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Abstract

Typical bogs in the boreal forest zone can be characterised by hummock and hollow micro-topography and sparsely vegetated surfaces. Their energy balance has been studied much less than for other types of surface, i.e. fields and forests. Micrometeorological measurements were carried out in central Sweden at two bogs in different summer seasons. From the measured profiles of wind speed, air temperature and humidity, the turbulent sensible and latent heat fluxes were calculated according to the Monin-Obukhov similarity theory. The daytime sensible and latent heat fluxes were typically of similar size, with the latent heat fluxes still being slightly higher. Independent measurements of turbulent, radiative and ground heat fluxes allowed to consider the surface energy balance closure. During fair weather conditions, the net radiation exceeded the sum of turbulent and ground heat fluxes by up to 200 W m^{-2} when measurements with ground heat flux plates were used in the analysis. It is difficult to attribute this discrepancy to errors in turbulent fluxes, because the fetch was long enough (400 m or more). Also, the size and shape of the two bogs and the positions of the tower were different, but the discrepancies in the energy budget were very similar. It is, however, known that measurements with heat flux plates in the peat are problematic. The ground heat flux measured with plates was very low and was considered to be the most unreliable component of the surface energy balance. An alternative method from the literature, which used temperature measurements in the peat and at the surface but did not require any information on the soil thermal properties near the surface, was used for alternative ground-heat-flux calculations. The use of this method improved the closure of the surface energy balance, but an about 100 W m^{-2} large discrepancy still remained unexplained. A further improvement is expected when lateral heat exchange in the hummocks could be taken into account.

1. Introduction

Wetlands are spread all over the Earth; specifically they occupy 10–20% of the boreal forest zone and even more in the northern parts, thus, being a considerable component effecting weather and climate. Much research by micrometeorologists in the past has been devoted to wetland evaporation – an important component of energy and water balances. At present, energy-partitioning data are available for different wetland types: aquatic wetlands (Souch et al., 1996; Burba et al., 1999), fens (Lafleur et al., 1997; Moore et al., 1994) and a variety of bogs (Campbell and Williamson, 1997; den Hartog et al., 1994; Moors et al., 1998; Spieksma et al., 1997; Thompson et al., 1999). However, wetlands have much less been studied than other surface types, i.e. fields and forests. Also, several studies with independent flux measurements have pointed out the problem of obtaining a good energy balance closure for this type of a complex surface (Lafleur et al., 1997; Thompson et al., 1999).

In this paper, the micrometeorological measurements over two bogs in central Sweden have been analysed. These bogs are typical bogs in the boreal forest zone, which are characterised by hummock and hollow micro-topography and sparsely vegetated surfaces. In other studies, the season-long measurements at the same bogs have mainly been analysed using the Bowen ratio method. This study, unlike the others, concentrates on short summer periods and the Monin-Obukhov similarity theory is used for calculating the turbulent fluxes. This approach allows to discover problems in the surface energy balance closure, which otherwise using the Bowen-ratio method is not possible. The present study is accompanied by another paper (Mölder and Kellner, 2002) which is dedicated to the excess resistance or the kB^{-1} factor for these bogs.

The purpose of this paper is to demonstrate that large discrepancies in the bog surface energy balance may occur. Since the discrepancies are strikingly similar despite of the fact that the measurements were made over two bogs with different size and shape and location of the measurement tower and that the fetches were long enough, it is concluded that the turbulent fluxes are measured accurately enough. It is confirmed that the ground heat flux measurements with plates in peat are unreliable and should not be used in combination with the Bowen ratio method. An alternative method to determine the ground heat flux, which is relying on temperature and moisture measurements in the peat, is shown to give larger values for the flux

and that in turn improves the surface energy balance closure, but it does not explain the whole discrepancy, however. It seems that to solve the problem, even more complex peat temperature and moisture measurements in combination with 3D modelling taking the structure of hummocks into account are required.

