Peatland evaporation across hemispheres: contrasting controls and sensitivity to climate warming driven by plant functional types

Leeza Speranskaya[1], David I. Campbell[1], Peter M. Lafleur[2], Elyn R. Humphreys[3]

[1] Environmental Research Institute, School of Science~~Faculty of Science and Engineering~~, University of Waikato, Hamilton, 3216, Aotearoa New Zealand
[2] School of Environment, Trent University, Peterborough, ON K9L 0G2, Canada
[3] Geography and Environmental Studies, Carleton University, Ottawa, ON K1S 5B6, Canada

Correspondence to: David I. Campbell (david.campbell@waikato.ac.nz)

Abstract. Peatlands store disproportionally large amounts of carbon per unit area, a function that is dependent on maintaining high and stable water tables. Climate change is likely to negatively impact carbon storage in peatlands, in part due to increases in vapour pressure deficit (VPD) driving higher evaporation (E) rates. However, the response of E to increasing VPD depends on the dominant vegetation type within peatlands. In this study, we used multiple years of eddy covariance (EC) measurements to compare E regimes at two peatlands with contrasting vegetation types — Kopuatai bog in Aotearoa New Zealand, dominated by the vascular ~~jointed~~ wire rush *Empodisma robustum*, and Mer Bleue bog in Canada, a 'typical' shrub and moss-dominated Northern Hemisphere peatland. We examined seasonal variability in E and equilibrium E (E_{eq}), energy balance partitioning, and the response of E, evaporative fraction (EF), and canopy conductance (g_c) to VPD. Mean annual E was 45% lower than mean annual E_{eq} at Kopuatai, but only 16% lower at Mer Bleue, demonstrating much greater limitations on E at Kopuatai. In addition, the mean midday (10:00–14:30) dry canopy Bowen ratio (β) at Kopuatai was 2.0~~1.96~~, compared to 0.8~~77~~ at Mer Bleue; therefore, the sensible heat flux (H) dominated over the latent heat flux (LE) at Kopuatai, and vice versa at Mer Bleue. The responses of E, EF, and g_c to increasing VPD at Kopuatai ~~differed from those at Mer Bleue in a way that resulted in~~ demonstrated stronger limitations on evaporative water loss ~~E above~~ for VPD ~~>~~ > 0.7 kPa compared to Mer Bleue~~at the former bog~~Kopuatai. The observed limitations at Kopuatai were attributed to strong stomatal control by *E. robustum* due to the rapid decrease in g_c with increasing VPD, however surface E could also be limited by its dense standing litter. At Mer Bleue, however, E was only weakly limited at VPD > 2 kPa, likely due to weak stomatal control over transpiration by the sparse shrub canopy and relatively large surface E from *Sphagnum* carpets. As such, the results of this study suggest that *E. robustum* drives a greater "hydrological resistance" to increasing VPD than the vegetation at Mer Bleue, leading to greater water retention at Kopuatai. This may enable greater resilience of the carbon sink function at Kopuatai to climatic warming and drying than at Mer Bleue.

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1 Introduction

Global peatlands have accumulated carbon (C) stocks of ~~at least~~ 500 Pg ~~or more~~ over thousands of years, resulting in a net cooling effect on the climate (Yu et al., 2010; Frolking and Roulet, 2007). This C stock is estimated to make up a third of global soil C (based on a median estimate of 1460.5 Pg), despite only occupying ~3% of Earth's land surface area (Scharlemann et al., 2014; Xu et al., 2018). Carbon accumulation as peat occurs in undisturbed peatlands when the rate of organic matter deposition exceeds decomposition, due to limitations imposed on decomposition by waterlogged conditions and the presence of decay-resistant plant litter (Joosten and Clarke, 2002; Holden, 2005). Therefore, long-term C sequestration in peatlands depends on maintaining a high and stable water table (Kim et al., 2021; Ma et al., 2022).

Evaporation (E)[1] is an important indirect influence on peat accumulation, as it reduces available water and contributes to water table drawdown. Evaporation consists of three main components — transpiration, surface E (either from water, soil, or non-vascular plant surfaces), and interception loss from vegetation surfaces — ~~,~~ and ~~is~~are influenced by a number of meteorological (solar radiation, vapour pressure deficit (VPD)) and surface factors (vegetation type and water table depth (WTD); Takagi et al., 1999; Shimoyama et al., 2003; Wu et al., 2010). In bog ecosystems, where precipitation is the sole water input (Holden, 2005), conservation of water is particularly important; this occurs through limitations imposed on E by bog vegetation (Campbell and Williamson, 1997), as well as limitations on lateral and vertical drainage by low hydraulic conductivity ~~in~~ of the highly decomposed peat soils (Fraser et al., 2001). As such, vegetation type is often a major factor regulating water loss ~~E~~ from bogs (Lafleur and Roulet, 1992; Takagi et al., 1999; Admiral et al., 2006).

The response of E to increasing atmospheric demand, i.e., increasing VPD, is of particular interest, as climate change-related warming has been predicted to elevate VPD (Ficklin and Novick, 2017; Fang et al., 2022). Plant responses to changing VPD are ~~is~~ known to affect transpiration rates and CO_2 uptake (Grossiord et al., 2020). ~~As~~ With increasing VPD ~~increases~~, contrasting E responses have been observed across different vegetation types (Takagi et al., 1999; Admiral et al., 2006; Massman et al., 2019) and ecosystems (Helbig et al., 2020). For example, using eddy covariance (EC) data from 95 boreal peatland and forest sites, Helbig et al. (2020) demonstrated that E rates were elevated by increasing VPD in both ecosystem types, however E rates were 30% higher in boreal peatlands than in boreal forests at high VPD. This suggests that the stability of peatland hydrologicaly regimes and C stores may be at risk under future changes to the climate.

Kopuatai bog is a warm-temperate, ombrotrophic peatland on Te Ika-a-Māui /North Island of Aotearoa New Zealand. The vegetation at Kopuatai is dominated by the vascular plant *Empodisma robustum*, which has been implicated in severely restricting E (Campbell and Williamson, 1997). The hypothesised mechanisms for this are stomatal control of transpiration

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[1] 'Evaporation' refers to "the bulk flux of water vapour from land, including transpiration". We ~~did~~ do not use the term 'evapotranspiration', as both evaporation and transpiration involve the transformation of water from a liquid to a vapour (Miralles et al., 2020).

60 and limitation of surface *E* due to restricted water vapour diffusion from the substrate through the dense standing litter layer (Campbell and Williamson, 1997; Thompson et al., 1999). ~~Studies on ecosystem C balances have shown that~~ Carbon uptake at Kopuatai is greater than in analogous Northern Hemisphere peatlands, and exhibits resilience to drought (i.e., high annual net ecosystem C uptake rates~~balance~~ despite drought disturbance in summer; Goodrich et al., 2017). This could be a result of the year-round growing conditions (Campbell et al., 2014), in contrast to the temperature-limited growing season lengths in

65 Northern Hemisphere peatlands which constrain C uptake (Roehm and Roulet, 2003; Lafleur et al., 2001; Helfter et al., 2015). However, high C uptake rates and drought resilience could also be indirectly attributed to the extremely low *E*, which maximises available water and maintains a high and stable water table. Therefore, the *resilience* of C uptake at Kopuatai could be due to *resistance* of the hydrologica~~ly~~l regime to environmental stressors through limitations on *E*~~, thereby preventing major shifts in the hydrological regime~~ (based on resistance and resilience definitions ~~are~~ from Nimmo et al., 2015). As such, *E*

70 limitation could be a very important self-regulation mechanism in this peatland ecosystem type.

Like Kopuatai, many~~P~~peatlands have formed in warm climates~~;~~, however, the majority of the global peatland area occurs in boreal regions of the Northern Hemisphere (Vitt, 2006). One such peatland is ~~the~~ Mer Bleue bog in Canada, a shrub and *Sphagnum* moss-dominated bog ecosystem located in a cool continental climate zone (Moore et al., 2002). As one of the most

75 studied Northern Hemisphere peatlands, Mer Bleue has ~~an extensive~~a long record of *E* measurements and knowledge of *E* processes. Daily *E* rates at Mer Bleue are comparable to many other Northern Hemisphere peatlands~~; *E* rates,~~ and ~~has~~ have been shown to be ~~reduced by deep~~affected by water table ~~depth~~s (*E* is ~~reduced~~limited by deep water tables; Lafleur et al., 2005), ~~and regulated by~~ available energy (~~, which~~ drives increases in *E*), and ~~by~~ VPD (~~,~~ the effect of which varies depending on the partitioning of *E* between vascular and non-vascular sources~~;~~ (Admiral et al., 2006). The average net annual C uptake

80 at Mer Bleue is much lower than at Kopuatai, primarily due to net C losses during the winter period~~,~~ and a shorter growing season (Roulet et al., 2007; Goodrich et al., 2017).

Knowledge of *E* at Kopuatai bog is limited to the results of two short-term studies (Campbell and Williamson, 1997; Thompson et al., 1999)~~; therefore, long-term *E* datasets from Kopuatai have not yet been examined~~, so our understanding of the variability

85 and mechanisms of *E* restriction by *E. robustum* is incomplete. In addition, it is not yet known how these limitations on *E* may affect the response of the ecosystem at Kopuatai to climate warming, including its C sink status. Therefore, the aim of this study is to compare the *E* regime at Kopuatai to that of Mer Bleue, as an example of a 'typical' Northern Hemisphere peatland, to better understand the ~~potential~~ relative sensitivity of these systems to hydrological change under continued climate warming. Compared with previous studies, our study ~~benefits from~~utilises extensive multi-annual data~~sets~~ ~~records~~ at each site, thereby

90 analysing *E* characteristics over a wide range of climate and weather conditions. The objectives of this study are to (1) compare seasonal variability in actual *E* and equilibrium *E* (E_{eq}) at Kopuatai and Mer Bleue, (2) investigate energy balance partitioning and (3) examine the responses of *E*, evaporative fraction (EF), and canopy conductance (g_c) to VPD at each site. Our hypothesis

is that differences in seasonal E limitations, energy balance partitioning, and responses of E to VPD, such that more water is conserved at Kopuatai relative to Mer Bleue, can be attributed to differences in vegetation. If this hypothesis is correct, it is

95   possible that the water-conserving traits of *E. robustum* will enable greater resistance of the hydrological regime, and hence greater resilience of the C stores, to climate warming compared to typical Northern Hemisphere peatlands.

2 Methodology

2.1 Site descriptions

2.1.1 Kopuatai bog

100   Kopuatai bog is a 96 km^2 ombrotrophic peatland located in a warm-temperate oceanic climate in the Waikato region of Aotearoa New Zealand (37.388º S, 175.554º E). Kopuatai is Aotearoa's largest undisturbed bog, ~~representing~~ a remnant of formerly widespread and diverse lowland wetlands; these ecosystems ~~, which~~ have been reduced to 10% of their previous extent due to widespread drainage, primarily for agriculture (McGlone, 2009; Dymond et al., 2021). Peat at Kopuatai has accumulated over the last 11,700 years at an average rate of 0.9 mm year^{-1}, with a maximum depth of 14 m (Newnham et al.,

105   1995; Shearer, 1997). Probing at the research site showed a peat depth of 11 m.

The dominant peat-forming vegetation at Kopuatai is *E. robustum* (Wagstaff and Clarkson, 2012), a vascular, evergreen jointed rush-like plant that is part of the family Restionaceae (known as 'restiads'; Wagstaff and Clarkson, 2012). At the field site, *E. robustum* has a mean leaf area index (LAI) of 1.32 (Goodrich et al., 2015) and a mean canopy height of 0.48 m. *E. robustum*

110   forms a dense, negatively geotropic surface root mat approximately 50 mm ~~deep~~ thick which can hold up to 15 times its dry weight in water (Campbell, 1964; Agnew et al., 1993; Clarkson et al., 2009). In addition, *E. robustum* ~~the~~ has a ~~standing litter of E. robustum~~ intercepts a considerable quantity of precipitation ~~(Campbell and Williamson, 1997). It has been hypothesised that this~~ dense standing litter layer (litter biomass = 0.92 kg m^{-2}, where total canopy biomass = 1.80 kg m^{-2}), which can ~~also~~ restrict water vapour diffusion from the peat surface by limiting turbulent transport (Campbell and Williamson, 1997; Keyte

115   Beattie, 2014). However, *E. robustum* can also restrict water loss via transpiration through strong stomatal control (Campbell and Williamson, 1997). The roots of *E. robustum* are the main material from which peat is formed, however live mosses and decayed canopy litter are also bound by the~~se~~ roots ~~for~~ and contribute to peat formation (Campbell, 1964; Agnew et al., 1993). Other vegetation types found at this site include sedges (*Machaerina* spp. and *Schoenus brevifolius*), isolated shrubs of *Leptospermum scoparium* (manuka) and *Epacris pauciflora*, as well as small patches of *Sporadanthus ferrugineus*, another

120   restiad plant.

