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Annual and seasonal variability in evapotranspiration and water table at a shrub-covered bog in southern Ontario, Canada

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Abstract:

Evapotranspiration (ET) was measured via the eddy covariance technique at a shrub bog peatland in southeastern Ontario for 5 years. For most of the study period the temperature was above normal. Precipitation was variable, but, in 2 years, late summer dry periods resulted in an extended period of deep drawdown of the water table (WT). Growing-season (May–September) daily ET varied considerably; maximum ET rates were 4 to 5 mm day^{-1}. Winter ET rates were an order of magnitude smaller than in summer, yet the total winter ET loss was important, accounting for 23 to 30% of the annual ET water loss. Annual precipitation exceeded annual ET by 1·55 to 1·94 times.

During the growing season, daily ET was closely related to daily potential evaporation (PET); however, the slope of this relationship was statistically different in some years. In contrast, ET and WT were only weakly related in most years. When ET was sorted into 5 cm WT classes there was no difference in mean ET across most WT classes; only the two deepest WT classes had significantly smaller mean ET. The ratio ET/PET followed the same pattern. We present a conceptual model of ET that relates WT, soil hydraulic properties and moss and vascular plant processes.

INTRODUCTION

Peatlands occupy about 14% and contain 59% of the soil carbon of the terrestrial landscape of Canada (Tarnocai, 1998; Roulet, 2000). Although peatlands can be classified based on hydrology, ecological function, soil characteristics, and plant assemblages, resulting in many different peatland sub-types, a broad division between fens and bogs is commonly made. The water balance is a key factor in determining peatland type. Fens are connected to regional groundwater flows and, thus, have water and nutrients moving into and out of the ecosystem, whereas bogs are hydrologically isolated and rely on precipitation as the only water and nutrient input source. Regardless of this fundamental difference in water supply, evapotranspiration (ET) is always a large component of the water balance of fens and bogs (Price and Maloney, 1994; Fraser *et al.*, 2001a) and, thus, can be a key determinant of ecological functioning. Water balance (and hence ET) is also a critical determinant of carbon sequestration in peatlands (Shurpali *et al.*, 1995; Lafleur *et al.*, 1997, 2003) and, therefore, is of prime importance in assessing peatland biospheric feedbacks to climate change. However, despite sporadic studies over the past four decades, ET from continental peatlands remains a relatively poorly understood process. In particular, there have been no long-term studies of annual cycles and interannual variation of ET.

Previous reviews of wetland ET report a wide range of daily ET values (Linacre, 1976; Ingram, 1983), but North American peatlands are underrepresented in this literature. In a more recent review, Roulet *et al.*

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(1997) suggest that ET from bogs tends to be smaller than for other peatland types. The factors contributing to this phenomenon are not fully understood, but it is likely that some combination of vegetation, surface topography, water table (WT), saturation deficit and energy supply are responsible (Roulet *et al.*, 1997). Regardless of this uncertainty of controls on ET, two issues that have persisted in wetland ET research are (1) the extent to which ET is controlled by WT depth below the peat surface, and (2) the relationship between ET and potential, or open water, evaporation (PET). Much early research suggested that the depth to WT has a strong control on peatland ET (see review by Ingram (1983)). Controlled experiments on peatland microcosms support this view (Nichols and Brown, 1980), whereas others suggest that there may be some difference in ET response to WT changes between fens and bogs (Brigham *et al.*, 1999). The relationship between ET and PET is both an interesting and useful concept for hydrologic studies. Because PET is more easily computed than ET it is widely used as a climatic indicator and for long-term water balance estimations (Burt and Shahgedanova, 1998). In the context of wetland ET, measures of PET have been used to assess whether wetland vegetation enhances or depresses ET compared with open water evaporation (Linacre, 1976; Lafleur, 1990) and, because of its limited data requirements, researchers have investigated whether PET may or may not be a reliable estimator of ET (Ingram, 1983; Koerselman and Beltman, 1988; Lafleur, 1990). Previous studies of North American peatlands suggest that ET is often closely related to, but typically less than, PET on a seasonal basis (Lafleur, 1990; Lafleur and Roulet, 1992; Kim and Verma, 1996).

Peatlands are important because of their role in global-scale carbon cycling. The magnitude and form of carbon exchange between peatlands and the atmosphere is a function of the moisture storage and, therefore, is directly coupled to the hydrology of the system (Moore *et al.*, 1998). A primary control for many biogeochemical processes is the location of the WT, because it determines the vertical distribution of the rates of oxic and anoxic decomposition. For example, methane emissions (Moore and Roulet, 1993) and the export of dissolved organic carbon (Fraser *et al.*, 2001b; Billet *et al.*, 2004) can be related either directly or indirectly to water storage in a peatland. Peatland ecosystem, biogeochemical, and carbon models all depend on a description of the location of the water (e.g. Frolking *et al.*, 2001, 2002; Yu *et al.*, 2002). The location of the water is obtained in these models by the solution of the water balance, of which ET is a major loss. Few ecosystem models possess a full physically based soil hydrology module, relying on simple functions between the WT position, runoff and ET. The relation between WT and runoff are well described (e.g. Verry *et al.*, 1988; Fraser *et al.*, 2001a), but simple functions between the WT and ET are more problematic. Many models use a potential ET that is adjusted by an empirically derived quotient of actual over potential ET whose value is related to the depth of WT (e.g. Granberg *et al.*, 1999; Hilbert *et al.*, 2000). However, there have been few studies of this relationship, and those used come from earlier studies such as Ivanov (1981), when there were no non-evasive and accurate methods of measuring ET. Ivanov (1981; see also Ingram (1983)) indicates a very rapid drop into ET for bogs when the water goes below the peatland surface, but most recent studies of peatland ET using micrometeorological techniques do not indicate the drop is that severe (Roulet *et al.*, 1997). Since this relationship is important for models of the system, in this paper we re-examine the relationship between the quotient of actual to potential ET and WT and assess how interannual variability in hydrology affects this quotient. If greater certainty is obtained in estimation of ET in a peatland, and hence of water storage, then this certainty is transferred to the biogeochemical and runoff models.

In the present study we examine a long-term record of ET at an ombrotrophic bog in eastern Ontario, Canada. This ombrotrophic peatland, the Mer Bleue bog, is characterized by a well-developed evergreen shrub canopy over a carpet of *Sphagnum* moss, and the surface topography is of well-differentiated hummocks and hollows. The 5 year record of data was collected between 1 May 1998 and 30 April 2003. The objective of the study was to examine the magnitude and interannual variation in ET at this site, and thus assess the importance of ET as a component of the water balance. Secondary objectives were to investigate the influence of the WT on ET and to explore the relationship between PET and ET, especially as it varies between years and with WT depth.

STUDY SITE

Mer Bleue bog is located 5 km east of Ottawa, Ontario (45·40°N lat., 75·50 °W long.) and lies in a post-glacial channel system that was eroded into the floor of the former Champlain Sea basin. It is estimated that the bog has formed over the past 8500 years, beginning as a fen and switching to the bog phase *ca* 6000 years BP. The climate of the region is cool continental, with a mean annual temperature of 5·8 °C and annual precipitation of 910 mm (1961–90 average; Environment Canada, 1993). The coldest month is January (−10·8 °C) and the warmest month July (20·8 °C). On average, 77% of the annual precipitation falls as rain; average growing-season (May to September) daily temperature and total precipitation are 17·0 °C and 416 mm respectively.