2. **Materials and Methods**

Season-long measurements were established at the bog Ryggmossen (60°00'N, 17°15'E; altitude 58 m) from May to November in 1994. The bog is situated ca. 25 km northwest of Uppsala in Sweden. The study aimed mainly to determine the evaporation by the Energy-Balance-Bowen-Ratio method (Phersson and Pettersson, 1997). The measurements were complemented with wind-speed and surface radiation-temperature measurements from 14 June to 12 July and the data from this period have been analysed here. The following year a new bog station was established on the bog Stormossen (60°07'N, 17°05'E; altitude 48 m), where continuous measurements were conducted mainly during the vegetation periods in 1996 and 1997 (Kellner, 2002; Kellner and Halldin, 2002). This bog is situated ca. 50 km northwest of Uppsala. High-quality measurements of surface radiation temperature were carried out here during the short period of 19–29 August 1996. This period has been used in the analysis.

2.1. Surface features

The surface looked similar on both bogs having a typical structure of hummocks and hollows (Fig.1). The concentration of hummocks was more variable on Ryggmossen, where the fraction of hummocks was estimated to be 0.14 and 0.43 for two different areas, respectively. On Stormossen, the fraction of hummocks was 0.30. Thus, roughly 30% of the bog was occupied by hummocks and 70% by hollows on both bogs. The height of the hummocks was also similar, varying between 0.20 and 0.40 m with a mean of 0.28 m. The vegetation consisted mostly of *Sphagnum* mosses and sparsely present low vascular plants. Hollows were dominated by *Sphagnum* species belonging to the *Cuspidata* section (*S. balticum, S. tenellum*) and Hare's-tail cottongrass (*Eriophorum vaginatum*) dominated the cover of vascular plants. Ridges and hummocks were made up by denser *Sphagnum* species (*S. fuscum, S. rubellum*). The cottongrass,

Fig. 1. A view over the Stormossen bog.

present on both hummocks and hollows, had a height of 0.2–0.3 m. On hummocks and elongated ridges, low Ericaceaeus shrub of heather (*Calluna vulgaris*) and crowberry (*Empetrum nigrum*) was an important feature. There was also a small amount of bog rosemary (*Andromeda polifolia*) present on hummocks, usually 0.12–0.15 m high. Occasional cloudberry plants (*Rubus chamaemorus*) could be found, usually on hummocks and in drier parts. Spots of lichens (*Cladonia*) also occurred on hummocks, but not abundantly. Single trees (*Pinus sylvestris*) – up to 1.5 m high, were present even in the central parts of the bogs and could slightly influence the measurements. However, the closest 25–30 m from the towers were tree free.

With dominating southerly and westerly winds, the fetch was 400 m or more over both bogs. The fetch was shortest in the northern direction. On Ryggmossen it was restricted by a nearly straight forest edge, about 200 m away. On Stormossen, the forest was only 70 m away, but in a form of a small island.

Ground water level was always below the surface of hollows during the study periods. Porosity of the peat was estimated to be 94–97% in the surface layers.

2.2. Instrumentation

2.2.1. Ryggmossen

Air temperature and humidity were measured at three levels: 1.1, 2.1, and 3.1 m with a Thermometer Interchange System (TIS) (In Situ Instrument, Ockelbo, Sweden) (Lindroth and Halldin, 1990). Absolute temperature was measured at the uppermost level; differential measurements were made between 1.1 and 2.1 m, and 2.1 and 3.1 m. The sensors changed their positions every 5 minutes in order to minimize systematic errors. The reversing sensors consisted of an air temperature sensor, and a dry and a wet temperature sensor for humidity which were placed in a ventilated radiation shield. Wind speed was measured on a separate mast with cup anemometers at 0.76, 1.21, 1.96, and 2.98 m. These were the same anemometers as used by Mölder et al. (1999). The two masts were separated by about 10 m.

