Energy fluxes and evaporation mechanisms in an Atlantic blanket bog in southwestern Ireland

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[1] Water and energy fluxes control the development of northern peatlands and influence their carbon budget. Blanket bogs are peatlands that occur in temperate maritime regions where precipitation is much greater than evapotranspiration (ET). In this paper, five years (October 2002–September 2007) of ET and energy fluxes derived from eddy-covariance measurements were analyzed in the context of the predicted climate change for Ireland. Monthly ET at the Glencar Atlantic blanket bog varied little, ranging between a minimum of 12 mm month^{-1} and a maximum of 56 mm month^{-1} over the five years, resulting in an annual ET average of 394 mm, with typical highest daily values of 2.5–3.0 mm. Compared to other peatland types, Glencar had lower summer ET and a lower ET/potential ET ratio, despite having higher precipitation and water table. The ET was limited not only by the low vapor pressure deficit and cool summer temperatures but also by the low cover of vascular plants and mosses (essential for transpiration). The energy budget was similar to other peatland types in terms of net radiation and sensible heat fluxes, but had lower latent and higher ground heat fluxes. A comparison among the five years suggests that the predicted climate change (greater winter precipitation, lower summer precipitation, and higher all year round temperatures) will probably increase winter ET, while the summer energy flux patterns will not be profoundly affected. However, if the frequency of summer rain events should diminish, the moss component of these ecosystems may become water stressed, ultimately leading to lower evapotranspiration.

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1. Introduction

[2] The development of peatlands is closely related to regional climate controls on precipitation and evaporation and is thus strictly controlled by the water and energy fluxes. The water balance in peatlands is coupled to carbon sequestration [*Lafleur et al.*, 1997, 2003; *Yurova et al.*, 2007], as the depth of the water table determines the soil temperature, the depth of the peat layer available for aerobic respiration, the soil chemical conditions, and the water available for plants that in turn influence their photosynthetic ability. As the water balance in peatlands is predicted to be affected by climate change [*Roulet et al.*, 1992], a better understanding of the water and energy fluxes is crucial if we are to understand the effect of the predicted climate change on these fragile ecosystems.

[3] Many studies in recent years have focused on the energy balance and evaporation process in different wetland types [e.g., *Campbell and Williamson*, 1997; *Kim and Verma*, 1996; *Kurbatova et al.*, 2002; *Mackay et al.*, 2007; *Shimoyama et al.*, 2003], but full annual measurements and multiyear comparisons are still rare in peatlands [*Lafleur*, 2008], as in other ecosystems [but see *Barr et al.*, 2007; *Ryu et al.*, 2008]. The ground heat flux in peatlands is an important component of the energy balance, especially in the wettest areas [*Lafleur et al.*, 1997; *Price*, 1991], but in general most of the net radiation is primarily consumed for latent and secondarily for sensible heat fluxes [*Rouse*, 2000; *Shimoyama et al.*, 2003; *Valentini et al.*, 2000]. Evapotranspiration (ET) is typically well correlated with, but considerably lower than, potential ET (PET) [*Humphreys et al.*, 2006; *Lafleur et al.*, 2005]. Despite this, ET appears to be relatively independent of water table depth [*Humphreys et al.*, 2006; *Lafleur et al.*, 2005] and similar in years with differing precipitation [*Kurbatova et al.*, 2002]. The mechanisms of ET vary in different peatland types, being strongly controlled by surface conductance in peatlands with high vascular plant cover [*Humphreys et al.*, 2006] or by available radiation in moss-dominated peatlands [*Kellner*, 2001; *Kurbatova et al.*, 2002; *Shimoyama et al.*, 2003].

[4] The only studies on evaporation and energy processes performed in a blanket bog, to the authors' knowledge, were done in the early 1990s in Newfoundland, southeastern Canada [*Price*, 1991, 1992]. Blanket bogs are so called because they blanket the landscape [*Tansley*, 1965] on slopes with gradients up to 20°–25° [*Clymo*, 1983; *Tallis*, 1998]. Their development is mostly independent of basins or topographical features where water can collect, and they are largely ombrotrophic, thus receiving water and nutrients only from atmospheric deposition, similarly to boreal raised bogs. The

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development of blanket bogs in Ireland requires cool summers, winter mean temperatures >4°C [*Doyle and Moore*, 1978], and high annual precipitation (>1250 mm yr^{-1}), with more than 225 rain days per year [*Hammond*, 1981; *Taylor*, 1983], so that precipitation exceeds ET by at least 200 mm over the April to September period [*Tallis*, 1998]. Globally, blanket bogs are rare ecosystems, accounting for ca. 3% of the world peatland area [*Foss et al.*, 2001], as their distribution is restricted to maritime temperate regions, but locally they can be very important. In the Republic of Ireland, blanket bogs cover about 13% of the national land area and contain about 45% of the national soil carbon stock [*Eaton et al.*, 2008; *Kiely et al.*, 2010]. *Price* [1992] found that the water loss from a moss-covered blanket bog in Newfoundland was dominated by stream discharge. Even if higher ET was measured during clear weather due to higher available radiation, ET was closer to but still far from its PET in rainy and foggy conditions, suggesting that ET is strongly linked to soil surface wetness and that PET cannot occur in moss-dominated peatlands [*Price*, 1991]. The carbon and CO_2 annual balances in Atlantic blanket bogs were reported to be similar to those of boreal raised bogs, although both gross ecosystem production and respiration were lower [*Koehler et al.*, 2010; *Sottocornola and Kiely*, 2010]. To better understand the functioning of blanket bogs, it is therefore important to extend the comparison with boreal raised bogs and other peatland types to the water and energy fluxes.

[5] In this paper we report on five years of evapotranspiration and energy fluxes. The aims of this paper are (1) to understand the water and energy fluxes in an Atlantic blanket bog by comparison to other peatland ecosystem types, (2) to identify the dominant mechanisms controlling evapotranspiration, and (3) to analyze the interannual variations of evapotranspiration and energy fluxes in the context of the predicted climate change. The data was analyzed based on the hydrological year, 1 October to 30 September.

2. Site Description

[6] The experimental site was a relatively intact Atlantic blanket bog located near Glencar, County Kerry, in southwestern Ireland (latitude 51°55′N, longitude 9°55′W). The peatland is situated in a valley at an elevation between 145 and 170 m above sea level and lies on sandstone bedrock. The characteristic feature of the bog is a spatially heterogeneous surface, with a mosaic of microforms, which differ in relative altitude, plant composition, water table depth, and chemical conditions [*Sottocornola et al.*, 2009]. We divided these microforms into four classes based on their relative elevation: hummocks, high lawns, low lawns, and hollows [*Laine et al.*, 2006; *Sottocornola et al.*, 2009]. The elevation difference between the highest and lowest microforms is typically 20–40 cm. Hollows are 50–300 cm oblong depressions covered by standing water for most of the year. The distribution of the microform composition inside the eddy-covariance footprint was estimated as 6% hummocks, 62% high lawns, 21% low lawns, and 11% hollows [*Laine et al.*, 2006]. Vascular plants cover about 30% of the bog surface, with the most common species being *Molinia caerulea* (purple moor grass), *Calluna vulgaris* (common heather), *Erica tetralix* (cross-leaved heath), *Narthecium ossifragum* (bog asphodel), *Rhynchospora alba* (white beak sedge), *Eriophorum angustifolium* (common cotton grass), *Schoenus nigricans* (black-top sedge), and *Menyanthes trifoliata* (bog bean). The bryophyte component is not widespread, about 25% of the bog surface, and the principal species include a brown moss, *Racomitrium lanuginosum* (woolly-hair moss), and *Sphagnum* mosses (bog mosses), covering about 10% each, so that large areas of the peatland are covered by bare soil. In the center of the Glencar bog, the upper acrotelm peat layer is mainly composed of sedge peat and has a bulk density of ~0.05 g cm^{-3} and a porosity of 95%, while the peat depth ranges between 2 m and >5 m (C. Lewis et al., Spatial variability of hydraulic conductivity and bulk density along a blanket peatland hillslope, submitted to *Ecohydrology*, 2010).

[7] The 30 year (1961–1990) average temperature at the Met Eireann synoptic weather station at Valentia (ca. 30 km west of Glencar) for the warmest month of the year (August) was 14.8°C and for the coldest (February) was 6.6°C. The 30 year average annual precipitation was 1430 mm. In the same period, the average annual number of rain days was 239. The study years of 2003–2007 in Valentia have been on average 1.0°C warmer and ca. 5% wetter than the 30 year averages (http://www.meteireann.ie/climate/valentia.asp).

