

ORCHIDEE-PEAT (revision 4596), a model for northern peatland

CO₂, water and energy fluxes on daily to annual scales

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84 **Abstract**

85 Peatlands store substantial amounts of carbon and are vulnerable to climate change.
86 We present a modified version of the ORCHIDEE land surface model for simulating
87 the hydrology, surface energy and CO₂ fluxes of peatlands on daily to annual time
88 scales. The model includes a separate soil tile in each 0.5 ° grid-cell, defined from a
89 global peatland map and identified with peat-specific soil hydraulic properties. Runoff
90 from non-peat vegetation within a grid-cell containing a fraction of peat is routed to
91 this peat soil tile, which maintains shallow water tables. The water table position
92 separates oxic from anoxic decomposition. The model was evaluated against
93 eddy-covariance (EC) observations from 30 northern peatland sites, with the
94 maximum rate of carboxylation (V_{cmax}) being optimized at each site. Regarding
95 short-term day-to-day variations, the model performance was good for GPP ($r^2 = 0.76$,
96 Nash-Sutcliff modeling efficiency, MEF = 0.76) and ecosystem respiration (ER, $r^2 =$
97 0.78, MEF = 0.75), with lesser accuracy for latent heat fluxes (LE, $r^2 = 0.42$, MEF =
98 0.14) and Net Ecosystem CO₂ Exchange (NEE, $r^2 = 0.38$, MEF = 0.26). Seasonal
99 variations in GPP, ER, NEE and energy fluxes on monthly scales showed moderate to
100 high r^2 values (0.57 – 0.86). For spatial across-sites gradients of annual mean GPP,
101 ER, NEE and LE, r^2 of 0.93, 0.89, 0.27, and 0.71 were achieved, respectively. Water
102 table variation (WT) was not well predicted ($r^2 < 0.1$), likely due to the uncertain
103 water input to the peat from surrounding areas. However, the poor performance of
104 WT simulation did not greatly affect predictions of ER and NEE. We found a
105 significant relationship between optimized V_{cmax} and latitude (temperature), which
106 better reflects the spatial gradients of annual NEE than using an average V_{cmax} value.

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113 **1. Introduction**

114 Peatlands cover only 3 – 5 % of the Earth’s land area, but store large amounts of soil
115 organic carbon (SOC). This carbon is primarily located in the boreal and sub-arctic
116 regions (75 – 80 %), while about 15 % are located in tropical regions (Frolking et al.,
117 2011; Page et al., 2011). Current estimates of the northern peatland SOC vary from
118 270 to 450 Pg C (Gorham, 1991; Turunen et al., 2002; Yu et al., 2010). Northern peat
119 accumulation occurred mainly during the Holocene, originating from plant litter
120 production that exceeds decomposition in water-logged soil conditions, with low pH
121 and low temperatures (Parish et al., 2008). The future of the carbon stored in these
122 peatlands under a warmer environment and altered hydrological regimes is very
123 uncertain. Logically, higher CO₂ concentrations and elevated temperatures will
124 stimulate higher carbon uptake because of longer growing seasons and higher
125 photosynthetic rates (Aurela et al., 2004; Adkinson et al., 2011). However, the
126 accumulation is also coupled with a high evaporative demand that will lower the
127 ground water table, resulting in increased heterotrophic respiration rates (i.e., carbon
128 loss) (Mertens et al., 2001; Sulman et al., 2009; Adkinson et al., 2011). In addition to
129 these potential climatic influences, other natural and anthropogenic disturbances
130 (permafrost thaw, drainage, fires, etc.) further play a role in determining the future
131 carbon balance of these vulnerable ecosystems (Turetsky et al., 2002; Parish et al.,
132 2008). Drainage and fires have particularly important impacts on the carbon balance
133 of the tropical peatlands (Page et al., 2002; Hooijer et al., 2010).

134 A number of peat carbon models have been reported in the literature. For example,
135 Frolking et al. (2010) developed the Holocene Peat Model (HPM), which includes
136 feedbacks between plant communities, water table, peat properties, and peat
137 decomposition. This model was applied at Mer Bleue bog in southern Canada and
138 validated with data from peat-core observations. HPM is a long-term peat
139 accumulation model that works at an annual time step but cannot simulate seasonal
140 variations of key water processes in peatlands. Wania et al. (2009a, 2009b) integrated
141 peatlands and permafrost into the Lund-Potsdam-Jena model (LPJ-WHy), where the

142 upper 0.3 m of peatland soils (the acrotelm) experiences a fluctuating water table and
143 the underlying layer (the catotelm) is permanently inundated. A constant soil moisture
144 modifier (0.35) was used to reduce acrotelm decomposition. Spahni et al. (2013)
145 adopted and improved LPJ-Why by considering the effects of varying water table
146 depth on acrotelm decomposition rates, using a weighted average of the aerobic and
147 anaerobic respiration modifier, and implementation of a dynamic nitrogen cycle. In
148 the dynamic global vegetation model (DGVM) CLIMBER2-LPJ, Kleinen et al. (2012)
149 quantified the fraction of oxic decomposition in the acrotelm by comparing the water
150 table position and the acrotelm height. Chaudhary et al. (2016, 2017) included a
151 dynamic multi-layer peat accumulation functionality in a customized Arctic version of
152 the Lund-Potsdam-Jena General Ecosystem Simulator (LPJ-GUESS). In their
153 approach, new layers of litter were added at the top of the soil every year, and the
154 remaining litter mass, after decomposition, was treated as a new individual peat layer
155 from the first day of the following year. The decomposition rate of peat, modulated by
156 temperature and moisture, declined over time. In these four peatland models, the
157 water table depth was calculated from a bucket model. In the context of Earth System
158 Modeling, the land surface processes are better represented by multi-layer schemes,
159 such as multi-layer plant canopy and root, multi-layer snow, multi-level soil carbon
160 and energy budgets (Best et al., 2011; Mcgrath et al., 2016; Zhu et al., 2016). To
161 model peatlands consistently in land surface models, a multi-layer soil hydrology
162 scheme is needed. Meanwhile, a more physically-based multi-layer scheme can
163 provide more prognostic power in predicting peatland water table dynamics.

164 In this study, we present the development of a multi-layer peat hydrology and
165 carbon model in the ORCHIDEE land surface scheme, with a focus on the water table
166 dynamics and its effects on the energy budgets, and on carbon decomposition
167 occurring within the oxic and the water-saturated part of the peat profile. CH₄ fluxes
168 and DOC loss through runoff are important components of the carbon balance of a
169 peatland (Chu et al., 2014; Olefeldt et al., 2012), but are not included in this study.
170 This new peat model is incorporated consistently into the land surface scheme in

171 order to conserve water, carbon and energy at scales from local sites to grid-based
172 large-scale applications in an Earth System Modeling context.

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174 **2. Model description**

175 **2.1 General structure of the model**

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

181 ORCHIDEE discretizes the vegetation into plant functional types (PFT): eight for
182 trees, two for natural C3 and C4 grasses, two for C3 and C4 crops, and one for
183 bare-soil type. Across the PFTs, plants are described with the same equations but
184 different parameter values, except for leaf onset and senescence that follow
185 PFT-specific equations (Botta et al., 2000). In grid-based simulations, PFTs are
186 grouped into three soil tiles: one with bare soil, one with all tree PFTs, and one with
187 all short vegetation. The water budget of each soil tile is calculated independently.
188 The version of ORCHIDEE implemented in this study uses the same (dominant) soil
189 texture for all the soil tiles of a grid cell to define the reference saturated hydraulic
190 conductivity (K_{s-ref}), and the saturated and residual volumetric water contents (θ_s , θ_r).
191 Dominant soil textural classes are taken from the Zobler's soil texture map (Zobler,
192 1986) at 1° resolution. The original five soil textures (fine, medium-fine, medium,
193 medium-coarse, coarse) in Zobler's map are reduced to three (fine, medium, coarse),
194 by grouping the medium-fine, medium, and medium-coarse into a single class.
195 Hydrological parameters of the three dominant soil textures are taken from Carsel and
196 Parrish (1988) (Table 1).

197 Each soil tile in ORCHIDEE has eleven vertical layers (up to 2.0 m) with
198 exponentially coarser vertical resolution (Fig. 1). The Fokker-Planck equation is used
199 to describe the vertical diffusion of water in the soil. The Mualem (1976) - Van

200 Genuchten (1980) model (Eq. 1 and 2) is used to define the hydraulic conductivity (K ,
 201 $m s^{-1}$) and diffusivity (D , $m^2 s^{-1}$) as a function of volumetric water content (θ , $m^3 m^{-3}$):

$$202 \quad K(\theta) = K_s \sqrt{\theta_f} (1 - (1 - \theta_f^{1/m})^m)^2, \quad (1)$$

$$203 \quad D(\theta) = \frac{(1-m)K(\theta)}{\alpha m} \frac{1}{\theta - \theta_r} \theta_f^{-\frac{1}{m}} (\theta_f^{-\frac{1}{m}} - 1)^{-m}, \quad (2)$$

204 where θ is the volumetric water content ($m^3 m^{-3}$), θ_s is the saturated water content (m^3
 205 m^{-3}), θ_r is the residual water content ($m^3 m^{-3}$), θ_f is the relative water content and is
 206 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
 207 inverse of the air entry suction (m^{-1}), and m is a dimensionless parameter.

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

$$211 \quad K_s(z) = K_{s-ref} * F_d(z) * F_{root}(z), \quad (3)$$

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

$$213 \quad F_{root}(z) = \prod_{j \in c} \max\left(1, \left(\frac{K_s^{max}}{K_{s-ref}}\right)^{\frac{1 - \alpha_j z}{2}}\right)^{f_j},$$

214 where K_{s-ref} is the reference top-soil saturated
 215 hydraulic conductivity determined by soil texture ($m s^{-1}$), K_s^{max} is the value of the
 216 coarser (sandy) texture and equals $8.25 \times 10^{-5} m s^{-1}$, α_j is a root profile decay factor
 217 for PFT j with a coverage fraction f_j , and c is the soil tile to which PFT j was assigned.