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2.1.2 Mer Bleue bog

Mer Bleue bog is a 28 km^2 ombrotrophic peatland (45.411° N, ~~–~~75.481° E) located near Ottawa, Canada, in a cool continental climate. Mer Bleue has many features in common with boreal peatlands~~,~~ but is located near the southern limit of the boreal climate zone (Hember et al., 2005). ~~This~~ Thise peatland was ~~formed~~ initiated 8,400 years ago~~, initially~~ as a fen, transitioning into a bog around 7,100–6,800 years ago (Roulet et al., 2007). At the research site, ~~Mer Bleue~~the bog is characterised by ~~a~~ hummock-hollow microtopography, and has peat depths of 5–6 m (Lafleur et al., 2005). The hummock height at Mer Bleue is 0.25 m, with a 70% cover of hummocks. The dominant vegetation consists of evergreen ericaceous and deciduous shrubs (e.g., *Chamaedaphne calyculata*, *Rhododendron groenlandicum*, *Kalmia angustifolium*, *Kalmia polifolia*, *Vaccinium myrtilloides*), with *Sphagnum* moss species as the dominant ground cover, including *S. capillifolium*, *S. papillosum*, and *S. magellanicum* (Bubier et al., 2006). The average shrub canopy height is 0.18 m (range = 0.10–0.30 m; Bubier et al., 2006); shrub vegetation makes up 61% of the total biomass on average, while *Sphagnum* capitula make up 30% (Moore et al., 2002). The total biomass ranges between 0.147 and 1.011 kg m^{-2}, while the LAI of dominant vascular species is 1.3 on average (Moore et al., 2002; Bubier et al., 2006).

### 2.2 Data collection and processing

2.2.1 Data collection

Flux tower and ancillary data~~Data has~~ have been collected at both sites for many years ~~–~~ in this study, data ~~collected between~~covering 1 January 2012 ~~and~~ to 31 December 2022 at Kopuatai (11 years) and 1 January 1999 ~~and~~ to 31 December 2018 at Mer Bleue (20 years) were used. At each site, 30-minute fluxes of latent heat (*LE*), sensible heat (*H*), soil heat (*G*) and net radiation (*R*$_n$), along with 30-minute data on environmental and weather variables, including air temperature (*T*$_{air}$), vapour pressure deficit (VPD), precipitation (*P*), and water table depth (WTD; measured relative to the hummock surface at Mer Bleue, while~~;~~ the Kopuatai peat surface lacks hummocks and hollows), were collected. Latent and sensible heat fluxes were measured using the eddy covariance (EC) technique (Burba, 2022). The EC system at Kopuatai is an open path system (Appendix A) situated at 4.25 m height, with uninterrupted fetch greater than 500 m in all directions (research site is shown in Fig. 1a). At Mer Bleue, a closed path EC system is situated at 3.0 m height, with a fetch greater than 500 m in all directions except south, where it is 200–300 m (~~research site is shown in~~ Fig. 1b).

Following collection, flux data were quality-controlled and gap-filled. ~~Full details of data processing, quality control, and gap-filling are provided in Goodrich et al. (2017) for Kopuatai. Gap-filled flux data were used for seasonal to annual E totals; other analyses used only filtered measurements.~~ For gap-filling of *LE* and *H* at Kopuatai, separate daytime and night-time neural network models used drivers of *R*$_n$, *T*$_{air}$, VPD, and modelled canopy wetness state (detailed below); further details on data processing, quality control, and gap-filling ~~is~~are provided in Goodrich et al. (2017)~~ for Kopuatai.~~. At Mer Bleue, gap-filling of

LE was carried out by developing a linear relationship between available energy (R_a) and *LE* for summer, and calculating a multiplier to adjust the estimated *LE* to observed *LE* over a moving window period (the window width ~~is~~ was 100 ~~consecutive available half~~ half-hours with available data moved in increments of 20 ~~half~~ half-hours). R_a was calculated as R_n minus the rate of change in *G* (calculated using peat temperature profiles) and energy storage terms (*J*) ~~and the ground heat flux (*G*), which was calculated using peat surface temperature profiles)~~. ~~Sensible~~ Gap-filled sensible heat fluxes were then calculated as the difference between R_a and *LE*. For both sites, gap-filled flux data were used for seasonal to annual *E* totals, while other analyses only used filtered measurements.

(a)

(b)
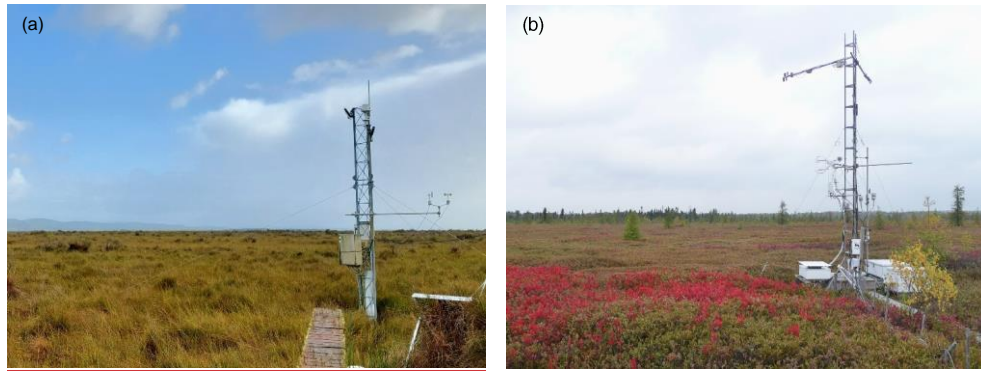
Figure 1. Images of the two sites including eddy covariance towers at (a) Kopuatai and (b) Mer Bleue.

2.2.2 Equilibrium evaporation

To provide a reference *E* rate at each site, the equilibrium evaporation (E_{eq}) was calculated using ~~gap-filled~~ 24-hour mean data ~~via the following equation~~:

$$E_{eq} = \frac{s(R_n - G)}{L_v(s + \gamma)} \tag{1}$$

where *s* is the slope of the saturation vapour pressure versus air temperature curve, L_v is the latent heat of vaporisation (dependent on T_{air}), and *γ* is the psychrometric constant (0.066 kPa ℃$^{-1}$). *G* was assumed to be 0 W m^{-2} due to the use of 24-hour mean data.

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The ~~proportion~~ ratio E/E_{eq}, i.e. the Priestley–Taylor α, was then calculated in order to be able to compare E regimes at the two sites despite differing climates. Gap-filled LE data were converted to $E = LE/L_v$ for this analysis.

~~E_{eq}~~ Equilibrium E was selected as a measure of potential E as it provides a more conservative estimate compared to other methods, such as the Penman equation (Granger, 1989). In addition, E_{eq} is less dependent on energy partitioning compared to Penman open water E (Thompson et al., 1999). As explained by Thompson et al. (1999), due to the high ratio of sensible to latent heat flux (i.e., a high Bowen ratio, ~~(β)~~) at Kopuatai, VPD is potentially larger than it would be above an extensive water surface in the same region, driving Penman open water E to an unrealistic level. Due to the lack of a VPD term in the E_{eq} equation, this effect is mitigated.

2.2.3 Energy balance partitioning and VPD analysis

The analysis of energy balance partitioning and the relationships of E, EF, and g_c with VPD involved the use of non-gap-filled E, R_n, LE, H, ~~and~~ VPD, and wind speed data, pre-filtered through quality control ~~processes~~ protocols. Further filtering was then carried out to obtain data for ~~These data were then filtered further – firstly, data were filtered by~~ growing season months (May–October at Mer Bleue and September–May at Kopuatai). In addition, all 30-minute data from both sites were filtered to select only "middle of day" (MoD) conditions (10:00–14:30 local standard time), ~~and~~ with an additional filter of $R_n \geq 200$ W m^{-2} applied to the VPD analysis. These 30-minute data were also filtered by dry or wet canopy conditions, which were identified using an antecedent precipitation index (API~~) at both Kopuatai and Mer Bleue (~~; Appendix B)~~.~~: ~~A~~an API ≤ 0.2 signifies a dry canopy, while API ≥ 1 indicates fully wet canopy conditions. These filtered 30-minute data were then used to calculate MoD means of all variables. Days with less than ~~three~~ five (50%) acceptable 30-minute MoD data points for all variables were removed to ensure representative MoD means. Overall, this filtering resulted in 5~~8~~6 % and 6~~6~~5 % of MoD dry canopy 30-minute data being rejected for Kopuatai and Mer Bleue, respectively~~, when obtaining dry canopy data~~. However, for wet canopy conditions, 90~~88~~ % (Kopuatai) and 92~~1~~ % (Mer Bleue) of MoD 30-minute data were rejected ~~for wet canopy data analyses~~. For the following analyses, 95 % confidence intervals were calculated for MoD means as the standard error multiplied by 1.96.

To analyse energy balance partitioning, ~~the~~ filtered growing season MoD mean LE and H data were binned by R_n (bin width = 50 W m^{-2}) for each site, taking the mean value of each bin. This was ~~done~~ calculated separately for dry and wet canopy conditions. Seasonal energy balance partitioning was also investigated by calculating monthly means of MoD dry canopy LE, H, and R_n; however, no other filters were applied to the data for this particular component of the analysis.

To demonstrate the relationship between evaporative water loss and ~~show the relationship of variables with~~ VPD, filtered dry canopy growing season MoD means of E, EF, and g_c were binned by VPD (0.1 kPa intervals), following Helbig et al. (2020),

taking the mean of each bin for all variables. ~~EF~~ Evaporative fraction was used to assess the change in energy balance partitioning into LE with increasing VPD~~,~~ and was calculated as:

$$EF = \frac{LE}{LE + H} \tag{2}$$

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The denominator $LE + H$ was used rather than R_n to prevent incomplete energy balance closure (Appendix C) from affecting our results. In addition, β was calculated as:

$$\beta = \frac{H}{LE} \tag{3}$$

210   Finally, g_c was calculated ~~as in~~ following Campbell and Williamson (1997):

$$\frac{1}{g_c} = \frac{(1 + \beta)\,\rho\,c_p\,\text{VPD}}{\gamma\,R_n} + \frac{r_a\,s\,\beta}{\gamma} - r_a \tag{4}$$

where ρ is air density (1.2 kg m^{-3}), c_p is the specific heat of air (1010 J kg^{-1} °C^{-1}), and r_a is aerodynamic resistance. Values of r_a were also calculated using the method from Campbell and Williamson (1997), which firstly required calculation of the
215   aerodynamic resistance to momentum transfer from the measurement height to the canopy (r_{aM}):

$$r_{aM} = \frac{u}{u_*^2} \tag{5}$$

where u is the horizontal wind speed and u_* is the friction velocity measured by the sonic anemometer.
Then, r_a was calculated as:

$$r_a = \frac{1.6}{k\,u_*} + r_{aM} \tag{6}$$

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where k is von Karman's constant (0.4).

2.2.4 Energy balance closure

Energy balance closure was imperfect at both sites, with 8~~4~~5% closure at Kopuatai and 89% at Mer Bleue (Appendix C). This could be due to a number of factors, such as mismatch between EC footprint characteristics for the turbulent and non-turbulent
225   energy balance terms, or increasing uncertainty of surface soil heat flux measurements due to peat accumulation, which

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increases the depth of soil heat flux plates over time. Energy imbalances could also be a result of a lack of sustained turbulence at these sites (Anderson and Wang, 2014), or due to the use of MoD means of energy balance components rather than 24-hour means (Leuning et al., 2012).