3. Methods

[8] The meteorological equipment included a net radiometer (CNR 1, Kipp & Zonen, The Netherlands) and a sensor for Q_{PAR}, photosynthetically active radiation (PAR Lite, Kipp & Zonen, The Netherlands). Wind speed was recorded with 3-D (Model 81000, R. M. Young Company, USA) and 2-D (WindSonic, Gill, UK) sonic anemometers. Air temperature (T_{air}) and relative humidity were measured at 2 m height with a shielded probe (HMP45C, Vaisala, Finland), while atmospheric pressure was recorded with a barometer (PTB101B, Vaisala, Finland). Soil water content was recorded with a time domain reflectometer (TDR) (CS615, Campbell Scientific, UK), while the ground heat flux (G) was measured with two soil heat flux plates (HFP01, Hukseflux Thermal Sensors, The Netherlands), buried at 5 cm below a high lawn surface and corrected for storage heat [*Campbell and Norman*, 1998; *Hsieh et al.*, 2009]. Precipitation was measured with two tipping bucket rain gauges (an ARG100, Environmental Measurements Ltd., UK, and an Obsermet OMC-200, Observator BV, The Netherlands). The water table level (WTL) was recorded under the low lawn vegetation with a pressure transducer (PCDR1830, Campbell Scientific, UK) placed inside a metal well pierced all along its height. A malfunction of the WTL transducer between November 2002 and May 2004 was corrected by detrending the recorded data based on interpolated manual measurements [*Laine et al.*, 2007]. Signals from all the meteorological sensors were monitored every minute and averaged over a 30 min period in a CR23X data logger (Campbell Scientific, UK).

[9] Evapotranspiration was calculated from the transformation of the latent heat flux (LE). Latent and sensible heat fluxes were estimated using an eddy-covariance (EC) system. The EC system was located on the same tower as the meteorological station, in a relatively flat area. It consisted of a 3-D sonic anemometer (Model 81000, R. M. Young Company, USA) and an open-path infrared gas analyzer for H_2O and CO_2 concentrations (LI-7500, LI-COR, USA) mounted 3 m above the high lawn vegetation. Data were recorded at 10 Hz, and fluxes were Reynolds averaged every half hour. The

30 min averaged LE was measured via the eddy-covariance technique as

$$LE \cong L_v \overline{w'\rho_v'}, \quad (1)$$

where L_v (kJ kg^{-1}) is the latent heat of vaporization, w' is the vertical wind velocity fluctuations (m s^{-1}), and ρ_v' is the water vapor density fluctuation (g m^{-3}). The 30 min averaged sensible heat flux (H) was also estimated via the EC technique as:

$$H \cong \rho_a c_p \overline{w'T'} \quad (2)$$

where ρ_a is the air density (kg m^{-3}), c_p is the specific heat capacity of moist air (J kg^{-1} °C^{-1}), and T' is the air temperature fluctuation (°C). The micrometeorological convention, used in this work, treated fluxes from the atmosphere as negative and fluxes from the ecosystem as positive.

[10] The quality of the data was ensured by a two-step quality check and filter process, first on the 10 Hz and then on the 30 min average fluxes. The 10 Hz LE and H data were removed online if the water vapor concentration calculated from the relative humidity and the temperature measured with the Vaisala probe in the previous half hour differed by more than ±200 mmol m^{-3} and ±3°C, respectively, from those measured with the EC sensors. The calculated 30 min average fluxes underwent a postfield data processing, which started with a double rotation, so that the mean horizontal wind speed was rotated into the mean wind direction and the mean vertical wind velocity was set to zero, by correcting the fluxes for the averaged 30 min angle between the horizontal and vertical axes. H was then corrected for air humidity [*Shotanus et al.*, 1983], while LE was corrected for variations in air density [*Webb et al.*, 1980]. The second quality check step involved a number of filters to discard bad flux estimates. The 30 min average flux data were rejected if (1) less than 95% of the 10 Hz data passed the online 10 Hz filters, (2) the estimate of the vertical angle gave unrealistic outputs (typically in low wind speed conditions), (3) the product between net radiation (R_n) and H gave a negative output, (4) less than 67% of the flux footprint length was estimated to have originated inside the peatland (see *Laine et al.* [2006] for details), or (5) the fluxes were measured during rain events, because the open-path gas analyzer is known to be unreliable in wet conditions. Finally, LE values were rejected for predetermined seasonally realistic threshold values for each month. We are confident of the goodness of our energy flux data, despite the Licor 7500 heating effect [*Burba et al.*, 2008], based on the good correlation between CO_2 fluxes measured by our eddy-covariance system with upscaled CO_2 fluxes measured with closed chambers [*Sottocornola and Kiely*, 2010].

[11] Between 25 May and 4 June 2003 no data were logged due to an electricity outage. The missing meteorological data were replaced with the last five good days of data before the outage and the first five days of good data after the outage except for precipitation. Precipitation data were obtained from the Valentia weather station data, multiplied by the averaged ratio between the slopes of the annual cumulative sums of precipitation in Glencar and in Valentia in the other years. Shorter meteorological gaps were replaced either with interpolation (all data up to 4 h gap, except radiation data) or with the average of the previous and the following seven days (radiation data, and all data for gaps longer than 4 h) [*Falge et al.*, 2001]. Missing short-wave incoming radiation (r^2 = 0.99; root-mean-square deviation [*Piñeiro et al.*, 2008], RMSD = 12.22 W m^{-2}) and missing net radiation (r^2 = 0.94; RMSD = 32.12 W m^{-2}) data were replaced by linear regressions with Q_{PAR}, when present. The soil heat flux suffered a break between 19 December 2004 and 9 March 2005. The missing data were replaced by the average of the measurements in the other years for the same period. The EC system suffered three breaks, between 21 May and 26 June 2003, between 21 January and 2 February 2005, and between 16 and 23 March 2005, which were replaced using the gap-filling equations based on meteorological data. For the five year periods, 58 days of EC data (or 3.2% of time) were lost and were therefore gap filled.

[12] After postprocessing and filtering, approximately 56% of LE data in the hydrological year 2002/2003 (59% of daytime LE; daytime being defined as when incoming short-wave radiation was ≥10 W m^{-2}), 56% in 2003/2004 (62% of daytime LE), 45% in 2004/2005 (47% of daytime LE), 54% in 2005/2006 (59% of daytime LE), and 51% in 2006/2007 (57% of daytime LE) were considered good and suitable for further analysis. Most of the rejected flux data occurred in wintertime. The gaps in the LE time series were filled with a linear regression, forced through the zero, between the 30 min LE derived from potential evapotranspiration (PET, see below) and 30 min measured LE for each year, established using the Curve Fitting Tool of MATLAB 7.0.1 (MathWorks Inc., USA). This relationship had an r^2 value (and RMSD) of 0.70 (23.07 W m^{-2}), 0.81 (19.53 W m^{-2}), 0.75 (22.98 W m^{-2}), 0.81 (19.08 W m^{-2}), and 0.80 (19.45 W m^{-2}) in 2002/2003, 2003/2004, 2004/2005, 2005/2006, and 2006/2007, respectively.

[13] The Penman-Monteith equation, with surface resistance set to zero, was used as an estimate of PET:

$$PET = \frac{\Delta * (R_n - G) + \rho_a * c_p * \left(\frac{VPD}{r_a}\right)}{L_v * (\Delta + \gamma)}, \quad (3)$$

where Δ is the slope of the relationship between saturation vapor pressure and temperature (kPa °C^{-1}), VPD is the vapor pressure deficit (kPa), r_a is the aerodynamic resistance (s m^{-1}), and γ is the psychrometric constant (kPa °C^{-1}). The surface conductance at the ecosystem level (G_s) is the inverse of the surface resistance and was estimated by a rearrangement of the Penman-Monteith equation.

[14] Missing H values were replaced by solving the energy balance equation for H:

$$H = (R_n - G) * I - LE, \quad (4)$$

where I is the energy closure imbalance. The energy balance closure, accounting for the partitioning of the available net radiation energy into the main energy fluxes to an ecosystem (LE, H, and G), was 70%, 71%, 77%, 71%, and 70% in the years 2002/2003, 2003/2004, 2004/2005, 2005/2006, and 2006/2007, respectively, with an r^2 value ranging between 0.83 and 0.91. The Bowen ratio (β) was calculated as

$$\beta = \frac{H}{LE}. \quad (5)$$

[15] The one-sided leaf area index (LAI) was measured over three years, 2004/2005 to 2006/2007, using a PAR/LAI Ceptometer (LP-80 AccuPAR, Decagon devices, Inc., USA).

