Moss beneath a leafless larch canopy: influence on water and energy balances in the southern mountainous taiga of eastern Siberia

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ABSTRACT

The southern mountainous taiga of eastern Siberia has a sparse larch canopy and an understory dominated by a thick moss layer. The physiology of moss is very different from that of other plants, as mosses lack roots and vascular systems and take up water directly. During May 2002 we conducted hydrological and meteorological measurements in the taiga of eastern Siberia to investigate the role of understory moss on water and energy balances within a leafless larch forest. We found that below-leafless canopy net all-wave radiation partitions into 39% latent heat flux and 39% sensible heat flux, while the mean daily Bowen ratio is about 1. Ground heat flux on the moss surface is also an important factor, as it comprises 22% of net all-wave radiation. Evaporation from moss beneath the leafless canopy was 24 mm during the 1-month observation period, representing 23% of the water flux into the larch forest. This finding implies that moss intercepted 23% of the water flux into the larch forest. In addition, evaporation from the moss understory during May 2002 comprised 22% of total evapotranspiration previously estimated above the canopy (April to October 2001). We conclude that moss is an important component of the water and energy balance in larch forests in the taiga region.

KEYWORDS

Eastern Siberia, leafless larch canopy, moss, water and energy balance

INTRODUCTION

The physiology of mosses is very different from that of other plants, as mosses lack roots and vascular systems and take up water directly. Mosses dominate the boreal landscape in central Canada (Rapalee *et al.,* 2001), and McFadden *et al.* (1998) noted that shading of the moss layer by the canopy reduces ground heat flux and increases sensible heat flux in shrub tundra in arctic Alaska. These results indicate that the moss layer strongly affects the energy balance and dominant landscape in boreal regions of North America. In a study of the effects of moss on water balance, Price *et al.* (1997) reported that moss intercepts 23% of annual throughfall precipitation input water in a boreal forest in northern Manitoba, Canada.

Although most previous studies of the effects of moss on water balance have been undertaken in North America, where the mosses cover land surfaces, mosses also dominate the understory landscape in southeastern Siberia; however, the effects of moss on water and energy balances in this region are not well understood. In a study of the effect of mosses and lichens on water and energy balances in northern Eurasia, Zhuravin (2004) demonstrated that reindeer moss intercepts 5 mm of precipitation during each rainfall event and estimated annual evaporation from the reindeer moss in the steppe forest of eastern Siberia to comprise 30% of evaporation from permafrost-taiga soils. These results also indicate that the moss layer restricts evaporation from the ground surface and that understory vegetation is an important land cover to consider when describing stream discharge in eastern Siberia.

Kelliher *et al.* (1997) and Ohta *et al*. (2001) found that understory evaporation is especially important in the plain taiga of eastern Siberia in the middle of the Lena Basin, because of the sparse upper canopy in this area. Ohta *et al*. (2001) measured evaporation from a single *Larix cjanderii* over the period mid-April to mid-October 1998 in an area dominated by cowberry understory and found that the measured understory evaporation represented 35% of total evapotranspiration recorded above the larch canopy. For a pine (*Pinus densiflora*) flatwoods forest in north Florida, USA, Powel *et al.* (2005) found that the contributions of the understory sensible and latent heat fluxes to the above open forest fluxes were approximately equal. Thus, if an overstory canopy is sparse, it is also important to consider the water and energy balances below the canopy.

The understory in the upper Lena Basin, southern mountainous taiga region, Siberia, comprises mosses and lichens, while the overstory is a sparse larch canopy. Kubota *et al*. (2004) calculated the water and energy balance in this region for the period April to October 2001. Seasonal variations in evapotranspiration above larch canopies in the plain taiga of the middle Lena Basin and mountainous taiga of the upper Lena Basin have been previously documented by Ohta *et al*. (2001) and Kubota *et al*. (2004), respectively. Seasonal variations in evapotranspiration are significant during the period following snowmelt when the larch canopy is leafless.

The Bowen ratio (ratio of sensible heat flux to latent heat flux) during May in the plain taiga is much higher than that measured in the southern mountainous taiga region at the same time of year, even though the timing of snowmelt is identical at both sites. The difference in Bowen ratios therefore reflects the difference in latent heat flux during the leafless period. This indicates that latent heat flux from understory moss in the southern mountain taiga is large even during the leafless period. The aim of the present study is to examine the effect of understory moss on the water and energy balances beneath a leafless larch canopy in the southern mountainous taiga region, Siberia.

2. Methodology

2. 1 Site Description

The catchment of the Nelka River (Mogot experimental watershed) is located in the southern mountainous region of eastern Siberia (55°N, 124°E), approximately 60 km north of Tynda, Amur region, Russia (Fig. 1). The Nelka River Basin is about 12 km long and 2.5 km wide, with a total area of 30.8 km^2. Slopes within the main valley face northeast and southwest, while elevation within the basin varies from about 550 to 1150 m above sea level. The meteorological observation site used in the present study (tower site in Fig. 1) is located at 608 m elevation, in the lower section of the main valley.