230   All analyses were carried out using MATLAB R2021b.

3 Results

3.1 Climate and hydrology

Mean annual precipitation (P) was 1213 ± 147 mm (± 95% confidence interval) at Kopuatai (2012–2022), compared to 879 ± 58.1 mm at Mer Bleue (1999–2018). Mean monthly P ranged between 49–139 mm and 50–100 mm at Kopuatai and Mer

235   Bleue, respectively, with the minimum monthly P occurring during the warm season at Kopuatai and the cool season at Mer Bleue (Fig. 21a). The mean monthly air temperature (T_{air}) range was much smaller at Kopuatai (9.3–19.0 °C) than at Mer Bleue (−10.0–20.2 °C) (Fig. 21b), with mean annual temperatures of 14.1 ± 0.27 °C and 6.2 ± 0.31 °C at the two sites, respectively. Mean annual VPD was 0.39 ± 0.013 kPa at Kopuatai and 0.38 ± 0.023 kPa at Mer Bleue, and monthly mean VPD ranged between 0.17–0.68 kPa and 0.07–0.77 kPa (Fig. 21c). Mean annual WTD was −82.6 ± 14.4 mm at Kopuatai and

240   −377 ± 19.8 mm at Mer Bleue. Monthly mean WTD had narrower ranges and was shallower at Kopuatai than at Mer Bleue year-round; as a result, the WTD ranges at these sites did not overlap (−153 to −28 mm and −460 to −278 mm, respectively; Fig. 21d).

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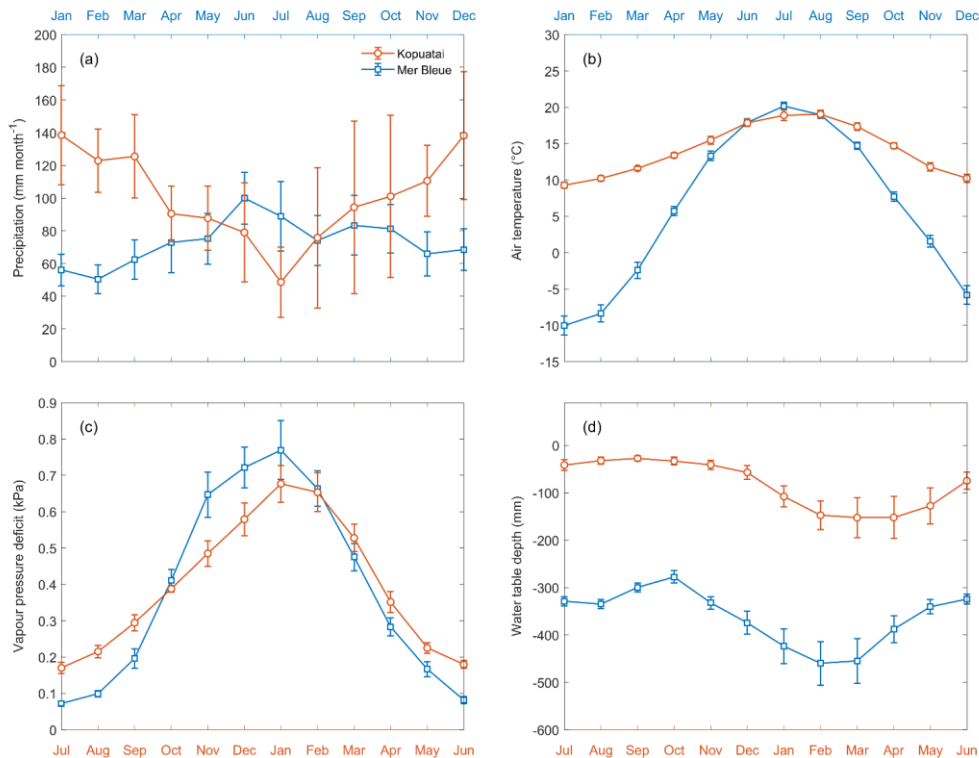
Figure 21. Mean monthly (a) precipitation (b) air temperature (c) vapour pressure deficit, and (d) water table depth at Kopuatai
(orange) and Mer Bleue (blue). These values were calculated using data between ~~1999–2018 (inclusive) at Mer Bleue and~~ 2012–2022
(inclusive) at Kopuatai and 1999–2018 (inclusive) at Mer Bleue. Error bars are 95% confidence intervals. Note that the Northern
and Southern Hemisphere seasons have been aligned by using separate *x*-axes for each site (Jan–Dec for Mer Bleue and Jul–Jun
for Kopuatai).

3.2 Evaporation and equilibrium evaporation

Mean annual E and E_{eq} were larger at Kopuatai compared to Mer Bleue, however, mean annual E/E_{eq} was lower at Kopuatai
(Table 1). In addition, growing season and year-round mean E/E_{eq} values were very similar at each respective site. At both
sites, mean monthly E was ~~below~~ less than E_{eq}, except during winter (Fig. 32). Both variables followed an expected seasonal
pattern of low values in winter and high values in summer, mostly driven by the amount of radiation ~~receipts~~ received. The
difference between E_{eq} and E was larger at Kopuatai than at Mer Bleue in non-winter months; the maximum difference between

10

monthly E_{eq} and E was 71 mm in January at Kopuatai, but only 21 mm in May at Mer Bleue ~~in May~~. Both E and E_{eq} were close to zero at Mer Bleue during winter (Dec–Feb), when ~~air temperature~~T_{air} was below 0 °C and the bog was ~~snow covered~~snow-covered, and both values were similar during spring (March) and autumn (October) months.

Table 1. Mean annual ecosystem evaporation (E) and equilibrium evaporation (E_{eq}), ~~and~~ with means and ranges of their ratios (i.e. Priestley–Taylor α) at each site ($n = 11$ and 20 years for Kopuatai and Mer Bleue, respectively). These values are given for both year-round data and for the growing season only (Sep–May at Kopuatai and May–Oct at Mer Bleue). Values in parentheses are 95% confidence intervals.

| Site | Annual | | | | Growing season only | | | |
	E (mm)	E_{eq} (mm)	E/E_{eq}	E/E_{eq} range	E (mm)	E_{eq} (mm)	E/E_{eq}	E/E_{eq} range
Kopuatai	578	910	0.64	0.57–0.70	482	816	0.59	0.52–0.65
	(± 13)	(± 18)	(± 0.022)		(± 11)	(± 19)	(± 0.023)	
Mer Bleue	450	530	0.85	0.76–0.95	388	466	0.83	0.70–0.94
	(± 17)	(± 13)	(± 0.026)		(± 16)	(±11)	(± 0.027)	
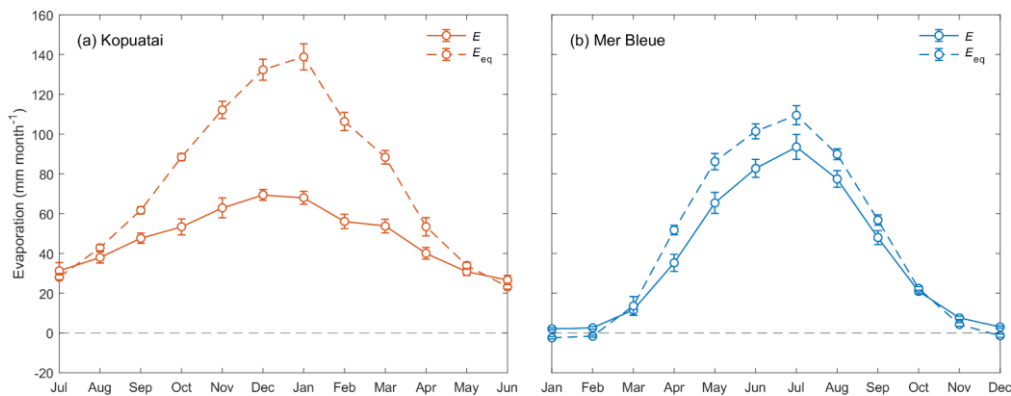
Figure 32. Mean monthly evaporation (*E*) and equilibrium evaporation (*E*$_{eq}$) at (a) Kopuatai and (b) Mer Bleue. Error bars represent 95% confidence intervals. Note that the *x*-axis for Kopuatai in the Southern Hemisphere starts from July (a six-month offset from the graph for Mer Bleue in the Northern Hemisphere).

270 **3.3 Dry canopy energy balance partitioning**

Seasonal energy balance partitioning was markedly different at each site. At Kopuatai, *H* was greater than *LE* in most months, with *LE* only comprising 21% of the annual R_n (Fig. 43). Between During autumn and winter (April to August), however, the difference between *H* and *LE* was smaller. In contrast, *LE* was a much larger component of the energy balance at Mer Bleue, representing 43% of the annual R_n due to *LE* exceeding *H* throughout most of the growing season. During the rest of the year,

275 however, *LE* was either less than or similar to *H*. There was also a difference in the seasonality of *LE*, *H*, and R_n between sites — at Kopuatai, all components of the energy balance reached a maximum during summer; *LE* and R_n peaked in mid-summer (January), while *H* peaked a month earlier. At Mer Bleue, *LE* and R_n also peaked during summer (in June and July, respectively), however *H* peaked in the middle of spring (April).

280 Mean monthly *LE* increased substantially (monthly range = 257 W m^{-2}) towards summer at Mer Bleue, while at Kopuatai, there was less monthly variation in *LE* (range = 79 W m^{-2}). Although the maximum monthly R_n (± 95% confidence interval) at Kopuatai was higher than at Mer Bleue (578 ± 26.0 W m^{-2} and 480 ± 17.7 W m^{-2}, respectively), maximum monthly *LE* at Kopuatai (124 ± 6.45 W m^{-2}) was lower than atrelative to Mer Bleue (264 ± 17.0 W m^{-2}). Consequently, the maximum monthly *H* was higher at Kopuatai than at Mer Bleue (304 ± 30.5 W m^{-2} and 191 ± 7.57 W m^{-2}, respectively). In addition, R_n

285 was particularly low in winter at Mer Bleue due to snow cover increasing albedo, and the lower solar receipt. During spring, R_n increased steeply (March and April) due to a decrease in albedo resulting followingfrom snowmelt. In contrast, Kopuatai does not receive snow, and seasonal albedo of the evergreen plant canopy does not vary substantiallyhardly varies (not shown).
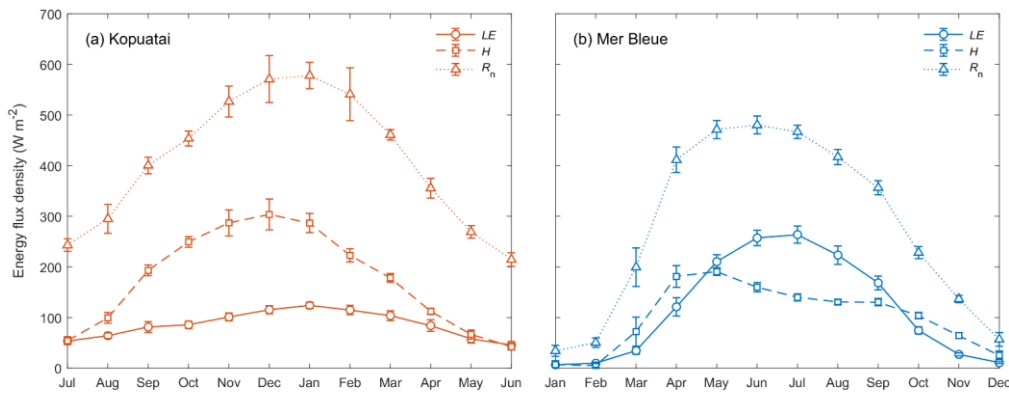
Figure 4~~3~~. Mean monthly energy balance partitioning (latent heat flux, *LE*, sensible heat flux, *H*, and net radiation, R_n) at (a) Kopuatai and (b) Mer Bleue for middle-of-day, dry canopy conditions. Error bars are 95% confidence intervals. ~~Note that the x-axis for Kopuatai starts from July (a six-month offset from the graph for Mer Bleue).~~ Note that the x-axis for Kopuatai in the Southern Hemisphere starts from July (a six-month offset from the graph for Mer Bleue in the Northern Hemisphere).