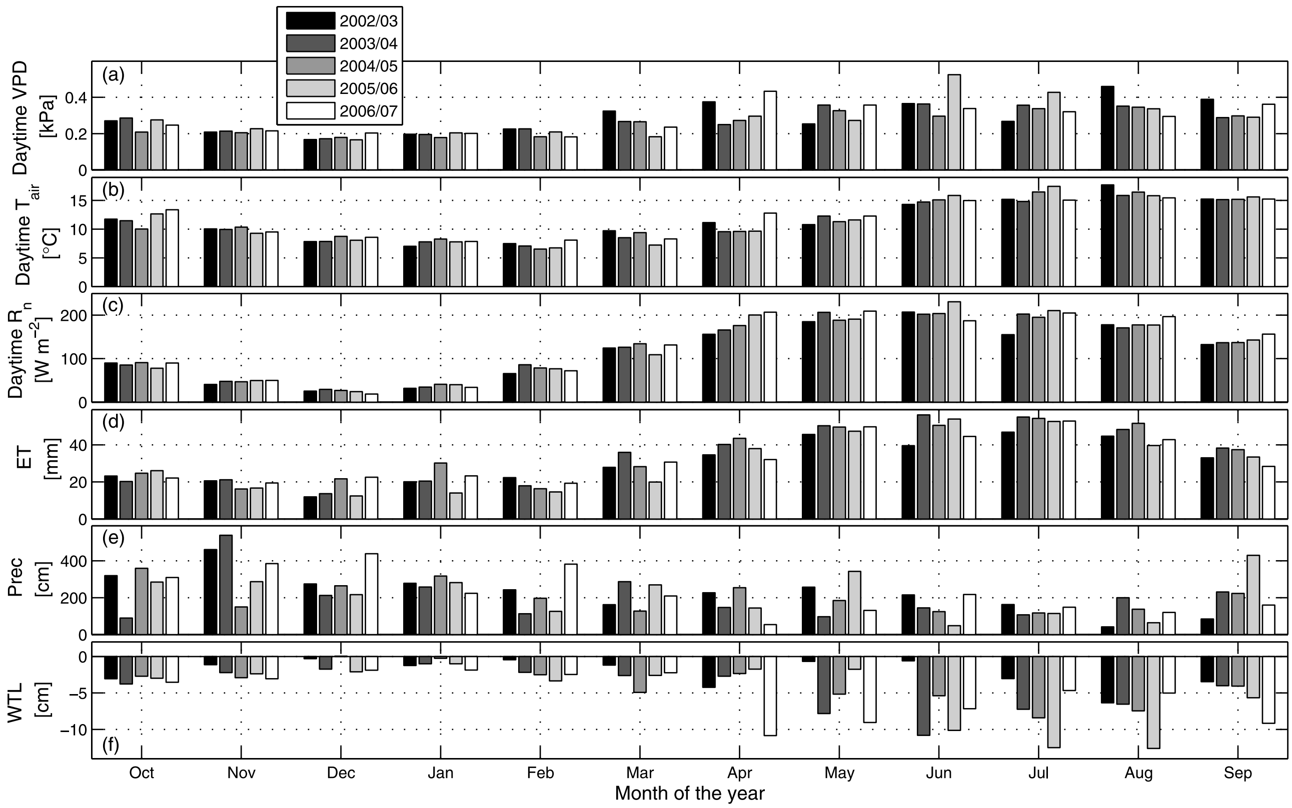

Figure 1. (a) Monthly daytime averages of vapor pressure deficit (VPD), (b) monthly daytime averages of air temperature (T_{air}), (c) monthly daytime averages of net radiation (R_n), (d) monthly sums of evapotranspiration (ET), (e) monthly sums of precipitation (Prec), and (f) monthly averages of water table level (WTL).

The measurements started in October 2004 and were performed at 134 points inside the footprint, under conditions of diffused light, which ensures the good performance of the instrument [*Garrigues et al.*, 2008].

4. Results

[16] The five-year study period was characterized in the spring (March to May) and summer (June to August) by a large variation of those environmental parameters that influence evapotranspiration: vapor pressure deficit, air temperature, and net radiation (Figure 1). The monthly trends of VPD, T_{air}, and R_n followed similar patterns over the five years, with daytime VPD showing the widest interannual variation (IAV), but with very small values (Figure 1a). The monthly averaged daytime T_{air} varied only between a minimum of 6.5°C in winter and a maximum of 17.7°C in summer during the five years (Figure 1b), while daytime R_n averages attained 200 W m^{-2} in the summer months (Figure 1c). Precipitation was abundant throughout the study period (Figure 1e), especially in autumn and winter but generally regular also during the summer, and showed a wide IAV (Table 1). The water table level remained close to the soil surface throughout the years, varying only between 2 cm above and 17 cm below the low lawn surface, as daily averages. The monthly WTL followed the precipitation patterns, dropping in spring to early summer 2003/2004 and 2006/2007 and summer 2005/2006 (Figure 1f).

[17] The annual evapotranspiration ranged between 369 and 424 mm and showed a small interannual variation (Figure 1d and Table 1). The monthly ET varied between 12 and 30 mm from October to February and peaked at 56 mm in June 2003/2004. In contrast, the daily ET showed a large day-to-day variation all year around, varying between 0.1 and 0.2 mm d^{-1} in winter and 2.5–3 mm d^{-1} in summer (Figure 2). The mean daily ET over a month ranged between a minimum

Table 1. Annual and April–September (in Parentheses) Sums of Evapotranspiration (ET), Precipitation (Prec), ET/Prec Ratio, and Averages of Water Table Level (WTL), Daytime Vapor Pressure Deficit (VPD), Daytime Air Temperature (T_{air}), and Daytime Net Radiation (R_n) at the Glencar Atlantic Blanket Bog

	ET (mm)	Prec (mm)	ET/Prec	WTL (cm)	Daytime VPD (kPa)	Daytime T_{air} (°C)	Daytime R_n (W m^{-2})
2002/2003 (Apr–Sep)	370 (240)	2724 (988)	0.14 (0.24)	−2.13 (−3.05)	0.29 (0.35)	11.50 (14.04)	116 (169)
2003/2004 (Apr–Sep)	418 (281)	2423 (925)	0.17 (0.30)	−4.38 (−6.51)	0.28 (0.33)	11.24 (13.72)	124 (181)
2004/2005 (Apr–Sep)	424 (281)	2454 (1040)	0.17 (0.27)	−3.83 (−5.46)	0.26 (0.31)	11.44 (14.00)	125 (180)
2005/2006 (Apr–Sep)	369 (262)	2607 (1143)	0.14 (0.23)	−4.89 (−7.39)	0.29 (0.36)	11.47 (14.32)	128 (192)
2006/2007 (Apr–Sep)	388 (247)	2776 (829)	0.14 (0.30)	−5.07 (−7.64)	0.28 (0.35)	11.78 (14.28)	130 (194)