Forest covers more than 90% of the area in the watershed. The larch forest (*Larix cjanderii*) has a plant area index (PAI) of 0.4, as measured from a fisheye photograph during the leafless period and defined as the summation of the area of one side of a tree per unit horizontal area. In 2002, snow melted during early May and larch leaves emerged in early June. Understory vegetation in the study area consists of a 10 to 15 cm thick layer of true mosses (*Aulacomnium turgidum*, *Cetrari cucullate*) and lichens (*Cladina arbuscula*); these mosses and lichens cover the ground over more than 90% of the watershed. The physical properties of the moss and soil at the study site are as follows: moss bulk density, 120 kg m^{-3}; soil particle mass density, 2200–2460 kg m^{-3}; soil bulk density, 280–560 kg m^{-3}; and saturated-soil filtration coefficient, 1.0×10^{-4}–3.0×10^{-4} m s^{-1}. In contrast with the moss and surface soil of arctic tundra in eastern Siberia (Sato, 2004), moss from the present study is denser and thicker. We were unable to locate a water table within the moss or surface soil layer, which is consistent with the findings of Suzuki *et al*. (2006) who demonstrated that most snowmelt water in the region infiltrates into the frozen ground and then refreezes within the organic soil layer. We assumed that following the disappearance of surface snow, the water table was located within the frost table.

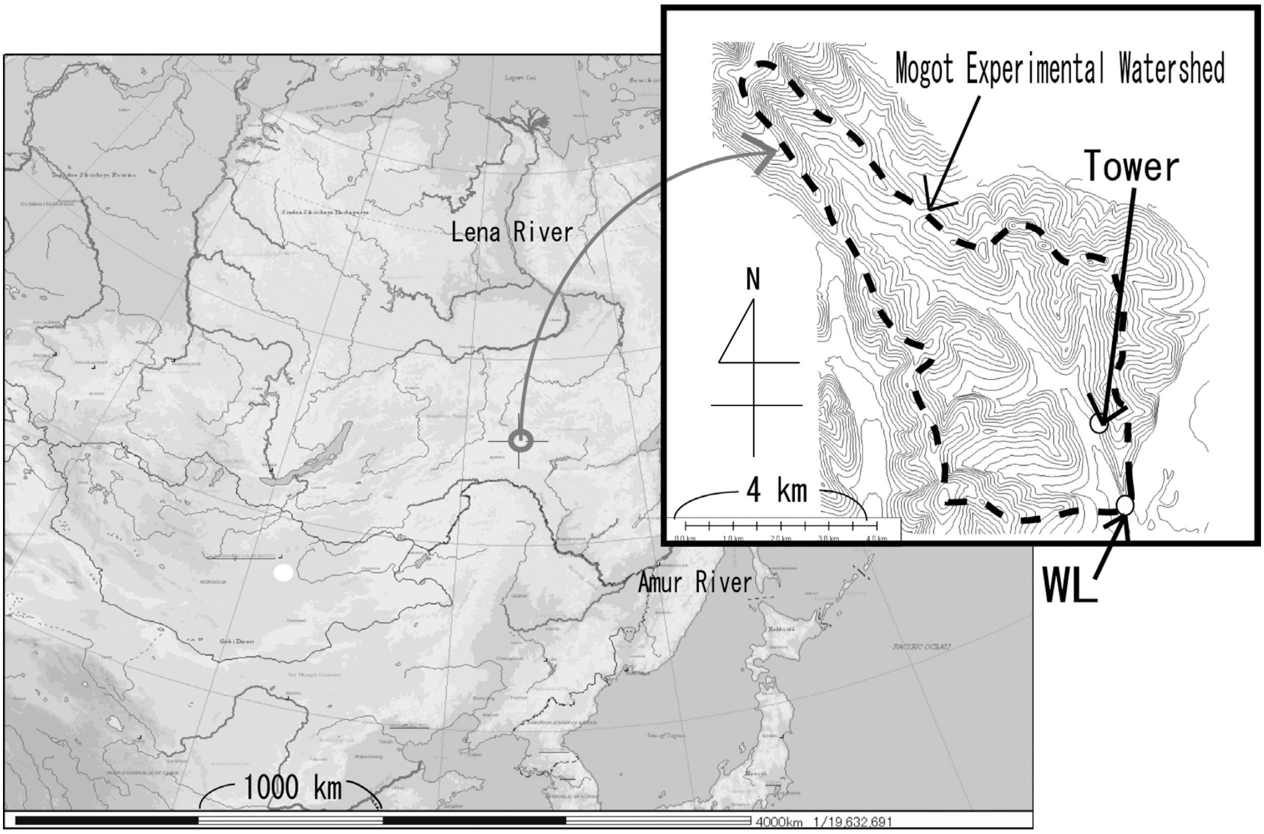

Figure 1 Location of observation site, eastern Siberia. An inset map denotes the catchment of the Nelka River (Mogot experimental watershed), Amur region (WL, water level measurement point; Tower, meteorological observation site).