Middle-of-day ~~Daily~~ mean energy balance partitioning during dry canopy conditions was also distinctly different between Kopuatai and Mer Bleue (Fig. 5~~4~~). At Kopuatai, *H* was a much larger component of the energy balance than *LE* (Fig. 5~~4~~a); *H* was greater than *LE* at $R_n \geq 4$~~2~~50 W m^{-2}, which was reflected in a mean Bowen ratio (*β*) of 2.0~~1.96~~ (*β* range based on binned *H* and *LE* values was 0.43~~37~~–3.11~~2.91~~). At Mer Bleue, however, *LE* was either similar to or greater than *H* ~~at $R_n \geq 350$ W m^{-2}~~ (Fig. 5~~4~~b). As a result, mean *β* was 0.80~~77~~, with a range of 0.63~~1~~–1.05.
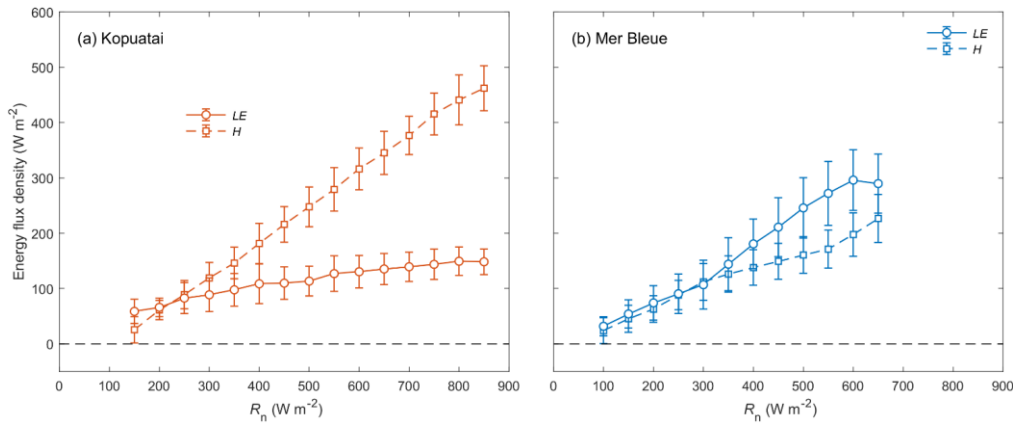
Figure 54. Relationship between binned ~~mean~~ middle-of-day ~~mean~~ latent and sensible heat fluxes (*LE* ~~and,~~ *H*)~~,~~ ~~and~~ versus net radiation (*R*$_n$) for dry canopy conditions at (a) Kopuatai and (b) Mer Bleue. Values are for the growing season only (Sep–May at Kopuatai and May–Oct at Mer Bleue). Error bars are standard deviations.

3.4 Wet canopy energy balance partitioning

During wet canopy conditions, the limitation on *LE* observed at Kopuatai under dry canopy conditions was not apparent (Fig. 65a); *LE* was greater than *H* at both low and high *R*$_n$ in these conditions (*β* ranged between 0.01 ~~0.01~~ 0.943, with a mean of 0.4851). Both *LE* and *H* increased at approximately the same rate with increasing *R*$_n$. At Mer Bleue, the relationship between *LE*, *H*, and *R*$_n$ under wet canopy conditions ~~was~~ appeared similar to dry canopy conditions, with a lower mean *β* of 0.587 and a range of ~~-~~0.378–0.853 (Fig. 65b).

14
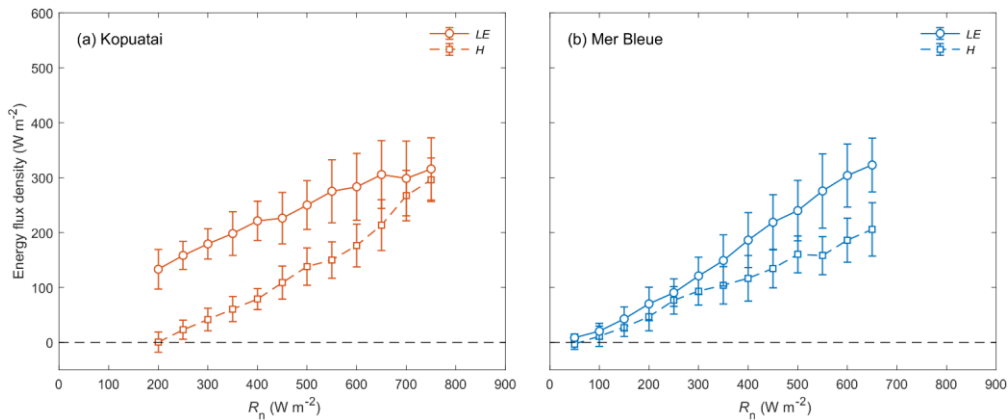
Figure 65. Relationship between binned ~~daily~~ mean middle-of-day ~~mean~~ latent and sensible heat fluxes (*LE* and, *H*), and versus net radiation (*R*ₙ) for wet canopy conditions at (a) Kopuatai and (b) Mer Bleue. Values are for the growing season only (Sep–May at Kopuatai and May–Oct at Mer Bleue). Error bars are standard deviations.

315 **3.5 Response of *E*, EF, and *g*c to VPD**

~~E~~Dry canopy ~~evaporation~~ *E* rates increased with increasing VPD at both sites, i.e. greater water loss occurred at high VPD (Fig. 76a). ~~B~~For VPD <~~elow~~ 2.0 kPa, the rate of increase in *E* with increasing VPD was 3.47 times larger at Mer Bleue (0.21721 mm hr⁻¹ /kPa⁻¹) than at Kopuatai (0.0640 mm hr⁻¹ /kPa⁻¹). This resulted in a higher *E* rate of 0.44 mm h⁻¹ at VPD = 2.0 kPa at Mer Bleue, compared to only 0.23 mm h⁻¹ at the same VPD at Kopuatai. Beyond VPD = 2.0 kPa, *E* showed little or no
320 change with increasing VPD at both sites.
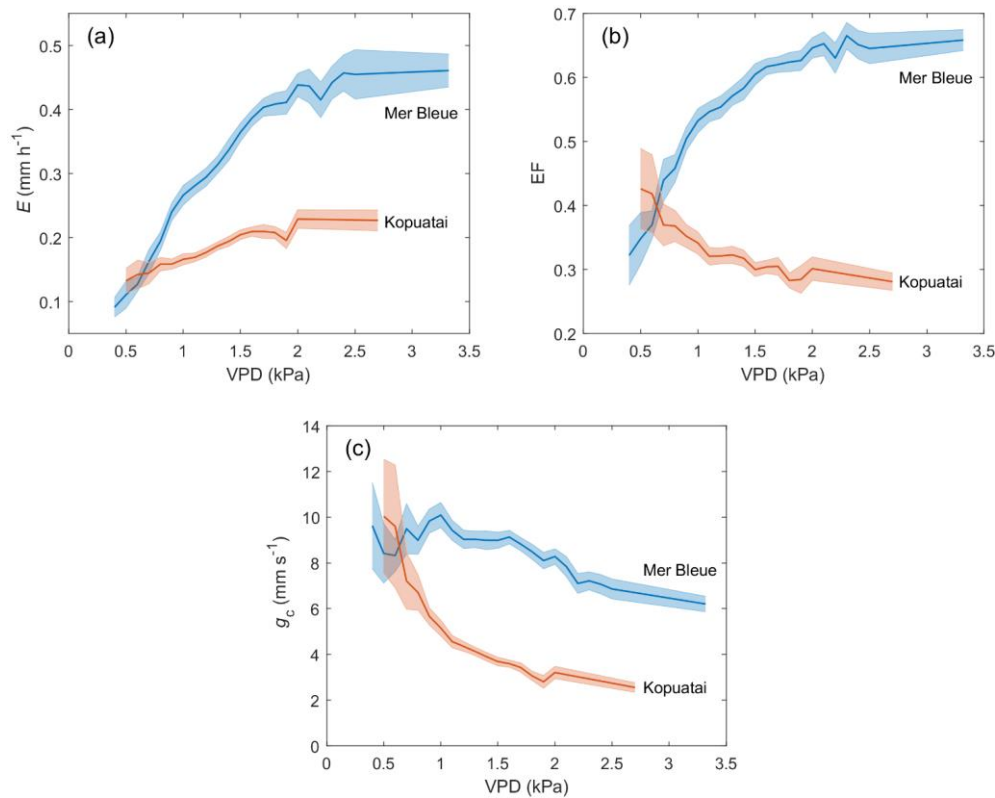
15

Figure 76. Middle-of-day mean growing season (a) evaporation (E), (b) evaporative fraction (EF), and (c) canopy conductance (g_c) for 0.1 kPa bins of vapour pressure deficit (VPD) during dry canopy conditions at Kopuatai and Mer Bleue. Shaded areas represent 95% confidence intervals.

At Kopuatai, EF decreased in response to increasing VPD, while the opposite trend was observed at Mer Bleue (Fig. 7b7). Thisese contrasting in responses of EF to increasing VPD was were also evident in 30-minute data (Appendix D). At Kopuatai, mean daytime EF decreased from 0.434 at VPD = 0.5 kPa to 0.28 at 2.7 kPa, and increased from 0.321 at 0.4 kPa to 0.66 at 3.3 kPa at Mer Bleue bog. At both sites, the rate of increase or decrease in EF was reduced at VPD > 1.0 kPa.

There was a steep decline in g_c with increasing VPD at Kopuatai (Fig. 7c8); mean g_c decreased from a maximum of 10.06 mm s^{-1} at a VPD of 0.5 kPa to a minimum of 2.557 mm s^{-1} at 2.7 kPa. In contrast, the pattern of declining g_c with increasing VPD was weak at Mer Bleue, decreasing from 9.6310 mm s^{-1} at 0.4 kPa to 6.203 mm s^{-1} at 3.3 kPa.

4 Discussion

4.1 Evaporation regimes

Our study demonstrates the crucial importance of vegetation characteristics in controlling water losses from peatlands. Kopuatai and Mer Bleue, two ombrotrophic bogs with different vegetation communities, display strikingly different E evaporation regimes, energy balance partitioning, and responses of E, EF, and g_c to VPD. Despite being in a warmer climate zone with warm winters, the E regime at Kopuatai was more conservative than at Mer Bleue. Although mean annual E and E_{eq} were 25% and 53% higher at Kopuatai than at Mer Bleue, mean annual E/E_{eq} (i.e, Priestley–Taylor α) was 28% lower at Kopuatai. This occurred because the mean annual E was 45% lower than mean annual E_{eq} at Kopuatai, while at Mer Bleue there was only a 16% difference. The large difference between E and E_{eq} at Kopuatai occurred due to the conservative E, andas well as the relatively high E_{eq}, resulting from the higher R_n (due to latitudinal differences), a warmer climate, and longer growing season compared to Mer Bleue. These results indicate that greater surface limitations were imposed on E at Kopuatai relative to Mer Bleue. The difference in E/E_{eq} between the two sites is highly likely to be a result of differences in functional vegetation types, as different vegetation communities, even at the same peatland, have been shown to result in different contrasting E regimes (Takagi et al., 1999; Strilesky and Humphreys, 2012). As such, Thethe substantial limitations on E observed at Kopuatai likely occurred due to the physiological and canopy structural features of the dominant vascular plant, *E. robustum*. However, some limitation on E was observed at Mer Bleue, as evidenced by the decrease in E/E_{eq} towards mid-summer. It is possible that this occurred due to stomatal closure in the shrub vegetation in response to high VPD (Admiral et al., 2006). However, this the impact of this limitation was weaker than at Kopuatai, likely due to high surface E from *Sphagnum* carpets at Mer Bleue (Admiral et al., 2006).

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At Kopuatai, the entire range of E/E_{eq} values tended to be lower than at most Northern Hemisphere peatlands, while the E/E_{eq} range at Mer Bleue overlapped with the lower end of most of these ranges (Table 2; we could not find equivalent studies for Southern Hemisphere peatlands). However, there were some northern peatland sites with E/E_{eq} ranges that were closer to those of Kopuatai. For example, a tree-dominated peatland in Canada had a lower E/E_{eq} than at Kopuatai, which could be attributed to stomatal limitation of transpiration (Brümmer et al., 2012), i.e., the same mechanism of E limitation as exhibited at Kopuatai, but to a greater extent. Of interest is also the Fäjemyr bog in Sweden, which had lower growing season E/E_{eq} values than most peatlands in Table 2 (but not Kopuatai), possibly due to a low water table and low surface conductance (Alekseychik et al., 2018). In addition, in an earlier study of E rates at Kopuatai, Thompson et al. (1999) reported lower E/E_{eq} values than those in this study; this could havelikely occurred due tobecause measurements being were made only during summer, when limitations on E are most prominent. Apart from these outliers, the E/E_{eq} values for Northern Hemisphere peatlands in Table 2 are generally much greater than at Kopuatai bog, indicating that *E. robustum* may be more adept at restricting E than the vascular and non-vascular vegetation in most Northern Hemispherenorthern peatlands.

4.2 Controls on evaporation

Our analysis focused on VPD as the driver of changes in E, EF, and g_c. However, VPD is strongly driven by T_{air} and humidity, with T_{air}, in turn, responding strongly to solar radiation via the surface radiation balance (Chang & Root, 1975; Grossiord et al., 2020). Disentangling the drivers of water vapour fluxes in vegetated environments is therefore challenging. At Kopuatai bog, Goodrich et al. (2015) used modified light-response models to disentangle the primary seasonal drivers of gross primary production (GPP) for the *E. robustum* canopy. Summertime GPP was strongly limited under high VPD conditions rather than high T_{air}, which they concluded was due to VPD-induced stomatal closure, implying that the transpiration component of E would be affected by changes in VPD. This variable has also been observed to drive stomatal response in other wetland settings (Takagi et al., 1998; Aurela et al., 2007; Otieno et al., 2012).