218 **2.2 Modifications in ORCHIDEE-PEAT**

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

223 **Modified peat plant parameters:**

224 As a response to the unique stress conditions in peatlands (i.e., oxygen deficit,
 225 nutrient limitation), peatland vegetation has shallow and extensive root systems
 226 (Boutin and Keddy, 1993; Iversen et al., 2015). Previous peatland models have

227 incorporated more than one PFT to represent peatland plants and dynamically
228 simulate fractional vegetation cover. For example, Wania et al. (2009b) separated
229 flood-tolerant C3 graminoids and *Sphagnum* moss in LPJ-WHY to represent
230 peatland-specific vegetation, with peatland extent defined from an organic soil map
231 and the fractional cover of PFTs determined by bioclimatic conditions including
232 temperature, water table depth, inundation stress etc.. Stocker et al. (2014) applied a
233 version of this model but removed the upper temperature limitation of the
234 peatland-specific PFTs and further included three additional PFTs — flood tolerant C4
235 grasses, tropical evergreen and tropical raingreen tree PFTs, with peatland extent
236 diagnosed by the TOPMODEL scheme. At present, however, ORCHIDEE-PEAT
237 lacks representation of dynamic moss and shrub covers, and we do not know the
238 fractional coverage of different vegetation types at each site in grid-based simulations.
239 Previous studies have shown that there are considerable overlaps between the plant
240 traits ranges among different plant functional types, while variations in plant traits
241 within a PFT can be larger than the differences in means of different PFTs (Verheijen
242 et al., 2013; Wright et al., 2005; Laughlin et al., 2010). Therefore, for simplicity, we
243 applied only the PFT of C3-grass with a shallower rooting depth to represent the
244 average of vegetation growing in northern peatlands.

245 Only one key photosynthetic parameter— V_{cmax} of this PFT has been tuned to match
246 with observations at each site. This simplification may cause discrepancies between
247 model output and observations. Druel et al. (2017) added non-vascular plants
248 (bryophytes and lichens), boreal grasses, and shrubs into ORC-HL-VEGv1.0. Their
249 work is in parallel with our model and will be incorporated into the model in the
250 future. It will then be possible to verify how many plant functional types are needed
251 by the model to reliably simulate the peatlands at site-level and larger scale. The
252 maximum rate of carboxylation (V_{cmax}) typically varies across peat sites (Rennermalm
253 et al., 2005; Bubier et al., 2011) and further varies with leaf nitrogen, phosphorus
254 content, and specific leaf area (Wright et al., 2004; Walker et al., 2014). For instance,
255 V_{cmax} for *Sphagnum* at the Old Black Spruce site (53.985 °N, 105.12 °W) in Canada

256 was 5, 14 and 6 $\mu\text{mol m}^{-2} \text{s}^{-1}$ during spring, summer and autumn, respectively, while
257 V_{cmax} for *Pleurozium* was 7, 5, and 7 $\mu\text{mol m}^{-2} \text{s}^{-1}$ during the three seasons (Williams
258 and Flanagan, 1998). Bui (2013) conducted a fertilization experiment at the Mer
259 Bleue bog (Canada, 45.41 °N, 75.52 °W) on the dominant ericaceous shrub and
260 reported that V_{cmax} values ranged between 6 and 179 $\mu\text{mol m}^{-2} \text{s}^{-1}$, with significantly
261 higher V_{cmax} values after addition of nitrogen (6.4 g N $\text{m}^{-2} \text{year}^{-1}$) at 20 times the
262 growing season ambient wet N deposition rate with or without phosphorus (P) and
263 potassium (K). In this study (Sect. 4.1), we calibrated V_{cmax} at each site so that
264 modeled peak gross primary production (GPP) matched peak values derived from
265 direct EC measurements, and then regressed this adjusted V_{cmax} value with
266 environmental and climate variables. We note that this adjustment of V_{cmax} may over-
267 or under-compensate for biases in other model parameters that impact maximum GPP,
268 such as leaf area index (LAI), specific leaf area (SLA), canopy light absorption
269 parameters, water and temperature stresses (Fig. S1).

270

271 **Peat-specific soils hydraulics:**

272 Peatlands generally occur in flat areas that are poorly drained and/or receive runoff
273 and sub-surface water from the surrounding landscape (Graniero and Price, 1999).
274 The low permeability catotelm peat layer is permanently saturated. In
275 ORCHIDEE-PEAT, the new soil tile added in a grid cell to represent peatland as a
276 landscape element was assumed to receive surface runoff from the other three soil
277 tiles (bare soil, trees, grasses) and has a drainage flux reduced to zero (Largeron et al.,
278 2017). Further, considering that the water table of a peatland can rise above the
279 ground surface, an above surface water reservoir with a maximum height of 10 cm
280 was added (Fig. 1b). In the model, the partitioning between water infiltration and
281 surface runoff is computed through a time-splitting procedure, with the maximum
282 infiltration rates described as an exponential probability density distribution
283 (d'Orgeval, 2006). The infiltration-excess water of peatland first fills the
284 above-surface water reservoir, then leaves the grid cell as runoff. Water in this

285 above-surface reservoir re-infiltrates into the peat soil on the next time step (Largeron
 286 et al., 2017). We verified that the measured standing water remained below 10 cm
 287 above the soil surface at 16 out of 20 northern peat sites where water table depth was
 288 recorded in this study (Table S1). The four exceptions were Winous Point North
 289 Marsh (US-WPT), Himmelmoor (DE-Hmm), an Alaska fen (US-Fen) and an Alaska
 290 bog (US-Bog), where observed water tables reached up to 77 cm, 39 cm, 46 cm and
 291 34 cm above the soil surface, respectively.

292 Peat soils cannot be described with any of the mineral soil textures used for other
 293 tiles (Table 1) because the low bulk density and high porosity increase the downward
 294 water percolation (Rezanezhad et al., 2016). Observed peat saturated hydraulic
 295 conductivity (K) and diffusivity (D) strongly vary in space, depth and time. This is
 296 partly related to the degree of decomposition and compression of organic matter
 297 (Gnatowski et al., 2010). Morris et al. (2015) reported near-surface saturated
 298 hydraulic conductivities (K) of $2.69 \times 10^{-2} \text{ m s}^{-1}$ to $7.16 \times 10^{-6} \text{ m s}^{-1}$ in bogs.
 299 Gnatowski et al. (2010) measured values of $5 \times 10^{-6} \text{ m s}^{-1}$ in a moss-covered peat,
 300 which was two orders of magnitude larger than for a woody peat ($5.56 \times 10^{-8} \text{ m s}^{-1}$).
 301 Peat hydraulic parameters values used in this study were applied after Largeron et al.,
 302 (2017), based on Letts et al. (2000) and Dawson (2006) (Table 1). The peat saturated
 303 hydraulic conductivity value of $2.45 \times 10^{-5} \text{ m s}^{-1}$ is comparable to the harmonic
 304 mean value ($6 \times 10^{-5} \text{ m s}^{-1}$) of Morris et al. (2015). The values of the other Van
 305 Genuchten parameters for peat (Table 1) are similar to those employed in other
 306 peatland models (Wania et al., 2009a; Wu et al., 2016).

307 The peatland water table depth (WT, cm) is diagnosed by summing water heights in
 308 the eleven soil layers, calculated from the relative water content (Largeron et al.,
 309 2017):

$$310 \quad \text{WT} = H_{\text{tot}} - \sum_{i=1}^{11} (\theta_{fi} * dz_i) - H_{\text{ab}}, \text{ with } \theta_{fi} = \frac{\theta_i - \theta_r}{\theta_s - \theta_r}, \quad (4)$$

311 where θ_{fi} is the relative volumetric water content of the i^{th} soil layer, θ_s is the saturated

312 water content ($\text{m}^3 \text{m}^{-3}$), θ_r is the residual water content ($\text{m}^3 \text{m}^{-3}$), dz_i is the distance
313 between node $i-1$ and node i (Fig. 1, m), H_{tot} is the total soil column height being
314 fixed to 2.0 m, and H_{ab} is the height of the water reservoir above soil surface (m).
315 Thus, when the water table is above the surface, the modeled WT takes negative
316 values.

317

318 **Decomposition of peat carbon controlled by water saturation:**

319 In the standard version of ORCHIDEE, plant litter carbon is added to two litter pools:
320 the metabolic and the structural pool. Decomposed litter carbon from these two pools
321 is then distributed into three soil carbon pools: the active, slow and passive pool,
322 similar to the CENTURY model (Parton et al., 1988). Both temperature and moisture
323 functions are used to control soil carbon decomposition rates (Text S1). In
324 ORCHIDEE-PEAT, these standard processes are kept the same as in Krinner et al.
325 (2005) for non-peatland vegetation (Fig. S2, black dashed box). For the peatland
326 vegetation, we added a peat carbon module, in which the three soil carbon pools
327 (active, slow, passive) are replaced by two pools forming distinct layers, following
328 Kleinen et al. (2012) (Fig. S2, red dashed box). Specifically, carbon from decomposed
329 litter pools is added to the acrotelm carbon pool where it is decomposed aerobically
330 above the simulated water table, and anaerobically below it. The permanently
331 saturated deep catotelm carbon pool receives a prescribed fraction of the acrotelm
332 carbon, and is decomposed only anaerobically at a very slow rate. While the acrotelm
333 depth is fixed to 30 cm in some peat decomposition models (Yurova et al., 2007;
334 Wania et al., 2009a; Spahni et al., 2013), we used the average of simulated minimum
335 summer water table position (WT_{min}) over the observational period to demarcate the
336 boundary between the acrotelm and the catotelm at each site to take into account local
337 site conditions. We conducted a “preparation run (S0)”, in which the model was run at
338 each site using the same protocol (Sect. 3.3), but with the peat carbon module
339 deactivated. WT_{min} was diagnosed from the output of S0 before feeding into the peat
340 carbon module in S1 and S2 (Sect. 3.3). Soil carbon exerts no feedback effects on the