Surface radiation temperature was measured with an infrared thermometer (IRT) (model 4000; Everest Interscience, Tucson, USA) measuring in the spectral band of 8–14 μm and having a viewing angle of 60°. It was installed at the top of the anemometer mast at 4-m height, was inclined 10° from the vertical, approximately towards the west. Thus, the IRT could see roughly a circle with a diameter of 4.5 m. Net radiation, and up and down dwelling short-wave radiation were measured with a Schenk net radiometer (type 8111; Vienna, Austria) and two Kipp & Zonen pyranometers (type CM5; Delft, The Netherlands), respectively, at about 1.5-m height.

Ground heat flux was measured with two plates (type Middleton CN3; Carter-Scott Design, Brunswick, Victoria, Australia) at 2-cm depth. Soil temperatures were not measured at this site.

2.2.2. Stormossen

Air temperature and humidity were measured at 1, 2, and 3 m with another, but a similar TIS. Cup anemometers (In Situ Instrument, Ockelbo, Sweden) were attached to the reversing arms of the TIS.

The same IRT as on Ryggmossen was used also here, but it was installed on a photo tripod some 15 m from the TIS at about 1.5-m height and was inclined 10° from the vertical to the southeast. It could see a spot on the ground having a diameter of 1.5 m.

Radiation and soil measurements were conducted in another station some 100 m from the TIS. The same net radiometer and pyranometers were used as on Ryggmossen. Ground heat fluxes (using the same plates as on Ryggmossen) and soil temperatures were measured at several locations along a hummock-hollow transect. One representative profile in a hummock and a hollow, respectively, is used in the analysis (Table 1). At this station, also soil water content measurements were made with a Time Domain Reflectometer (TDR) (Tektronix 1502C; Beaverton, OR, USA), by using horizontally placed probes (Dynamax Inc., Houston, Tx., USA) at a hummock-hollow transect (Kellner and Halldin, 2002).

Since a Schenk net radiometer measures separately fluxes from the upper and lower hemispheres and also the body temperature, it allows evaluation of the surface temperature if also the reflected short-wave radiation is known. This was done to obtain a more representative surface temperature for the ground heat flux calculation.

A mobile IRT (model 4000; Everest Interscience, Tucson, USA) with 15° viewing angle was used to measure surface temperature variations over Ryggmossen in 1995.

The air temperature sensors were calibrated by manufacturer (In Situ Instruments, Ockelbo, Sweden) several years ago. As they are made of platinum, they are very stable. The Ryggmossen TIS sensors were checked in stirred water after the campaign. The anemometers were calibrated before the campaign in a small wind tunnel against a reference hand-held anemometer, the latter being calibrated at the Estonian Hydrological and Meteorological Institute. The In Situ anemometers were calibrated prior to the experiment at a large wind tunnel of the Building Institute in Gävle, Sweden. The IRT was checked against a black body (Reemann's design) and the output was accurate within 0.1–0.3 K. A laboratory calibration in sandy soil was carried out for all the soil heat flux plates. The thermocouples in the soil were made of a standard copper-constantan cable, so its standard sensitivity was used. The Schenk net radiometer was calibrated properly at Ultuna in 1992, and once a year at Marsta (Halldin et al., 1999) (both places near

Uppsala). The TDR measurements were laboratory calibrated by using samples from Stormossen (Kellner and Lundin, 2001).

2.3. Weather conditions

2.3.1. Ryggmossen

First half of the period (14 June – 12 July 1994) was cloudy with five days of rain – totally 25 mm. The second half had few clouds and no precipitation. Maximum temperatures increased gradually from 12 to 28 °C during the period. Night temperatures were falling to nearly 0 °C at the beginning of the period and 8–15 °C in the later part. Winds were 1–5.5 m s^{-1}, predominantly from the south, southwest, and west.

2.3.2. Stormossen

During the shorter period (19–29 Augusti 1996) the weather did not change much. Skies were clear or with a few clouds; daytime maximum air temperatures 20–27 °C, minimums at nights 7–17 °C; winds were less than 4 m s^{-1} from the southeast and southwest. In the later part of the period, 26–29 August, there were more clouds and occasional small amounts of rain. The total amount of rain was less than 4 mm.