The steep decline in EF with increasing VPD at Kopuatai suggests strong surface controls on E at this site. A similar negative relationship between midsummer LE/R_n and VPD was shown by Takagi et al. (1999) at a section of a peatland invaded by vascular vegetation, which was attributed to stomatal closure. This is also likely to be the main factor limiting E from Kopuatai due to the non-linear decrease in canopy conductance (g_c) with increasing VPD, a trend that has also been observed in other peatlands (Humphreys et al., 2006; Peichl et al., 2013; Runkle et al., 2014; Alekseychik et al., 2018). However, it has also been hypothesised that the standing litter layer formed by *E. robustum* reduces E (Campbell and Williamson, 1997); this canopy feature has been observed to limit E in marsh, restored wetland, and dryland ecosystems (Goulden et al., 2007; Villegas et al., 20122010; Eichelmann et al., 2018). Standing litter restricts E by decoupling the subcanopy environment from atmospheric turbulence, and by preventing solar radiation from reaching the surface, which minimises the variability of T_{air} and VPD below

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the litter layer (Goulden et al., 2007; Eichelmann et al., 2018). Although ~~the results of this study~~we cannot separate the effects
390   of stomatal closure and standing litter on E, it is likely that both of these factors act in tandem to severely restrict E at Kopuatai.

Table 2. Summary of studies reporting ~~Ranges of~~ the ratio of evaporation to equilibrium evaporation (~~-~~E/E_{eq}~~-~~) ~~calculated~~ for peatlands globally (including this study), with a description of the type of variability covered in the range of E/E_{eq} values, and the time period for which they were calculated.

Location	Dominant vegetation types	E/E_{eq} ~~(i.e., Priestley-Taylor α)~~	Range type	Time period	Reference
Kopuatai bog, Aotearoa New Zealand	*Empodisma robustum*	0.57–0.70	Interannual variability	Year-round	This study
		0.52–0.65	Interannual variability	Growing season (Sep–May)	This study
	Empodisma robustum	0.34	N/A	Growing season (Nov–Mar)	Thompson et al. (1999)
	Sporadanthus ferrugineus [a]	0.58	N/A	Summer period (Jan–Mar)	Thompson et al. (1999)
Mer Bleue bog, Canada	Shrubs and *Sphagnum* moss	0.76–0.95	Interannual variability	Year-round	This study
		0.70–0.94	Interannual variability	Growing season (May–Oct)	This study
Plotnikovo, Russia	Sedges, shrubs, and *Sphagnum* moss	0.99–1.29 (1999) 0.96–1.07 (2000)	Seasonal variability	Growing season (Apr–Oct)	Shimoyama et al. (2004)
Sandhill fen, Canada	Trees, shrubs, and brown moss	0.79–1.04	Interannual variability	Snow-free periods (May–Nov)	Sonnentag et al. (2010)
Alberta, Canada	Trees, shrubs, and various mosses	0.55–0.57	Interannual variability	Year-round	Brümmer et al. (2012)
Degerö Stormyr, Sweden	Shrubs, grasses, and *Sphagnum* moss	0.86–1.17	Interannual variability	Year-round	Peichl et al. (2013)
Siikaneva-1 & Siikaneva-2, Finland	Shrubs, sedges, and *Sphagnum* moss	1.09–1.21 & 1.11–1.13	Interannual variability	Growing season (May–Oct)	Alekseychik et al. (2018)
Fäjemyr bog, Sweden	Shrubs, sedges, *Sphagnum* moss, and sparse trees	0.66–0.71	Interannual variability	Growing season (May–Oct)	Alekseychik et al. (2018)
Seven peatlands in Canada	Shrubs, sedges, mosses (all peatlands), trees, and herbs (some peatlands)	0.82–1.05	Spatial variability	Midsummer period (Jul–Aug)	Humphreys et al. (2006)

[a] *A late-successional tall restiad plant that dominates portions of Kopuatai bog, but is not present at the EC site*

At Mer Bleue, E rates were almost double those of Kopuatai at high VPD, and there was a greater absolute increase in dry
canopy LE with increasing R_n at Mer Bleue than at Kopuatai (an increase of 254 W m^{-2} compared to 93 W m^{-2}, respectively),
indicating weaker water loss restrictions at Mer Bleue. Weak restrictions likely occurred because of the large contribution of
Sphagnum moss E during well-watered conditions, as moss E is enhanced substantially by increasing VPD (Admiral and
Lafleur, 2007). Since LE increased with increasing R_n, and E and EF increased with increasing VPD, both of these factors were
important controls on E and energy partitioning at Mer Bleue. Similar positive correlations between LE and R_n (or available
energy, R_n–G) at daily and monthly scales have previously been observed at other peatlands (Lafleur and Roulet, 1992;
Kurbatova et al., 2002; Brümmer et al., 2012), in addition to positive relationships between daily E and VPD (Wu et al., 2010;
Peichl et al., 2013; Wang et al., 2020).

There were also reduced rates of increase in E and EF with increasing VPD at Mer Bleue (i.e., a 'saturating' effect; also
observed in by data presented by Peichl et al., 2013), which only became evident at high VPD (above ~2.0 kPa for E and ~1.0
kPa for EF; Figs. 76 and 7). This relatively weak E limitation was likely caused by stomatal control of transpiration by vascular
vegetation (Admiral et al., 2006), as a slight decrease in g_c was observed with increasing VPD. A similar relationship between
surface conductance and VPD has previously been observed at Mer Bleue (Humphreys et al., 2006). It has also been suggested
that E may become limited at high VPD if the transport rate of water through mosses is insufficient to meet the atmospheric
demand (Liljedahl et al., 2011). While we cannot determine whether this occurred at Mer Bleue using the data available, it is
possible that this may have been a contributing factor to limitations on E.

While there was almost no difference in energy balance partitioning between dry and wet canopy conditions at Mer Bleue, the
canopy wetness state had a major effect at Kopuatai. During dry canopy conditions, H was the dominant convective flux, as
the rate of increase in LE with increasing R_n was suppressed. However, LE became dominant over H during wet canopy
conditions, with a much greater rate of increase in LE with increasing R_n compared to dry canopy conditions. A previous study
at Kopuatai also reported dominance of LE over H when the canopy was rain-wetted, and vice versa during dry canopy
conditions (Campbell and Williamson, 1997). This contrast in energy partitioning likely occurred due to suppression of E from
the moist peat surface by the dense standing litter layer of *E. robustum* during dry canopy conditions.

The responses of E and EF to increasing VPD at Mer Bleue were consistent with previous findings by Helbig et al. (2020),
which synthesised data from 35 boreal peatlands, including Mer Bleue; however, the response at Kopuatai bog was closer to
that of the boreal forests included in their study. As such, the response of E to VPD at Kopuatai bog is distinctive compared to
boreal peatlands. This may be a critical adaptation that allows peat formation in a climate zone that is uncharacteristic for
ombrotrophic peatlands (McGlone, 2009) due to the combination of moderate precipitation and a higher mean annual
temperature than at Northern Hemisphere peatlands. Tropical peatlands also experience higher temperatures, however annual

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precipitation tends to be much higher than at Kopuatai (>2500 mm in Southeast Asia, for example; Page et al., 2006), which enables wet conditions to be maintained~~maintains adequately wet conditions~~. Therefore, it is likely that the dominance of *E. robustum* at Kopuatai is crucial to the persistence of this peatland in ~~its unusual~~ an atypical peatland climate zone due to
435 restrictions imposed on transpiration and sub-canopy *E*, as these adaptations likely contribute to maintaining a shallow and stable water table.

4.3 Implications for future peatland water balances

Northern Hemisphere peatlands, such as Mer Bleue, may be at risk of increased evaporative water loss as VPD increases due to climate warming (Helbig et al., 2020). This could lead to more frequent low water tables and water deficits, which in turn
440 may reduce net C uptake (Zhong et al., 2020; Kwon et al., 2022). The effect of low water tables on the C balance has previously been observed at Mer Bleue, where ~~decreases in~~lowering of water levels at a beaver pond near the EC site caused a decrease in C uptake; further modelling also predicted that a beaver pond water table below ~1.7 m would cause Mer Bleue to switch from a C sink to a source (He et al., 2022). Similar impacts were observed at Kopuatai~~D~~ during a severe drought in 2013, where ~~Kopuatai~~ monthly total ecosystem respiration increased in response to a slightly deeper water table, leading to a small
445 reduction in the annual net C balance (Goodrich et al., 2017). ~~A~~At a drainage-affected bog near Kopuatai, ~~the~~multi-year data indicated that the water table was substantially lower ~~mean~~ year-round and ~~water table at a drained *E. robustum* bog near Kopuatai also~~ caused lower C uptake rates compared to Kopuatai, but likely remained a C sink due to the tolerance of *E. robustum* to a low and fluctuating water table (Ratcliffe et al., 201~~8~~9). Therefore, ~~the~~ C uptake ~~of~~at both ~~peatlands~~Kopuatai and Mer Bleue could be impacted by decreased water tables; however, under increased VPD due to climate warming, it appears
450 that Kopuatai may be able to retain more water than Northern Hemisphere peatlands through strong constraints on *E*. This greater water retention at Kopuatai could enable current high and stable net annual C uptake rates (Goodrich et al., 2017) to be maintained despite warmer and potentially drier conditions in the future (Lawrence et al., 2022). Therefore, we propose that the previously observed resilience of C uptake at Kopuatai to dry conditions (Goodrich et al., 2017) primarily results from "hydrological resistance" to increasing VPD driven by the water conservative properties of the *E. robustum* canopy.

455 **5 Conclusions**

We compared ecosystem *E* regimes, energy balance partitioning, and the response of *E* to VPD at two peatlands — Kopuatai bog in Aotearoa New Zealand and Mer Bleue bog in Canada. Our motivation was to determine whether regulation of water losses in these peatlands with different vegetation communities enables hydrological resistance to climatic drying. Our results demonstrated that the *E* regime was much more conservative at Kopuatai than at Mer Bleue at high~~,~~ likely due to restrictions
460 imposed on g_c by the dominant vegetation species, *E. robustum*~~VPD because of greater limitations on *E*, which likely occurred due to reduced g_c~~. At Mer Bleue, *E* was only weakly limited at high VPD, as the impacts of reduced shrub g_c were likely offset by water loss from non-vascular moss surfaces. The greater limitations on *E* observed at Kopuatai indicate hydrological

resistance of this vascular plant-dominated ecosystem to hydro-climatic change. Importantly, this resistance likely contributes to resilience of the net C sink at Kopuatai, despite being located in a warm-temperate climate zone, and is thus ~~could be~~ a key

465   self-regulation mechanism. As a result, it appears that Kopuatai may be better equipped to conserve water and maintain high net C uptake rates than Mer Bleue, and perhaps other Northern Hemisphere peatlands, in the face of climate change-induced warming and drying. Further investigation of E partitioning into transpiration, interception loss, and peat surface E, and the role of the dense standing litter layer for E regulation at Kopuatai may yield additional insights into this observed hydrological resistance.

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Appendices

Appendix A

Table A1. Methods and instruments used for data collection at Kopuatai and Mer Bleue.

Variable	Kopuatai	Mer Bleue
Latent heat flux (LE)	4.25 m CSAT3 & CSAT3B (CSI); LI-7500 (LI-COR)	3.0 m 1012R3 & R3-50 (Gill); LI-6262 & LI7000 (LI-COR)
Sensible heat flux (H)	4.25 m CSAT3 & CSAT3B (CSI)	1012R3 & R3-50 (Gill)
Soil (peat) heat flux (G)	HFP01 (Hukseflux); TCAV (CSI)	N/A
Net radiation flux density (R_n)	2 m NR01 (Hukseflux)	CNR1 (Kipp & Zonen)
Air temperature (T_{air}) and vapour pressure deficit (VPD)	4.2 m HMP155 (Vaisala)	2 m HMP various models (Vaisala)
Precipitation (P)	0.6 m TB03 (Hydrological Services)	0.3 m TM525 tipping bucket gauge (Texas Instruments)
		Winter snowfall from Environment Canada weather station at Ottawa Airport
Water table depth (WTD)	Dipwell, WL1000 (Hydrological Services)	Float & potentiometer, and OTT PLS

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Appendix B

The antecedent precipitation index (API) is an exponential function used to predict the duration of canopy wetness after a rainfall event, with inputs of rainfall depth and time since rainfall (Keyte Beattie, 2014). Initially conceived by Woods and Rowe (1996) for predicting catchment moisture conditions prior to a rain event, the API function was then modified by Smith (2003) to estimate canopy wetness state:

$$\text{API} = \sum_{i=1}^{j} \frac{P_i}{1.104 \times 1.024^i} \tag{B1}$$

where P_i is precipitation (mm) measured during the ith half-hour period before the current half hour, and j is the moving window size in half hours (48 in this study). An example of modelled canopy drying using the API function is shown in Fig. ~~ure~~ B1. An API value of 0.2 units or less approximately represents a dry canopy, meaning that E is predominantly sourced from peat surface E and transpiration. When the API value is greater than or equal to 1, the vegetation canopy is ~~deemed~~ wet and interception loss is the dominant source of E.