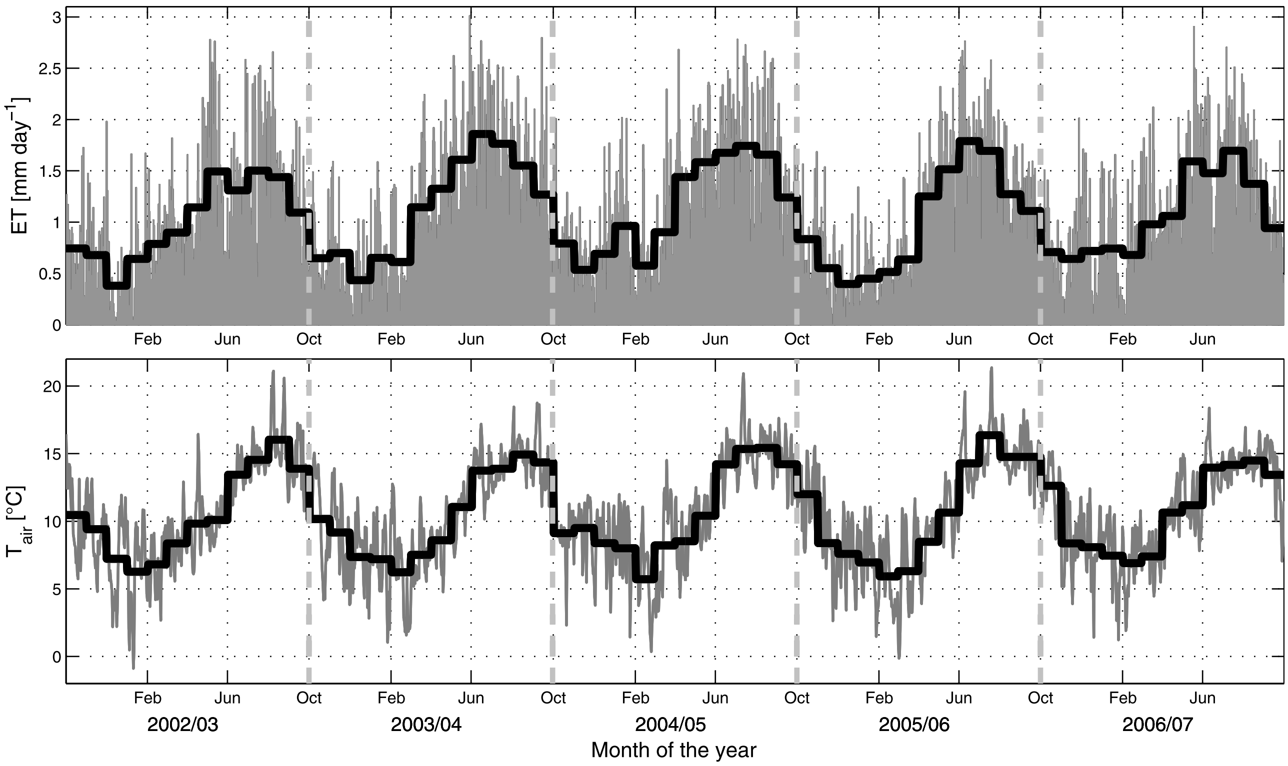

Figure 2. (a) Daily evapotranspiration (ET, bars) and superimposed monthly mean ET (heavy black line) for the period 1 September 2002 to 31 October 2007. (b) Daily air temperature (T_{air}) average (gray line) and superimposed monthly T_{air} mean for the same period.

of 0.4 mm in December 2002/2003 and a maximum of 1.9 mm in June 2003/2004, with typical highest values between 1.3 and 1.8 mm d^{-1} in June and July. In winter, ET appeared to follow the air temperature, often exceeding 1.5 mm d^{-1} during days warmer than 10°C. The 2004/2005 winter showed a different development from that of the other winters, in that the lowest monthly ET occurred in the dry November, while the warm December had higher ET than February, and January had higher ET than March, due to very mild T_{air} (Figures 1 and 2). The winter 2006/2007 was very mild as well and showed very high ET between November and January. The ET ranged between 240 and 281 mm during the 6 months April to September, accounting for about 69% of the total annual ET. The ET/precipitation ratio was very low, even during the April to September period, when it varied between 0.23 and 0.30, in the five years (Table 1).

[18] During the April to September period, the precipitation was very abundant and ranged between 829 and 1143 mm, being on average 38% of total annual precipitation (Table 1). Rainfall events typically occurred very frequently, such that, over five years, there were only 10 occasions lasting longer than 8 days, when the rain was <1 mm d^{-1} (Figure 3). In the middle of the day during the growing season the surface conductance typically varied between 3 and 25 mm s^{-1}, while the Bowen ratio ranged between 0.5 and 1.5 (but April to September averages at noon between 5.1 and 9.1 mm s^{-1} and between 0.81 and 1.05, respectively, in the five years). G_s and β showed an opposite development, with G_s having the lowest and β the highest values toward the end of periods without any wet day (August 2002/2003; mid-May 2003/2004 and mid-May 2004/2005; start of June 2005/2006; mid-April, mid-May, and end of August 2006/2007), while high G_s and low β occurred in periods with high rain frequency (May and July 2002/2003; end of June 2003/2004; end of May 2004/2005; end of June 2006/2007) (Figure 3).

[19] The spring in 2002/2003, 2003/2004, and 2006/2007 experienced very different weather conditions (Figure 1). Low radiation and cool temperatures in mid-April and end of May 2002/2003 (Figure 4) caused the lowest ET of the five years for these periods despite high WTL (down to 0.6 mm d^{-1} in April and 0.8 mm d^{-1} in May 2002/2003), while higher radiation and higher temperatures in spring 2003/2004 and 2006/2007 resulted in high ET (up to 1.4 mm d^{-1}). The highest ET values were recorded in summer 2005/2006 in association with the highest values of VPD, T_{air}, and R_n. Despite these peaks, the total April to September ET in 2005/2006 (262 mm) was lower than that of summers experiencing lower VPD, T_{air}, and R_n, such as 2003/2004 and 2004/2005 (both with 281 mm) (Table 1 and Figure 4).

[20] The latent heat flux related well with net radiation (Table 2). Between 69% and 79% of the variation in daytime LE during the April to September period was explained by R_n. The amount of R_n consumed for LE in this period was between 0.23 and 0.30, being highest in 2004/2005 and lowest in 2005/2006 and 2006/2007. The daily ET exhibited a very close relationship with daily PET in all five years (Table 3), with coefficients of determination between 0.52 and 0.77 (r^2 of 0.65 for the five years together). The ET/PET ratio ranged between 0.38 and 0.50, being highest in 2004/2005 and lowest in 2005/2006, in the same way as the measured ET. Figure 5a shows the daily ET relative to the depth

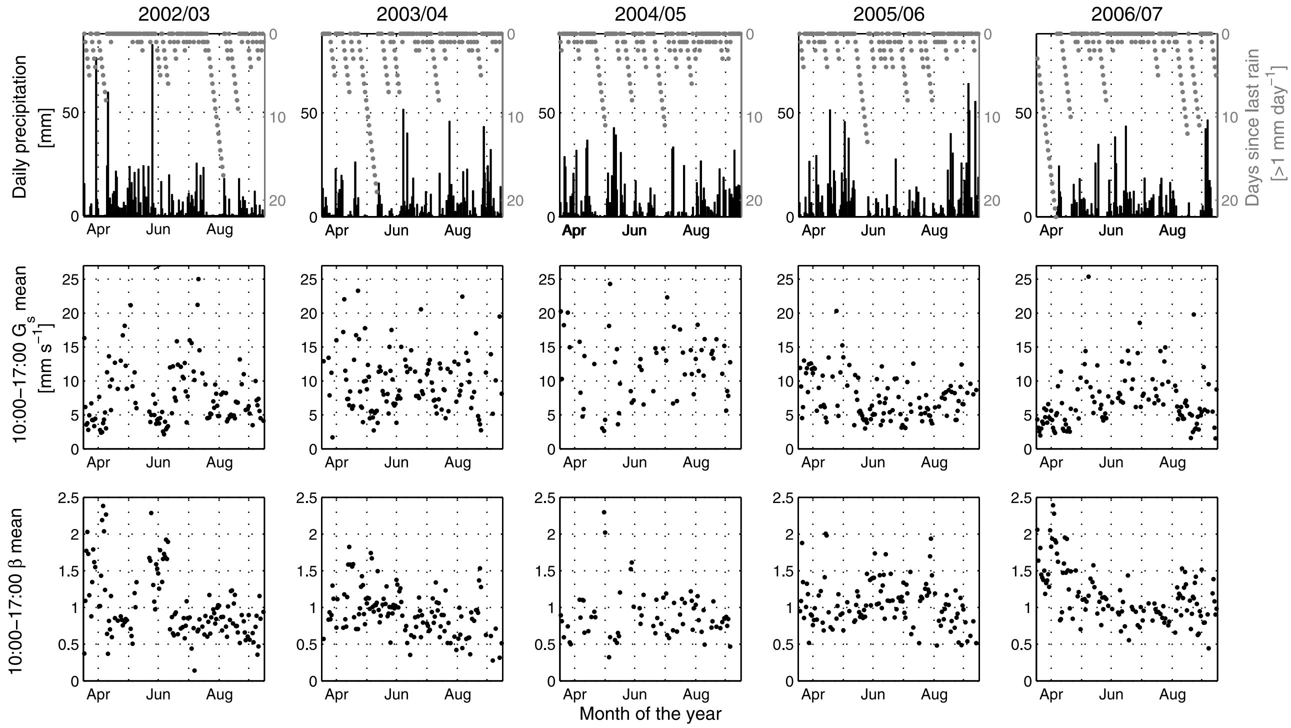

Figure 3. Daily precipitation and number of days since previous rainfall event (>1 mm d^{-1}); averages of surface conductance (G_s) and of Bowen ratio (β) between 10:00 A.M. and 5:00 P.M. (1000 and 1700 LT) for days with ≥80% of measured 30 min fluxes in this interval, during the April to September period in the five studied years.