Mer Bleue bog is approximately 2800 ha in area, roughly oval shaped with an east–west orientation. Two longitudinal lobes of fluvial sand/gravel material dissect the western end of the bog, creating three separate arms. The research site is located in the northernmost of these arms and has access from a road running along the beach ridge. In this section the bog is slightly domed in the middle, with peat depths varying from 5–6 m near the tower site and decreasing to about 2 m at the edge, where a series of beaver ponds create a moat around the bog. Around the tower site the bog surface has a hummock–hollow microtopography with mean relief between hummock tops and hollow bottoms of 0·25 m. Hummocks make up roughly 70% of the surface area in the footprint of the tower. The WT is usually at or below the bottom of the hollows and can vary considerably within the growing season.

The dominant vascular vegetation is evergreen ericaceous shrubs (*Chamaedaphne calyculata*, *Ledum groenlandicum*, *Kalmia augustifolium*) and a deciduous shrub (*Vaccinium myrtilloides*). The shrub canopy is between 20 and 30 cm in height, and the total leaf area index (one-sided) of the shrubs is about 1·3. A sparse cover of sedges (*Eriophorum vaginatum*) is present on hummocks, but was not included in the LAI estimate. Trees (*Picea mariana*, *Larix laricina*, *Betula papyrifera*) exist on parts of the bog, but are largely absent from the study site. The ground cover on both hummocks and hollows is *Sphagnum* moss (*S. capillifolium*, *S. fuscum*, *S. magellanicum*). Biomass for the major species was measured in 1999. Total above-ground and below-ground biomass for the vascular species averaged 356 ± 100 g m^{-2} and 1820 ± 660 g m^{-2} respectively and *Sphagnum* capitula biomass was 144 ± 30 g m^{-2} (Moore *et al.*, 2002). See Moore *et al.* (2002) and Bubier *et al.* (2003) for further details on the vegetation characteristics.

METHODS

Instrumentation was situated on a 6 m tower located 250 m from the southern edge of the bog and was accessed by a board-walk. Fetch surrounding the tower site was limited only to the south (200–300 m); for all other bearings the fetch ranged from 500 to >1500 m. Along the board-walk, 15 m south of the tower were two small huts for storage and instrumentation. The huts were supplied with 120 V AC line power. Most instrumentation was located on the tower or within a 10 m radius of the huts.

Fluxes of carbon dioxide, heat and water vapour were measured at the site. However, for the purpose of this study we report on the water vapour flux measurements only. Additional details of all instrumentation at the site can be found in Lafleur *et al.* (2001, 2003). The latent heat flux Q_E was measured via the eddy covariance technique. As such Q_E is determined from instantaneous deviations of vertical wind velocity w' and water vapour density ρ_v' as follows

$$Q_E = L_v \overline{w' \rho_v'} \tag{1}$$

where the overbar represents a time-average mean of the instantaneous product of w' and ρ_v' (i.e. the covariance of these quantities), and L_v is the latent heat of vaporization. A dimensional analysis shows that dividing through by L_v produces the units of mass per unit area per time, which is converted to a water depth per time by assuming the density of water is 1000 kg m^{-3}. Integration over time produces daily ET depth in millimetres.

We measured w' with a three-dimensional sonic anemometer (model 1012R3 Solent, Gill Instruments, UK) and ρ_v' with an open-path krypton hygrometer (model KH20, Campbell Scientific, Logan, UT, USA). These instruments were mounted on the instrument tower at a height of 3·0 m from the mean elevation of the hummock tops on a boom 50 cm in length and oriented into the prevailing wind direction (northwest). Signals were logged on a datalogger (model CR7X, Campbell Scientific, Logan, UT, USA) using a scan frequency of 10 Hz. Appropriate covariances were computed using the datalogger covariance program for two 15 min subsampling intervals, which were then averaged to compute 30 min fluxes. Post-processing of the flux data included a correction for oxygen absorption by the krypton hygrometer, two-dimensional coordinate rotation of the sonic anemometer data and correction for fluctuations in air density (Webb *et al.*, 1980).

The quality of the eddy covariance flux measurements can be assessed in various ways. One common approach is to examine energy balance closure, whereby the sum of the turbulent fluxes of sensible and latent heat are compared with the sum of available energy from net radiation and energy storage and conduction. Energy balance closure for the Mer Bleue measurement system (daily values) was reported by Lafleur *et al.* (2001, 2003), who showed that closure of about 90% was typically achieved. This level of closure is comparable or better than that reported in other studies (Twine *et al.*, 2000; Wilson *et al.*, 2002). A more direct method is to intercompare different measurement systems. Fluxes obtained from the open-path eddy covariance system at Mer Bleue were compared for a brief time in 2001 against the AMERIFLUX roving system (see http://public.ornl.gov/ameriflux/Standards/roving-system/roving_system.cfm), which uses a similar three- dimensional sonic anemometer (SAT1/3K, Applied Technologies Inc., Boulder, CO, USA) and a closed-path infrared gas analyser (6262 IRGA, LiCor, Lincoln, NB, USA). The two systems were in close agreement (root-mean-square error of 28·7 W m^{-2}), with a small systematic difference of about 10% favouring the Mer Bleue system (Figure 1).

In addition to ET, air temperature and relative humidity at 2·0 m were measured with a probe (HMP35, Campbell Sci., Utah, USA) and wind speed at 2·0 m was measured with a cup anemometer (model 12 102, R.M. Young, MI, USA). Wind direction was measured via a vane mounted at 2·5 m. Net radiation Q^* was measured with a net radiometer mounted at the top of the tower. Initially, we used a net radiometer (CN1, Middleton Instruments, Melbourne, Australia) aspirated with dry air pumped through a desiccant, but this was later replaced with a self-aspirating instrument (Q^*6, REBS, Seattle, WA, USA). A field comparison between

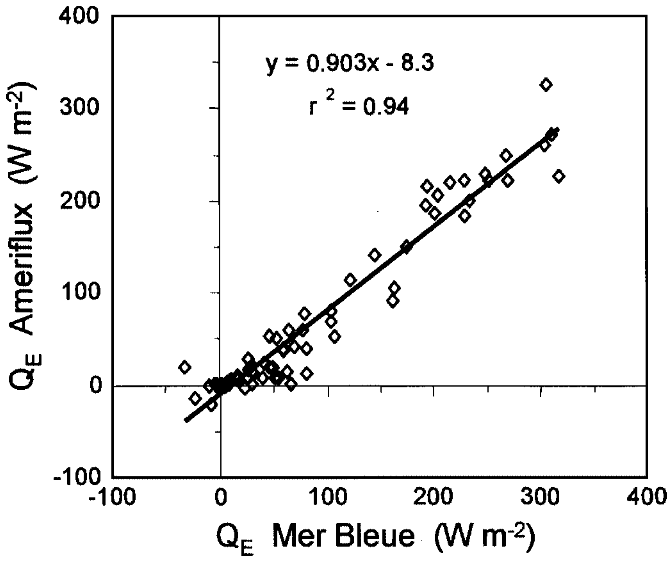

Figure 1. Comparison of 30 min latent heat flux Q_E measurements from the Mer Bleue eddy-covariance measurement system using an open-path hygrometer against the AMERIFLUX roving closed-path eddy-covariance system. Data are from June 2001

the two instruments gave good agreement ($Q^*_{REBS} = 0{\cdot}98Q^*_{Midd} + 10{\cdot}4$ W m^{-2}, $r^2 = 0{\cdot}89$). Depth to the WT was monitored in two wells, one in a hummock and one in a hollow, using a float and counterweight attached to a potentiometer. Frequent manual measurements ensured the accuracy of the electronic system. In this paper we report WT depths relative to the mean hummock moss surface. Data from all instruments were recorded on the datalogger every 5 s and averaged every 30 m.