Predictions of canopy wetness using ~~the~~ API have been shown to correspond reasonably well with leaf wetness sensor measurements at Kopuatai, using an API period of 18 hours for the upper canopy, 36 hours for the standing litter layer, and 60 hours for the lower canopy (Keyte Beattie, 2014). In this study, we defined wet canopy periods as times when the upper canopy was saturated, i.e., when interception loss likely made up the majority of E, so an 18-hour API period would likely be appropriate for this study. However, in order to ~~obtain a~~ conservative~~ly~~ identifi~~cation~~y ~~of~~ periods with a dry upper canopy, i.e., for greater certainty that the canopy is dry when API ≤ 0.2, a slightly longer period of 24 hours was used. While this approach has only been tested in the field at Kopuatai, for consistency we used the same function for separating wet and dry canopy measurements at Mer Bleue. Given the relatively sparse shrub canopy and absence of standing litter at Mer Bleue, API should provide conservative estimates of canopy dryness. The use of MoD data in this study is beneficial as it would have reduced the impact of early morning wetting from dew, therefore reducing the number of instances where API predicted canopy wetness incorrectly.
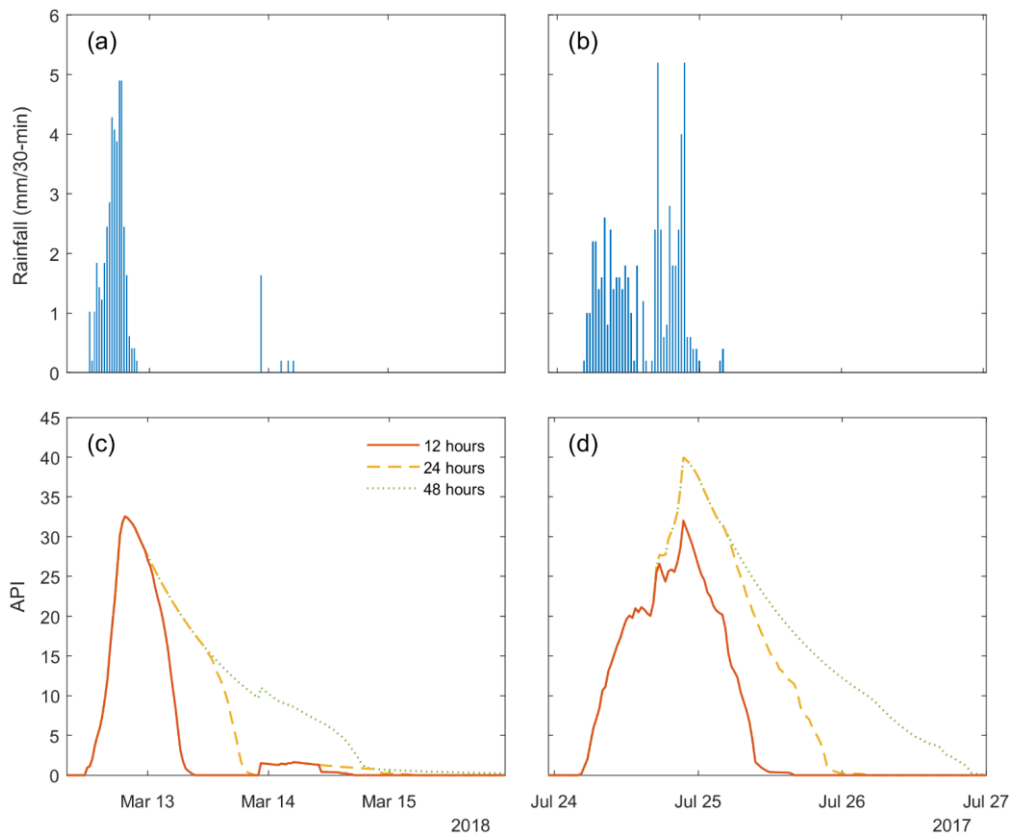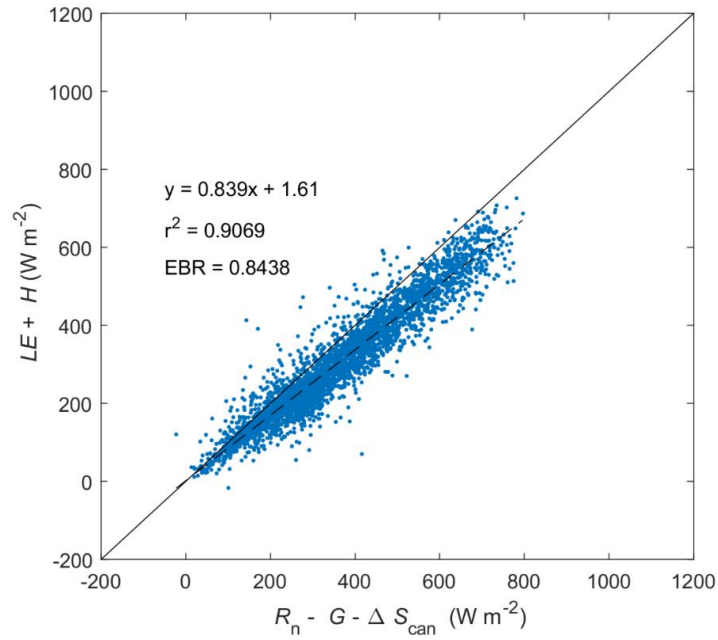
Figure B1. Examples of predicted canopy drying after rainfall using the antecedent precipitation index (API) with 24, 48, and 96 half hour time parameters. The rain event in (a) and (c) is from the Kopuatai dataset, while (b) and (d) consist of Mer Bleue data.

Appendix C

Figure C1. Energy balance closure at Kopuatai for 2012–2022 (inclusive), based on ~~daily~~ middle-of-day means of energy balance components. LE: latent heat flux; H: sensible heat flux; G: soil heat flux; R_n: net radiation; ΔS_{can}: canopy heat storage change. EBR is the energy balance ratio.
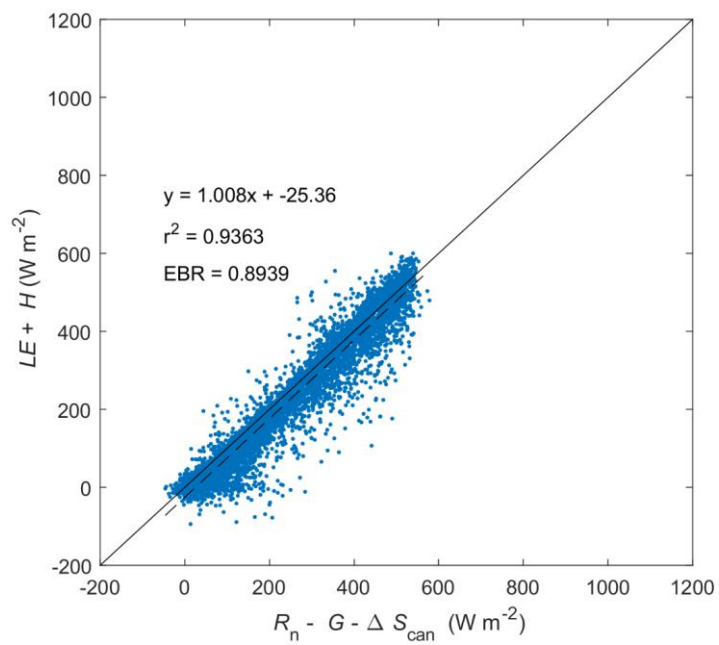
Figure C2. Energy balance closure at Mer Bleue for 1999–2018 (inclusive), based on ~~daily~~ middle-of-day means of energy balance components. For term definitions, see Fig.~~ure~~ C1. *G* is assumed to be 10% of R_n, while ΔS_{can} is assumed to be 3% of R_n. EBR is the energy balance ratio.

Appendix D
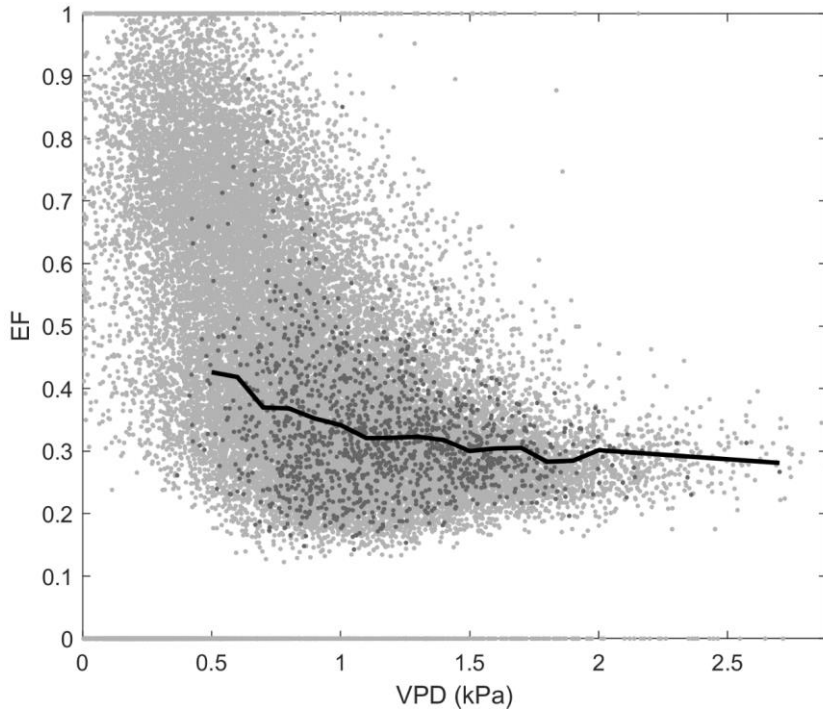
Figure D1. Relationship between ~~the~~ evaporative fraction (EF) and vapour pressure deficit (VPD) at Kopuatai bog. Light grey data points represent raw, ~~unfiltered~~middle-of-day 30-minute eddy covariance data, while dark grey data points show growing season (Sep–May), dry canopy, middle-of-day mean data used to calculate the binned means (black line).
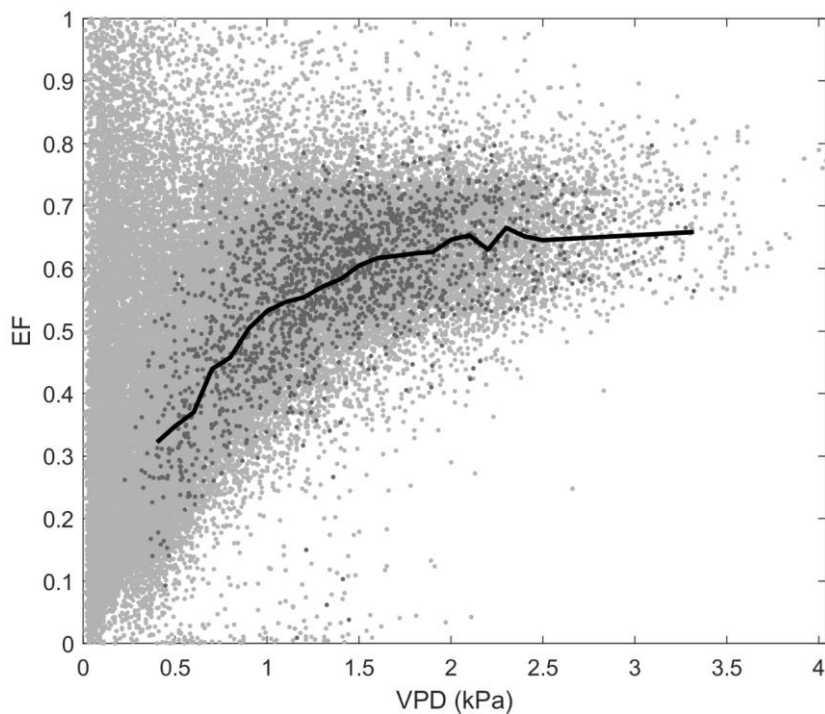
520 **Figure D2. Relationship between evaporative fraction (EF) and vapour pressure deficit (VPD) at Mer Bleue bog. Light grey data points represent raw, ~~unfiltered~~ middle-of-day 30-minute eddy covariance data, while dark grey data points show growing season (May–Oct), dry canopy, middle-of-day mean data used to calculate the binned means (black line).**

Data availability

Data sets used in this paper are available on Zenodo at ~~https://doi.org/10.5281/zenodo.8226863~~
525 https://doi.org/10.5281/zenodo.8226862 (Speranskaya et al., 2024~~3~~).