3. Theory

3.1. Atmospheric surface layer

Atmospheric surface layer profiles of wind speed, u, air temperature, T, and humidity, q, are given as (Brutsaert, 1982):

$$u = \frac{u_*}{k}\left(\ln\left(\frac{z}{z_{ou}}\right) - \Psi_u\left(\frac{z}{L}\right) + \Psi_u\left(\frac{z_{ou}}{L}\right) \right), \tag{1}$$

$$T = T_s + \frac{T_*}{k}\left(\ln\left(\frac{z}{z_{oT}}\right) - \Psi_T\left(\frac{z}{L}\right) + \Psi_T\left(\frac{z_{oT}}{L}\right) \right) \tag{2}$$

and

$$q = q_s + \frac{q_*}{k}\left(\ln\left(\frac{z}{z_{oq}}\right) - \Psi_q\left(\frac{z}{L}\right) + \Psi_q\left(\frac{z_{oq}}{L}\right)\right),\tag{3}$$

where T_s and q_s are the surface values; u_* is the friction velocity; T_* and q_* are the turbulent scales; k=0.4 is the von Kármán constant; Ψ_u, Ψ_T, and Ψ_q are the integrated stability correction functions; z is the height, z_{ou}, z_{oT}, and z_{oq} are the roughness lengths, and L is the Obukhov length. The indices u, T, and q denote that the corresponding quantity refers to wind speed, temperature or humidity, respectively.

The fluxes of sensible, H, and latent heat, LE, are given:

$$H = -\rho c_p u_* T_* \tag{4}$$

and

$$LE = -\lambda \rho u_* q_* \tag{5}$$

where ρ is the density of air, c_p is the specific heat of air at constant pressure and λ is the latent heat of vapourisation of water.

3.2. Ground heat flux

As soil heat flux measurements with plates are uncertain (Halliwell and Rouse, 1987), we have also used the method by de Silans et al. (1997). An advantage of the method is that it does not require any information on the soil physical properties. To apply this method, temperatures have to be measured at a certain depth in the soil and also at the surface. Ground heat flux has to be measured or calculated at the same depth as the measured temperature in the soil. The essence of the method is as follows. When temperature, soil heat flux, and depth are scaled suitably, the differential transfer equations take the same form for both the temperature and the flux. Therefore, the mathematical operator that transforms the scaled temperature at a depth to that at the surface is the same that transforms the scaled flux at a depth to the flux at the surface. Some useful expressions are given below.

Variations in temperature, T, and soil heat flux, G, at a specific depth z can be expressed with help of Fourier series:

$$T(z,t) = T_z + \sum_{i}^{n} A_{zi} \sin(i\omega t + \varphi_{zi}) \tag{6}$$

and

$$G(z,t) = G_z + \sum_{i}^{n} B_{zi} \sin(i\omega t + \delta_{zi}),$$ (7)

where T_z and G_z are average temperature and flux at the depth z, respectively; A_{zi} and B_{zi} are amplitudes of the i-th harmonic, n is the number of harmonics, φ_{zi} and δ_{zi} are phase shifts of the i-th harmonic, and ω is the frequency of the main harmonic.

Similarly, temperature and flux at the surface are given:

$$T(0,t) = T_o + \sum_{i}^{n} A_i \sin(i\omega t + \varphi_i)$$ (8)

and

$$G(0,t) = G_o + \sum_{i}^{n} B_i \sin(i\omega t + \delta_i),$$ (9)

where T_o, G_o, A_i, B_i, φ_i and δ_i have the same meaning as above, but represent the surface.