341 soil temperature and hydraulic in the structure of our model, thus S0 and S1 produce
 342 the same simulated water table. WT_{\min} values were estimated based on current climate
 343 due to the lack of knowledge of initiation histories of these sites. For the long-term
 344 carbon accumulation estimations, the Holocene climate may be a better proxy since
 345 northern peatlands show peak initiation in the early Holocene (Yu et al., 2010). By
 346 comparing the height of the acrotelm (Fig. S2, Eq. 9) with the WT depth, we derived
 347 the fraction of the acrotelm where carbon decomposes under oxic (β) vs. anoxic
 348 conditions ($1-\beta$). Acrotelm height (H_A , Eq.10) was calculated from acrotelm carbon
 349 stock (C_A in Eq. 5-7), acrotelm carbon fraction ($C_{f,A}$) and acrotelm bulk density (ρ_A).
 350 Decomposition of peat carbon is controlled by temperature (f_T) and parameterized as
 351 an exponential function: $f_T = Q_{10}\exp((T-T_{\text{ref}})/10 \text{ }^\circ\text{C})$ with $Q_{10} = 2.0$ and $T_{\text{ref}} = 30 \text{ }^\circ\text{C}$
 352 (Text S1). Soil carbon fluxes are given by:

$$353 \quad F_{AC} = k_p f_T C_A, \quad (5)$$

$$354 \quad R_{A,o} = \beta k_A f_T C_A, \quad (6)$$

$$355 \quad R_{A,a} = (1 - \beta) \nu k_A f_T C_A, \quad (7)$$

$$356 \quad R_C = k_C f_T C_C, \quad (8)$$

$$357 \quad \beta = \begin{cases} \beta = 1, & WT_{\min} - WT \leq 0 \\ \beta = \frac{H_A - (WT_{\min} - WT)}{H_A}, & 0 < WT_{\min} - WT < H_A \\ \beta = 0, & WT_{\min} - WT \geq H_A \end{cases}, \quad (9)$$

$$358 \quad H_A = \frac{C_A}{\rho_A \cdot C_{f,A}}, \quad (10)$$

359 where F_{AC} is the carbon flux from acrotelm to catotelm; $R_{A,o}$ is aerobically
 360 decomposed acrotelm carbon; $R_{A,a}$ is anaerobically decomposed acrotelm carbon; R_C
 361 is decomposed carbon in catotelm; C_A is carbon stored in the acrotelm; C_C is carbon
 362 stored in the catotelm; and β is the fraction of acrotelm under oxic conditions. A
 363 10,100 years' spin-up was conducted to initialize peat depth at each site (Sect. 3.3).
 364 Following the study of Kleinen et al. (2012), the catotelm formation rate $k_p = 1.91 \times$
 365 10^{-2} yr^{-1} , the acrotelm decomposition rate $k_A = 0.067 \text{ yr}^{-1}$, the catotelm decomposition
 366 rate $k_C = 3.35 \times 10^{-5} \text{ yr}^{-1}$, the ratio of anaerobic to aerobic CO_2 production $\mu = 0.35$,

367 carbon fraction in the acrotelm peat $C_{f,A} = 0.50$, the acrotelm density $\rho_A = 35.0 \text{ kg m}^{-3}$,
368 carbon fraction in the catotelm peat $C_{f,C} = 0.52$, and the catotelm density $\rho_C = 91.0 \text{ kg}$
369 m^{-3} .

370

371 **3. Validation of ORCHIDEE-PEAT at northern hemisphere peatland** 372 **eddy-covariance sites**

373 **3.1 Sites description**

374 To evaluate the performance of ORCHIDEE-PEAT in simulating CO_2 , water and
375 energy fluxes on daily to annual time scales, we compiled data from 30 northern
376 peatland sites where eddy-covariance data and physical variables (water table, snow
377 depth, soil temperature) were collected (Fig. 2, Table 2). These sites are spread
378 between the temperate to the arctic climate zones, and include nine bogs and 18 fens.
379 A marsh and two wet tundra sites (note that these two wet tundra sites are neither a
380 fen nor a bog, hereafter they are referred to as ‘tundra’) with a $\sim 30\text{--}50 \text{ cm}$ thick
381 organic layer are also included in this study. Among them, six sites are underlain by
382 permafrost and one site is in a thermokarst area. The peatland fractional cover in the
383 0.5° grid cell containing each site is from the Yu et al. (2010) map (Fig. 2, Table 2). A
384 short description of all sites can be found in Supplementary Materials.

385

386 **3.2 Meteorological forcing data**

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

393 Time series of half-hourly air temperature, wind speed, wind direction, long-wave
394 incoming radiation, short-wave incoming radiation, specific humidity, atmospheric
395 pressure, and precipitation were used to drive ORCHIDEE-PEAT. All variables were

396 from measurements made at each flux tower where CO₂ and energy (latent heat (LE)
397 and sensible heat (H)) fluxes, water table position, soil temperature, and snow depth
398 were recorded on a half-hourly time step. The linearly interpolated 6-hourly
399 CRU-NCEP 0.5 ° global climate forcing dataset was used to fill the gaps in the driving
400 variables. A linear correction was applied to meteorological forcing variables (except
401 precipitation) in the CRU-NCEP dataset to match observations before gap-filling. For
402 precipitation, no correction was applied. At CA-Wp2 and CA-Wp3, meteorological
403 forcing data were measured only during the growing season, so CRU-NCEP data were
404 linearly corrected using relationships derived from the available data. For some sites,
405 several meteorological variables were not measured, such as long-wave incoming
406 radiation at NO-And, atmospheric pressure, short-wave incoming radiation, and
407 long-wave incoming radiation at CZ-Wet. In these cases, uncorrected CRU-NCEP
408 data were used.

409

410 **3.3 Model setup**

411 ORCHIDEE-PEAT was first spun-up for 10,100 years, forced by the preindustrial
412 atmospheric CO₂ concentration of 285 ppm, with repeated site-specific observational
413 meteorological fields, and present-day vegetation fractions for each site. In reality, the
414 climate changed through the Holocene, but since the initiation and climate history of
415 each site are unknown, we assumed a constant present-day climate condition and
416 peatland area. Thus, this model is only suitable for simulating water, energy and CO₂
417 fluxes from peat on time scales ranging from days to decades. To accelerate the
418 spin-up, ORCHIDEE-PEAT was first run for 100 years to reach the equilibrium for
419 hydrology and soil thermal conditions, fast carbon pools and soil carbon input from
420 dead plants. Then, a sub-model simulating only soil carbon dynamics (with fixed
421 daily litter input from the previous simulation) was run for 10,000 years to accumulate
422 soil carbon. Peatlands can reach equilibrium only when the addition of carbon equals
423 carbon lost, which is attained on time scales of 10⁴ years (Clymo, 1984; Wania et al.,
424 2009b). The catotelm carbon pool in this study was still not fully equilibrated even

425 after 10,100 years due to the low carbon decomposition rate in this reservoir ($3.35 \times$
426 10^{-5} yr^{-1} , Kleinen et al., 2012). The modeled peat carbon pool thus depends on the
427 time length of spin-up, which was fixed at 10,100 years, while in the real world, peat
428 age at some sites can be younger. For example, the sample from the second last 10 cm
429 peat segment at CA-Wp1 has an un-calibrated radiocarbon date of ~2200 years
430 (Flanagan and Syed, 2011). Since we focus on carbon and water fluxes on daily to
431 annual scales in this study, rather than on the simulation of peat carbon stocks, we
432 conducted a sensitivity analysis of modeled heterotrophic respiration to the length of
433 the spin-up, which shows only a slight increase of catotelm respiration with increasing
434 simulation time (Fig. S3). After the spin-up, transient simulations were conducted for
435 each site, forced by repeated site-specific climates and rising atmospheric CO_2
436 concentration during the period 1901-2015. Finally, the model outputs corresponding
437 to the respective measurement periods (all during 1999-2015) were compared to
438 observed time series for each site.

439 Two sets of simulations were conducted. In the first one (S1), soil water content
440 and water table position (WT) were modeled by ORCHIDEE-PEAT, and the WT was
441 used in the carbon module to define the fraction of oxic and anoxic decomposition in
442 the acrotelm. S1 was performed for all the 30 sites. In the second set (S2) of
443 simulations, we prescribed water table in the model to equal to observed values
444 (WT_{obs}). That is, soil moisture at layers below the measured water table was
445 prescribed as saturated ($\theta(z > \text{WT}_{\text{obs}}) = \theta_s$), while soil moisture above WT_{obs} was
446 simulated. WT_{obs} was further used in the carbon module in S2. S2 was performed only
447 for a subset of eight sites where at least two years of water table measurements were
448 available and where there were sufficient observations to gap-fill the WT_{obs} time
449 series (Table 2). For these sites, the gaps of WT_{obs} were filled with the mean value of
450 the same period from other years of measurement (Table S2). The simulation S2 was
451 designed to check if the model performance will improve (or deteriorate) when
452 prescribing WT exactly to its observed value, since WT is known to be a critical
453 variable impacting peat water, CO_2 and CH_4 fluxes (Dušek et al., 2009; Parmentier et

454 al., 2011; Strack et al., 2006). Fixing the simulated water table to WT_{obs} in S2 violated
 455 the water mass conservation of the model, but allowed us to evaluate the carbon
 456 module independently from the hydrological module biases.

457

458 **3.4 Measures for evaluating model performance**

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

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

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

$$469 \text{RMSD} = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - y_i)^2}, \quad (11)$$

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

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

$$476 \text{SDSD} = (SD_s - SD_m)^2; \text{ with } SD_s = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2}, \text{ } SD_m = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \bar{y})^2},$$

477 (12)

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

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

$$481 \text{LCS} = 2SD_s SD_m (1 - r); \text{ with } r = \left[\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y}) \right] / (SD_s SD_m), \quad (13)$$

482 where r is the Pearson's correlation coefficient.

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

$$489 \text{MEF} = 1 - \frac{\sum_{i=1}^n (x_i - y_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2}, \quad (14)$$

490

491 **4. Results**

492 **4.1 Site-specific V_{cmax} reduces errors in carbon flux simulations**

493 Out of the 30 sites, 22 sites provided observed daily GPP (based on measured NEE).
494 The values of optimized V_{cmax} at each site were listed in Table 3. The optimized V_{cmax}
495 varied from 19 to 89 $\mu\text{mol m}^{-2} \text{s}^{-1}$ (Table 3), with a mean value of 40 $\mu\text{mol m}^{-2} \text{s}^{-1}$. The
496 calibration of V_{cmax} may compensate for biases in other model parameters. A brief
497 comparison between simulated and reported (measured/estimated) LAI and
498 aboveground biomass showed that there are no systematic errors (Fig. S1).