Precipitation was measured at the site during snow-free periods only, using a tipping-bucket gauge (TE252M, Texas Electronics Inc., Dallas, TX, USA), and recorded on the datalogger. Totals from this gauge were checked against two manual precipitation gauges installed on site. Wintertime precipitation records were obtained from the Meteorological Services of Canada weather station at Ottawa Airport, located 15 km southwest of Mer Bleue. Snow on the ground at Mer Bleue was measured by snow surveys periodically through the winters.

Flux data treatment

All data was checked for quality assurance, and various filtering techniques were applied. Data were first filtered for periods when instrument calibration or maintenance took place and times of known instrument malfunction. Data were also filtered for the limited fetch direction to the south, which also removed any influence from the tower, board-walk and instrument hut. Data were then examined on a monthly basis for extreme values and values greater than ±3 standard deviations were removed from the data set.

Data analyses involving relationships between ET and environmental variables used 'good days' only. A good day was considered any day with 36 or more 30 min periods of measured ET data, with the missing 30 min gaps filled as outlined below. For other analyses (e.g. monthly and annual sums) we used a complete record of gap-filled ET data. Although there are no standard methods of gap filling, some methods are preferable to others (Falge *et al*., 2001). In this study we used the following procedures. Periods of less than six consecutive half-hour gaps were filled by linear interpolation between the nearest measured data points. Longer periods were filled using linear regression relationships between 30 min Q_E and Q^*. For gaps of hours to a few days, we developed these relationships using data collected for 5 days prior to and following the gap. When meteorological data, including Q^*, were not available the gaps were filled with average data derived from compiling the 30 min ensemble average diurnal trend for periods of 10 days prior to and following the gap. Gaps longer than 5 days were filled with relationships developed from data collected in other years at the same time. Only two such long data gaps occurred (1 to 21 May 1998 and 11 April to 20 June, 2001). Overall, 25·3% of the 5 year ET record was missing and required gap filling.

PET calculation

PET was computed via the modified Penman–Monteith approach, where the surface resistance is set equal to zero:

$$\mathrm{PET} = \frac{1}{L_v}\frac{s(Q^* - G) + c_a D_a/r_a}{s + \gamma} \tag{2}$$

where s is the slope of the saturation vapour pressure versus temperature relationship, G is energy storage and conduction in the soil, c_a is the heat capacity of the air, D_a is the saturation deficit of the air (also called vapour pressure deficit), r_a is the aerodynamic resistance, and γ is the psychrometric constant r_a was computed from knowledge of wind speed and surface roughness length z_o according to Thom (1975). We used a constant $z_o = 0{\cdot}077 \pm 0{\cdot}001$ m (mean plus/minus standard error), which was computed from sonic anemometer data for several snow-free months.

RESULTS

Meteorology and WT

Air temperature during the study period was usually above normal; the average seasonal anomaly for the 5 year period was $+1{\cdot}2\,^{\circ}C$ (Figure 2). Periods of near- or below-normal temperatures occurred in the summer and fall of 2000 and winter and spring of 2003. Precipitation p departures from normal were much more irregular. Notable periods were as follows. The spring and summer months of 2000 were wetter than normal, the spring and early summer of 1999 were drier than normal. During the growing season, WT depth was variable in all years, but typically below the peat surface (Figure 3). Some interannual differences were apparent, where the summer of 2000 had consistently high WTs, and the summers of 2001 and 2002 experienced extended WT drawdown in late summer (August and September). Seasonal mean (May to September) WT depths varied from $-50{\cdot}3$ cm in 1999 to $-34{\cdot}1$ cm in 2000.

Growing-season ET

Daily ET varied considerably throughout the year and from day to day (Figure 4). Maximum values occurred in midsummer and ranged between 4 and 5 mm day^{-1} in most years, with somewhat higher extremes recorded in the wet year of 2000. Monthly mean daily ET was greatest in June and July, varying from 3·3 to 2·2 mm day^{-1}. Total growing-season ET was similar in the first 3 years of the study (1998, 1999, 2000), but was smaller in the following 2 years (2001 and 2002). Variations in seasonal air temperature and solar radiation did not follow the same pattern (Table I). Total ET also showed poor correspondence with P. For example, the summer with the highest P (2000) had a similar total ET as 1998, which had 115 mm less P. The smallest total growing-season ET occurred in the driest year (2002). Total ET approached total P in 1998 only; in all other growing seasons P exceeded ET, indicating there was an excess of precipitation (Table I). The largest excess occurred during the wettest summer (2000), when P exceeded ET by 34%.

Annual ET

ET decreased dramatically during non-growing-season months (Figure 4). The smallest daily rates occurred in winter months and were an order of magnitude less than in the growing period, with typical values between 0·1 and 0·5 mm day^{-1}. As a result, cumulated water-year ET (October to September) showed very little change

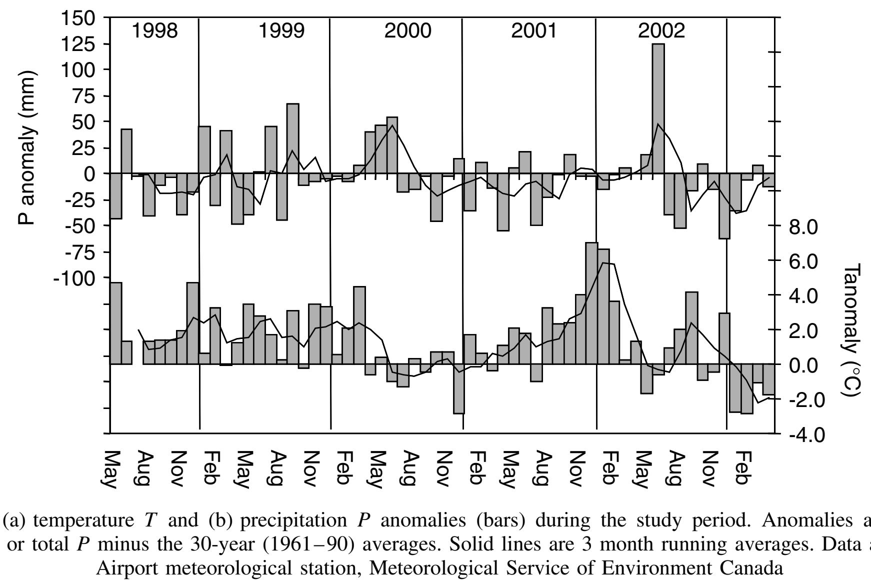

Figure 2. Monthly (a) temperature T and (b) precipitation P anomalies (bars) during the study period. Anomalies are computed as the monthly average T or total P minus the 30-year (1961–90) averages. Solid lines are 3 month running averages. Data are from the Ottawa Airport meteorological station, Meteorological Service of Environment Canada

