Tellus (2002), 54B, 537-551
Printed in UK.

TELLUS
ISSN 0280-6509

Inter-annual and seasonal variations of energy and water vapour fluxes above a *Pinus sylvestvis* forest in the Siberian middle taiga

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(Manuscript received 9 July 2001; in final form 21 January 2002)

ABSTRACT

Long-term eddy covariance measurements of energy and water fluxes and associated climatic parameters were carried out above a Scots pine (*Pinus sylvestris*) forest in the middle taiga zone of Central Siberia. Data from June 1998 through October 2000 are presented. With the exception of winter 1998/1999, data collection over this period were more or less continuous. A distinct seasonality in surface energy exchange characteristics was observed in all years. In early spring in the absence of physiological activity by the vegetation, about 80% of the net radiation was partitioned for sensible heat, resulting in Bowen ratios, β, as high as 8. In the 1-2 wk period associated with onset of photosynthesis in spring, evaporation rates increased rapidly and β rapidly dropped. However, even during summer months, sensible heat fluxes typically exceeded latent heat fluxes and β remained above 2.0. Observed daily evaporation rates varied between 0.5-1.0 mm d^{-1} in spring and autumn and 1.5-2 mm d^{-1} in midsummer. The overall average for the three growing seasons examined was 1.25 mm d^{-1}. Precipitation was on average 230 mm for the growing period, with evaporation over the same time being about 190 mm for both 1999 and 2000. This represented only about 35% of the equilibrium evaporation rate. There was typically a positive hydrological balance of 40 mm for the growing season as a whole. However, in all three years examined, evaporation exceeded precipitation totals by 20-40 mm in at least one calendar month during summer.

During the growing season, daily averaged surface conductances varied between 0.15 and 0.20 mol m^{-2} s^{-1} (3-4.5 mm s^{-1}) in dry or cool months and 0.30-0.35 mol m^{-2} s^{-1} (6.5-8 mm s^{-1}) in moist and warm months. Despite a negative hydrological balance during midsummer, there was little evidence for reduced canopy conductances in response to soil water deficits. This may have been the consequence of roots accessing water from within or just above a perched water table, located at about 2 m depth.

1. Introduction

Coniferous forests dominate the boreal region and typically exert a greater influence on vegetation-atmosphere exchange than do deciduous forests or other vegetation types of the circumpolar zone such as tundra. This is because of their albedo, surface roughness, physiology and, with the exception of Larix species, their evergreen habit (Rauner, 1972; Baldocchi et al., 2000).

Summertime eddy covariance measurements of

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energy, water and carbon fluxes over Siberian boreal forests were undertaken in 1993 (*Larix gmelinii* in eastern Siberia: Kelliher et al., 1997; Hollinger et al., 1998) and 1996 (*Pinus sylvestris* in central Siberia: Kelliher et al., 1998; Kelliher et al., 1999; Valentini et al., 2000). The latter studies, undertaken close to the site of the current investigation, showed central Siberian *P. sylvestris* forests to be conservative in their water use, with typical daily average evaporation rates of 1-3 mm d^{-1} (for an overview see Schulze et al., 1999 and Kelliher et al., 2001). Associated with these low evaporation rates were high daytime ratios of sensible to latent heat flux (Bowen ratio, β). The latter were typically greater than 2, even under well watered conditions. Lower surface conductances and increased β associated occurred in the absence of regular rainfall events. Noting the low water holding capacity of the sandy soils in which *P. sylvestris* is typically found, both Kelliher et al. (1998) and Valentini et al. (2000) interpreted this as indicating direct effects of occasional inadequate soil moisture on central Siberian Scots pine water use during summer.

Long-term measurements of energy and mass fluxes in Siberian boreal forests were initiated in 1998 as part of the EUROSIBERIAN CARBONFLUX project. This component of the project sought a more precise understanding of ecosystem carbon budgets and the relationship between carbon balance and energy and water flux balance considerations at the ecosystem level.

Here we report on inter-annual and seasonal variations of energy, water fluxes and associated climate variables of a representative *Pinus sylvestris* forest in the middle taiga of central Siberia.

2. Methods

2.1. Site description

The measurement site was located near the village of Zotino, about 30 km west of the Yenisei river at the eastern edge of the West Siberian Plain (60°44'N, 89°09'E). The eddy tower was established in a fire successional pine forest (*Pinus sylvestris L.*) with lichen understorey (Wirth et al., 1999). The stand was 200 yr old, extending at least 0.5 km in all directions (Fig. 1). Stand structure was relatively homogeneous with a stem density of 478 ha^{-1}; basal area was 30 m^2 ha^{-1}; LAI was 1.5 m^2 m^{-2}; and biomass (dry weight) was 10.7 kg m^{-2} (Wirth et al., 1999). In that paper the stand is designated as '200_{ld}'.

As for most of the *P. sylvestris* forests in the area, the stand was located on gently undulating, alluvial sands with no underlying permafrost. The soils of the area generally classified as Inceptisols. At the measurement site, based on the soil temperature, moisture regime and nutrient status, the soil is characterised according to the US Classification System (Soil Survey Staff, 1999) as a Typic Dystrustept (C. Czimcik, personal communication). Generally the clay content in the mineral soil is less than 5%, and the soil was stone free except for few examples that were found at 1.25-1.50 m depth. In soil pits and auger holes within the vicinity of the tower a shallow layer of very densely packed, sandy clay was repeatedly found between the depth of 1.50-2.00 m, with rusty spots in this lens indicating a fluctuating water table. Underneath this sandy clay layer coarse sands prevailed (C. Czimcik, personal communication).

The layer of clay-rich material at about 2.0 m depth is potentially of importance for tree water supply in summer (see later discussion), and in auger samples taken for soil moisture measurements (see Section 2.3) fine roots were sometimes found in this layer (A. Arneth, personal communication).