Author contribution

DIC and PML initiated the project and developed the methodology with LS. DIC collected and processed data from Kopuatai, and PML and ERH collected and processed data from Mer Bleue. LS analysed the data and wrote the manuscript draft. DIC, PML, and ERH contributed to review and editing of the manuscript.

References

Admiral, S. W. and Lafleur, P. M.: Partitioning of latent heat flux at a northern peatland, Aquat. Bot., 86, 107-116, https://doi.org/10.1016/j.aquabot.2006.09.006, 2007.

Admiral, S. W., Lafleur, P. M., and Roulet, N. T.: Controls on latent heat flux and energy partitioning at a peat bog in eastern Canada, Agr. Forest Meteorol., 140, 308-321, https://doi.org/10.1016/j.agrformet.2006.03.017, 2006.

Agnew, A. D. Q., Rapson, G. L., Sykes, M. T., and Bastow Wilson, J.: The functional ecology of *Empodisma minus* (Hook, f.) Johnson & Cutler in New Zealand ombrotrophic mires, New Phytol., 124, 703-710, 1993.

Alekseychik, P., Mammarella, I., Lindroth, A., Lohila, A., Aurela, M., Laurila, T., Kasurinen, V., Lund, M., Rinne, J., Nilsson, M. B., Peichl, M., Minkkinen, K., Shurpali, N. J., Tuittila, E.-S., Martikainen, P. J., Tuovinen, J.-P., and Vesala, T.: Surface energy exchange in pristine and managed boreal peatlands, Mires and Peat, 21, 1-26, https://doi.org/10.19189/MaP.2018.OMB.333, 2018.

Anderson, R. G. and Wang, D.: Energy budget closure observed in paired Eddy Covariance towers with increased and continuous daily turbulence, Agr. Forest Meteorol., 184, 204-209, https://doi.org/10.1016/j.agrformet.2013.09.012, 2014.

30

560 Aurela, M., Riutta, T., Laurila, T., Tuovinen, J.-P., Vesala, T., Tuittila, E.-S., Rinne, J., Haapanala, S., and Laine, J.: CO_2 exchange of a sedge fen in southern Finland - the impact of a drought period, Tellus B, 59, https://doi.org/10.1111/j.1600-0889.2007.00309.x, 2007.

Brümmer, C., Black, T. A., Jassal, R. S., Grant, N. J., Spittlehouse, D. L., Chen, B., Nesic, Z., Amiro, B. D., Arain, M. A.,
565 Barr, A. G., Bourque, C. P. A., Coursolle, C., Dunn, A. L., Flanagan, L. B., Humphreys, E. R., Lafleur, P. M., Margolis, H. A., McCaughey, J. H., and Wofsy, S. C.: How climate and vegetation type influence evapotranspiration and water use efficiency in Canadian forest, peatland and grassland ecosystems, Agr. Forest Meteorol., 153, 14-30, https://doi.org/10.1016/j.agrformet.2011.04.008, 2012.

570 Bubier, J. L., Moore, T. R., and Crosby, G.: Fine-scale vegetation distribution in a cool temperate peatland, Can. J. Botany, 84, 910-923, https://doi.org/10.1139/b06-044, 2006.

Burba, G.: Eddy Covariance Method for Scientific, Regulatory, and Commercial Applications, LI-COR Biosciences, Lincoln, Nebraska, USA, 702 pp., 2022.
575

Campbell, E. O.: The restiad peat bogs at Motumaoho and Moanatuatua, Transactions of the Royal Society of New Zealand : Botany, 2, 1964.

Campbell, D. I. and Williamson, J. L.: Evaporation from a raised peat bog, J. Hydrol., 193, 142-
580 160, https://doi.org/10.1016/S0022-1694(96)03149-6, 1997.

Campbell, D. I., Smith, J., Goodrich, J. P., Wall, A. M., and Schipper, L. A.: Year-round growing conditions explains large CO_2 sink strength in a New Zealand raised peat bog, Agr. Forest Meteorol., 192-193, 59-68, https://doi.org/10.1016/j.agrformet.2014.03.003, 2014.
585

Chang, J. and Root, B.: On the relationship between mean monthly global radiation and air temperature, Arch. Met. Geoph. Biokl., 23, 13-30, https://doi.org/10.1007/BF02247305, 1975.

Clarkson, B. R., Schipper, L. A., and Silvester, W. B.: Nutritional niche separation in coexisting bog species demonstrated
590 by ^{15}N-enriched simulated rainfall, Austral Ecol., https://doi.org/10.1111/j.1442-9993.2009.01939.x, 2009.

Dymond, J. R., Sabetizade, M., Newsome, P. F., Harmsworth, G. R., and Ausseil, A.: Revised extent of wetlands in New Zealand, N. Z. J. Ecol., 45, 1-8, https://doi.org/10.20423/nzjecol.45.32, 2021.

595 Eichelmann, E., Hemes, K. S., Knox, S. H., Oikawa, P. Y., Chamberlain, S. D., Sturtevant, C., Verfaillie, J., and Baldocchi, D. D.: The effect of land cover type and structure on evapotranspiration from agricultural and wetland sites in the Sacramento– San Joaquin River Delta, California, Agr. Forest Meteorol., 256-257, 179-195, https://doi.org/10.1016/j.agrformet.2018.03.007, 2018.

600 Fang, Z., Zhang, W., Brandt, M., Abdi, A. M., and Fensholt, R.: Globally Increasing Atmospheric Aridity Over the 21st Century, Earth's Future, 10, https://doi.org/10.1029/2022ef003019, 2022.

Ficklin, D. L. and Novick, K. A.: Historic and projected changes in vapor pressure deficit suggest a continental-scale drying of the United States atmosphere, J. Geophys. Res.: Atmos., 122, 2061-2079, https://doi.org/10.1002/2016jd025855, 2017.

605

Fraser, C. D. J., Roulet, N. T., and Lafleur, P. M.: Groundwater flow patterns in a large peatland, J. Hydrol., 246, 142-154, https://doi.org/10.1016/S0022-1694(01)00362-6, 2001.

Frolking, S. and Roulet, N. T.: Holocene radiative forcing impact of northern peatland carbon accumulation and methane 610 emissions, Global Change Biol., 13, 1079-1088, https://doi.org/10.1111/j.1365-2486.2007.01339.x, 2007.

~~Goodrich, J. P., Campbell, D. I., and Schipper, L. A.: Southern Hemisphere bog persists as a strong carbon sink during droughts, Biogeosciences, 14, 4563-4576, https://doi.org/10.5194/bg-14-4563-2017, 2017.~~

615 Goodrich, J. P., Campbell, D. I., Clearwater, M. J., Rutledge, S., and Schipper, L. A.: High vapor pressure deficit constrains GPP and the light response of NEE at a Southern Hemisphere bog, Agr. Forest Meteorol., 203, 54-63, https://doi.org/10.1016/j.agrformet.2015.01.001, 2015.

Goodrich, J. P., Campbell, D. I., and Schipper, L. A.: Southern Hemisphere bog persists as a strong carbon sink during 620 droughts, Biogeosciences, 14, 4563-4576, https://doi.org/10.5194/bg-14-4563-2017, 2017.

Goulden, M. L., Litvak, M., and Miller, S. D.: Factors that control Typha marsh evapotranspiration, Aquat. Bot., 86, 97-106, https://doi.org/10.1016/j.aquabot.2006.09.005, 2007.

625

Granger, R. J.: An examination of the concept of potential evaporation, J. Hydrol., 111, 9-19, https://doi.org/10.1016/0022-1694(89)90248-5, 1989.

Grossiord, C., Buckley, T. N., Cernusak, L. A., Novick, K. A., Poulter, B., Siegwolf, R. T. W., Sperry, J. S., and McDowell,
630   N. G.: Plant responses to rising vapor pressure deficit, New Phytol., 226, 1550-1566, https://doi.org/10.1111/nph.16485, 2020.

He, H., Moore, T., Humphreys, E. R., Lafleur, P. M., and Roulet, N. T.: Water level variation at a beaver pond significantly impacts net CO_2 uptake of a continental bog, Hydrol. Earth Syst. Sc., 27, 213-227, https://doi.org/10.5194/hess-27-213-2023, 2023.

635

Helbig, M., Waddington, J. M., Alekseychik, P., Amiro, B. D., Aurela, M., Barr, A. G., Black, T. A., Blanken, P. D., Carey, S. K., Chen, J., Chi, J., Desai, A. R., Dunn, A., Euskirchen, E. S., Flanagan, L. B., Forbrich, I., Friborg, T., Grelle, A., Harder, S., Heliasz, M., Humphreys, E. R., Ikawa, H., Isabelle, P.-E., Iwata, H., Jassal, R., Korkiakoski, M., Kurbatova, J., Kutzbach, L., Lindroth, A., Löfvenius, M. O., Lohila, A., Mammarella, I., Marsh, P., Maximov, T., Melton, J. R., Moore, P. A., Nadeau,
640   D. F., Nicholls, E. M., Nilsson, M. B., Ohta, T., Peichl, M., Petrone, R. M., Petrov, R., Prokushkin, A., Quinton, W. L., Reed, D. E., Roulet, N. T., Runkle, B. R. K., Sonnentag, O., Strachan, I. B., Taillardat, P., Tuittila, E.-S., Tuovinen, J.-P., Turner, J., Ueyama, M., Varlagin, A., Wilmking, M., Wofsy, S. C., and Zyrianov, V.: Increasing contribution of peatlands to boreal evapotranspiration in a warming climate, Nat. Clim. Change, 10, 555-560, https://doi.org/10.1038/s41558-020-0763-7, 2020.

645   Helfter, C., Campbell, C., Dinsmore, K. J., Drewer, J., Coyle, M., Anderson, M., Skiba, U., Nemitz, E., Billett, M. F., and Sutton, M. A.: Drivers of long-term variability in CO2 net ecosystem exchange in a temperate peatland, Biogeosciences, 12, 1799-1811, https://doi.org/10.5194/bg-12-1799-2015, 2015.

Hember, R. A., Lafleur, P. M., and Cogley, J. G.: Synoptic controls on summer evapotranspiration from a bog peatland in
650   southern Canada, Int. J. Climatol., 25, 793-809, https://doi.org/10.1002/joc.1154, 2005.

Holden, J.: Peatland hydrology and carbon release: why small-scale process matters, Philosophical Transactions of the Royal Society A: Mathematical Physical and Engineering Sciences, 363, 2891-2913, https://doi.org/10.1098/rsta.2005.1671, 2005.

655   Humphreys, E. R., Lafleur, P. M., Flanagan, L. B., Hedstrom, N., Syed, K. H., Glenn, A. J., and Granger, R.: Summer carbon dioxide and water vapor fluxes across a range of northern peatlands, J. Geophys. Res.: Biogeo., 111, https://doi.org/10.1029/2005jg000111, 2006.

Joosten, H. and Clarke, D.: Wise use of mires and peatlands, Totnes, 2002.

660

Keyte Beattie, A. M.: The role of *Empodisma robustum* litter in CO_2 exchange at Kopuatai bog, University of Waikato, Hamilton, New Zealand, 2014.

Kim, J., Rochefort, L., Hogue-Hugron, S., Alqulaiti, Z., Dunn, C., Pouliot, R., Jones, T. G., Freeman, C., and Kang, H.: Water
665 Table Fluctuation in Peatlands Facilitates Fungal Proliferation, Impedes *Sphagnum* Growth and Accelerates Decomposition, Front. Earth Sci., 8, https://doi.org/10.3389/feart.2020.579329, 2021.

Kurbatova, J., Arneth, A., Vygodskaya, N. N., Kolle, O., Varlargin, A. V., Milyukova, I. M., Tchebakova, N. M., Schulze, E. D., and Lloyd, J.: Comparative ecosystem–atmosphere exchange of energy and mass in a European Russian and a central
670 Siberian bog I. Interseasonal and interannual variability of energy and latent heat fluxes during the snowfree period, Tellus B, 54, https://doi.org/10.3402/tellusb.v54i5.16683, 2002.