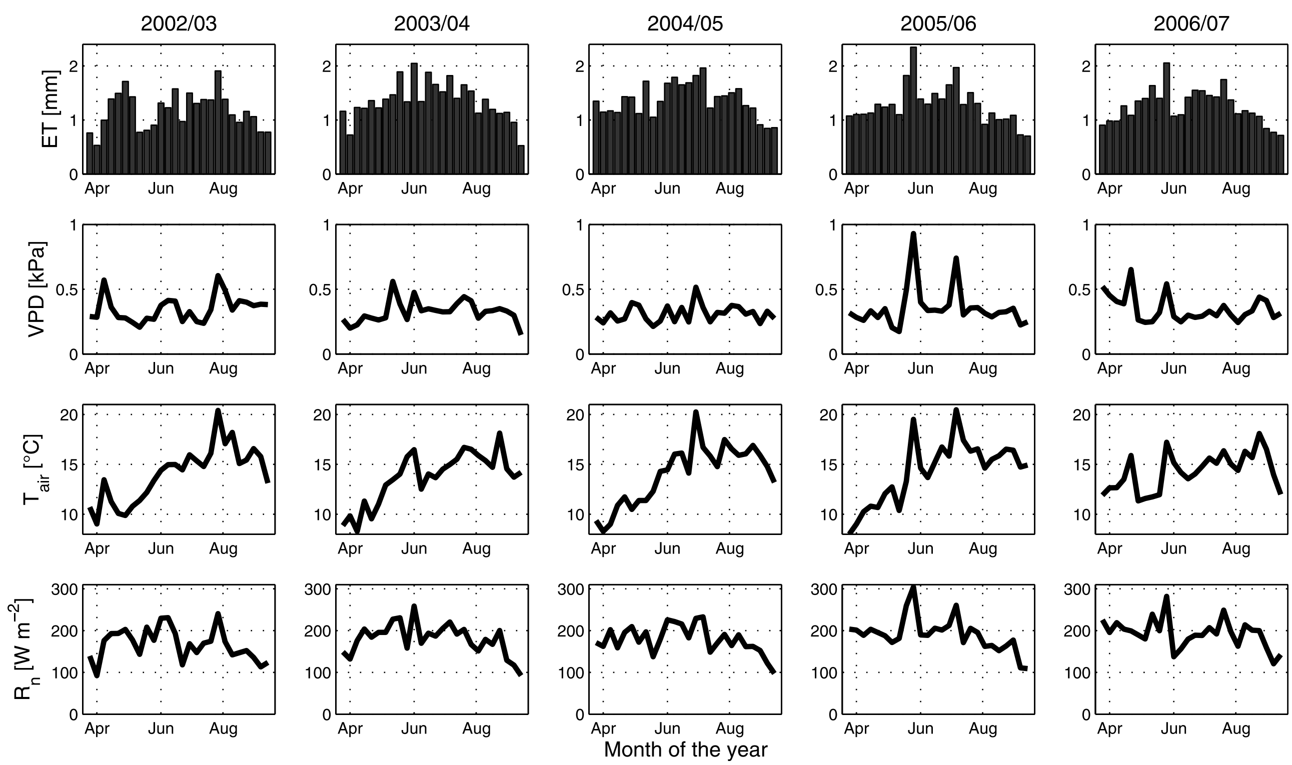

Figure 4. Daily sums of evapotranspiration (ET, averaged over 7 days) and daily means of vapor pressure deficit (VPD), air temperature (T_{air}) and net radiation (R_n), averaged over 7 days, during the period April to September in the five studied years.

Table 2. Slope, Intercept, r^2, Number of Occurrences (n), Root-Mean-Square Deviation (RMSD), and Sum-of-Squares Error (SSE) of the Linear Regression Explaining 30 Min Measured Daytime Latent Heat Fluxes (LE) With 30 Min Measured Daytime Net Radiation (R_n) in the April–September (Apr–Sep) Periods of the Five Studied Years Separately and All Years Together at the Glencar Atlantic Blanket Bog

	Slope	Intercept	r^2	n	RMSD	SSE × 10^6
Apr–Sep 2002/2003	0.29	20.57	0.74	2244	24.23	1.32
Apr–Sep 2003/2004	0.25	22.54	0.73	2253	24.52	1.35
Apr–Sep 2004/2005	0.30	21.56	0.69	1798	32.16	1.86
Apr–Sep 2005/2006	0.24	20.12	0.79	2135	21.56	0.99
Apr–Sep 2006/2007	0.23	20.89	0.77	2093	22.14	1.00
Apr–Sep 2002–2007	0.26	21.68	0.72	10523	25.73	6.97

of the water table level below the surface of the low lawn vegetation. This suggests no clear dependence of ET on WTL. Besides, we note in Figure 5b that the mean ratio of daily ET/PET is almost constant at ca. 0.45 for all WTL values, except the deepest class (but only one observation). Daytime G_s appeared related to VPD, with G_s decreasing sharply with increasing values of VPD (Figure 6). The fitted line in Figure 6 is a weak fit ($r^2 = 0.31$; RMSD = 2.71 mm s^{-1}) that was added to convey a qualitative sense of the relationship and to compare it with a range of Canadian peatland types [*Humphreys et al.*, 2006].

[21] The daily averages of energy fluxes in the five years showed a high interannual variation in R_n with consequent variation in the partitioning among the other energy flux components (Figure 7). The daily R_n average ranged between a minimum of −60 W m^{-2} in winter months and a maximum of 200 W m^{-2} in summer months, with considerably lower values in 2004/2005. The daily soil heat flux mean varied between −15 W m^{-2} in winter and 20 W m^{-2} in summer, with little year-to-year variation. The daily averages of LE and H ranged between 0 and −50 W m^{-2}, respectively, in winter and about 80 W m^{-2} in summer. LE and H were the components of the energy balance that showed the highest variation in the five years. In 2004/2005, the daily LE average exceeded 50 W m^{-2} for most of the summer, while it regularly dropped below this value in the drier summer 2005/2006, together with a rise in H. The energy balance had very different patterns in dry and wet days (Figure 8). The typical rain day during the growing season showed R_n lower than 200 W m^{-2}, LE exceeding H for the whole day, both well beneath 100 W m^{-2}, and G lower than 50 W m^{-2}. In rain-free days, R_n could exceed 700 W m^{-2}, which was consumed more for H than for LE in extended dry periods, but more for LE after a rain period. This pattern was especially clear at the beginning and end of the growing season, while LE and H were more similar when the vascular plants were fully developed. The typical peak value for LE and H was 200–250 W m^{-2}. G showed wide differences in dry and wet days, too, with around noon minimum values of about 50 W m^{-2} in rain days and a maximum of more than 150 W m^{-2} in dry days.

5. Discussion

[22] The annual precipitation in the Glencar Atlantic blanket bog ranged between 2423 and 2776 mm (Table 1). At the nearby Met Eireann synoptic weather station at Valentia (30 km west of the study site), the precipitation for the 2003–2007 period was 5% higher than its 30 year (1961–1990) average (http://www.meteireann.ie/climate/valentia.asp). The precipitation in Glencar is therefore about twice the minimum of the 1250 mm required for the development of such an ecosystem in Ireland [*Hammond*, 1981; *Taylor*, 1983]. Rainfall in Glencar was more abundant and frequent during the growing season (Figures 1 and 3, Table 1) than in boreal raised bogs [*Admiral et al.*, 2006; *Kurbatova et al.*, 2002], so the lowest water table level in our study site was 17 cm below the soil surface, whereas in boreal raised bogs it typically varies between 20 and 60 cm below the surface [*Kellner*, 2001; *Lafleur et al.*, 2005; *Shimoyama et al.*, 2004].

[23] The annual evapotranspiration in Glencar ranged between 369 and 424 mm, which is similar to an Irish managed grassland, despite much higher precipitation in the peatland and similar R_n [*Jaksic et al.*, 2006]. ET in Glencar was estimated as only 15% of the total precipitation on average (Table 1), which is far less than what was observed in other ecosystem types in humid temperate climates (grasslands ~30%, forests ~60% [*Kiely*, 1997]) and in boreal raised bogs (54% [*Lafleur et al.*, 2005]). Most of the water in our study site left the system as stream discharge (about 2000 mm in 2007 [*Koehler et al.*, 2009]), as observed in a blanket bog in Newfoundland [*Price*, 1992]. This is due to the sloping topography, to the high amount of precipitation received by the ecosystem, and to the low summer ET.