2.2. Instrumentation

2.2.1. Eddy covariance measurements. Water vapour, heat and momentum fluxes were measured at a height of 27 m (about 5 m above the average tree height and 4 m above the highest nearby trees). The measurement system consisted of a triaxial sonic anemometer (model Solent R3, Gill Instruments, Lymington, UK) and a fast response CO_2/H_2O non-dispersive infrared gas analyser (model 6262-3, LiCor Inc., Lincoln, NB, USA). The air was drawn from an inlet at the top of the tower, 10 cm below the sonic measurement height through BEV-A-Line tubing (29 m length and 1/4" inner diameter) and two aerosol filters (ACRO 50 PTFE, 1 μm pore-size, Gelman, Ann Arbor, MI, USA) at a flow rate of 5.8 L min^{-1} (pump unit: KNF Neuberger, Germany). The outputs from the sonic anemometer and infrared gas analyser were read at 20 Hz through RS-232

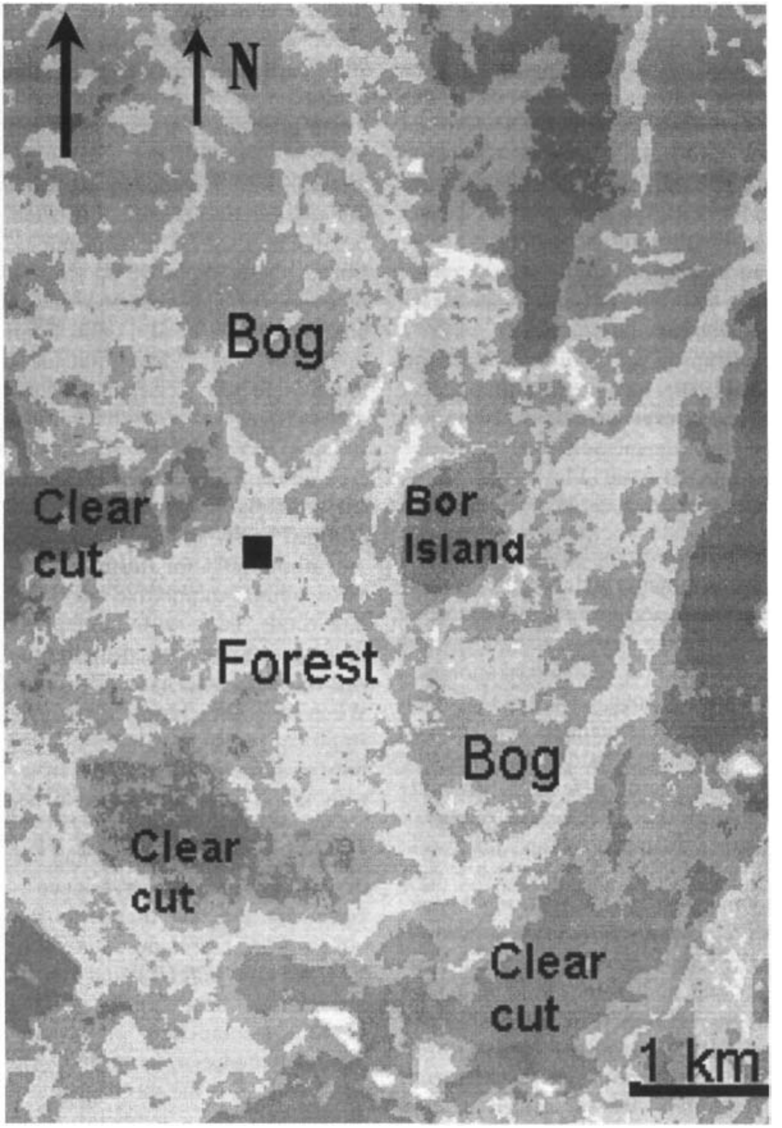

Fig. 1. A space image of the Zotino site kindly donated by D. Mollicone. A white square shows the eddy tower spot. The main landscape types on the image have been reconstructed by comparison with a forest inventory map. (Shades of grey are as follows: dark grey is closed forests; medium grey is bogs; lighter grey is clear cuts of different ages.)

ports onto 386-class computers, and all data were stored for subsequent analysis. Pressure in the infrared gas analyser was about 10 mbar above ambient as measured by the internal pressure sensor of the infrared gas analyser and was accounted for by the internal software.

The fluxes were calculated offline as simple covariances of 30 min high-frequency time series of vertical wind velocity with temperature or water vapour density. The time lag between measurements of vertical wind velocity and scalar densities due to transport in the tube was estimated by cross-correlation between both time series to be equal to approximately 4.8 s for water vapour.

The data were corrected by shifting the time series by the estimated time lag.

Frequency losses due to damping in the tube and analyser response were corrected using the approach by Eugster and Senn (1995). The correction parameter was determined from the cospectral analysis of vertical wind, temperature and water vapour time series. Water vapour dilution corrections were made with internal software of the LiCor 6262, and corrections of differences of the air pressure in the sampling cell and in the atmosphere were calculated automatically with a built-in pressure transducer. Coordinate rotation as in McMillen (1988) was applied. Ecosystem level carbon dioxide fluxes were also determined as part of this experiment and are presented elsewhere in the current issue (Lloyd et al., 2002; Shibistova et al.).

2.2.2. Supporting meteorological measurements. Radiative flux measurements included total downward and upward radiation using a pyradiometer (LXG055), and shortwave downward and upward radiation using a Kipp and Zonen pyrranometer (CM14, Kipp and Zonen, Delft, Holland). Additional measurements included air temperature (HMP35D, Vaisala, Helsinki, Finland), air humidity (HMP35D, Vaisala, Helsinki, Finland) and wind velocity (A100R, Vector Instruments). These sensors were installed below the sonic anemometer on a boom. At ground level a rain gauge was also installed (#52203, Young Instruments, Traverse City, MI, USA) located in close proximity to the eddy flux tower. Soil heat fluxes were measured at five locations with heat flux plates (Rimco HP3/CN3) installed at depth of 0.05 m. For measurement of soil temperatures, platinum resistance thermometers (Geratherm, Geschwenden, Germany) were installed in two locations close to the towers at depths 0.05 m, 0.15 cm, 0.50 m and 1.0 m, respectively. At both sites, the environmental data were collected every 10 s and stored as 10-min averages on data loggers (Campbell CR21X and D13000, Delta-T, Burwell, UK). For comparison with half-hourly eddy flux data, 30-min averages of the environmental data were subsequently calculated.