The unknown parameters for $G(0,t)$ are related to the other, known parameters as:

$$B_i = \left(\frac{C_o \kappa_o}{C_z \kappa_z}\right)^{1/2} \frac{A_i}{A_{zi}} B_{zi},$$ (10)

$$\delta_i = \delta_{zi} + (\varphi_i - \varphi_{zi})$$ (11)

The factor in Eq. (10) containing heat capacities, C, and thermal conductivities, κ, is given through average temperatures:

$$\left(\frac{C_o \kappa_o}{C_z \kappa_z}\right)^{1/2} = \left(\frac{T_z}{T_o}\right)^2$$ (12)

This factor specifies also the ratio of average fluxes:

$$\left(\frac{G_o}{G_z}\right)^2 = \left(\frac{C_o \kappa_o}{C_z \kappa_z}\right)^{1/2}$$ (13)

4. Data processing

4.1. Profiles and fluxes

The measured profiles of wind speed, temperature, and humidity were fitted to the theoretical Eqs. (1) − (3) using the least square method and an iteration procedure (Zilitinkevich, 1970; Mölder, 1997). The universal stability functions given by Högström (1996) were used. Fitting of profiles gave the turbulent scales u_*, T_*, and q_*, which in turn gave the fluxes of H and LE, according to Eqs. (4) and (5).

Daytime measurements of profiles have been analysed only, the selection criterion being a positive net radiation ($R_n > 0$ W m^{-2}). Wind profiles measured at Ryggmossen were checked graphically, profile by profile. Those uncertain profiles, where some of the anemometers had not been rotating properly at low winds, were excluded from the analysis. For Stormossen, all profiles, where some of the measured wind speeds was below 1 m s^{-1}, were also excluded from the analysis.

4.2. Ground heat flux

Calculations according to the above-given theory are based on measured temperatures and water contents in August 1996. Fortunately, the measured soil water content was almost constant over the study period. Moreover, in each of the examined profiles (hummock and hollow), a layer with nearly constant water content with depth could be distinguished, where also a pair of temperature sensors was available (Table 1). In the hummock profile, water content was about 40% at 10 and 20 cm depths. Temperature sensors were also available at these depths. In the hollow profile, water content was near 95% at 15 and 25 cm depths, and temperatures were measured at 14 and 20 cm. Since water content was nearly constant, it allows us to determine the thermal conductivity confidently and calculate ground heat fluxes from temperature gradients/differences.

Thermal conductivity is a function of volumetric water content of soil, x_w (%), in peat (Farouki, 1986). Moreover, the relationship $\kappa = 0.0048 x_w + 0.04$ for peat is similar for many organic materials

Table 1 Volumetric water content of peat and positions of thermometers at Stormossen during the study period in 1996.

Depth (cm)	Hummock profile		Hollow profile	
	Water content (%)	Position of thermometer	Water content (%)	Position of thermometer
5	38		60	X
6		X		
10	35	X		X
14				X
15			95	
20	40	X		X
25			94	
30	62			
40	90	X		

(Laurén, 1997). Using this relationship, we obtain for the hummock profile with 38% water content $\kappa = 0.22$ W m^{-1} K^{-1} and for the hollow profile with 94% water content $\kappa = 0.49$ W m^{-1} K^{-1}.

Fourier series calculation was done according to Van Wijk and De Vries (1963). For the hummock profile, temperatures at 10 and 20 cm were fitted with Fourier series. The logarithmic amplitudes and phase shifts at the two depths were connected with a linear relationship. This was always within a nearly linear region when, for instance, the i-th harmonic's amplitudes from all the depths were plotted versus the depth. Amplitudes and phase shifts were interpolated to the depths of 15 cm, which is the middle point of the considered layer, and 15.1 cm. Temperature courses were calculated at these depths as Fourier series. Ground heat flux was calculated using the calculated temperature difference between 15 and 15.1 cm. This was done similarly for the hollow profile, where temperatures at 14 and 20 cm were used to calculate the temperature and flux at 17 cm (additional level at 17.1 cm).

Two versions for the soil surface temperature were used: temperatures measured with the Everest IRT and temperatures deduced from Schenk net radiometer and pyranometer measurements. This enabled us to calculate two versions of G at the surface.

The Fourier series analysis was done for each day separately, calculating ω with the 24 h period and using four harmonics only.

The G values using the Everest and Schenk meters were averaged for both the hummock and the hollow profile. These in turn were weight averaged, giving a 0.30 weight to hummocks and 0.70 weight to hollows.