[24] The annual ET in Glencar was about 10% higher than in a Canadian raised bog [*Lafleur et al.*, 2005]. Northern peatlands are typically located in boreal, subarctic, or arctic regions, where climatic conditions are very different from those in our study site. The winter in Glencar is characterized by mild temperatures (lowest monthly T_{air} average +6°C), generally with no frozen soil or snow cover, so the ET was very variable, with typical winter values higher than 0.5 mm d^{-1} but with maxima of almost 2 mm d^{-1} during days with high daytime T_{air} (Figure 2). These values are higher compared to the typical winter ET values between 0.1 and 0.5 mm d^{-1} in a Canadian boreal raised bog (where January temperature average is −10°C [*Lafleur et al.*, 2005]). The ET during the growing season was on the contrary considerably lower in our study site compared to other peatland types. The midsummer monthly mean ET in Glencar ranged between 1.3 and 1.8 mm d^{-1} (Figure 2), by comparison with values between 2 and 3.3 mm d^{-1} of boreal raised bogs [*Humphreys et al.*, 2006; *Kellner*, 2001; *Kurbatova et al.*, 2002; *Lafleur*

Table 3. Slope, r^2, Number of Occurrences (n), Root-Mean-Square Deviation (RMSD), and Sum-of-Squares Error (SSE) of the Linear Regressions, Forced Through the Zero, Explaining Daily Evapotranspiration With Potential Evapotranspiration, in the Five Studied Years Separately and All Years Together[a]

	Slope	r^2	n	RMSD	SSE
2002/2003	0.41	0.52	100	0.42	17.59
2003/2004	0.43	0.73	98	0.33	10.52
2004/2005	0.50	0.77	50	0.31	4.69
2005/2006	0.38	0.69	79	0.35	9.55
2006/2007	0.43	0.75	71	0.31	6.99
2002–2007	0.42	0.65	398	0.37	53.54

[a]Data points are days with >75% of measured 30 min flux data.

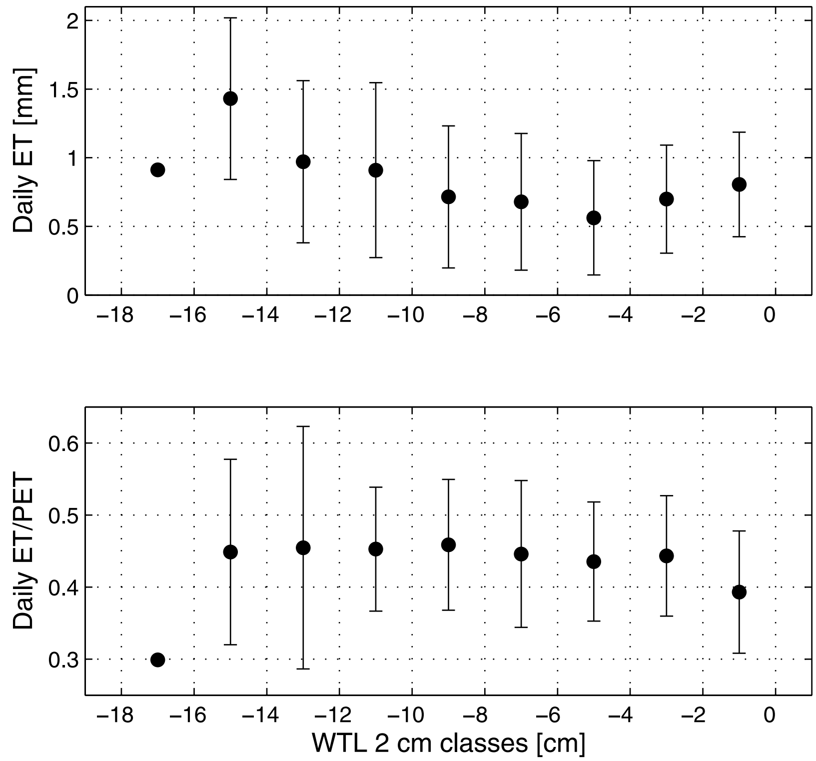

Figure 5. (a) Daily evapotranspiration (ET) plotted for 2 cm water table level (WTL) classes for the 2004/2005 to 2006/2007 April to September periods together. Points represent mean values, while bars represent standard deviations. (b) Same as Figure 5a, except ratio of daily ET to potential ET (PET).

et al., 2005]. The typical maximum daily ET in Glencar was between 2.5 and 3 mm d^{-1} (Figure 2), compared to maxima between 4 and 5.5 mm d^{-1} in raised bogs [*Lafleur et al.*, 2005; *Shimoyama et al.*, 2004].

[25] ET in wetlands is controlled by three main drivers [*Roulet et al.*, 1997]: (1) available energy (R_n–G); (2) atmospheric ability to hold and transport vapor (VPD, r_a); (3) vegetation and soil ability to conduct water to the atmosphere (G_s). In this respect, Glencar showed summer R_n values similar to those of other northern peatland ecosystems (Figure 7) [*Admiral et al.*, 2006; *Kurbatova et al.*, 2002; *Shimoyama et al.*, 2004]. On the other hand, the higher aerodynamic resistance (median values between 30 and 45 s m^{-1} in Glencar compared to typical values of 20–35 s m^{-1} in other peatlands) [*Roulet et al.*, 1997], lower VPD, T_{air} [e.g., *Admiral et al.*, 2006; *Shimoyama et al.*, 2003], and G_s [*Admiral et al.*, 2006] compared to some raised bogs explain the lower measured summer ET in our study site. Additionally, the vascular plants, which enhance ET, in Glencar were quantified to cover only about 30% of the ground [*Sottocornola et al.*, 2009], or a leaf area index maximum of 0.6 m^2 m^{-2}, compared to a maximum of about 1.3 m^2 m^{-2} in a raised bog [*Lafleur et al.*, 2003]. Conversely, these parameters are unable to explain the difference from some other peatland ecosystems. The Stormossen raised bog in central Sweden [*Kellner*, 2001] showed similar R_n, aerodynamic resistance, and surface resistance, but higher summer ET and ET/PET ratio (between 0.61 and 0.77) and lower β than Glencar, despite lower maximum LAI (0.3 m^2 m^{-2}) [*Kellner*, 2001]. Besides, the Cape Race peatland in Newfoundland, which is a blanket bog like Glencar, showed higher G_s and 40%–50% higher typical maximum daily ET in summer, despite lower VPD, similar T_{air}, and frequent fog events, which reduced the ET [*Price*, 1991, 1992]. The difference in ET between Glencar and these peatlands is probably due to differences in the ground cover and peat surface wetness, since our study site has a much lower occurrence of free water and moss cover. In Glencar hollows cover only 11% of the peatland, compared to almost 50% of the Stormossen Swedish bog [*Kellner and Halldin*, 2002], while the soil surface is covered by bryophytes for only 25% (10% and 15% by *Sphagnum* and brown mosses, respectively) and by bare peat for more than 50%, compared to an almost full *Sphagnum* cover in Stormossen [*Kellner*, 2001], as typically occurs in raised bogs [*Glaser et al.*, 1990; *Humphreys et al.*, 2006; *Lafleur et al.*, 2005], but also in the Cape Race blanket bog [*Price*, 1991].

[26] Despite the low moss cover in Glencar, the latent heat flux was strongly driven by net radiation (Table 2), as was found in moss-dominated peatlands [*Kellner*, 2001; *Kurbatova et al.*, 2002; *Shimoyama et al.*, 2003]. Furthermore, dry periods in spring had relatively more effects on G_s and β than similarly long rain-free periods in the summer, when they were moderated by the presence of the vascular plants, emphasizing the importance of the moss communities and bare peat in our study site (Figures 3 and 8). In Glencar, β typically ranged between 0.5 and 1.5 in the April to September periods of the five measured years (Figure 3), which is higher than what was observed in other northern peatlands. Summer β varied between 0.60 and 0.70 in a Siberian bog