2.3. Data analysis

Data are presented here for the period 11 June 1998 to 10 October 2000, with a winter break in the first year from October 1998 through March 1999. The data quality was checked using a stationarity test (Foken and Wichura, 1996). Non-stationary data (the sum of the variances of six 5-min intervals of a time series deviated by more than 50% of the variance of the total 30-min interval) were excluded from further analysis. Data under rain events and 1 h after were rejected because the sonic's sensors might have malfunctioned due to moisture on them, although, using time series of high-frequency raw data and spectral analysis. Grelle et al. (1999) found that 95% of them were valid. Data outside the instrument limits were also rejected. Coverage of qualified data was generally 70-80% with the exception of January 2000. This was an unusually cold month, even for central Siberia, and the sonic anemometer tended to malfunction when ambient temperatures dropped below about -52 °C. Data coverage was only about 30% for this month.

To obtain cumulative seasonal and/or annual flux totals, gaps with missing data were filled. Short gaps were filled using interpolation between two available data points before and after a gap. When possible, longer gaps were filled using empirical regressions, net radiation being a function of photosynthetically active radiation, and with latent heat and sensible heat fluxes being functions of net radiation.

Energy balance closure may serve as a quality check for eddy covariance measurements. Following the law of energy conservation, net radiation (R_n) is equal to the sum of latent heat (λE), sensible heat (H), and soil transfer heat (G). The canopy heat storage (δH) may also be a significant component of the energy balance. It was calculated as $\delta H = \rho c_p(\delta T/\delta t)z$, where ρ is the air density, c_p is the specific heat of air at constant pressure, δT is the temperature difference for the time interval δt (30min), and z is the height of measurements. The term $\delta(\lambda E)$ was calculated as equal to $\rho\lambda(\delta q/\delta t)z$, where λ is the latent heat of the vaporization of water, and δq is the specific humidity difference for the time interval δt (30min).

Based on daytime half-hourly data for these fluxes in the well mixed atmosphere [photosynthetically active radiation, PAR, greater than 10 μmol m^{-2} s^{-1} and friction velocity, u*, greater than 0.33 m s^{-1}) and at least 1 h after rain, energy balance closure, evaluated as ($H + \lambda E$) versus

$[R_n - G - (\delta H + \delta LE)]$, varied between 74% to 81% for the three vegetative seasons examined (Table 1).

We examined radiation balance closure in relation to wind direction and the 90%-fetch distance calculated from Schuepp et al. (1990). The qualified 30-min closure ratio $(H + \lambda E + G + S)/R_n$ and fetch distance were bin-averaged for each 45° segment and plotted against wind direction for the 1999 growing season with a fairly good closure (Fig. 2). This shows that the best closure, around 85%, was associated with winds from the western hemisphere (180-360°) with fetch distances about 650 m from our sufficiently homogenous forest. Closure of about 76% was associated with easterly winds with smaller fetch distances of 470 m (Fig. 2). This lower energy balance area represents wind coming from the general direction of the nearby bog (Fig. 1).

Some energy closure imbalance for eddy covariance studies is common, but its magnitude can vary widely from only a few per cent (Jarvis et al., 1997; Hollinger et al., 1999) to as much as 30% (Anthoni et al., 1999; Wilson and Baldocchi, 2000), with average shortfalls of 10-20% (Kelliher et al., 1996; Goulden et al., 1996). Energy imbalance is related to different causes: instrumentation (Verma et al., 1986), spatial homogeneity of the radiation and eddy covariance footprints (Schmid et al., 2000), or incomplete detection and measurement of all turbulent and advective energy fluxes (Anthoni et al., 1999). As with Anthoni et al. (1999), we may also relate our energy balance incompleteness to the influence of our stand structure with fairly large gaps in the vicinity of the tower. Significant upwelling radiation may develop above those gaps which is not registered by the radiometer.

Table 1. *Slope, intercept and R^2 of the half-hourly energy balance closure ($H + \lambda E$ against R_n-G-heat storage) for each of 1998-2000 growing seasons*

Year	Slope	Intercept (W m^{-2})	R^2
1998	0.74	0.4	0.93
1999	0.81	1.9	0.89
2000	0.78	4.9	0.87

Surface conductance (G_s) for water vapour transfer was calculated by the inversion of the Penman-Monteith equation: taking the aerodynamic resistance as $\bar{u}/u*^2$ where $\bar{u}$ is the mean wind velocity and $u*$ is the friction velocity. Average daily surface conductances were calculated from half-hourly data qualified for conditions of the well mixed atmosphere [$u* > 0.33$ m s^{-1} and positive available energy $(R_n - G)$]. Very high values of G_s from the wet surface were rejected.

Equilibrium evaporation was estimated as a limit of the Penman-Monteith equation as at the

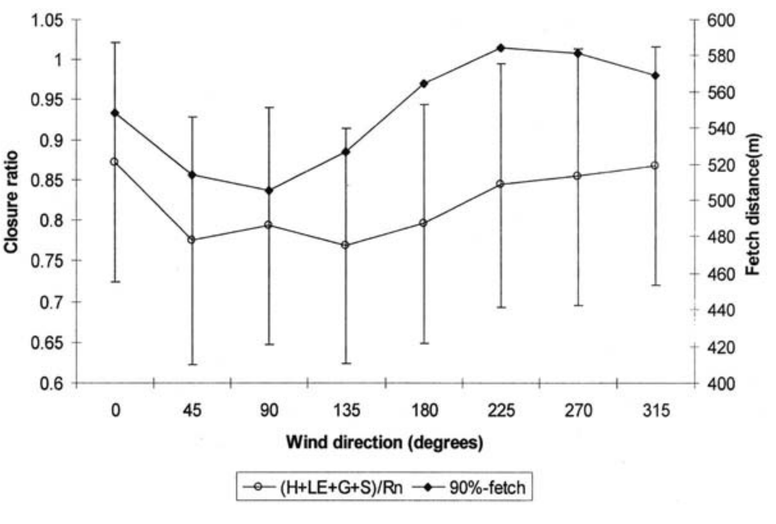

Fig. 2. Energy balance closure ratio $(H + \lambda E + G + S/R_n)$ and fetch distance plotted against wind direction bin-averaged for each 45° for the 1999 growing season. Error bars are one standard deviation.

same rate that evaporation occurs from a free water table with the vapour pressure deficit equal to zero and G_s equal to infinity (Baldocchi et al., 2000).