5. Results and Discussion

5.1. Roughness length z_{ou}

No displacement height, d, was included in Eqs. (1) – (3) and in the analyses, because the hummocks were relatively low and the grass was low and sparse. If we had used a d greater than zero, the turbulent fluxes would have been smaller. The bad closure of the surface energy balance discussed in the next section would then be even worse.

Daily mean values of the roughness length z_{ou} for Ryggmossen vary between 1 and 3 cm with an average value of 1.86 cm. No significant dependence on wind direction was observed. The scatter in the Stormossen data was much higher; z_{ou} values could exceed 20 cm and the mean was 7.4 cm. We cannot see any reason for Stormossen z_{ou} to be more than three times higher than for Ryggmossen because the surfaces were very similar. A careful inspection of the Stormossen wind data, profile by profile, revealed that many profiles supported z_{ou}=2 cm and that the series giving too high values of z_{ou} could have been due to an underestimated wind speed at the lowest measurement level. The cup anemometer could have been stalled at low wind speeds, if not continuously then at least occasionally. Therefore, it was decided to use z_{ou}=2 cm even for Stormossen data analysis. In order to reduce random errors in u_* estimates, all the wind profiles were finally evaluated with a fixed z_{ou}.

5.2. Surface energy balance – partitioning of components and closure

Seasonal variations of surface energy fluxes have been studied elsewhere (Kellner, 2001). Here we have only looked at short summer periods, where IRT and wind-profile measurements were available.

For Ryggmossen midday R_n is about 500 W m^{-2} (Fig. 2). G measured with plates is only 40–50 W m^{-2}. H and LE are nearly equal, LE usually slightly larger than H; values between 100 and 200 W m^{-2}. Energy balance is not closed, R_n being over 100 W m^{-2} higher than the sum of H, LE, and G.
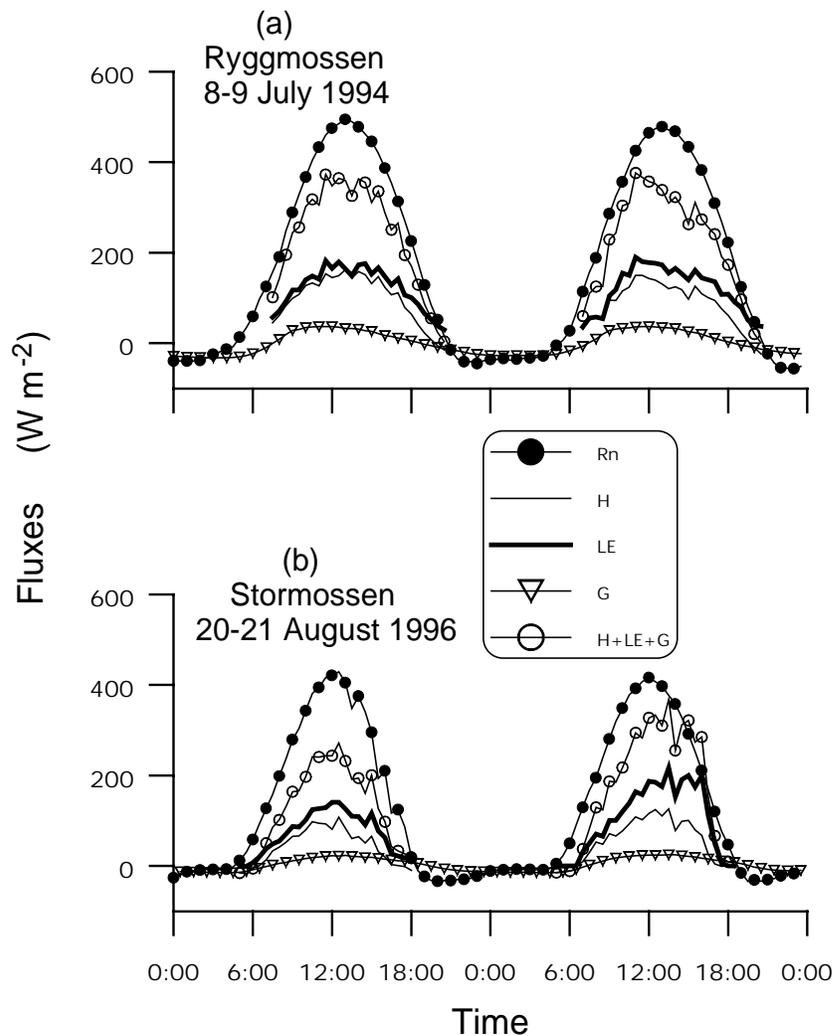