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

506 For the 22 sites where NEE and ER measurements were available, the errors in the
507 three carbon fluxes GPP, ER, NEE were significantly reduced by optimizing V_{cmax} at
508 each site (Table 4, Fig. 4, Fig. S4). With site-specific V_{cmax} values (site-by-site model
509 performances are shown in Fig. S5 to S10 in Supplementary Materials), the overall
510 (all the daily data from all the 22 sites) performance of the model was high for GPP

511 ($r^2 = 0.76$, MEF = 0.76), ER ($r^2 = 0.78$, MEF = 0.75), and lower for NEE ($r^2 = 0.38$,
512 MEF = 0.26) (Fig. 4, Table 4). Seasonal variations in carbon fluxes were well
513 captured by the model ($r^2 = 0.61$ to 0.86). The spatial across-sites gradients of annual
514 mean GPP and ER were generally good, with r^2 of 0.93 and 0.89, and lower for NEE
515 ($r^2 = 0.27$). Compared to simulations with a fixed V_{cmax} (the mean of the optimized
516 values of $40 \mu\text{mol m}^{-2} \text{s}^{-1}$), there were large improvements in capturing spatial
517 gradients of carbon fluxes with a site-specific V_{cmax} (e.g. r^2 increased from 0.20 to
518 0.93, from 0.27 to 0.89 and from 0.16 to 0.27 for GPP, ER and NEE, respectively,
519 while the RMSD reduced by 63%, 48%, and 9%). This result indicates that
520 model-data disagreement can be largely reduced by using site-specific V_{cmax} instead
521 of a fixed (mean) value. In future regional simulations, spatial variations in V_{cmax}
522 should be taken into account. There was, however, no significant improvement in LE,
523 H and WT by using site-specific V_{cmax} values (Table4). The model performance was
524 poor for predicting daily anomalies of all fluxes, with $r^2 < 0.20$. For both temporal and
525 spatial variation, the MEF of the WT were negative, and r^2 smaller than 0.10,
526 indicating that the model had a low predictive capability for the WT. Possible reasons
527 for this could be: 1) Peat disturbance was not parameterized; i.e., the removal of
528 beaver dams resulted in a decline of water level at US-Los; water level at US-WPT,
529 CZ-Wet and RU-Che were manipulated. 2) The model diagnosed all peatland sites as
530 fens by routing runoff from non-peatland areas into the peatland soil tile, whereas in
531 reality, bogs receive water and nutrients only through precipitation. In other words,
532 we included an extra water source for bogs other than rainfall. However, the model
533 did not perform better for fens (Fig. 3f), possibly because the amount of water that
534 was routed into the fen was in error. 3) WT depends on water input from surrounding
535 non-peatland areas: the greater the peatland fraction in the grid cell, the smaller runoff
536 input from other soils to the peatland, hence resulting in a deeper water table in the
537 peatland (Fig. S11). The peatland area fraction derived from the map of Yu et al.
538 (2010) cannot represent local area providing water for fens. 4) For global applications,
539 the effects of micro-relief were not represented in the model, although they have been

540 shown to be an important regulator of the local hydrology cycle (Gong et al., 2012;
541 Shi et al., 2015).

542 To better understand the influence of the water table dynamics on ER and NEE in
543 the model, we compared the second set of simulations (S2, with observed water table
544 used in the carbon module to define the fraction of oxic and anoxic decomposition in
545 the acrotelm) with the first set (S1, water table calculated by the model).
546 ORCHIDEE-PEAT showed only a small improvement in reproducing ER and NEE
547 when WT_{obs} was used (Table 5 and 6). To illustrate this effect, we took the
548 Lompoloj änkki (FI-Lom) fen site as an example, in which WT was most severely
549 underestimated among the 22 sites where NEE and ER measurements were available
550 (Fig. S8). While modeled WT varied between 5 and 54 cm below the surface, WT_{obs}
551 was always above the soil surface. Fig. 5a showed that in comparison to S1, there was
552 no aerobic respiration and larger anaerobic respiration in the acrotelm in S2. Due to
553 the smaller acrotelm respiration (aerobic + anaerobic) in S2, carbon input from
554 acrotelm to catotelm was larger and consequently, more carbon accumulated in the
555 catotelm in S2. Thus, the catotelm respiration in S2 was higher than that in S1 (Fig.
556 5c), even though the catotelm respiration rate was very small. Because the growth of
557 the peatland vegetation was not constrained by water in the model, the simulated GPP
558 values were similar between S1 and S2 (Fig. 5a). With similar GPP but smaller soil
559 respiration (sum of the acrotelm and the catotelm respiration), S2 simulations thus
560 resulted in more negative NEE values than S1 (higher net CO_2 uptake). Simulated leaf
561 onset occurred earlier than observed at Lompoloj änkki site, causing the ecosystem to
562 switch from carbon source to carbon sink in May, while the start of the carbon uptake
563 was observed to occur later (Fig. 5b). Although the modeled NEE was similar in
564 amplitude to the observations, the day-to-day variations of this flux were not captured
565 (Fig. 6), causing an overestimation (more negative values) of NEE in the warm period
566 (May-September).

567 The influence of WT on respiration was parameterized as the separation of oxic (β
568 in Eq. 6) vs. anoxic ($1-\beta$ in Eq. 7) decomposition in the acrotelm. Although absolute

569 values of simulated WT in S1 and WT_{obs} in S2 were quite different (Fig. S8), the
570 values of β were not very different (Fig.S12). Therefore, the simulated WT was good
571 enough to properly replicate ER (Fig.S13). An additional simulation (S3) performed
572 at FI-Lom showed that if WT was more severely underestimated, e.g. WT in S3 was
573 consistently 20 cm deeper than in S1, the acrotelm was exposed to oxygen for longer
574 time, resulting in larger ER and hence smaller carbon sequestration in S3 (Fig.S12,
575 Fig.S13).

576
577

578 **4.2 Relationship between optimized V_{cmax} and meteorological variables**

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

586 There was no significant difference between optimized V_{cmax} among peatland types
587 (fen vs bog, $p = 0.16$), climate zones (temperate vs boreal vs arctic, $p = 0.17$), or
588 dominant vegetation types (grasses and/or mosses dominated vs shrubs and/or trees
589 dominated, $p = 0.67$) (Fig. S14). However, we found a significant positive relationship
590 between V_{cmax} and the growing season mean air temperature (Fig. S15, Table 6, V_{cmax}
591 $= 2.78T + 8.74$, with $r^2 = 0.19$, $p < 0.05$) and a significant negative relationship
592 between V_{cmax} and the latitude (Fig. S15, Table 6, $V_{cmax} = -0.92LAT + 93.56$, with $r^2 =$
593 0.23 , $p < 0.05$).

594 To verify the applicability of the empirical relationship found across sites between
595 optimized V_{cmax} and the latitude (Fig. S15), we used the seven sites where there were
596 no GPP observations available (US-Bes, DE-Hmm, US-Ics, PL-wet, SE-Sto, CA-Wp2
597 and CA-Wp3) as cross-validated sites. We compared model performance in
598 simulating NEE, with V_{cmax} being calculated according to the empirical relationship,

599 and with V_{cmax} being fixed to its mean value of all 22 sites from Table 3 ($40 \mu\text{mol m}^{-2}$
600 s^{-1}). The model performance in reproducing spatial gradients of NEE was improved
601 when the V_{cmax} values derived from the empirical relationship were used (Fig. S16b,
602 with RMSD reduced by 11%, r^2 increased from 0.20 to 0.38, and MEF increased from
603 -0.04 to 0.17). This implies that, compared to a fixed V_{cmax} , the usage of V_{cmax} value
604 from the empirical relationship can better capture spatial gradients of NEE. It is worth
605 mentioning that the empirical relationship was built on climate conditions from the
606 last two decades (1999-2015), and thus may change in the future when the climate
607 changes.

608

609 **4.3 Soil temperature and a snow depth underestimation in the model**

610 For most of the sites, soil temperature was underestimated in winter and
611 overestimated in summer by our model (Figs. 7 and 8, results from sites DK-Nuf and
612 CA-Wp1 are shown as illustrative examples). One possible reason for the
613 underestimation of soil temperature in winter is the underestimation of snow depth
614 (Fig. 9), since snow insulates the soil changing thermal conditions in comparison to a
615 snow-free surface. The underestimation of the snow depth can be caused by the bias
616 in snow processes of the model, such as underestimation of snow mass, and/or
617 overestimation of snow density and subsequently overestimation of snow compaction,
618 and/or overestimation of sublimation. The insulation effect of the moss layer and the
619 top organic layer are not included in this study, which may explain why soil
620 temperature was overestimated in summer but underestimated in winter.
621 ORCHIDEE-PEAT calculates one energy budget for the vegetation and soil columns
622 in one grid cell. Key parameters used for solving the heat diffusion equations in the
623 soil, such as soil heat capacity and thermal conductivity, were prescribed by the
624 dominant soil texture in the grid cell (Gouttevin et al., 2012). Nevertheless, similarly
625 to the case of the hydrology module, the three default (coarse, medium, fine) soil
626 textures cannot represent thermal properties of a peat soil (Paavilainen and P ä v ä n e n ,
627 1995; Abu-Hamdeh and Reeder, 2000).

628

629 **5. Discussion**

630 ORCHIDEE-PEAT groups various peatland vegetation into one plant functional type
631 (PFT). This PFT cannot represent the true range in vegetation composition (shrubs,
632 sedges, mosses etc.) of peatlands. However, by optimizing the value of V_{cmax} at each
633 site, simulated GPP well represented observations and yielded reasonable soil carbon
634 input. The V_{cmax} values estimated in this study ranged from 19 to 89 $\mu\text{mol m}^{-2} \text{s}^{-1}$, with
635 a mean value of 40 $\mu\text{mol m}^{-2} \text{s}^{-1}$. These values were not fully comparable with values
636 reported for a specific vegetation type, as they are averages for all plants growing in
637 the peatland ecosystem. As stated in Sect. 2.2, observed V_{cmax} varies strongly among
638 different species and sites. V_{cmax} of mosses at the Old Black Spruce site (Canada)
639 ranged from 5 to 14 $\mu\text{mol m}^{-2} \text{s}^{-1}$ (Williams and Flanagan, 1998). In a nutrient addition
640 experiments conducted by Bubier et al. (2011), V_{cmax} for ericaceous shrubs in a
641 temperate bog ranged from 67 to 137 $\mu\text{mol m}^{-2} \text{s}^{-1}$, with V_{cmax} for *Vaccinium*
642 *myrtilloides*, *Ledum groenlandicum* and *Chamaedaphne calyculata* valued at $84.6 \pm$
643 $13.5 \mu\text{mol m}^{-2} \text{s}^{-1}$, $78.1 \pm 13.4 \mu\text{mol m}^{-2} \text{s}^{-1}$, and $132.1 \pm 31.2 \mu\text{mol m}^{-2} \text{s}^{-1}$ in the plots
644 with no nutrient addition. The optimized model V_{cmax} in our study was within the
645 range of these observations. Meanwhile, the values we inferred from sites to match
646 peak GPP are comparable to those used in other land surface models: the McGill
647 wetland model used a value of 17 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for evergreen shrubs (St-Hilaire et al.,
648 2010); the CLASS-CTEM model (Wu et al., 2016) used 60, 50, 40 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for
649 evergreen shrubs, deciduous shrubs and sedges, respectively; the values for mosses in
650 these two models were adapted from the study of Williams and Flanagan (1998). Here
651 we found that optimized V_{cmax} has a significant positive relationship with temperature,
652 and a significant negative relationship with latitude of chosen peatland sites. A
653 decrease of V_{cmax} with latitude in the northern hemisphere, like the one inferred from
654 optimized sites values, has also been documented by Walker et al. (2017), who
655 assumed that V_{cmax} was constrained by the rate of N uptake, with the rate of N uptake
656 calculated as a function of soil C, N and mean annual air temperature. We speculate