2.3. Soil water content determinations

Throughout the 1998 growing season, soil samples were collected using a hand auger designed for sandy soils (Eijkelkamp, Giesbeek, The Netherlands). Cores were drilled to 2 m and samples taken at depths 0-10, 10-20, 20-30, 60-70, 90-100 and 190-200 cm. Three sampling sites were chosen within the vicinity of the eddy covariance tower, and within each site three sample cores were taken to include under-tree, edge of clearing and middle of clearing samples. Sites were sampled on a rotation basis, with one site sampled every 3-4 d.

Samples of 100-200 g were collected in plastic bags and weighed with a balance accurate to 0.1 g. With bags fully open, samples were then dried in solar ovens for 3-4 d until constant weight was achieved. The walls of the ovens were constructed from polystyrene or cardboard sheeting covered internally in reflective foil, and the top covering was of clear plastic. Enough ventilation was maintained in the ovens to allow removal of water vapour as the samples dried. Temperatures measured in the ovens reached around 70 °C at peak solar elevation. We consider the gravimetric method satisfactory for inferring seasonal changes in soil moisture based on measurements repeated at the same locations using the same instrument.

3. Results and discussion

3.1. General climatology

In Table 2, climatology, energy and water fluxes for the three growing seasons with long-term averages (when applicable) are presented. The long-term climatological data (1930-1980) is the average from three regular weather stations located within 50 km of the measurement site: Vorogovo (61°01′N, 89°34′E), Sym (60°22′N, 88°26′E), and Yartsevo (60°16′N, 90°13′E). These three stations form a triangle with the measurement site in the centre.

For our site and taking a 5 °C threshold, the long-term average length of the growing season is 132 d, lasting roughly from early May to late September. During the two full years of observation, it was greater than the long-term average 145 and 135 d for 1999 and 2000, respectively. All three vegetative seasons were also warmer than the 1930-1980 average. This is consistent with this general region of Siberia having shown dramatic increases in average summer temperature over the last 30 yr or so (Arneth et al., 2001), more or less unparalleled across the entire northern hemisphere landmass (Serreze et al., 2000). Detailed information on soil temperatures is not provided here, but is provided in Shibistova et al. (2002).

From Table 2 it can also be seen that the summers of 1998-2000 were drier than the 50-yr normal. Hot and dry weather often occurs during the summer in the continental climate of Siberia. Some adverse effects of soil water deficits on ecosystem evaporation rates and plant productivity for *P. sylvestris* growing on deep sandy soils with poor water retention characteristics may occur (Kelliher et al., 1998; Schulze et al., 1999; Valentini et al., 2000; Arneth et al., 2001). However, in the presence of a perched water table at 2-3 m pine trees commonly develop a primary root long enough to reach available water (Orlov and Koshelkov, 1971). In this way, a deficiency of soil moisture during summer may be supplemented by ground water and may not effect evaporation rates.

3.2. Seasonal patterns in energy fluxes

3.2.1. Albedo. The annual course of surface albedo above the forest canopy is shown in Fig. 3. During the summer, the course of albedo was very smooth with values of about 0.10. This falls in the usual range for conifer reflectance (Baldocchi et al., 2000), although Scots pine forest reflectance itself, as given by Budyko (1974), is somewhat higher: 0.12-0.14. During the spring and autumn when snow was present, albedo varied between 0.10 and 0.20. In winter, it was typically between 0.2 and 0.4, but with intermittently high values of as much as 0.8 during short periods with freshly fallen snow. For comparison, albedo of a nearby bog was 70-80% over the entire winter period (Kurbatova et al., 2002). Budyko (1974) gives higher albedos for all seasons, but his measurements were made from aircraft allowing for

Table 2. *Summary of climatology and energy and mass fluxes for growing seasons (May-September) of 1998-2000 and winter 1999-2000 for Zotino site along with long-term norms averaged for three adjacent weather stations located as far from the site as 30-50 km*

Variable	1998[a)]	1999	2000	Long-term average[b)] (May-Sep)	1999-2000 (Oct-Apr)
Air temperature;	13.5	12.7	12.9	11.6	
(Average of three weather stations) (°C)	(12.9)	(12.3)	(12.9)		
January temperature (°C)				-24.0	-28.2
July temperature (°C)	20.0	21.4	16.9	18.0	
Growing season length with temperature > 5 °C (d)	-	145	135	132	
Average soil temperature at 0.05 m (°C)	11.9	8.3	8.7		-1.4
Average daytime water vapour pressure deficit (hPa)	6.9	7.0	6.4	4.7	1.0
Total net radiation (MJ m^{-2})	1065	1385	1445	1260	210
Total sensible heat flux (MJ m^{-2})	460	597	633		70
Total latent heat flux (MJ m^{-2})	365	468	482		13.5
Average Bowen ratio	1.25	1.27	1.31		
Total precipitation (mm)	213	233	228	335	225
Measured evaporation (mm)	147	189	196		
Hydrological balance (soil water and runoff)	66	44	32		

a) An incomplete growing season.
b) Long-term averages are taken from Reference books on climate of the USSR.

Temperature and precipitation observation periods are: 1932-1980 for station Yartsevo, 1937-1980 for station Sym, and 1939-1980 for station Vorogovo.

Net radiation observation periods are: 1959-1964 for station Alexandrovskoye and 1958-1963 for station Vanavara. Both stations are located at latitude 60°N.

landscape-based measurements rather than for one ecosystem.

3.2.2. Net radiation. On average for the three growing seasons (May-September) of 1998-2000, net radiation (R_n) was about 1400 MJ m^{-2} and annual R_n was 1600 MJ m^{-2} (Table 2). This is towards the upper end of the range given for the boreal forest zone in the former Soviet Union: 850-1750 MJ m^{-2} (Pivovarova, 1977).