Fig. 2. Surface energy balance components. Measurements at different bogs and periods show similar energy partitioning and closure of the balance. Ground heat flux G is measured with plates.

For Stormossen midday R_n is greater than 400 W m^{-2} (Fig. 2). The plate-measured G is below 30 W m^{-2}. That is even lower than for the previous year. However, this is not so striking as both net radiation and soil heat flux normally decreases from mid June to end of August. H is about 100 W m^{-2}. LE is larger than H and up to 200 W m^{-2}. Energy balance closure is as bad as up to 200 W m^{-2}. A discrepancy is present, more or less, on every analysed day.

As we see, LE is not considerably exceeding H. Because the surface can get very hot relative to the air (8–10 K higher), considerable sensible heat fluxes occur.

Similar bog energy partitioning was obtained by den Hartog et al. (1994): H and LE from direct, eddy correlation measurements were approximately equal and nearly 150 W m^{-2}. Moors et al. (1998) report for a drained bog that sensible heat fluxes reach typically 100–200 W m^{-2} but latent heat fluxes are rather high, 300–400 W m^{-2}. Note that their LE is calculated as a residual term of the surface energy balance.

Den Hartog et al. (1994) report a good surface energy balance closure of about 90%. Thompson et al. (1999) obtained good closure (91%) with fetches above 600 m and poor closure (78%) with limited fetches below 300 m. Lafleur et al. (1997) got similarly poor closure with both good and bad fetches, the distinction criterion being about 400 m. We obtained poor closure of about 75% although our fetches above 400 m can be classified to be good rather than bad.

The two bogs were different in size, shape, and orientation relative to the north, also, the distance from the masts to the nearest forest was different, but the discrepancy in the energy budget is very similar. It is difficult to attribute this problem to the profile measurements, rather the ground heat flux needs to be estimated better. An attempt is given below.