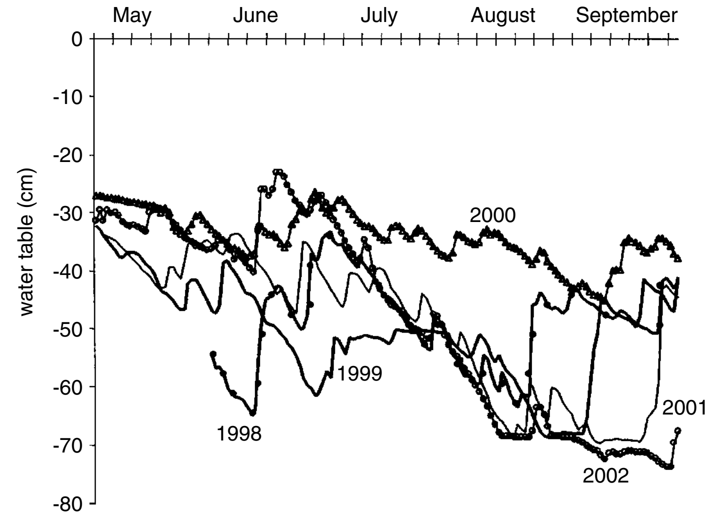

Figure 3. WT depths recorded at Mer Bleue bog during growing season, 1 May to 31 October, for the five study years, 1998 to 2002. Reference level (i.e. 300 depth) is the mean peat hummock surface. Mean hollow surface would be equal to a depth of −15 cm

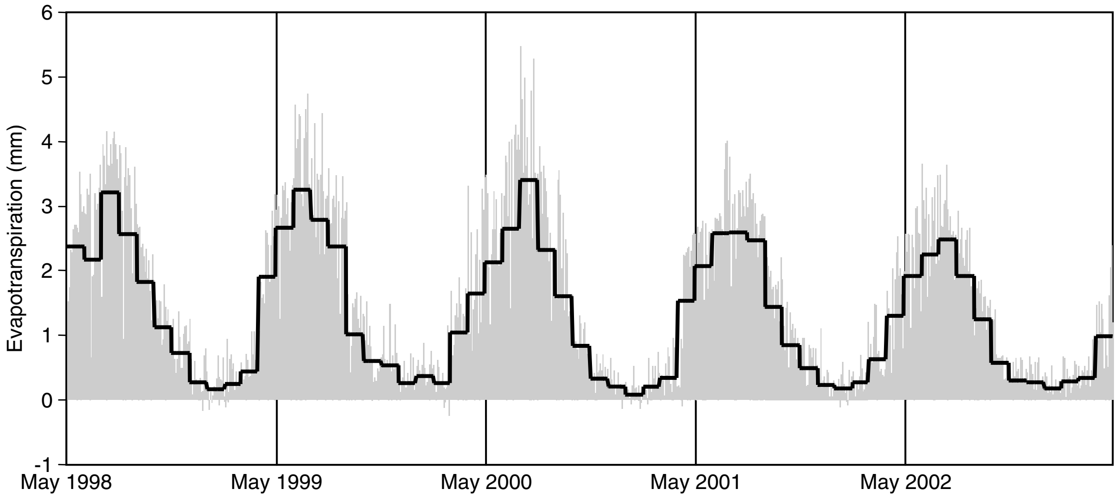

Figure 4. Daily ET (bars) and superimposed monthly mean ET (heavy black line) at Mer Bleue bog for the study period 1 May 1998 to 30 April 2003

during winter months, but increased immediately after snowmelt (Figure 5). Although the largest increase in cumulative ET occurred in the growing-season months, total non-growing-season (October to April) ET accounted for 24–29% of total annual ET. In comparison, non-growing-season total P represented between 47 and 56% of annual P. Therefore, a large precipitation excess (i.e. positive $P - \mathrm{ET}$) was built up over the non-growing season, and continued through the growing season (Figure 5). Annual $P - \mathrm{ET}$ varied from 300 to 500 mm.

Relationship between ET, PET, and WT

Daily ET was smaller than, but closely related ($r^2 \geq 0{\cdot}56$) to, daily PET in all years (Figure 6). Slopes of the yearly linear relationship between ET and PET varied from 0·590 (1998) to 0·436 (2002). Only slopes for

Table I. Growing-season (May to September) total ET, precipitation P, and PET at Mer Bleue bog. T is mean daily air temperature and I_s is daily mean incident solar radiation

	1998	1999	2000	2001	2002	All years
P (mm)	383	481	498	388	380	426[a]
ET (mm)	372	370	371	342	301	351[a]
P/ET	1·02	1·30	1·34	1·13	1·26	1·21
T (°C)	17·5	17·8	15·5	17·2	16·9	17·0[a]
I_s (W m^{-2})	211	223	201	221	223	216[a]

[a] 5-year means.

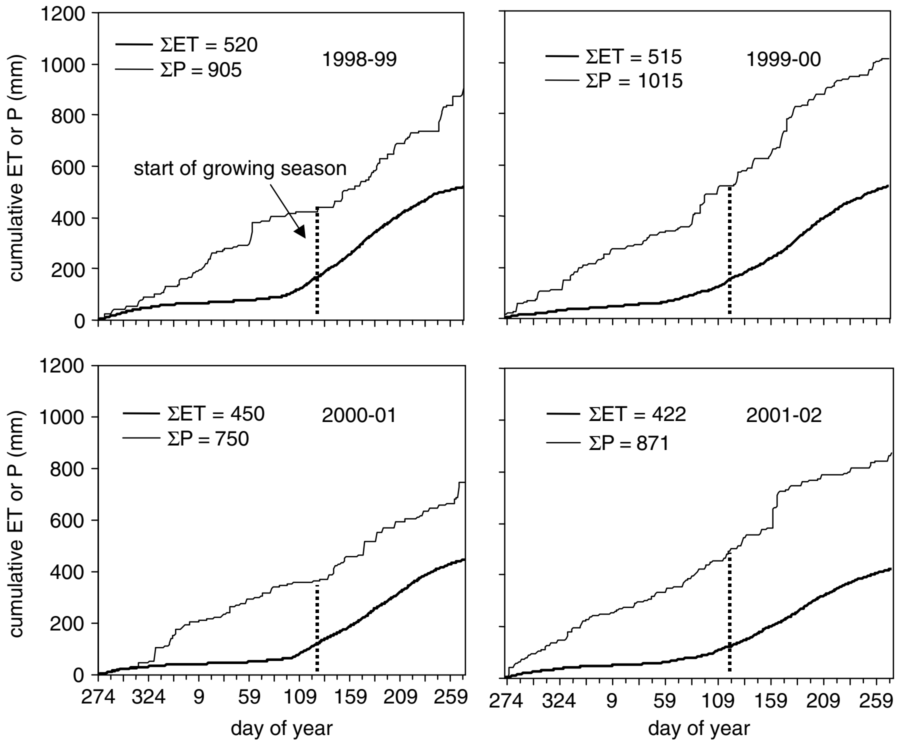

Figure 5. Annual cumulative ET and precipitation P at Mer Bleue bog for water-year 1 October to 30 September. Vertical dashed line represents 1 May, the division between growing and non-growing periods as defined in this study

