonal variability					Mean seasonal variability				
GPP	0.92	0.03	0.81	0.86	0.86	1.36	0.02	1.83	0.70	0.69
ER	0.51	0.05	0.22	0.86	0.86	0.65	0.05	0.37	0.77	0.77
NEE	0.80	0.00	0.64	0.61	0.54	0.95	0.01	0.88	0.50	0.35
LE	11.49	7.75	124.23	0.83	0.78	11.47	7.46	124.02	0.83	0.78
H	17.85	65.77	252.65	0.57	0.11	17.85	66.40	252.30	0.57	0.11
WT	9.87	8.32	88.88	0.06	-1.38	9.77	12.73	82.69	0.12	-1.33
	Anomalies					Anomalies				
GPP	1.03	0.03	1.02	0.18	0.01	1.10	0.02	1.19	0.13	-0.13
ER	0.61	0.08	0.29	0.19	0.17	0.64	0.07	0.34	0.16	0.10
NEE	0.96	0.12	0.81	0.07	-0.07	0.99	0.12	0.85	0.04	-0.14
LE	27.43	26.14	726.25	0.07	-0.94	27.46	26.19	727.76	0.07	-0.94
H	28.09	81.43	707.43	0.12	-1.12	28.10	82.12	707.49	0.12	-1.12
WT	13.25	0.40	174.69	0.10	-0.47	13.43	0.47	179.41	0.09	-0.51

Table 5. Model performance measures of ER simulations for the site-by-site comparison, the comparison across sites, mean seasonal cycle and anomalies, using modeled (S1) and observed (S2) water table (WT).

	Modeled WT used (S1)					Observed WT used (S2)				
Site	RMSD	SDSD	LCS	r^2	MEF	RMSD	SDSD	LCS	r^2	MEF
CZ-Wet	1.45	0.86	0.87	0.81	0.68	1.51	1.05	0.79	0.81	0.66
DE-Bou	0.78	0.03	0.50	0.69	0.64	0.77	0.03	0.50	0.69	0.65
DE-Sfn	0.96	0.10	0.79	0.61	0.59	0.97	0.09	0.82	0.60	0.58
FI-Lom	0.46	0.00	0.19	0.85	0.84	0.45	0.02	0.18	0.85	0.84
IE-Kil	0.44	0.01	0.01	0.09	0.51	0.42	0.01	0.01	0.13	0.48
SE-Deg	0.69	0.26	0.19	0.75	0.62	0.64	0.16	0.23	0.75	0.68
SE-Faj	0.58	0.07	0.08	0.87	0.60	0.59	0.08	0.07	0.88	0.59
US-Los	0.63	0.01	0.39	0.85	0.85	0.60	0.00	0.35	0.87	0.87
Overall	0.79	0.09	0.51	0.78	0.76	0.79	0.09	0.51	0.78	0.76
Across sites	0.31	0.01	0.06	0.82	0.76	0.32	0.01	0.06	0.82	0.74
Seasonal	0.45	0.06	0.15	0.91	0.89	0.44	0.07	0.13	0.92	0.89
Anomalies	0.62	0.07	0.31	0.21	0.19	0.63	0.08	0.31	0.20	0.17

Table ~~5~~6. Model performance measures of NEE simulations for the site-by-site comparison, the comparison across sites, mean seasonal cycle and anomalies, using modeled (S1) and observed (S2) water table (WT).

	Modeled WT used (S1)					Observed WT used (S2)				
Site	RMSD	SDSD	LCS	r^2	MEF	RMSD	SDSD	LCS	r^2	MEF
CZ-Wet	2.97	3.61	4.38	0.46	0.37	2.86	3.22	4.27	0.50	0.41
DE-Bou	1.30	0.02	1.40	0.31	-0.21	1.31	0.03	1.41	0.31	-0.23
DE-Sfn	2.98	2.98	4.27	0.20	0.02	2.98	3.08	4.15	0.21	0.02
FI-Lom	1.05	0.01	0.94	0.46	0.21	1.08	0.02	0.95	0.49	0.16
IE-Kil	0.48	0.000	0.16	0.29	-0.37	0.49	0.002	0.16	0.32	-0.44
SE-Deg	0.64	0.03	0.33	0.51	0.09	0.57	0.01	0.29	0.51	0.26
SE-Faj	0.65	0.01	0.33	0.31	-0.36	0.65	0.02	0.33	0.32	-0.39
US-Los	3.15	0.05	8.78	0.47	-3.37	3.10	0.06	8.57	0.39	-3.23
Overall	1.95	0.20	3.52	0.02	-0.35	1.92	0.18	3.42	0.04	-0.31
Across sites	0.67	0.27	0.16	0.40	0.29	0.65	0.26	0.14	0.46	0.32
Seasonal	1.30	0.05	1.64	0.25	0.13	1.27	0.03	1.58	0.28	0.17
Anomalies	1.18	0.22	1.17	0.003	-0.34	1.17	0.21	1.17	0.001	-0.33

Table ~~6~~7. The results of the ANOVA analysis – the variance of optimized V_{cmax} in relation to chosen variables.

Variable	F-ratio	p-value	r^2 (%)
T	4.67	0.04*	18.95
P	0.95	0.34	4.52
NET_RAD	0.22	0.64	1.11
WUE	0.39	0.54	1.91
WB	1.35	0.26	6.32
LAT	6.08	0.023 *	23.30

* indicates statistical significance at a significance level of 0.05