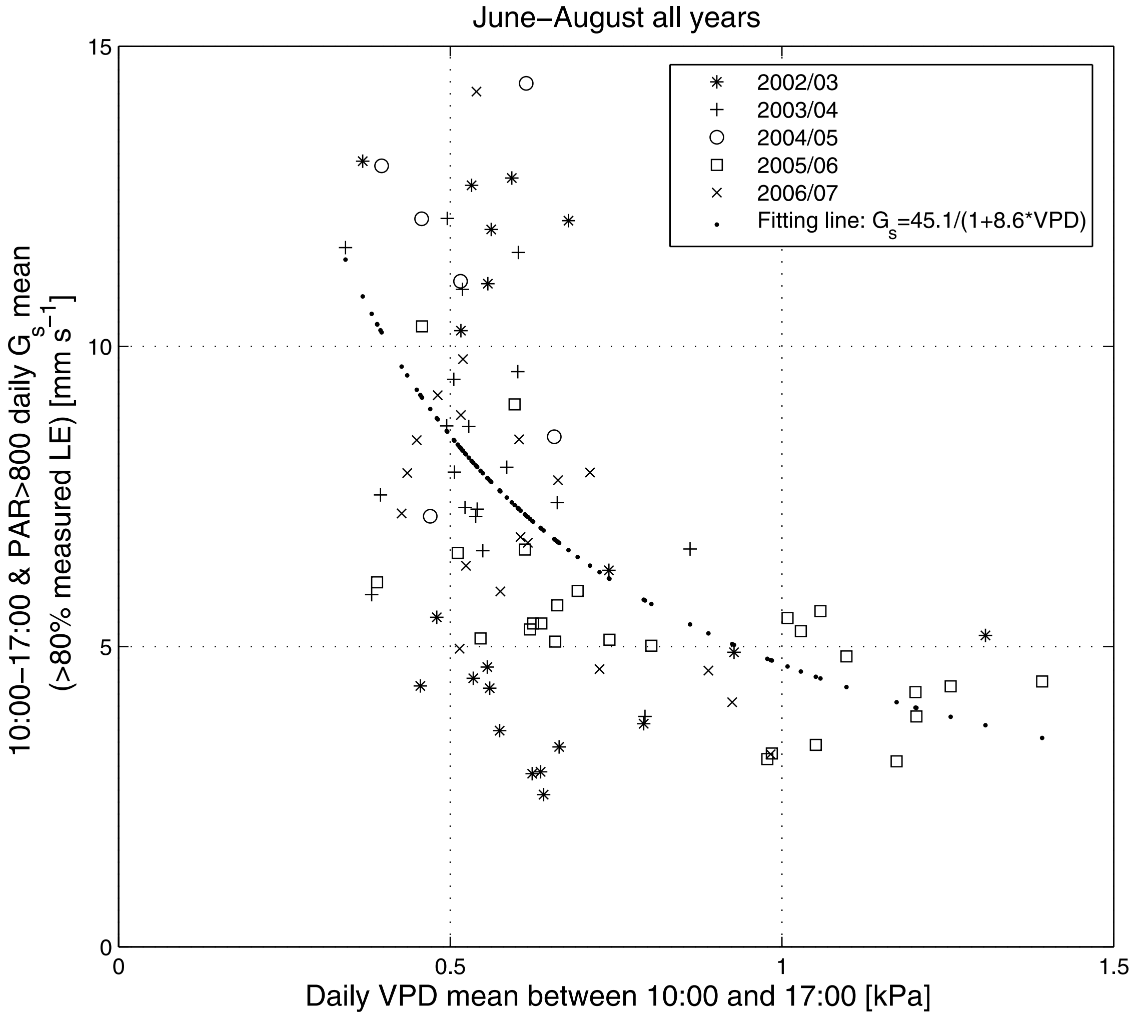

Figure 6. Relationship between daytime daily averages of surface conductance (G_s) and vapor pressure deficit (VPD) measured between 10:00 A.M. and 5:00 P.M. (1000 and 1700 LT). Only days with >80 % of measured *LE* data between 10:00 A.M. and 5:00 P.M. are shown.

[*Shimoyama et al.*, 2003] and averaged 0.46 in a subarctic wetland in Canada [*Eaton et al.*, 2001]. Moreover, ET in the Glencar Atlantic blanket bog ranged between 0.36 and 0.49 of PET (Table 3), which is lower than what was found in a boreal raised bog in a five-year study (between 0.44 and 0.59 [*Lafleur et al.*, 2005]). PET is defined as the maximum ET from an area completely and uniformly covered by growing vegetation with continuous and adequate moisture [*Brutsaert*, 2005]. Since the water table level in Glencar was never limiting ET (Figure 5), as occurred in other northern peatlands [*Humphreys et al.*, 2006; *Lafleur et al.*, 2005], the low β and ET/PET ratio were therefore likely due to the low plant cover and consequent low transpiration.

[27] Surface conductance in our study site showed a stronger response to VPD (Figure 6) than in a range of Canadian peatland types [*Humphreys et al.*, 2006]. *Humphreys et al.* [2006] suggested that the different responses of G_s to VPD are due to different types and relative abundance of the moss vegetation. While the peatland surfaces in the Stormossen Swedish bog and in the Cape Race blanket bog are almost completely covered by *Sphagnum* mosses, in Glencar it is mainly covered by bare peat and brown mosses. The latter are less efficient in holding moisture and in withdrawing water from deeper peat depths than *Sphagnum* mosses [*Hayward and Clymo*, 1982]. Bare peat has a lower specific yield than living *Sphagnum* mosses, so that when the upper soil layer dries, the remaining water probably becomes less available for evaporation because the drying soil has higher water retention forces than living *Sphagnum* mosses. Moreover, the bare peat surface tends to form a crust when dry, likely isolating the peat top from lower wet layers. The sharp decrease of G_s with increasing VPD supports the hypothesis that, once the peat surface dries out, the bare peat and brown moss cover in Glencar insulates the surface, contributing little to the ecosystem evaporation and transpiration [*Humphreys et al.*, 2006], ultimately reducing the ability of the ecosystem to conduct water from the soil to the atmosphere [*Roulet et al.*, 1997].

[28] The energy balance closure averaged 71% for the five years. A similar closure was observed in a North American wetland [*Mackay et al.*, 2007], while it was higher in some other bogs, ranging between 80% and 90% [*den Hartog et al.*,

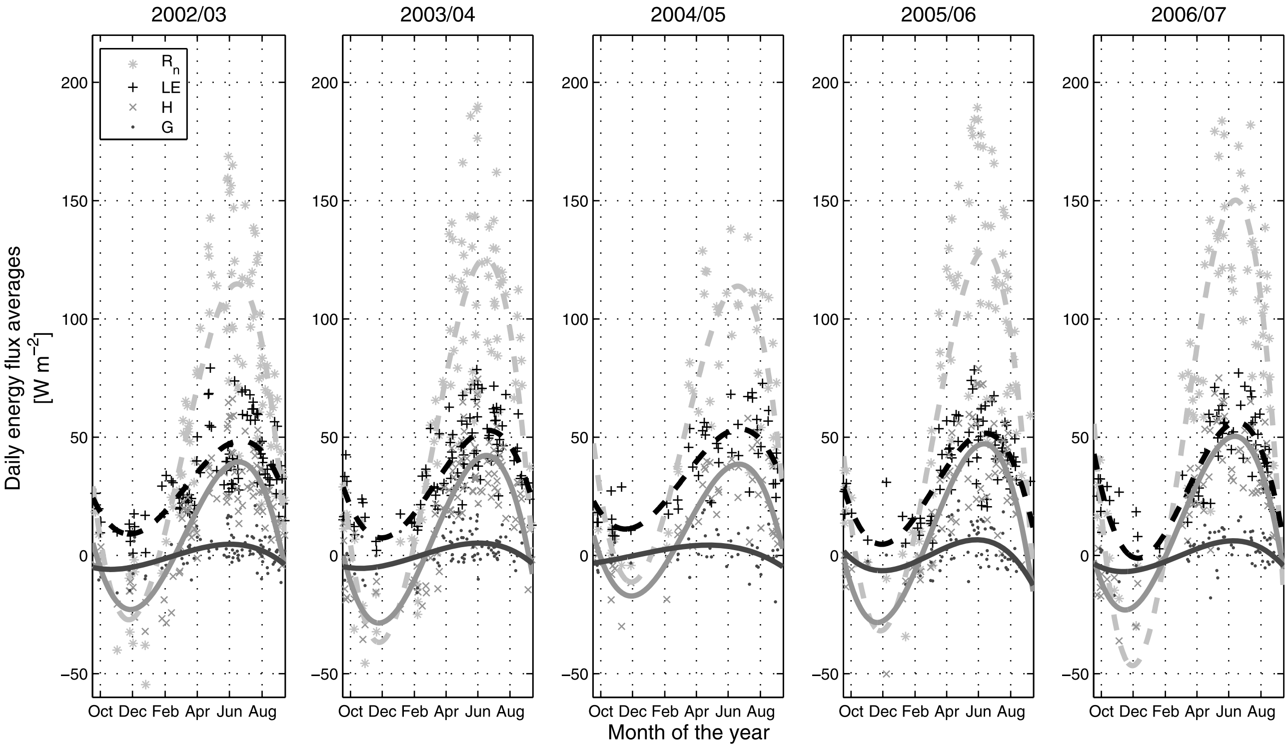

Figure 7. Annual variation in net radiation (R_n), latent heat flux (LE), sensible heat flux (H), and ground heat flux (G) in the five studied years. Only daily values with >75% of measured 30 min *LE* data are shown. Superimposed: cubic polynomial fitting lines for each flux.