1998 and 2002 were statistically distinct from all other slopes ($p = 0.05$), whereas 1999 and 2000 and 1999 and 2001 were statistically indistinct pairs. Slopes for 2000 and 2001 were not similar. Despite the statistically significant difference in slopes, the small numerical differences suggested that a single relationship for all years of data could be achieved with little loss of accuracy. The combined relationship for all years explained 64% of the variation in ET, with a linear slope of 0·517. In contrast, WT was only a weak determinant of ET (Figure 7). Although ET versus WT relationships were significant ($p \leq 0.05$) in all years, these relationships were considerably poorer ($r^2 \leq 0.22$) than the PET relationships. The greatest level of explanation ($r^2 = 0.22$) occurred in the wettest summer (2000).

In order to investigate further the influence of WT on ET data, the ET rates were sorted into 5 cm WT classes, and means of ET and the ratio ET/PET were computed for each WT class and statistically compared

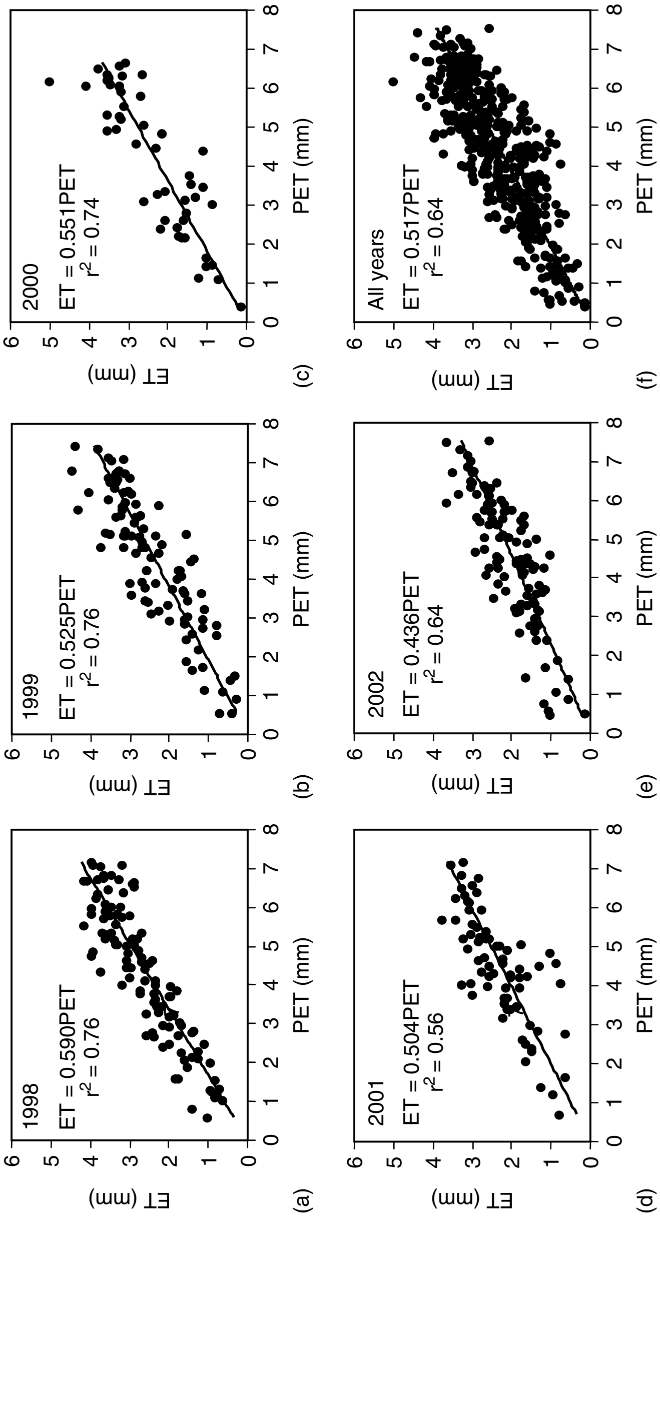

Figure 6. Relationship between daily ET and PET for growing seasons (a)–(e) and all years combined (f). Lines shown are best-fit least squares regression forced through the origin. Data points are days with greater than 36 half-hours of measured data

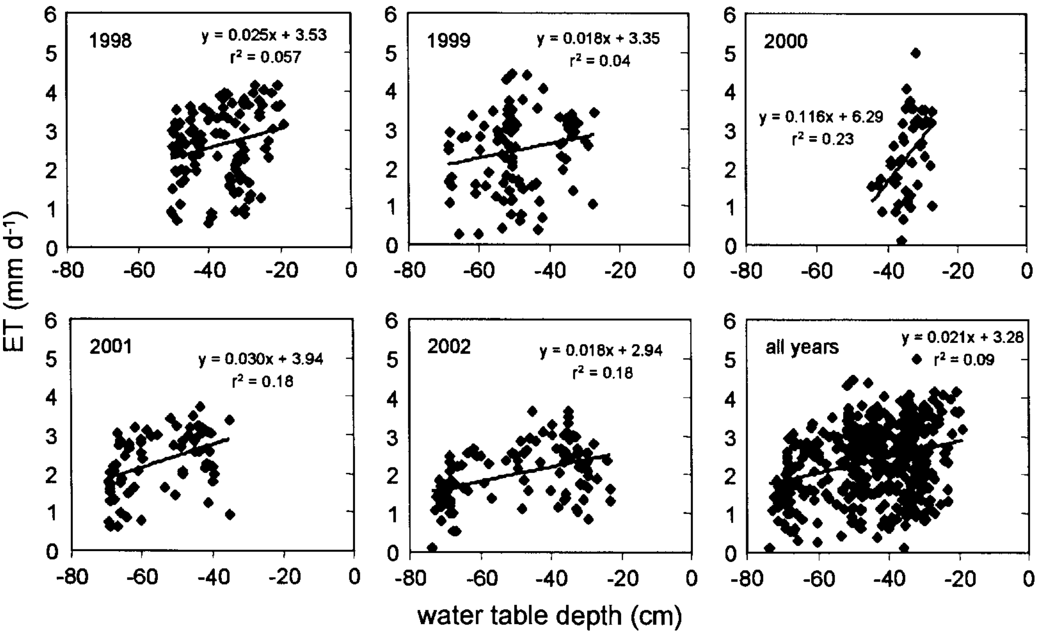

Figure 7. Relationship between ET and WT depth for growing seasons (a)–(e) and all years combined (f). Lines shown are best-fit least squares regression. ET data points are days with greater than 36 half-hours of measured data; WT points are daily mean values

with the adjacent classes (Figure 8). The trend in ET means showed little variation across the majority of range of WT depths, with much smaller mean daily ET occurring at the deepest WTs. Significant differences in ET means were found only between the two shallowest WT classes (<25 and 27·5 cm, midpoint of the class) and between the three deepest classes (62·5, 67·5 and >70 cm). The ET/PET ratio followed a similar trend to the ET data, with similar ET/PET ratios for most WT classes, and significantly smaller mean ratios were found for the deepest WT classes. Careful examination of the data did not reveal an explanation for the significant difference between the 42·5 and 47·5 cm WT classes.