657 that the dependence of optimized V_{cmax} on latitude found in Sect. 4.2 can be attributed
658 to two effects. First, there is an increase of the length of the growing season increases
659 as latitude decreases. Simultaneously, temperature and incoming solar radiation,
660 increases. Longer growing season may enhance vegetation productivity (Fang et al.,
661 2003; Nemani et al., 2003; Piao et al., 2007). Second, temperature influences the
662 nutrient availability for plants. The decomposition of plant litter and the release of
663 nitrogen can be enhanced by high temperature, although litter decomposition is also
664 driven by soil moisture, vegetation composition, litter quality and their interactions
665 with temperature (Aerts, 2006; Cornelissen et al., 2007; Gogo et al., 2016). Because
666 nitrogen (N) is one key element in proteins that are involved in photosynthesis
667 process, photosynthesis capacity is highly correlated to N availability (Evans, 1989;
668 Takashima et al., 2004; Walker et al., 2014). Since the N cycle is not explicitly
669 included in the ORCHIDEE-PEAT, the relationship between V_{cmax} and the latitude
670 (and temperature) possibly reflected the impact of N on photosynthesis rates.

671 Previous studies have shown that peatlands can have contrasting responses to
672 variations in water table depth. Concerning sites analyzed in our study, Aurela et al.
673 (2007) reported that at the nutrient-poor fen FI-Sii site, drought increased respiration
674 and thus diminished carbon uptake; Adkinson et al. (2011) reported that reduced
675 water availability constrained photosynthesis capacity at the rich fen CA-Wp3 and
676 consequently suppressed NEE, while the poor fen CA-Wp2 did not show a significant
677 response to the lower water table. At the moderately rich treed fen CA-Wp1 site,
678 Flanagan and Syed (2011) reported that both photosynthesis and respiration increased
679 in response to the warmer and drier conditions; Hurkuck et al. (2016) stated that
680 temperature and light played a more important role than water table depth in
681 controlling respiration and photosynthesis at the DE-Bou bog. Based on the field
682 observations, the timing, duration and intensity of drought have a major impact on the
683 responses of peatland ecosystems. Lund et al. (2012) demonstrated that at the raised
684 bog SE-Faj, a relatively short but severe drought that occurred in the middle of
685 growing season of 2006 amplified respiration while a long-lasting drought that

686 occurred at the beginning of growing season of 2008 reduced GPP. Lafleur et al.
687 (2005) and Sulman et al. (2009) concluded from their studies at CA-Mer bog and
688 US-Los fen that wetter peatlands would show stronger relationship between
689 respiration and water table than drier peatlands because in a narrow range of the upper
690 soils, small increases in WT (shallower WT) can result in a large increase in soil
691 water content and therefore respiration decrease, while below a critical level, soil
692 water content shows only small increase with increasing WT and respiration changes
693 are not so pronounced. Sulman et al. (2010) found that wetter conditions decreased
694 respiration at fens but increased respiration at bogs, mainly due to different vegetation
695 composition at these two types of peatland: the fen sites had more shrubs and sedges
696 while the bog sites had more mosses. In this study, we did not distinguish between
697 fens and bogs, and growth of peatland vegetation was not constrained by water table
698 depth in the model. Therefore, the sensitivity of GPP to WT fluctuations in
699 observations was not included in the model. As a consequence, the model neither
700 captured the reported decrease of photosynthesis due to drought at CA-Wp3
701 (Adkinson et al., 2011) and SE-Faj (Lund et al., 2012), nor the increase of
702 photosynthesis as a result of lower water table at CA-Wp1 (Flanagan and Syed, 2011).
703 However, the model can reproduce the pattern that above a critical level (acrotelm
704 depth), peat respiration decreases with increasing WT (Fig.5, Fig.S13), as reported at
705 site CA-Mer and US-Los (Lafleur et al., 2005; Sulman et al., 2009).
706 ORCHIDEE-PEAT adequately captured the daily, seasonal and across-sites annual
707 variations in GPP (with $r^2 = 0.75, 0.86, \text{ and } 0.93$, respectively) and ER (with $r^2 = 0.78,$
708 $0.86, \text{ and } 0.89$, respectively), but did not perform as well in reproducing NEE
709 variations (with $r^2 = 0.38, 0.61, \text{ and } 0.27$, respectively). Note that in the two-layer soil
710 carbon scheme, the dependence of soil respiration on temperature was parameterized
711 as an exponential function of the soil layers-weighted average temperature (Text S1),
712 the vertical temperature gradient in the soil profile was ignored by the model.
713 However, field studies have shown that soil temperature is one of the most important
714 predictors of respiration and values of Q_{10} coefficient depend on the soil depth

715 (Lafleur et al., 2005; D'Angelo et al., 2016).

716 Correct representation of peatland hydrology is a challenging problem in
717 large-scale land surface models (Wania et al., 2009a; Wu et al., 2016). The simulated
718 water table by ORCHIDEE-PEAT depends on water inflows from the surrounding
719 non-peatland areas, and a water routing analysis on sub-grid scales can be included to
720 improve the model performance for water table in the future (Ringeval et al., 2012;
721 Stocker et al., 2014). Other studies have shown that microtopography exerts important
722 influences on hydrological dynamics of peatlands, however, to capture the influence
723 of microtopography on water table, high-resolution micro-topographic feature and
724 vegetation information are needed (Gong et al., 2013; Shi et al., 2015).

725 The poor correspondence between simulated and observed energy fluxes was not
726 completely unexpected, since ORCHIDEE-PEAT only calculates one energy budget
727 for the whole grid-cell and not for each soil tile/PFT present in the same grid cell. A
728 site-varied and/or time-varied correction of LE and H measurements to force energy
729 balance closure, and parameterizations of an independent energy budget at peatland
730 would be helpful for better comparison of simulated and observed energy fluxes at
731 peatland.

732

733 **6. Conclusions**

734 We developed ORCHIDEE-PEAT to simulate soil hydrology and carbon dynamics in
735 peatlands. The model was evaluated at 30 northern peatland sites (Europe, USA,
736 Canada, Russia). The optimization of V_{cmax} reduced the errors in the simulated carbon
737 budget. The model, generally, reproduced the spatial gradient and temporal variations
738 in GPP, ER, and NEE well. Water table depth was poorly simulated, possibly due to
739 uncertainties in water input from non-peatland areas in the grid cell, and to a lack of
740 representation of micro-relief, as well as the lack of consideration of peat disturbance.
741 A significant relationship between V_{cmax} and latitude was found. This may be
742 attributed to the influence of temperature on growing season length and nutrient
743 availability. For ER and NEE, the improvement brought by forcing the carbon module

744 to use observed WT values (WT_{obs}), instead of calculated by the model, was small,
745 indicating that the simulated WT was reliable to predict ER and NEE properly.

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

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761 **Competing interests**

762 The authors declare that they have no conflict of interest.

763

764 **Code availability**

765

766 The access of the source code is available online via the following address:

767 (<http://forge.ipsl.jussieu.fr/orchidee/browser/perso/chunjing.qiu/ORCHIDEE>), but its

768 access is restricted. Readers interested in running the model should follow the

769 instructions at <http://orchidee.ipsl.fr/index.php/you-orchidee>, and contact the

770 corresponding author for a username and password.

771

772

773 **Data availability**

774 Measured Eddy Covariance fluxes and related meteorological data can be obtained
775 from the FLUXNET database (<http://fluxnet.ornl.gov/>), the Ameriflux database
776 (<http://ameriflux.lbl.gov/>), and from investigators upon request. Model outputs are
777 available at:

778 <https://files.lsce.ipsl.fr/public.php?service=files&t=c12c831ef46cd2bf6d1f61b6e65f8>
779 c98.

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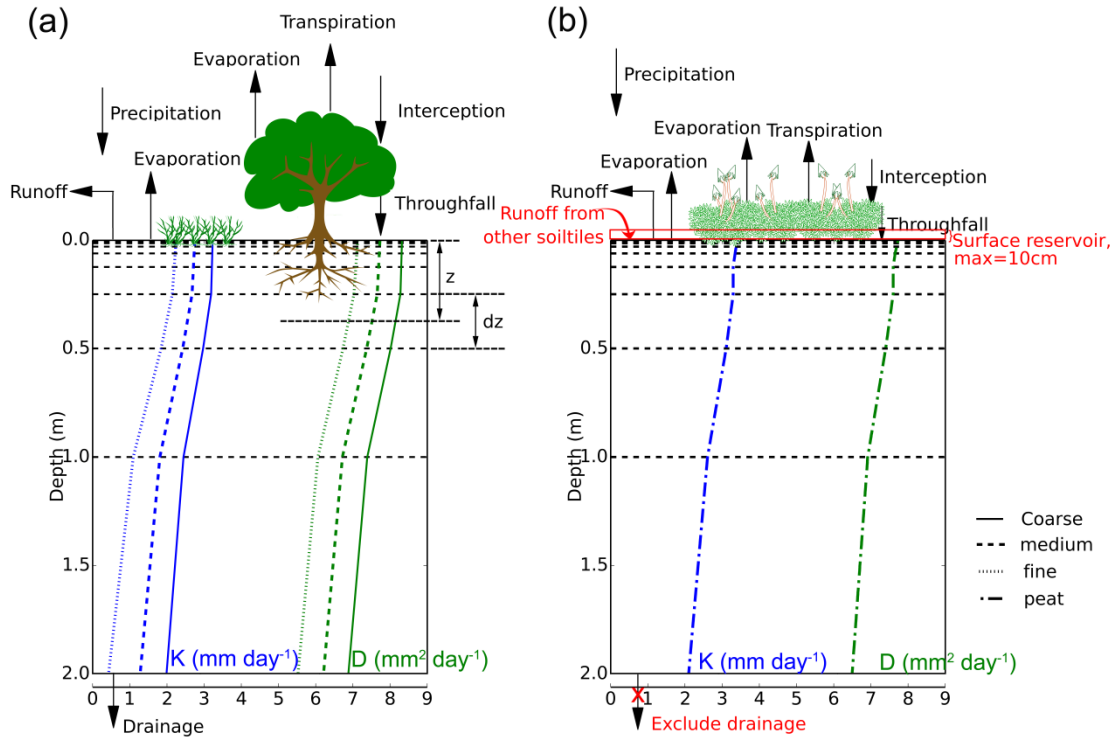
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1223 **Figures and Tables**