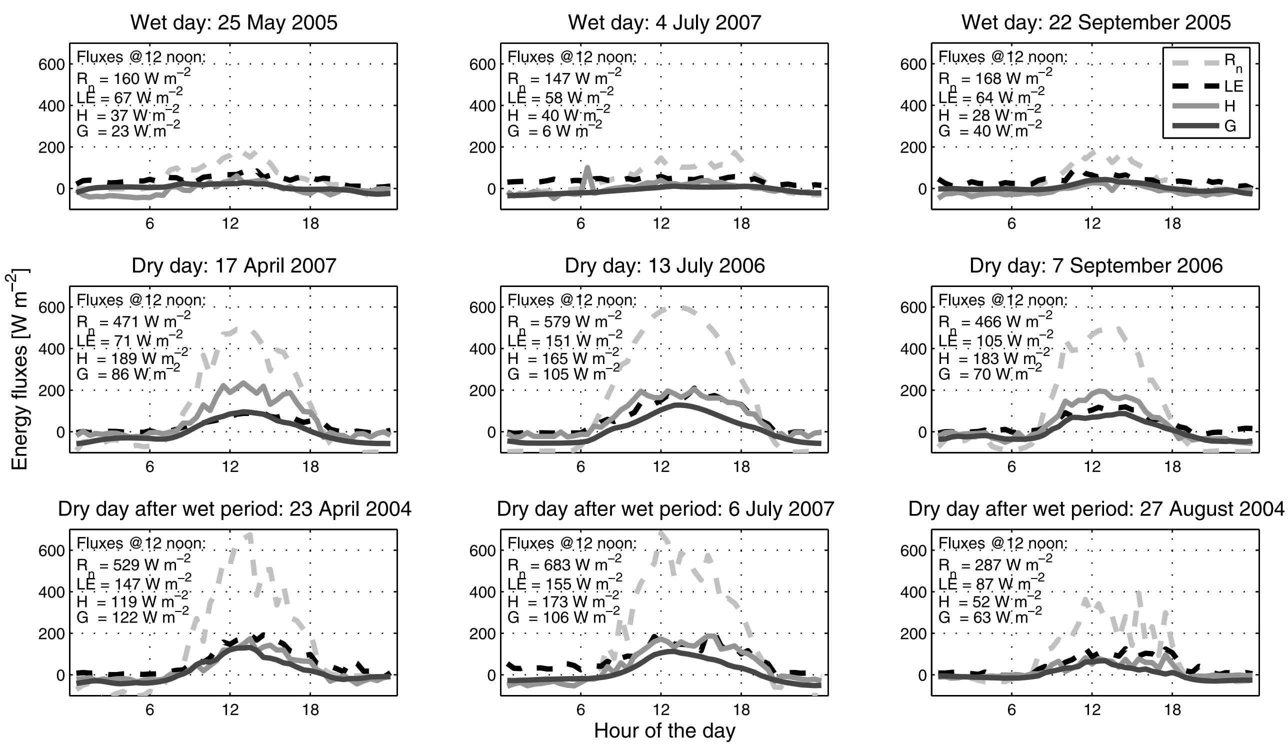

Figure 8. Diurnal variation of the energy fluxes in three rain days, in three dry days during rain-free periods, and in three dry days following a rain period, at the start, peak, and end of the growing season. R_n = net radiation, LE = latent heat flux, H = sensible heat flux, and G = ground heat flux. At the top left of each subplot are the average flux values at 12 P.M. (1200 LT).

1994; *Lafleur et al.*, 2003; *Shimoyama et al.*, 2003]. A full closure of the energy balance is difficult to achieve in short vegetation ecosystems [*Foken*, 2008; *Thomas and Foken*, 2007] and is very rare in peatland ecosystems, partly due to the difficulty of properly measuring the ground heat flux, which is expected to be very important in ecosystems with low vascular plant cover [*Kurbatova et al.*, 2002]. As well as similar net radiation, Glencar showed typical summer G daily averages between 5 and 7 W m^{-2} as in the Stormossen boreal raised bog [*Kellner*, 2001]. The sensible and latent heat fluxes had a high seasonal and interannual variation (Figure 7), but with considerably lower daily LE and slightly higher or similar daily H averages compared to boreal raised bogs [*Kellner*, 2001; *Kurbatova et al.*, 2002; *Shimoyama et al.*, 2003]. The diurnal variation of the energy fluxes in Glencar showed a higher G and smaller R_n, LE, and H maxima compared to a Canadian boreal raised bog [*Admiral et al.*, 2006]. The higher available energy consumed for LE than for H in dry days after a rain period supports the hypothesis that the brown mosses and bare peat need frequent rainfalls in Glencar to contribute to the peatland ET (Figures 3 and 8).

[29] Since ET in Glencar was independent of water table level (Figure 5) but dependent on atmospheric conditions (Figure 4 and Table 2), it is no surprise that ET in spring to early summer 2002/2003 was much lower than in the other years due to lower T_{air}, VPD, and R_n (Figure 3), despite the generally higher WTL (Figure 1). Nevertheless, although the atmospheric conditions were more suitable for ET in summer 2005/2006 rather than in summers 2003/2004 and 2004/2005, ET was lower in the former (Table 1 and Figure 3). This apparent contradiction is partly explained by the later vascular plants leaf emergence [*Sottocornola and Kiely*, 2010] and partly by the lower frequency of rain events in 2005/2006 (Figure 3). Precipitation in summer 2003/2004 and 2004/2005 was more frequent and abundant, with shorter breaks between rain events, compared to summer 2005/2006, when infrequent rain events likely caused the peat surface and the brown moss vegetation to dry, thus contributing less to ET and triggering lower G_s and higher β.

[30] Midcentury climate scenarios for Ireland under climate change predict mean monthly temperature increases between 1.2°C and 1.4°C (highest in the summer and autumn), a decrease in summer precipitation (of 5%–10%), and an increase in winter precipitation (of 5%–10%) [*Dunne et al.*, 2008; *Fealy and Sweeney*, 2007], a trend that has been detected in the west of the country from the mid-1970s [*Hoppe and Kiely*, 1999; *Kiely*, 1999]. The Glencar peatland is a very rainy blanket bog, with precipitation exceeding ET by 582 mm or more over the April to September period, almost 3 times the amount required for the development of Atlantic blanket bogs in Ireland [*Tallis*, 1998]. Moreover, the ratio between ET and precipitation was low and relatively stable during the five years, suggesting that climate change will possibly have a small effect on the partitioning of available energy as heat fluxes and on the water budget of this ecosystem. Nevertheless, a decrease in precipitation amount and frequency in the summer will probably cause water stress to the moss layer, with consequent ecosystem decrease in summer ET and in CO_2 uptake. Besides, even a slight drop of the water table is expected to affect the chemistry of the bog water, which together will likely impact the vegetation composition and distribution [*Sottocornola et al.*, 2009]. In contrast, the increased winter ET will probably be supported by the increase of winter precipitation.

6. Conclusion

[31] This work indicated that the Glencar Atlantic blanket bog has higher winter and lower summer evapotranspiration rates, and higher summer Bowen ratios, than other peatland ecosystem types. The high evapotranspiration in winter is likely driven by the mild Irish temperatures, while the lower evapotranspiration in summer is due to the lower temperature and lower vapor pressure deficit compared to other northern latitude peatlands. Additionally, the different evapotranspiration pattern is also due to the lower plant cover in Glencar, particularly of the moss layer (10% *Sphagnum* mosses, 15% brown mosses, >50% bare peat), since our study site identified evapotranspiration mechanisms typical of moss-dominated peatlands. Once the peat surface dries out, the bare peat and brown mosses in Glencar stop evaporating; the former tends to form a crust, likely insulating the surface, while the *Sphagnum* communities in other peatland ecosystems are able to hold water and withdraw it from deeper peat depth. Consequently, the predicted reduction in amount and frequency of summer precipitation (under climate change) will probably further limit the water to the soil surface, causing water stress to the moss vegetation, which will possibly trigger a decrease in evapotranspiration and in CO_2 uptake by the peatland ecosystem.

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