Based on the previous analyses, data from all years were pooled and then sorted into three classes of WT depth: shallow, WT < 25 cm; intermediate, 25 ≤ WT ≤ 64·9 cm; deep, WT ≥ 65 cm). Daily ET was plotted against PET for each group, producing three statistically distinct ($p = 0{\cdot}05$) relationships (Figure 9). The slope of the ET/PET relationship decreased with decreasing WT depth.

DISCUSSION

The results of this study indicate a number of characteristics of the association between ET and PET, and how the association changes, or does not change, when the WT is at different depths below the surface. Although the actual parameter values of these relationships may be specific to Mer Bleue, the relationships themselves should be quite general and, therefore, of use for biogeochemical and runoff modelling. First, we discuss the pattern of ET and PET, then how these patterns are associated with the depth of WT, and we conclude with some discussion on the implications of our findings for the wider issues of peatland biogeochemistry and runoff hydrology.

ET from this continental bog follows a distinct seasonal cycle, with daily ET peaking in midsummer and falling to minimum rates during winter. Although daily winter ET is an order of magnitude less than summer ET, total ET over the 7 month non-growing season is an important component of the annual water balance, comprising about 25% of annual ET for this site. Total growing-season ET was remarkably similar

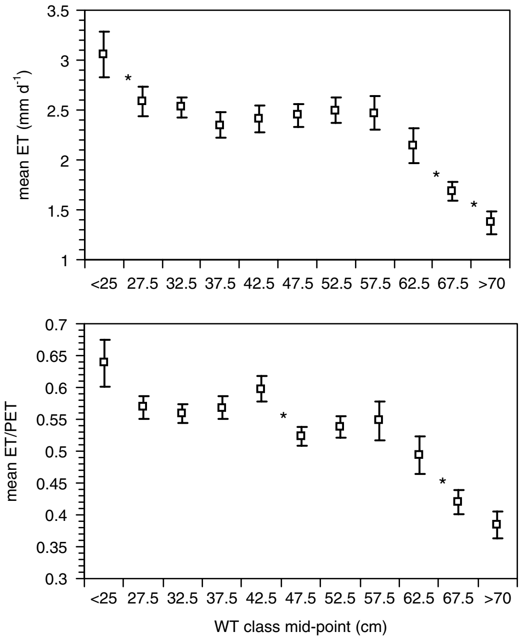

Figure 8. (a) ET plotted for 5 cm WT depth classes. Open box is the mean, and whiskers are standard errors. Asterisk represents a significant difference ($p < 0{\cdot}05$) between mean ET for two adjacent WT classes. (b) As (a), except ratio of daily ET to PET

in 3 years of the study (∼370 mm) and was less in the following 2 years (342 and 301 mm), both of which experienced marked late-summer WT drawdown (Figure 3). Total growing-season precipitation varied from 380 to 498 mm and was similar to, or larger than, total growing-season ET. This created a water excess in most growing seasons, which, combined with the large water excess of the non-growing period, produced an annual water excess ranging from 300 to 500 mm (Figure 5). This finding is consistent with estimates for the region given in the *Hydrological Atlas of Canada* (Environment Canada 1978), which indicates annual $P >$ ET by 300 to 500 mm in eastern Ontario.

Growing-season ET at Mer Bleue was within the range of ET that has been measured at other Canadian peatland sites (Table II). Although Mer Bleue ET was within the reported range, it falls toward the lower end of the range. This finding broadly agrees with the conclusion of Roulet *et al.* (1997), that bogs and mineral-poor fens tend to have lower ET rates than other peatland types. Such broad comparisons should be interpreted cautiously, because of differences in methodologies, lengths of study periods, widely ranging geographic locations and climate regimes, and varying meteorological conditions. However, these two peatland types are both characterized by extensive *Sphagnum* moss ground covers and average WTs below the mean moss height. Growing-season ET was shown to be closely related ($0{\cdot}56 \leq r^2 \leq 0{\cdot}76$) to PET in all years, suggesting that PET could be a reasonable means to estimate ET at this bog (Figure 6). However, the slopes of the ET/PET relationship were statistically different between some years; most notably, the driest year had a significantly smaller slope than other years. Although a single ET/PET relationship for all years combined gave reasonable results (Figure 6), further analysis suggested that better predictability could be achieved by considering WT depth in the relationship (Figure 9).

Growing-season daily ET was, on average, smaller than PET. The mean ET/PET ratio for all days was 0·517, suggesting there was strong surface control on ET at this site. Even the wettest year (2000) had our ET/PET ratio of only 0·55. Although some early peatland studies reported ET/PET ratios $\geq 1{\cdot}0$ (see review by Ingram (1983)) most of these studies measured ET in small tanks (lysimeters), which do not necessarily simulate natural conditions. More recent peatland studies using micrometeorological techniques to measure

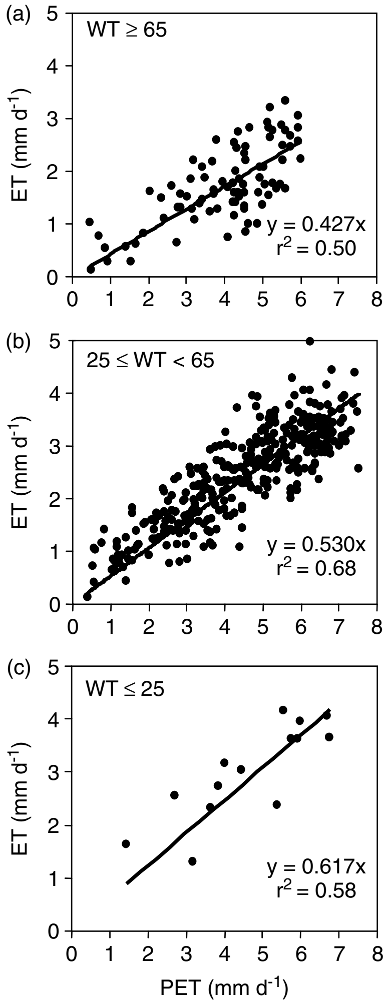

Figure 9. Relationship between the ratio of daily ET to PET and WT depth for three WT depth ranges: (a) deep, WT < -65 cm; (b) intermediate $-40 \leq$ WT ≤ -60 cm; (c) shallow, WT > -25 cm

ET suggest ET/PET $<1{\cdot}0$, with values ranging between 0·3 and 0·8 (Lafleur, 1990; Lafleur and Roulet, 1992; Campbell and Williamson, 1997; Phersson and Pettersson, 1997; Kellner, 2001; Kurbatova *et al.*, 2002). Bogs tend to be at the lower end of this range. One exception was the study by Kim and Verma (1996), who reported ET/PET $\approx 1{\cdot}0$ for a wet mineral-poor fen in northern Minnesota. Thus, it seems likely that, for most northern peatland ecosystems, PET is an upper limit to evaporation rates, but is rarely achieved. Several factors could contribute to the departure of ET/PET from unity, yet it seems likely that the overall water availability to the surface and its relationship to WT depth may be the most important factor.