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1228 **Fig. 1.** Schematic of the hydrology module in ORCHIDEE. (a) water balance components in
 1229 (a) a soil tile with either trees or grasses, (b) a peatland soil tile. Black dashed lines indicate
 1230 the position of nodes in the eleven soil layers of the model. Blue lines: vertical profile of
 1231 saturated hydraulic conductivity for different soil textures. Green lines: diffusivity for
 1232 different soil textures. Vertical axis indicates soil depth, the horizontal axis indicates values
 1233 of saturated hydraulic conductivity (K, mm day⁻¹) and diffusivity (D, mm² day⁻¹), and scales
 1234 are logarithmic based 10.

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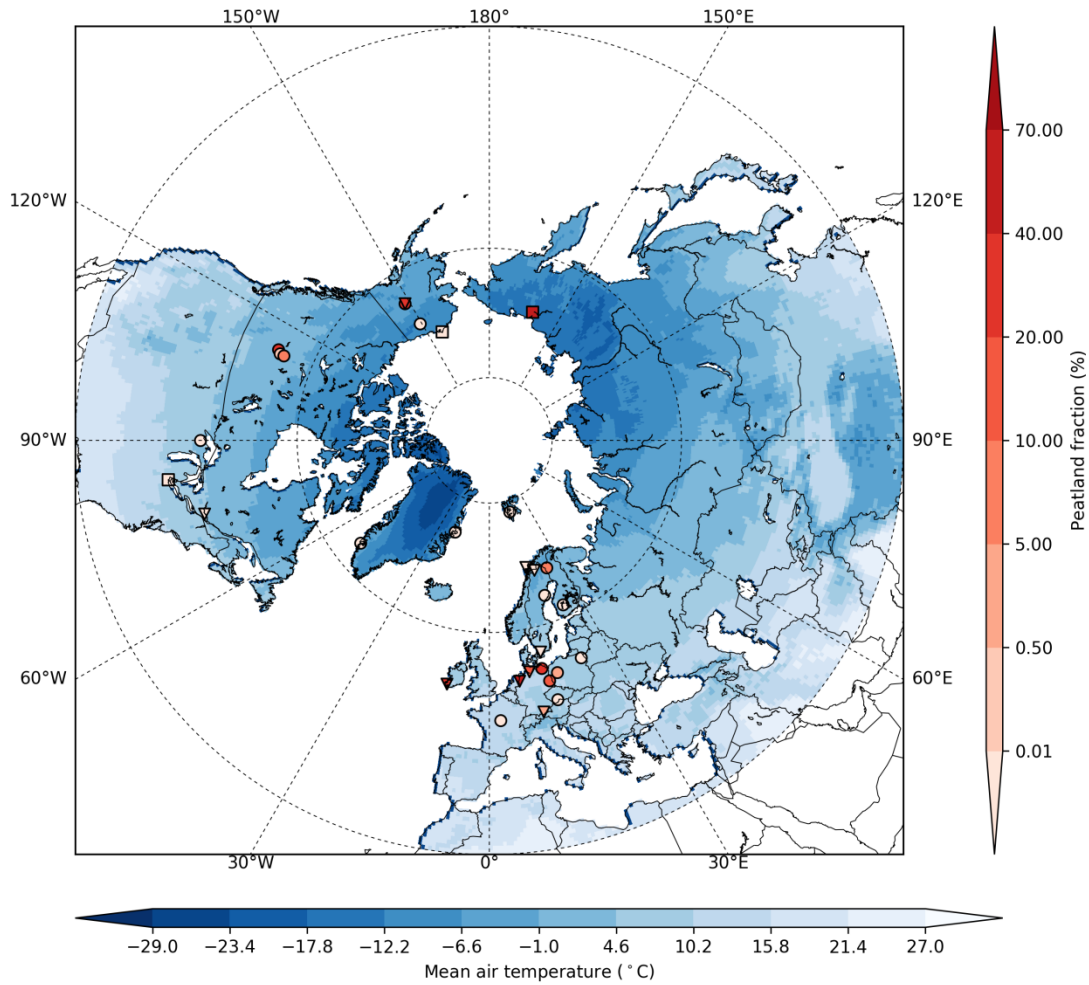
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1243 **Fig. 2.** The distribution of 30 peatland sites used in this study. Triangles are bogs; circles are
1244 fens; squares are tundra and marsh. Colors of the markers indicate peatland fractions in the
1245 0.5° grid cell. Mean air temperatures is the annual mean from 1999 to 2015, based on the
1246 6-hourly CRU-NCEP 0.5° global database.

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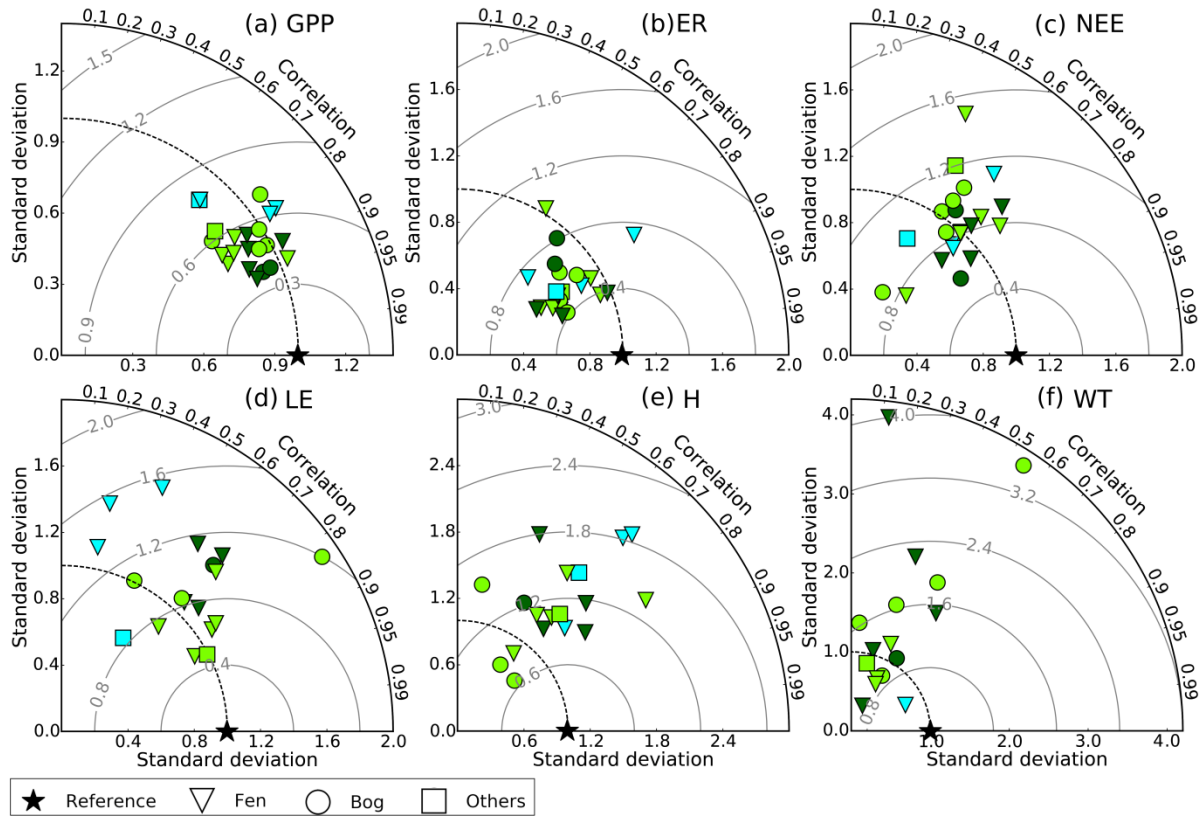
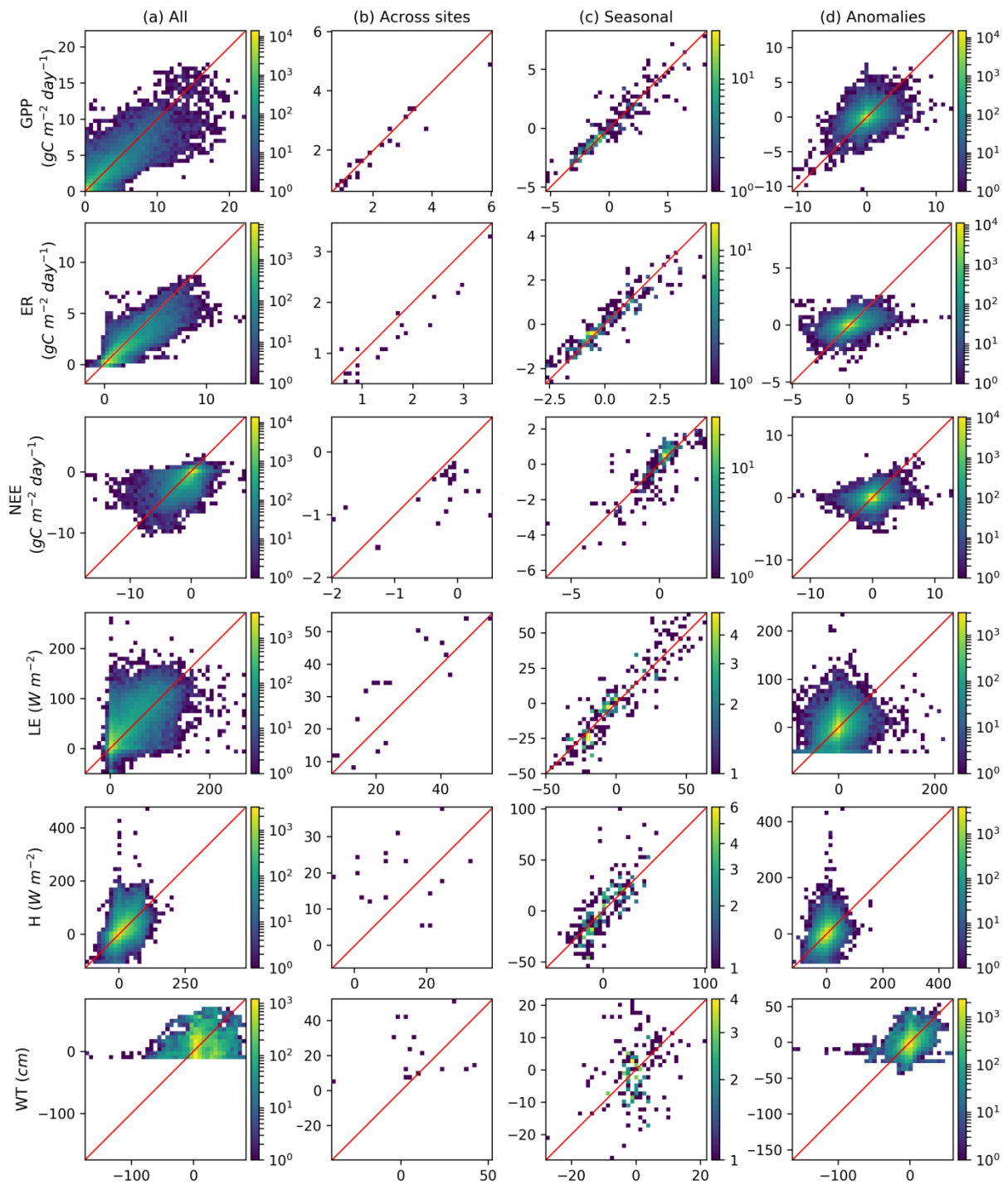