In Fig. 3 the annual courses of 7-d running averages of R_n for 1998-2000 are shown. On clear days in June and July, noon values of R_n were as high as 400-500 W m^{-2} (not shown). These values are quite comparable to R_n above a jack pine forest in Canada (Baldocchi and Vogel, 1996). Although average values during midsummer were 150-200 W m^{-2}, the observed seasonality was strong. Values were typically only around 100 W m^{-2} in May, 70 W m^{-2} in April and August, 30 W m^{-2} in March and September. In October, R_n was around zero; from November to mid-February R_n was slightly negative. Net radiation was generally positive above the forest canopy after February despite the presence of ground snow cover till about mid-May.

3.2.3. Latent (λE) and sensible heat (H). In Fig. 3 7-d running averages of both fluxes for 1998-2000 are shown. The seasonal pattern of H followed the pattern of R_n to a greater extent than that of λE. During the growing season, the course of λE was rather stable, with noticeable peaks after events of heavy rains. In winter, from November through March, latent heat was about zero, except for two periods, each of about 7 d duration in late November 1999 and early 2000. The higher evaporation fluxes in March 2000 were preceded by significant snowfall events and were accompanied by maximum air temperatures around 0°C. Thus evaporation of melted water, particularly from a partially wet canopy, may have been involved. By contrast, the November 1999 peak is more enigmatic. Although daytime weather

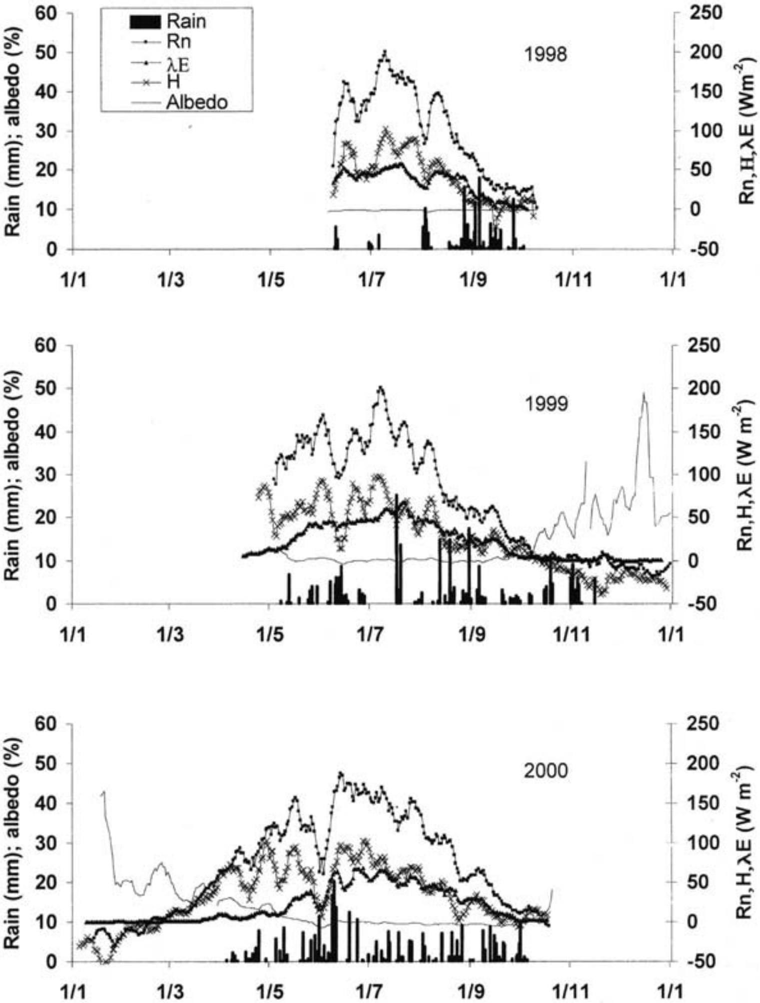

Fig. 3. Seven-day running averages of daily albedo, net radiation (R_n), latent heat (λE), sensible heat (H) and daily precipitation (not smoothed) for 1998-2000.

was clear and sunny, with the net radiation sometimes being positive towards the middle of the day, air temperatures remained below -20 °C with little snowfall occurring around this time.

As for net radiation, sensible heat fluxes remained negative from October till the end of February. After this period, but before the start of the growing season in April, about 80% of R_n was partitioned into sensible heat flux, with only 10% of R_n partitioned for latent heat (Fig. 4). After the snow melted, latent heat flux gradually increased during May, presumably as a consequence of both increased stomatal opening associated with the onset of photosynthesis, as well as evaporation of liquid water from the forest floor during and after the snow melt period.

On average for the growing season, sensible heat fluxes were greater than latent heat fluxes by 25-30% (Table 2). Both fluxes varied in the range 60-100 W m^{-2} during summer and 20-40 W m^{-2} in autumn (Figs. 3c and 3d). Sensible heat fluxes remained greater than latent heat fluxes till midsummer. Only in August 2000 did λE exceed H (Fig. 5). But, nevertheless, the general trend was for sensible heat to decline during the growing season and for latent heat to steadily rise. Our

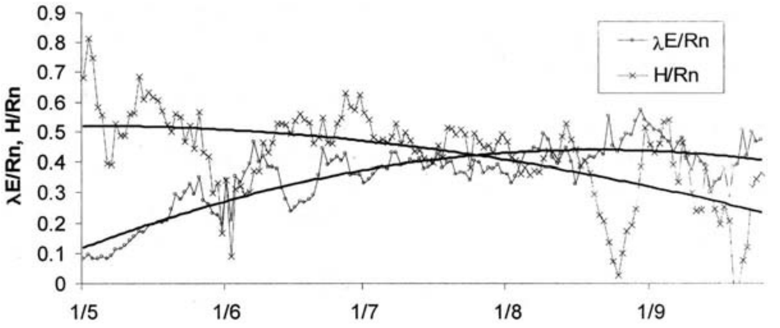

Fig. 4. Seasonal variation of daily (under positive net radiation) latent heat fluxes and sensible heat fluxes during the 2000 growing season.