At the Mer Bleue bog it appears that WT variations had little influence on ET: daily ET was not well correlated with WT depth in any year (Figure 6). Binned averages of ET showed little change across a wide range of WT depths; only at WT ≈ -65 cm below the hummock surface (-40 cm below the hollow bottom) and deeper did the ET regime seem to undergo a bulk change, where mean ET rates were smaller for the deeper WT condition (Figure 8). This finding is inconsistent with early literature from controlled tank experiments showing that ET decreases as WT drops from 0 to 15 cm below the peat surface (review in

Table II. Summary of ET rates from Canadian peatlands. Data are reported mean and maximum values for the summer (June–August) period. Peatland type as reported by the authors; rich and poor refer to mineral-rich and mineral-poor fens

Study	Peatland type	Geographic region	ET (mm day^{-1})	
			Mean	Maximum
Munro (1979)	Wooded swamp	Southern Ontario	3·5	4·6
Roulet and Woo (1986)	Fen	Low Arctic	4·5	6·0–7·0[a]
Lafleur (1990)	Rich fen	James Bay Lowland coast	2·9	5·0–6·0[a]
Price (1991)	Blanket bog	Southeast Newfoundland	2·5	n/a
Lafleur and Roulet (1992)	Poor fen	Southern James Bay Lowland	2·5	n/a
Price and Maloney (1994)	Patterned fen	Labrador	3·1	4·5
Price and Maloney (1994)	Bog	Labrador	2·2	n/a
Moore *et al*. (1994)	Fen	Central Quebec/Labrador	2·7[b]	n/a
Lafleur *et al*. (1997)	Poor fen	Northern Manitoba	1·8[b]	n/a
Joiner *et al*. (1999)	Poor fen	Northern Manitoba	n/a	3·0–3·5[a]
Eaton and Rouse (2001)	Fen	Hudson Bay coast	1·9–4·0[b,c]	n/a
This study	Shrub bog	Eastern Ontario	2·2–3·3[c]	4·0–5·0

[a] Estimated from a data figure.
[b] Computed from seasonal total ET.
[c] Range of values from more than 1 year of observations.

Ingram (1983)). Later, Nichols and Brown (1980) used tank experiments in growth chambers to show that ET was greater when WT = −5 to −15 cm than when the WT was at the moss surface. Most recent authors do not discuss a specific relationship between ET and WT. Exceptions are Kim and Verma (1996), who found a modest correlation between the ET/PET ratio and WT at their Minnesota fen site, and Kellner (2001), who noted a low correlation between surface resistance to ET and WT at a Swedish bog. In both of these studies, however, WT was never deeper than −25 cm below the peat surface.

Our findings suggest that the relationship between WT and ET at the Mer Bleue site is complex. Since ET appeared to be unaffected by WT until it dropped below 65 cm, some explanation for this phenomenon is warranted. One possible explanation is that this result was a seasonal effect. It is notable that these very deep WTs only occurred in late summer (i.e. late August and September); thus, the reduced ET may have been due to changing meteorology (e.g. declining light and/or cool temperatures). Meteorological conditions were different between midsummer and September, the air temperature was an average 4·5 °C lower and the received solar radiation was 35% smaller in September than in July. However, meteorological conditions were unlikely responsible for the change in the ET/PET ratio for WT −65 cm and deeper (Figure 9). The variables driving ET and PET are similar; therefore, any seasonal change in a driving variable for ET would also be reflected in PET. Instead, we are inclined to believe that the main cause for the ET reduction was restricted water supply to the surface, resulting in reduced moss evaporation in combination with decreased transpiration from vascular plants. In order to elucidate these processes we propose the conceptual model of ET shown in Figure 10. Water supply for ET is linked to the WT depth through the soil hydrology and plant physiology.

Although not depicted in Figure 10, peat hydraulic properties are a key feature of the conceptual model. Hydraulic properties of peat soil have been studied by many authors; for reference, here we draw on the comprehensive review of this work provided by Letts *et al*. (2000). Peat soils, especially those composed of decayed *Sphagnum*, such as in Mer Bleue, are known to have high porosities ($\geq$0·85) at all soil depths. In contrast, pore-size distribution varies markedly with depth, such that large pores dominate the upper profile and will decrease by two to three orders of magnitude with depth. The result of this is that hydraulic conductivity is large in the upper soil and decreases rapidly with depth, usually becoming constant at some depth, typically near 50 cm. Fraser *et al*. (2001a) showed this behaviour for the Mer Bleue bog. One result of this characteristic is that the bog efficiently sheds water when WT is high, so that even under the wettest

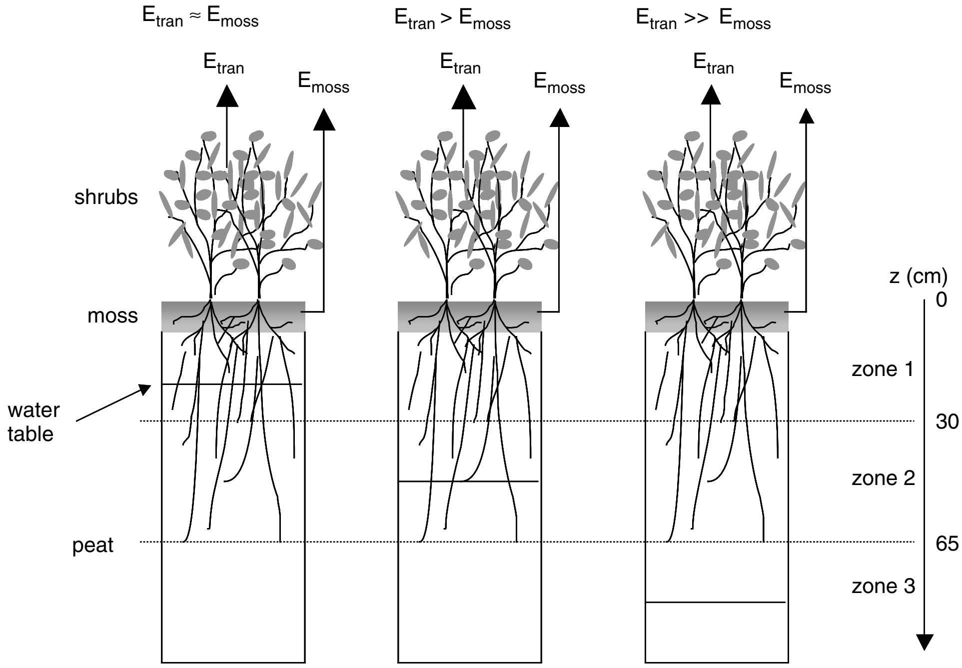

Figure 10. Conceptual model of ET at Mer Bleue bog. Figure shows three stages of ET with WT at different depths. E_{tran} is transpiration from the vascular plant canopy and E_{moss} is moss evaporation. Size of the arrows indicates relative size of ET. Z is depth below the *Sphagnum* surface

conditions the WT rarely exceeds the surface in the peat hollows, thus leaving the hummocks in a perpetual unsaturated state. During the 5 years of this study the shallowest WT depth recorded was 20 cm from the hummock tops (5 cm above the hollow surface). Specific yield also varies from greater values ($\geq$0·6) near the surface to lower values ($\leq$0·2) at depth. Many of these changes occur in the first metre of the peat profile. The implications of these hydraulic properties for WT changes are that: (1) when WT is near the surface, a decrease in the WT results in rapid dewatering of the peat and low moisture contents; (2) when the WT is at depth (i.e. 0·5–1·0 m), a drop in WT leaves considerably more moisture held in the soil immediately above the WT. ET is linked to the soil hydrology through the separate plant pathways for moss and vascular plants.