Fig. 3. Taylor diagrams of: (a) GPP ($\text{g C m}^{-2} \text{ day}^{-1}$); (b) ER ($\text{g C m}^{-2} \text{ day}^{-1}$); (c) NEE ($\text{g C m}^{-2} \text{ day}^{-1}$); (d) LE (W m^{-2}); (e) H (W m^{-2}) and (f) Water table depth (WT, cm). All statistics were calculated using daily averaged data. 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.



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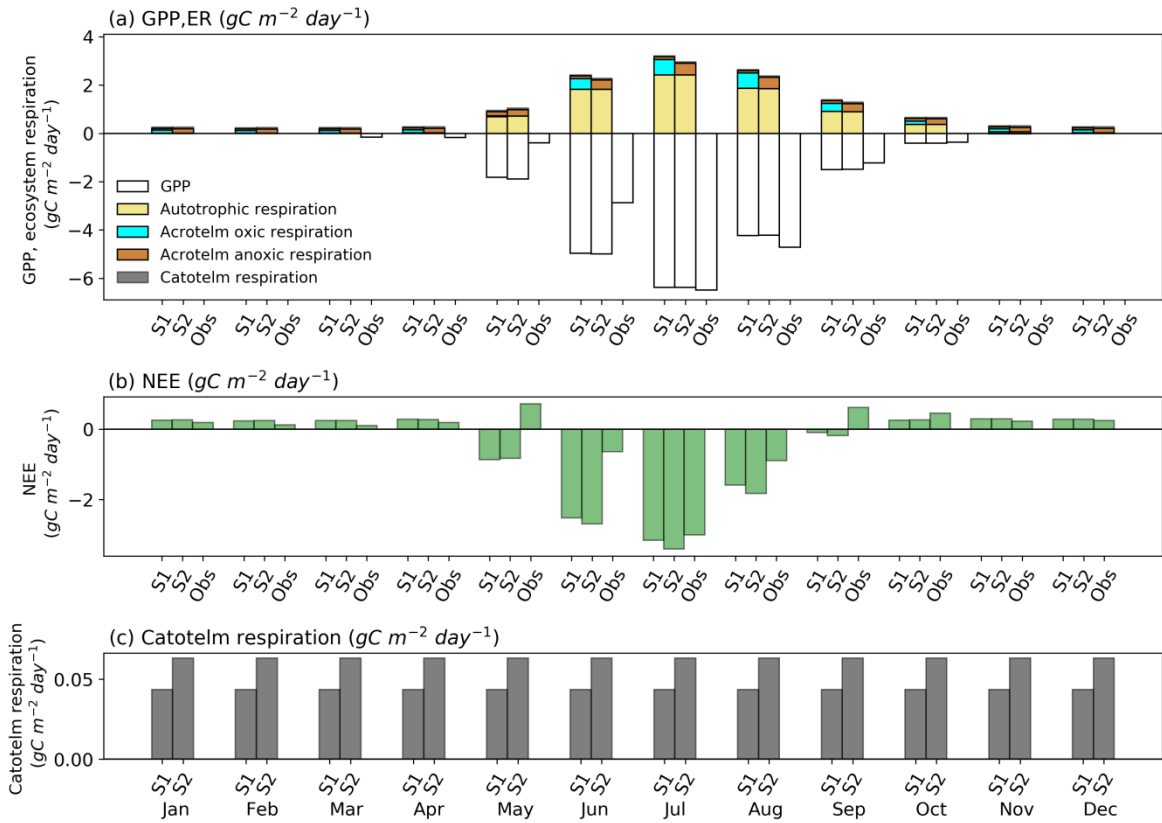
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Fig. 4. Observed (x-axis) versus simulated (y-axis) fluxes (GPP, ER, NEE, LE, H, and WT) at the 22 sites where GPP derived from EC measurements were available. Fluxes were simulated using site-specific optimized V_{cmax} . The colors of points indicate 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.

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1275 **Fig. 5.** Monthly mean (averaged over 2007–2009) of (a) GPP and ecosystem respiration(ER);
 1276 (b) NEE; (c) catotelm respiration at Lompoloj änkki fen site (FI-Lom). S1: simulated water
 1277 table (WT) was used in the carbon module; S2: observed WT values (WT_{obs}) was used; ob:
 1278 measured NEE. The graph inserted shows catotelm respiration. By convention, a source of
 1279 CO_2 to the atmosphere is a positive number.

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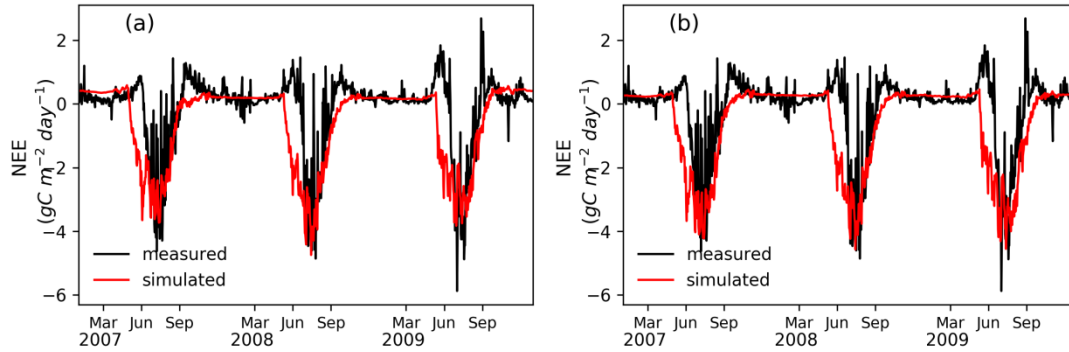
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1291 **Fig. 6.** Observed and simulated daily mean NEE at FI-Lom fen site in a) S1 (Simulated WT
1292 was used in the carbon module); (b) S2 (modeled water table was assimilated to observed
1293 values (WT_{obs}) and was used in the carbon module).

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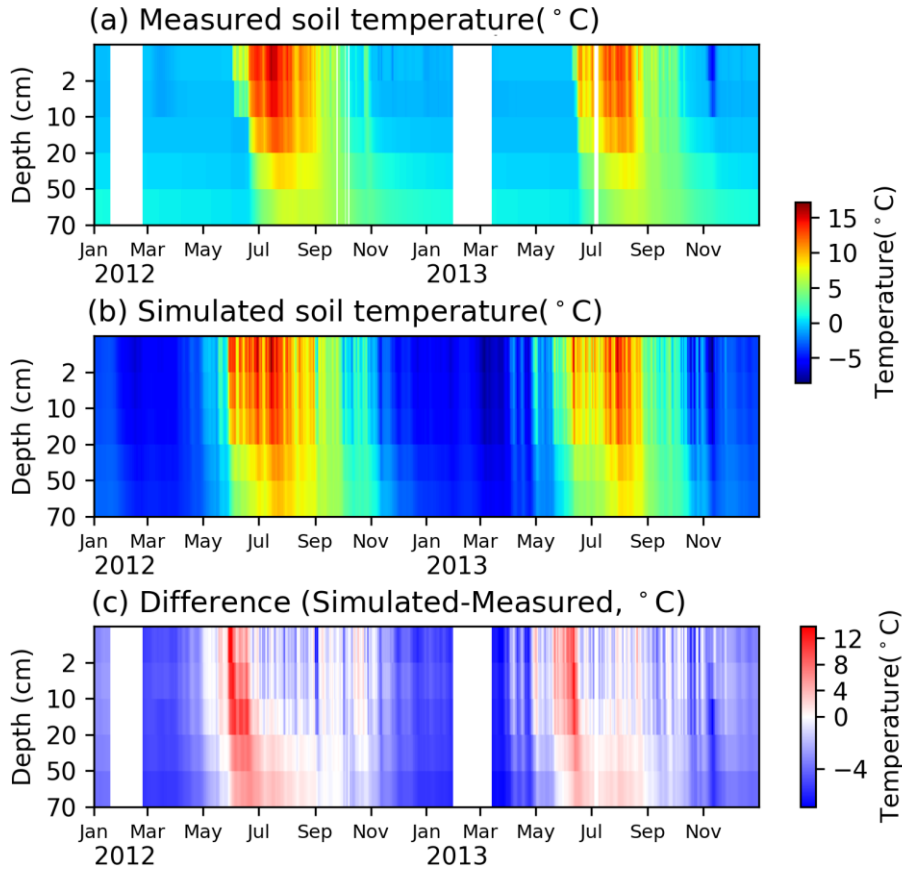
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1313 **Fig. 7.** Measured (a), simulated (b) soil temperature, and their difference (c) at DK-Nuf
1314 (64.13 °, -51.39 °) fen site. Soil temperature was measured at 2, 10, 20, 50 and 70 cm below
1315 soil surface. To compare simulated soil temperatures with the measurements, we linearly
1316 interpolated simulated soil temperature in different layers to the depths of the measurements.