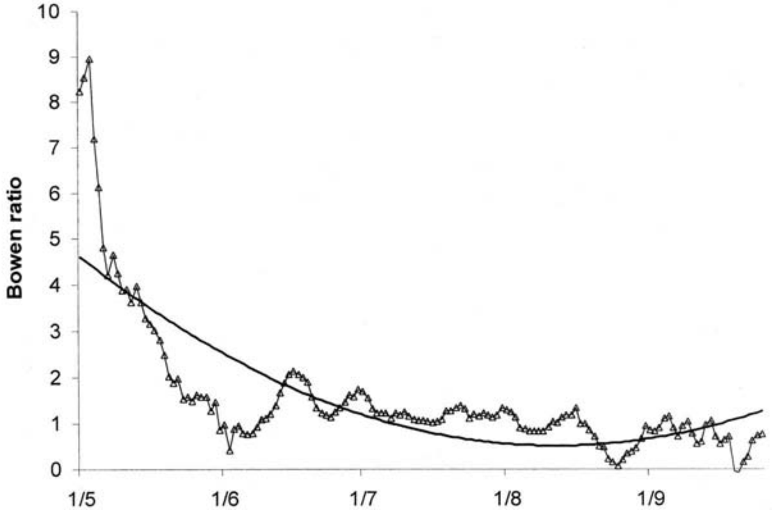

Fig. 5. Seasonal variation of daily (under positive radiation) Bowen ratio during the 2000 growing season.

ratios are similar magnitude to other studies: H/R_n varying between 0.5-0.7 and $\lambda E/R_n$ varying between 0.3-0.5 in the first half of the growing season; 0.4-0.5 for both ratios in midsummer; and 0.3 for H/R_n and 0.6 for $\lambda E/R_n$ in the second half of the growing season (Baldocchi et al., 2000). The seasonal course of ratios H/R_n and $\lambda E/R_n$ demonstrates that in the continental climate of the boreal zone, after the dormant period, a greater part of available energy is partitioned for sensible heat transfer while the environment is not favorable for the physiological activity of plants. As physiological activity commences in May, about one half of available energy is partitioned towards evaporation, a substantial fraction of which is biologically controlled through stomatal conductance and its links to the photosynthetic process. Rauner (1972) indicated that in the early spring, along with the advection of warm air in anticyclones across European Russia, that boreal forest energy exchange tends to promote fast warming of the boundary layer within 15-20 d. This can also be seen in the aircraft profile data of Lloyd et al. (2002), where convective boundary layers with heights greater than 1 km are detectable as early as mid-March above the Zotino tower.

3.3. Seasonal water balance

The seasonal and monthly water regimes over the three growing seasons are given in Tables 2 and 3 and Fig. 3. Mean annual precipitation for the site may be approximated as the 3-yr average of the three neighboring stations (470 mm), with 60% of precipitation falling during the growing season. Growing season precipitation was only about 230 mm in both 1999 and 2000, and thus about 100 mm less than the 1936-1980 average (Table 2). Rain events during summer are rather sporadic in central Siberia (Fig. 3). July 1998 was abnormally dry and yielded only 10 mm of rain fallen in two rains (Fig. 3). In July 1999 there were ten periods of rain resulting in two-thirds of the long-term normal. Rain events in July 2000 were quite regular - about 20 rains, although total precipitation resulted in only half the long-term normal.

Evaporation measured over the forest was conservative, being about 190 mm for the both growing seasons (Table 2). This value is lower than that estimated by Kelliher et al. (1997) for a nearby *P. sylvestris* stand at 265 mm. Their calculations were based on the assumption that dry canopy evaporation rates throughout the growing season were similar to those measured during a midsummer campaign. From Fig. 3 and Table 3 it is clear, however, that daily water use varies considerably during the growing season, with values in spring and fall being substantially lower. Moreover, their wet canopy evaporation (intercepted water), calculated as 20% of precipitation measured at Bor weather station during 1980-1989, was likely an overestimate. Precipitation measured at three other stations around our site during 1998-2000 was 25% less. Our value of total evaporation measured over a long-term period follows the general pattern of Jarvis et al. (1997), Grelle et al. (1999) and Baldocchi et al. (1997; 2000): evaporation from boreal forests during the growing seasons are in the range 190-250 mm for continental climates (Central Canada, Siberia) and 300-400 mm for maritime climates (Sweden).

The hydrological balance, evaluated as rain minus evaporation, was positive for the growing season as a whole in 1999 and 2000. Quite often in summer evaporation can exceed precipitation by a considerable amount (Table 3).

The ratio between actual and equilibrium evaporation rates E/E_{eq} (or relative evaporation as used in Russian literature; Budyko, 1974) was very stable over all three growing seasons. This ratio was typically 0.30-0.40 during the summer months and 0.20-0.25 in the spring (Table 3). These low values do not necessarily show that precipitation does not meet water demand of the given eco-

Table 3. *Monthly water fluxes over a central Siberian pine forest*

	Rain (mm mo^{-1})	Evaporation (mm mo^{-1})	Hydrological balance (mm mo^{-1})	Daily rate E (mm d^{-1})	E/E_{eq}	Daily surface conductance (mmol m^{-2} s^{-1})
1998						
Jun	52	35	17	1.2	0.38	325
Jul	10	52	-42	1.7	0.29	160
Aug	56	42	14	1.4	0.39	245
Sep	91	18	73	0.6	a)	a)
1999						
May	29	26	3	0.8	0.25	180
Jun	56	46	10	1.5	0.37	310
Jul	55	59	-4	1.9	0.37	190
Aug	61	38	23	1.2	0.41	355
Sep	32	20	12	0.7	a)	a)
2000						
May	43	26	17	0.8	0.22	235
Jun	30	52	-22	1.7	0.37	300
Jul	37	61	-24	2.0	0.38	250
Aug	62	40	22	1.3	0.37	270
Sep	59	17	42	0.6	a)	a)

a) Months with less than 50% qualified data.