Evaporation from a moss surface is primarily derived from a dense crown of live material called the capitulum, where photosynthesis is also occurring. On the order of 1–2 cm thick, the capitulum is composed of small groups of branches supporting arrays of tightly packed single-cell leaves and water-holding structures termed hyaline cells. Although some vapour may diffuse from the dead and decaying moss below, because of its tight packing and complete coverage the vast majority of water evaporated must come from the capitulum. The capitulum is supported by a stem that does not conduct water; instead, water is conducted up the side of the stem by capillary flow in a network of small pores created by the dead leaves and branches. Although it has a low storage capacity, the *Sphagnum*-peat structure is able to conduct water upwards, supplying demand at the capitulum. The efficiency of this conducting network decreases with WT depth. The consequences of this are such that supply is able to keep up with demand when WT is close to the surface, and there is no storage change in the capitulum, and as WT drops the demand may exceed supply and the capitulum storage in reduced. Evaporation (and photosynthesis) from *Sphagnum* is known to decrease when water content reaches a critical value (Williams and Flanagan, 1996). That limit is difficult to detect in field studies; it is undoubtedly species related, but for hummock *Sphagnum* may represent a WT depth of about 30 cm (Hayward and Clymo, 1982). When WT is very deep and little rain has occurred, the hyaline cells will empty and the severe desiccation causes a noticeable colour change in mosses and evaporation is highly restricted (Hayward and Clymo, 1982; Ingram, 1983).

We envision three stages of ET in the conceptual model. When the WT is high, Figure 10a, ET proceeds at a rate unrestricted by moisture supply to both the mosses and vascular plants. Moss evaporation E_{moss} and transpiration from the vascular plant cover E_{tran} are depicted as being approximately equal. The exact partitioning will depend upon species composition and the leaf area of the vascular cover. The lower limit of this stage, WT $= -30$ cm, is an estimate derived from the literature and will vary among peatlands and moss species. As the WT falls below -30 cm, the second stage of ET occurs (Figure 10b), when E_{moss} may become restricted due to reduced water supply to and storage in the moss capitulum. Moss hummocks will then become warmer and the canopy air becomes drier because of the smaller vapour input to the canopy from the moss surface, which then enhances the E_{tran} from the shrub canopy, possibly also from hollow mosses, which are not likely water limited. Thus, the overall ET rate is unchanged over a wide range of WT depths, as shown in Figure 8. Although we could not partition ET between the vascular canopy and moss surface in this study, Kim and Verma (1996) presented a theoretical model of ET and field observations that suggest such a compensating mechanism is possible in peatlands. The third stage (Figure 10c) is reached when the WT falls below the maximum rooting depth of the vascular plants. For Mer Bleue the rooting depth of the vascular plants varies between hummocks and hollows. Relative to the surface of the moss, the maximum root densities in hummocks and hollows are between 20 and 40 cm and between 20 and 30 cm respectively. This means that roots are clearly present and that ET can be support by both E_{moss} and E_{trans}, i.e. stage 1. However, the maximum root depth is 50 to 60 cm and 30 to 40 cm, and fine roots, the roots that are presumably most involved in the extraction of peat pore water, extend throughout the root profile (Moore *et al*., 2002); thus, the shrubs can support E_{tran} through stage 2. The limit of roots is 60 cm for hummocks and 40 cm for hollows. When the WT falls below the maximum rooting depth, moisture supply to the vascular plants becomes limiting and E_{tran} decreases. Also, the hollow mosses' water supply becomes limited and at some WT depth the moisture storage in the hummock moss capitulum is exhausted and these mosses show visible signs of desiccation. Field observations at Mer Bleue indicated moss desiccation (colour change and papery texture) on at least two occasions during the study: in late August 1999, when the WT fell briefly to -65 cm, and during the extended drought in September 2002, when the WT exceeded -70 cm. ET is reduced during this third stage because E_{tran} is reduced and E_{moss} is severely restricted.

The specific relationship between ET and PET and WT depth will vary with the plant type and density, the profile and density of roots, and the hydraulic properties of the peat. If a site-specific model is desired, or one wishes to evaluate a hydrologic model at one peatland, then site-specific information would be needed. But, for generic models of peatland hydrology to be used in the simulation of carbon cycling and biogeochemistry, such as Granberg *et al*. (2001), the relationship provided here is an advance over what was previously available. These models require simple parameterization of ET, because seldom are the input variables that are required to run a land-surface process model (such as CLASS; Comer *et al*., 2000) available. The generality of the relationships presented here need to be evaluated for other peatlands across several ecoclimatic regions; but this should now be possible, since there are a number of sites in Canada, Alaska, Scandinavia, and Russia where continuous, more accurate, and precise measurements of the surface energy balance, and hence ET, and hydrology of peatlands are being done (e.g. AMERIFLUX, http://public.ornl.gov/ameriflux; Fluxnet Canada, http://www.fluxnet-canada.ca; and sites run by individual teams). Synthesizing the results from all these studies using the conceptual model proposed here, once these sites' measurements are published or are available to the public, would be highly desirable for the modelling community.

The other generalization that can be made for the current study concerns part of the reason why ombrotrophic peatlands display a significant amount of homeostasis. In the literature, the strong negative feedback is attributed to a four to five orders of magnitude drop in hydraulic conductivity in the top metre of peat (Ingram, 1982; Clymo, 1984). It is clear that this is the primary factor, but our results also indicate that there is a further mechanism to conserve stored water once the WT drops to below the rooting depth of the shrubs. This further strengthens the negative feedback, reducing water loss from a peatland.

The conceptual model presented here was formulated from observations of ET at Mer Bleue and knowledge of soil and plant processes. It is, of course, largely untested, but in that regard it provides a basis for future research into ET processes in peatlands. The challenges will be to devise a means for partitioning ET between E_{trans} and E_{moss} and to determine how applicable the model might be to a variety of peatland types.

CONCLUSIONS

The main findings of this study can be stated as follows:

- ET is an important component of the water balance of this ombrotrophic bog.
- Winter ET, although small, is important for annual water budget estimates.
- On an annual or seasonal basis, ET is less variable than P and the variations in ET are poorly related to variation in P.
- ET at the bog was usually about half of PET.
- The rooting depth of vascular plants represents a critical limit of WT depth (65 cm below the hummock surface for Mer Bleue), above which ET is unaffected by changes in WT, whereas below this depth ET is limited to some degree by water supply.
- The conceptual model presented here suggests that the ET regime is a complex interaction of soil hydrology, moss and vascular plant factors.

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