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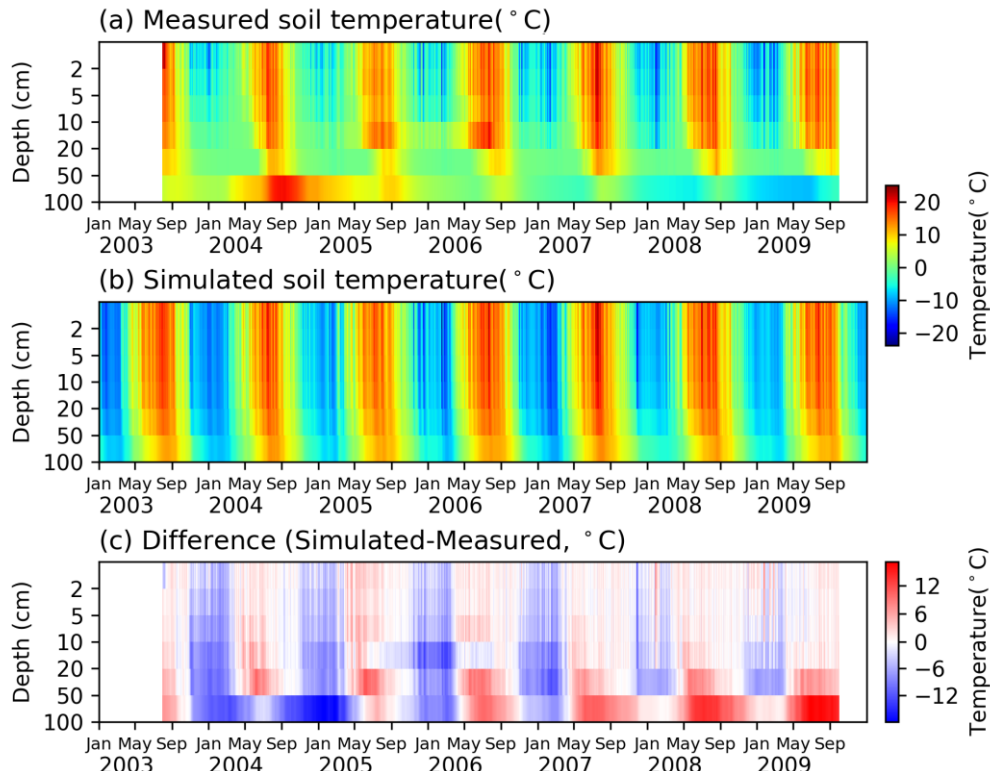
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1327 **Fig. 8.** Measured (a), simulated (b) soil temperature, and their difference (c) at CA-Wp1

1328 (54.95 °, -112.47 °) fen site. The measured soil temperature (a) is the mean of a hummock and

1329 a hollow. Soil temperature was measured at 2, 10, 20, 50 and 100 cm below soil surface. To

1330 compare simulated soil temperatures with the measurements, we linearly interpolated

1331 simulated soil temperature in different layers to the depths of the measurements.

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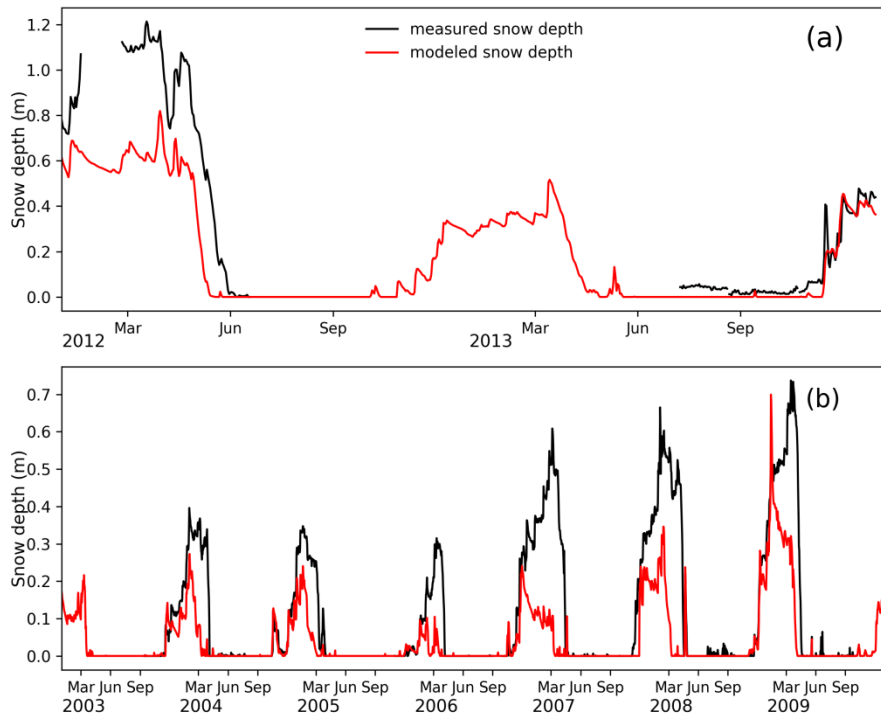
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1343 **Fig. 9.** Simulated versus measured snow depth (m) at (a) DK-Nuf fen and (b) CA-Wp1 fen.

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1348 **Table 1.** Van Genuchten parameters used for different soil texture classes for non-peat soils
1349 (coarse, medium, fine), and for peat. θ_s is the saturated water content ($\text{m}^3 \text{m}^{-3}$), θ_r is the
1350 residual water content ($\text{m}^3 \text{m}^{-3}$); $K_{s\text{-ref}}$ is the reference saturated hydraulic conductivity (m s^{-1});
1351 α is the inverse of the air entry suction (m^{-1}); n is a dimensionless parameter. In Eq. 1 and Eq.
1352 2, $m = 1-1/n$.

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	$K_{s\text{-ref}}$ (m s^{-1})	n	α (m^{-1})	θ_s ($\text{m}^3 \text{m}^{-3}$)	θ_r ($\text{m}^3 \text{m}^{-3}$)
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(°C)	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 vegetation: 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 cover: trees, grasses			Vanselow-Algan et al., 2015

n	DE-Zrk	53.9	12.9	temperate	fen	584	8.7	<0.5	23.16%	2013	grasses				Franz et al., 2016
										-2014					
n	CA-Wp3	54.5	-113.3	boreal	fen	504	2.1	670	29.77%	2004	grasses,mosses	1.1	0.157		Adkinson et al., 2011
										-2006					
n	CA-Wp1	55.0	-112.5	boreal	fen	504	2.1	540	0.20%	2003	trees, shrubs, mosses	2.6	1.08		Flanagan and Syed, 2011
										-2009					
n	CA-Wp2	55.5	-112.3	boreal	fen	504	2.1	730	8.07%	2004	shrubs,grasses, mosses	1.5	0.231		Adkinson et al., 2011
										-2006					
y	SE-faj	56.3	13.6	temperate	bog	700	6.2	140	Mean	2005	shrubs,grasses, mosses			dwarf shrub: 0.153;Sphagnum: 0.192; graminoid: 0.077	Lund et al., 2007, 2012
										-2009					
n	FI-Sii	61.8	24.2	boreal	fen	713	3.3	162	Mean	2005	shrubs,grasses, mosses	0.55		(maximum value, occurs in June-July)	Aurela et al., 2007; Riutta et al., 2007
										-2014					
n	DK-NuF	64.1	-51.4	arctic	fen	750	-1.4	40	Mean	2008	grasses,mosses	0.7			Westergaard-Nielsen et al., 2013
										-2014					
y	SE-Deg	64.2	19.6	boreal	fen	523	1.2	270	Mean	2001	shrubs,grasses, mosses	0.47		moss: 0.065; vascular : 0.049	Sagerfors et al., 2008; Nilsson et al., 2008; Peichl et al., 2014
										-2005					
n	US-Bog	64.7	-148.3	boreal, thermokarst	bog	146	-2.2	100	28.01%	2011	trees, mosses				Euskirchen et al., 2014
						(GS)				-2015					
n	US-Fen	64.7	-148.3	boreal	fen	146	-2.2	100	28.01%	2011	grasses, forbs				Euskirchen et al., 2014
						(GS)				-2015					
y	FI-Lom	68.0	24.2	boreal	fen	521	-1	269	5.08%	2007	shrubs,grasses,	1.3			Aurela et al., 2009

											-2009	mosses			
n	SE-Sto	68.4	19.1	boreal, permafrost	bog	322	-0.14	360	Mean	2014	shrubs,grasses, -2015	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	shrubs, grasses -2011			Euskirchen et al., 2012, 2016	
n	RU-Che	68.6	161.3	arctic, permafrost	tundra	200	-12.5 -215	4	64.09%	2002	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	shrubs,grasses, -2014	mosses		Lund et al., 2015	
n	US-Bes	71.3	-156.6	arctic, permafrost	tundra	173	-12	4	Mean	2005	grasses,mosses -2008			Zona et al., 2009	
n	DK-Zaf	74.5	-20.6	arctic, permafrost	fen	211	-9	35	Mean	2008	grasses,mosses -2011	0.65	0.471	Stiegler et al., 2016	
n	NO-Adv	78.2	15.9	arctic, permafrost	fen	190	-6.7	17	Mean	2011	shrubs,grasses, -2014	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} ($\mu\text{mol m}^{-2} \text{s}^{-1}$) 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, LE, H and 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} ($40 \mu\text{mol m}^{-2} \text{s}^{-1}$) at all sites.

Flux	Site-specific optimized V_{cmax}					Mean V_{cmax} (constant value, $40 \mu\text{mol m}^{-2} \text{s}^{-1}$)				
	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).

Site	Modeled WT used (S1)					Observed WT used (S2)				
	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 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).

Site	Modeled WT used (S1)					Observed WT used (S2)				
	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 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