The alternative method to calculate ground heat fluxes could only be applied on Stormossen data, because soil temperature and wetness measurements were not available for Ryggmossen. Both the measured and calculated fluxes show similar features (Fig. 3): the flux in hollows is about twice the flux in hummocks, the shape of the hollow curves is symmetrical while the maximum is skewed towards morning hours in the case of hummocks. The most important result is that the calculated area-averaged fluxes are about 60 W m^{-2} higher than the measured ones at noon.
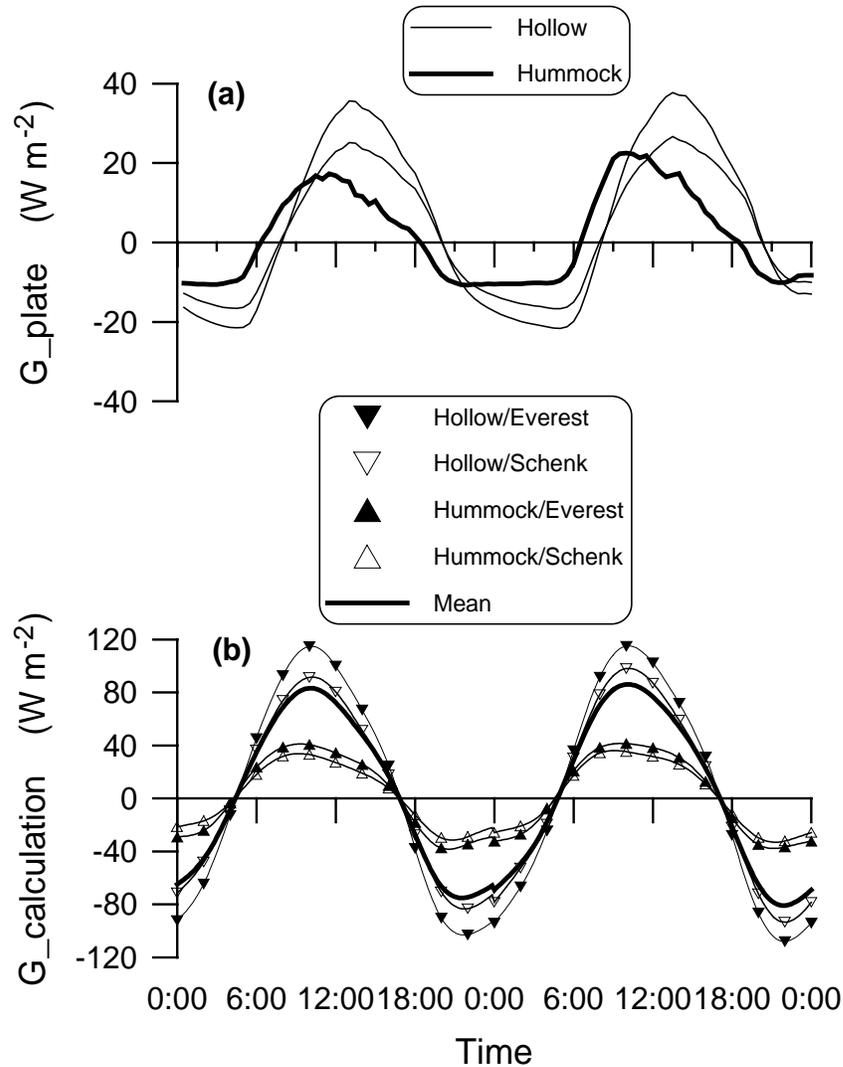
Fig. 3. Ground heat fluxes on 20–21 August 1996 at Stormossen: (a) measured with plates (two in the hollow); (b) calculated with the method by de Silans et al. (1997).

One problem is that a radiometer cannot measure just the mosses surface temperature but also sees the vegetation. The sparse grass vegetation could presumably be cooler than the mosses (due to transpiration and good ventilation by wind), meaning that T_o was actually higher and so was G. On the other hand, Kellner (2001) found it reasonable that the mosses were responsible for the major part of the evapotranspiration at Stormossen whereas the crop cover, consisting of both transpiring leaves and a large part of non-transpiring twigs and dead leaves, reached high daytime temperatures and dominated the flux of sensible heat.

Using the new method to calculate G allows to improve the surface energy balance closure by 60 W m^{-2}, but that is not enough to close the budget properly. Still, a discrepancy of 100 W m^{-2} remains unexplained. One possible explanation is that the ground heat flux is even higher than predicted by the alternative method. Kellner (2002) has pointed out the importance of lateral heat exchange in hummocks. His model simulations required much higher heat inputs into the hummocks in order to fit the simulated temperatures in the hummocks with the corresponding measured temperatures

6. Conclusions

Micrometeorological measurements at two bog sites in central Sweden have been analysed to estimate the surface energy balance components. Turbulent fluxes of sensible and latent heat are partitioned almost equally, the latent heat fluxes still being systematically higher. The surface energy balance closure is poor, discrepancies of up to 200 W m^{-2} appear. As the discrepancies at the two bogs are very similar, there should not be any fetch-related problem in profile measurements. One reason for the poor closure might be that the ground heat flux that is measured with plates is erroneously too low, probably due to bad thermal contact between the plate and the peat. Calculations with an alternative method from the literature, which is based on soil temperature measurements and knowledge of peat moisture content, give fluxes that reach 80 W m^{-2} near noon. This improves the energy balance closure, but some 100 W m^{-2} still remains unexplained. We believe that very detailed peat temperature and moisture measurements in combination with 3D modelling taking the structure of hummocks into account can give a new insight into these problems. For the time being, the ground heat flux plates should be avoided when the Bowen ratio method is used.

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