system. They do, however, indicate significant regulation of evaporation rates through stomatal control. *Pinus sylvestris* in central Siberia may be subject to greater evaporation deficits than most other boreal ecosystems. For a jack pine forest in continental Canada E/E_{eq} was typically above 0.5 (Baldocchi et al., 1997) and for a mixed Scots pine and Norway spruce forest in maritime Sweden the ratio was around 0.7 (Grelle et al., 1999). Interestingly, even above the bog at the Zotino site, relative evaporation does not exceed 0.5, probably because peat decreases surface evaporation through a mulching effect (Kurbatova et al., 2002). Rauner (1972) pointed out that in the moister European part of Russia E/E_{eq} is typically close 1.0 for both conifers and deciduous stands with LAI greater than 3.0. Because E/E_{eq} may well be a good reflection of LAI and maximum available soil water (Rauner, 1972; Baldocchi and Vogel, 1997; Baldocchi et al., 2000; Kelliher et al., 2001) it is likely that the low E/E_{eq} for the forest studied here are a consequence of the low LAI of our forest (1.5) and low soil water content of our well drained sandy soil (Kelliher et al., 1998).

3.4. *Surface conductance*

Surface conductance (G_s) for water vapour transfer exerts a biological control for evaporation along with climatic factors such as solar radiation, air humidity, and soil moisture. Based on surveys of stomatal resistance data, Baldocchi et al. (2000) analysed factors causing canopy resistances of boreal conifer forests to be large. They identified short-term factors including partial stomatal conductances due to low soil moisture and high humidity deficit and long-term factors, including low LAI and low maximal stomatal conductances due to biochemical constrains.

Mean monthly values varied between 0.15-0.35 mol m^{-2} s^{-1}. For the continental climate of Central Siberia, periods of 10 d or more without rain may be quite common in midsummer (Kelliher et al., 1998), and thus the hydrological balance may be negative, as our study showed, in July 1998 and June-July 2000 (Table 3). Daily conductances for these months were as low as 0.15-0.2 mol m^{-2} s^{-1} (Table 3). Nevertheless, it is common for dry periods in midsummer also to be associated with higher vapour pressure deficits, D_c. Even in the absence of soil water deficits, higher D_c during rain-free periods would be expected to reduce conifer stomatal conductances during these times (Schulze et al., 1999; Zimmermann et al., 2000). We have therefore attempted to separate the effects of soil water deficits and D_c on G_s by plotting the latter as a function of D_c for sunny days (integral PAR > 40 mol m^{-2} d^{-1}), grouping data according to the period of time elapsed since the last rainfall (Fig. 6). In the figure, we substituted soil moisture for the time elapsed since the last rain because daily soil moisture measurements were not available. This shows a very strong dependence of G_s on D_c, but with little obvious effect of time since the last rainfall on that response. The strong dependence of G_s on D_c results in ecosytsem evaporation rates staying more or less constant, despite D_c varying widely from day to day (Schulze et al., 1999).

This suggests that there was little direct effect of soil moisture status on canopy conductances for the current study. This differs from the conclusions of Kelliher et al. (1998) and Valentini (2000), also working in *P. sylvestris* stands the same region in 1996. However, of relevance here is that Kelliher et al. (1998) were working in an more open stand with no evidence of any water table being present within the top 3 m of soil (S. Grigoriev, A. Varlagin and A. Sogachev, unpublished excavation, 1996). By contrast, regular sampling for soil moisture determinations during the summer of 1998 showed a relatively impermeable clay layer at around 2 m depth for the forest studied here, with the water content at this depth significantly greater that the soil above. Moreover, the water content at 1.9-2.0 m depth declined significantly during the dry summer of 1998 (Fig. 7). Occasional fine roots were also found in the 1.9-2.0 m soil samples (Arneth, personal observation), suggesting that this may have been the dominant soil water source during the rain-free period.

Likewise, the regenerating forest studied by Valentini et al. (2000) was only 12 yr old (2.5 m tall). Even if a similar water source were to have been available at depth, it is unlikely that the root systems of the young trees would have been sufficiently developed to gain access to it. It therefore seems likely that water uptake during the extended dry periods in the current study was sustained by the access of the tree root system to this deep water; which was not available in the case for the