Kwon, M. J., Ballantyne, A., Ciais, P., Qiu, C., Salmon, E., Raoult, N., Guenet, B., Gockede, M., Euskirchen, E. S., Nykanen, H., Schuur, E. A. G., Turetsky, M. R., Dieleman, C. M., Kane, E. S., and Zona, D.: Lowering water table reduces carbon sink
675 strength and carbon stocks in northern peatlands, Global Change Biol., 28, 6752-6770, https://doi.org/10.1111/gcb.16394, 2022.

Lafleur, P. M. and Roulet, N. T.: A comparison of evaporation rates from two fens of the Hudson Bay Lowland, Aquat. Bot., 44, 59-69, https://doi.org/10.1016/0304-3770(92)90081-S, 1992.

680

Lafleur, P. M., Roulet, N. T., and Admiral, S. W.: Annual cycle of CO2 exchange at a bog peatland, J. Geophys. Res.: Atmos., 106, 3071-3081, https://doi.org/10.1029/2000jd900588, 2001.

Lafleur, P. M., Hember, R. A., Admiral, S. W., and Roulet, N. T.: Annual and seasonal variability in evapotranspiration and
685 water table at a shrub-covered bog in southern Ontario, Canada, Hydrol. Process., 19, 3533-3550, https://doi.org/10.1002/hyp.5842, 2005.

Lawrence, J., Mackey, B., Chiew, F., Costello, M. J., Hennessy, K., Lansbury, N., Nidumolu, U. B., Pecl, G., Rickards, L., Tapper, N., A.Woodward, and A.Wreford: Contribution of Working Group II to the Sixth Assessment Report of the
690 Intergovernmental Panel on Climate Change, in: Climate Change 2022: Impacts, Adaptation and Vulnerability, edited by:

34

Pörtner, H.-O., Roberts, D. C., Tignor, M., Poloczanska, E. S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., S. Löschke, Möller, V., Okem, A., and Rama, B., Cambridge University Press, Cambridge, UK and New York, NY, USA, 1581–1688, https://doi.org/10.1017/9781009325844.013, 2022.

695 Leuning, R., van Gorsel, E., Massman, W. J., and Isaac, P. R.: Reflections on the surface energy imbalance problem, Agr. Forest Meteorol., 156, 65-74, https://doi.org/10.1016/j.agrformet.2011.12.002, 2012.

Liljedahl, A. K., Hinzman, L. D., Harazono, Y., Zona, D., Tweedie, C. E., Hollister, R. D., Engstrom, R., and Oechel, W. C.: Nonlinear controls on evapotranspiration in arctic coastal wetlands, Biogeosciences, 8, 3375-3389, https://doi.org/10.5194/bg-8-3375-2011, 2011.

700

Ma, L., Zhu, G., Chen, B., Zhang, K., Niu, S., Wang, J., Ciais, P., and Zuo, H.: A globally robust relationship between water table decline, subsidence rate, and carbon release from peatlands, Communications Earth & Environment, 3, https://doi.org/10.1038/s43247-022-00590-8, 2022.

705

Massmann, A., Gentine, P., and Lin, C.: When Does Vapor Pressure Deficit Drive or Reduce Evapotranspiration?, J. Adv. Model. Earth Sy., 11, 3305-3320, https://doi.org/10.1029/2019MS001790, 2019.

McGlone, M. S.: Postglacial history of New Zealand wetlands and implications for their conservation, N. Z. J. Ecol., 33, 1-23, 710 2009.

Miralles, D. G., Brutsaert, W., Dolman, A. J., and Gash, J. H.: On the Use of the Term "Evapotranspiration", Water Resour. Res., 56, e2020WR028055, https://doi.org/10.1029/2020WR028055, 2020.

715 Moore, T. R., Bubier, J. L., Frolking, S. E., Lafleur, P. M., and Roulet, N. T.: Plant biomass and production and CO_2 exchange in an ombrotrophic bog, J. Ecol., 90, 25-36, https://doi.org/10.1046/j.0022-0477.2001.00633.x, 2002.

Newnham, R. N., de Lange, P. J., and Lowe, D. J.: Holocene vegetation, climate and history of a raised bog complex, northern New Zealand based on palynology, plant macrofossils and tephrochronology, The Holocene, 5, 267-282, 1995.

720

Nimmo, D. G., Mac Nally, R., Cunningham, S. C., Haslem, A., and Bennett, A. F.: Vive la resistance: reviving resistance for 21st century conservation, Trends Ecol. Evol., 30, 516-523, https://doi.org/10.1016/j.tree.2015.07.008, 2015.

35

Otieno, D., Lindner, S., Muhr, J., and Borken, W.: Sensitivity of peatland herbaceous vegetation to vapor pressure deficit influences net ecosystem CO_2 exchange, Wetlands, 32, 895-905, https://doi.org/10.1007/s13157-012-0322-8, 2012.

Page, S. E., Rieley, J. O., and Wüst, R.: Lowland tropical peatlands of Southeast Asia, in: Peatlands - Evolution and Records of Environmental and Climate Changes, edited by: Martini, I. P., Martinez Cortizas, A., and Chesworth, W., Elsevier, Amsterdam, The Netherlands, 145-172, https://doi.org/10.1016/s0928-2025(06)09007-9, 2006.

Peichl, M., Sagerfors, J., Lindroth, A., Buffam, I., Grelle, A., Klemedtsson, L., Laudon, H., and Nilsson, M. B.: Energy exchange and water budget partitioning in a boreal minerogenic mire, J. Geophys. Res.: Biogeo., 118, 1-13, https://doi.org/10.1029/2012jg002073, 2013.

Ratcliffe, J. L., Campbell, D. I., Clarkson, B. R., Wall, A. M., and Schipper, L. A.: Water table fluctuations control CO_2 exchange in wet and dry bogs through different mechanisms, Sci. Total Environ., 655, 1037-1046, https://doi.org/10.1016/j.scitotenv.2018.11.151, 2019.

Roehm, C. L. and Roulet, N. T.: Seasonal contribution of CO_2 fluxes in the annual C budget of a northern bog, Global Biogeochem. Cy., 17, https://doi.org/10.1029/2002gb001889, 2003.

Roulet, N. T., Lafleur, P. M., Richard, P. J. H., Moore, T. R., Humphreys, E. R., and Bubier, J.: Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland, Global Change Biol., 13, 397-411, https://doi.org/10.1111/j.1365-2486.2006.01292.x, 2007.

Runkle, B. R. K., Wille, C., Gažovič, M., Wilmking, M., and Kutzbach, L.: The surface energy balance and its drivers in a boreal peatland fen of northwestern Russia, J. Hydrol., 511, 359-373, https://doi.org/10.1016/j.jhydrol.2014.01.056, 2014.

Scharlemann, J. P. W., Tanner, E. V. J., Hiederer, R., and Kapos, V.: Global soil carbon: understanding and managing the largest terrestrial carbon pool, Carbon Manag., 5, 81-91, https://doi.org/10.4155/cmt.13.77, 2014.

Shearer, J. C.: Natural and anthropogenic influences on peat development in Waikato/Hauraki Plains restiad bogs, J. R. Soc. N. Z., 27, 295-313, https://doi.org/10.1080/03014223.1997.9517540, 1997.

Shimoyama, K., Hiyama, T., Fukushima, Y., and Inoue, G.: Seasonal and interannual variation in water vapor and heat fluxes in a West Siberian continental bog, J. Geophys. Res., 108, https://doi.org/10.1029/2003jd003485, 2003.

Shimoyama, K., Hiyama, T., Fukushima, Y., and Inoue, G.: Controls on evapotranspiration in a west Siberian bog, J. Geophys. Res., 109, 2004.

Shimoyama, K.: Seasonal and interannual variation in water vapor and heat fluxes in a West Siberian continental bog, J. Geophys. Res., 108, https://doi.org/10.1029/2003jd003485, 2003.

Shimoyama, K.: Controls on evapotranspiration in a west Siberian bog, J. Geophys. Res., 109, https://doi.org/10.1029/2003jd004114, 2004.

Smith, J.: Fluxes of Carbon Dioxide and Water Vapour at a Waikato Peat Bog, The University of Waikato, Hamilton, New Zealand, 2003.

Sonnentag, O., Van Der Kamp, G., Barr, A. G., and Chen, J. M.: On the relationship between water table depth and water vapor and carbon dioxide fluxes in a minerotrophic fen, Global Change Biol., 16, 1762-1776, https://doi.org/10.1111/j.1365-2486.2009.02032.x, 201009.

Speranskaya, L., Campbell, D. I., Lafleur, P. M., Humphreys, E. R.: Data-sets for "Peatland evaporation across hemispheres: contrasting controls and sensitivity to climate warming driven by plant functional types" - Version 2, Zenodo [data set], https://doi.org/10.5281/zenodo.8226862https://doi.org/10.5281/zenodo.8226863, 20243.

Strilesky, S. L. and Humphreys, E. R.: A comparison of the net ecosystem exchange of carbon dioxide and evapotranspiration for treed and open portions of a temperate peatland, Agr. Forest Meteorol., 153, 45-53, https://doi.org/10.1016/j.agrformet.2011.06.006, 2012.

Takagi, K., Tsuboya, T., and Takahashi, H.: Diurnal hystereses of stomatal and bulk surface conductances in relation to vapor pressure deficit in a cool-temperate wetland, Agr. Forest Meteorol., 91, 177-191, https://doi.org/10.1016/S0168-1923(98)00078-1, 1998.

Takagi, K., Tsuboya, T., Takahashi, H., and Inoue, T.: Effect of the invasion of vascular plants on heat and water balance in the Sarobetsu mire, northern Japan, Wetlands, 19, 246-254, https://doi.org/10.1007/BF03161754, 1999.

Thompson, M. A., Campbell, D. I., and Spronken-Smith, R. A.: Evaporation from natural and modified raised peat bogs in New Zealand, Agr. Forest Meteorol., 95, 85-98, https://doi.org/10.1016/S0168-1923(99)00027-1, 1999.

790 Villegas, J. C., Breshears, D. D., Zou, C. B., and Law, D. J.: Ecohydrological controls of soil evaporation in deciduous drylands: How the hierarchical effects of litter, patch and vegetation mosaic cover interact with phenology and season, J. Arid Environ., 74, 595-602, https://doi.org/10.1016/j.jaridenv.2009.09.028, 2010.

Vitt, D. H.: Functional Characteristics and Indicators of Boreal Peatlands, in: Boreal Peatland Ecosystems, edited by: Wieder,
795 R. K., and Vitt, D. H., Springer-Verlag, Berlin, Germany, 9-24, https://doi.org/10.1007/978-3-540-31913-9_2, 2006.

Wagstaff, S. J. and Clarkson, B. R.: Systematics and ecology of the Australasian genus *Empodisma* (Restionaceae) and description of a new species from peatlands in northern New Zealand, PhytoKeys, 39-79, https://doi.org/10.3897/phytokeys.13.3259, 2012.
800
Wang, M., Wu, J., and Lafleur, P.: Comparison of energy fluxes between an undisturbed bog and an adjacent abandoned peatland pasture, Agr. Forest Meteorol., 291, https://doi.org/10.1016/j.agrformet.2020.108086, 2020.

Woods, R. and Rowe, L.: The changing spatial variability of subsurface flow across a hillside, J. Hydrol., 35, 49-84, 1996.
805
Wu, J., Kutzbach, L., Jager, D., Wille, C., and Wilmking, M.: Evapotranspiration dynamics in a boreal peatland and its impact on the water and energy balance, J. Geophys. Res., 115, https://doi.org/10.1029/2009jg001075, 2010.

Xu, J., Morris, P. J., Liu, J., and Holden, J.: PEATMAP: Refining estimates of global peatland distribution based on a meta-
810 analysis, Catena, 160, 134-140, https://doi.org/10.1016/j.catena.2017.09.010, 2018.

Yu, Z., Loisel, J., Brosseau, D. P., Beilman, D. W., and Hunt, S. J.: Global peatland dynamics since the Last Glacial Maximum, Geophys. Res. Lett., 37, n/a-n/a, https://doi.org/10.1029/2010gl043584, 2010.

815 Zhong, Y., Jiang, M., and Middleton, B. A.: Effects of water level alteration on carbon cycling in peatlands, Ecosystem Health and Sustainability, 6, https://doi.org/10.1080/20964129.2020.1806113, 2020.