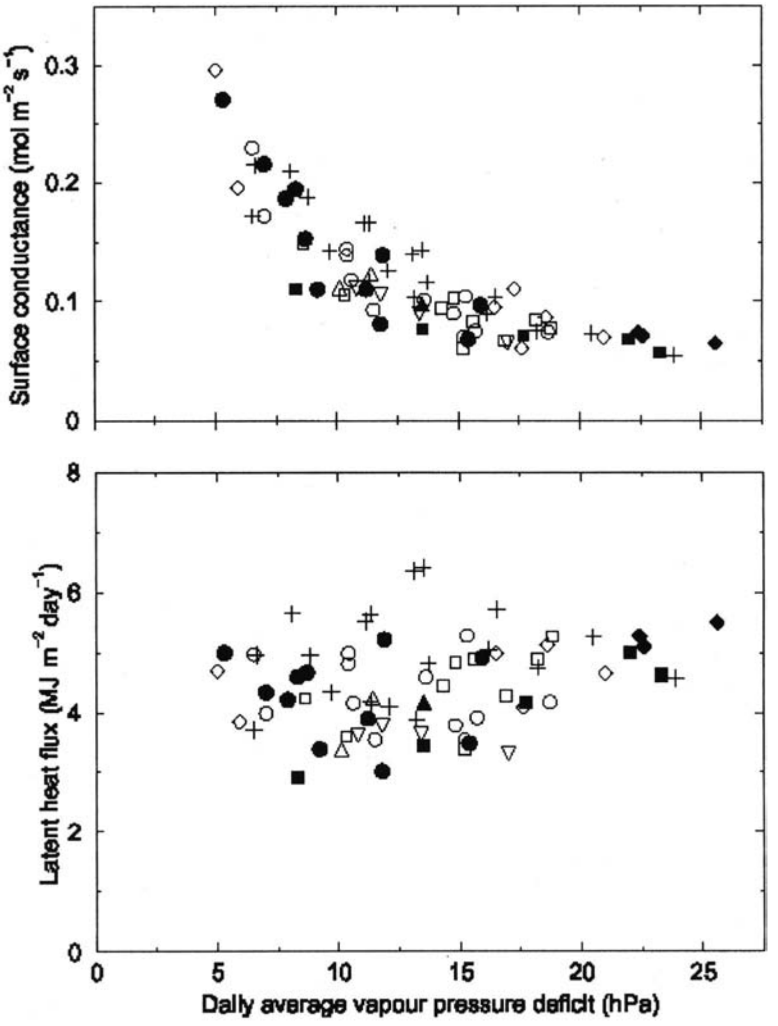

Fig. 6. Effect of time with rainfall on the relationship between daily surface conductance or ecosystem evaporation rate on daily average vapour pressure deficit during summer. (○, ●, +) 1-5 d after rainfall; (■, □) 6-10 d after rainfall; (◆, ◇) 11-15 d after rainfall; (△, ▲) 16-20 d after rainfall; (▽, ▼) 21-25 d after rainfall (open symbols, 1998; closed symbols, 1999; +, 2000). Data presented are only for days between 1 June and 30 August with a integrated photosynthetic photon flux density of more than 40 mol m^{-2} d^{-1}.

forests studied by Kelliher et al. (1998) and Valentini et al. (2000).

4. Summary

Seasonal energy (all components of heat energy balance) and water (rain, evaporation) fluxes over a *Pinus sylvestris* ecosystem in Central Siberia showed little inter-annual variation over the three growing seasons of 1998-2000, less than 5% of the 3-yr mean. About 80% of available energy was partitioned for sensible heat in early spring in the absence of any photosynthetic activity, resulting in a Bowen ratio as high as 8. This decreased quickly with the onset of photosynthesis in spring, but generally speaking sensible heat fluxes prevail over latent heat flux through the summer period. Evaporation is about one third of potential, with maximum daily evaporation rates

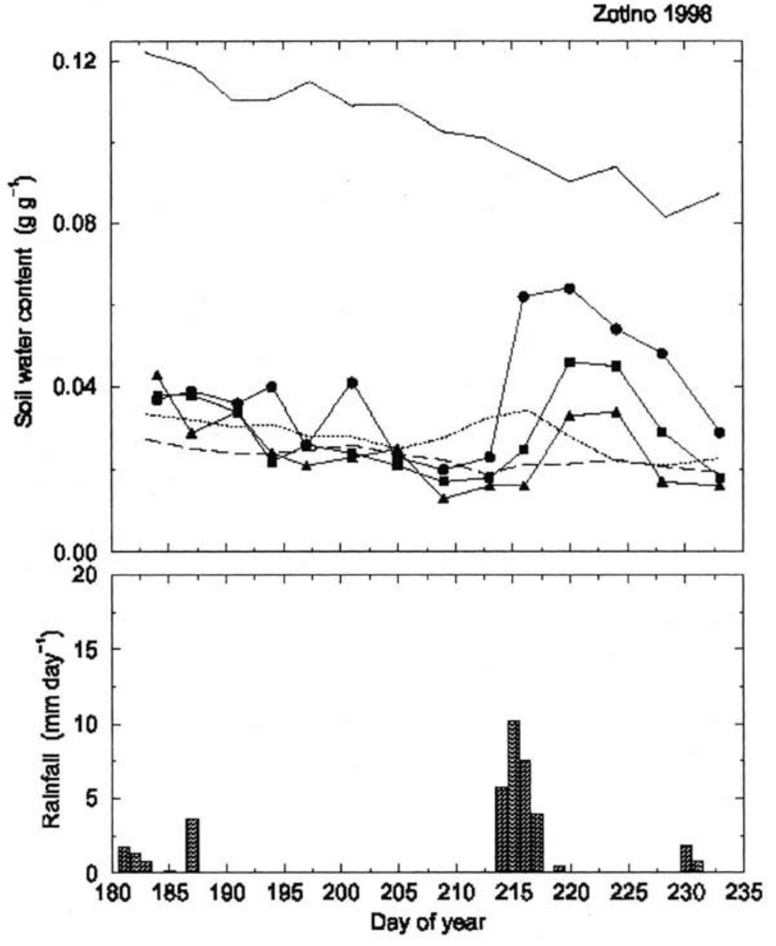

Fig. 7. Variation in soil water content and daily precipitation during summer 1998. (●) 0-0.1 m depth; (■) 0.1-0.2 m depth; (▲ 0.2-0.3 m depth; (- - -) 0.6-0.7 m depth; (······) 0.9-1.0 m depth; (——) 1.9-2.0 m depth. Due to greater heterogeneity in soil physical properties and water content at depths below 0.5 m, three-point running averages of the original data are shown for lower depth samples for increased clarity of presentation.

in the midsummer 2 mm d^{-1}. In the dry climate of central Siberia, daily averaged surface conductances were low, 0.15-0.35 mol m^{-2} s^{-1}. These are consistent with those for other boreal forests of dry climates, but 2-3-fold less than boreal forests growing in moister climates. Despite extended dry periods during summer, there were no indications of reductions in stand level evaporation rates to soil water deficits. This was probably a consequence of the presence of a perched water table around 2 m depth.

5. Acknowledgements

The authors are indebted to all participants of Siberian expeditions during 1998-2000, initiating and maintaining eddy covariance measurements over the 22-month period of this study. The senior author thanks Yelena Parfenova for her assistance with 1998 and 1999 campaign logistics, as well as for help in preparing this manuscript. Thanks to Galina Zrazhewskaya for providing logistical support throughout 2000. The senior author would especially like to thank Inge and Waltraud Schulze who, along with other family members, kept the eddy equipment running during the severest frosts in January 2000.

This work would also not have been possible without the help and goodwill of the people of the village of Zotino. We are especially grateful to Alexander Dolgushin and the Bachman and Kislitsyn families for their assistance.

We also thank Danilo Mollicone and Sebastien Lafont who provided images and vegetation classifications for the Zotino site (Fig. 1), and Claudia Czimcik for information on soil characteristics and classification.

The senior author thanks two anonymous referees for valuable comments.

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