2.2 Measurements

For most of the observation period (28 April to 31 May 2002 for hydrological measures and 28 April to 30 June 2002 for meteorological measures), the forest was leafless and free from snow cover. We observed hydrological and meteorological elements at sites above and below the larch forest canopy and at the mouth of the Nelka River. Hydrological measurements included precipitation measured with a Tretyakov gauge at 0800 and 2000 h each day, snow water equivalent measured via a snow survey (total snow density at 50 m intervals and snow depth at 10 m intervals) along the main valley near the meteorological station every 10 to 15 days, and river discharge recorded at the mouth of the Nelka River using both automatic water level and direct flow measurements at site WL (see Fig. 1). Meteorological observations included turbulent fluxes, air temperature, relative humidity, wind speed, incident short-wave radiation, reflected short-wave radiation, and net all-wave radiation. Turbulent fluxes above the moss and beneath the larch canopy at the tower site were measured using a three-dimensional ultrasonic anemometer (DA-600, Kaijo, Tokyo, Japan) and an open-path infrared gas analyzer (AH-300, Kaijo). The measurement interval for turbulent fluxes was 10 Hz. Data were collected by a data logger (LG-300, Oriental Electronics Inc., Kyoto, Japan) and written to a hard disk every hour. Measurements of air temperature, relative humidity, wind speed, incident short-wave radiation, reflected short-wave r adiation, and net all-wave radiation were made above the larch canopy at a height of about 10 m and again at a height of 1.85 m above the soil surface.

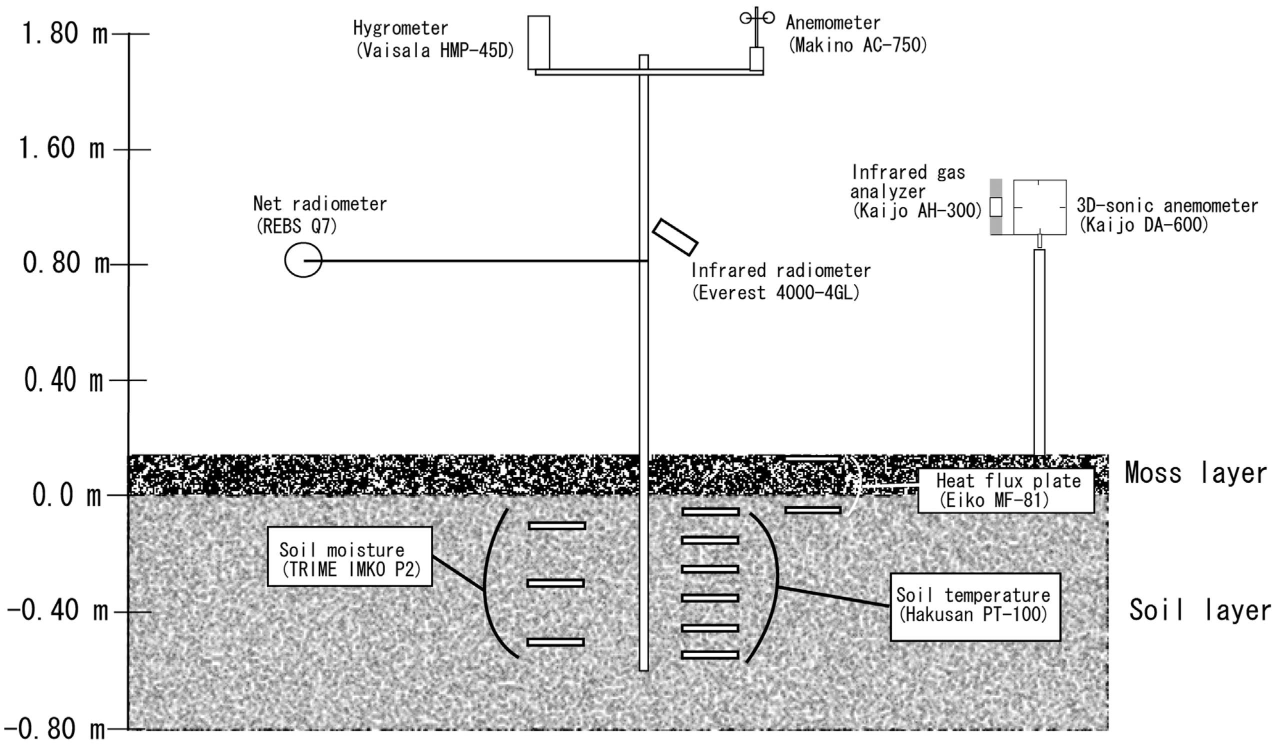

Figure 2. Schematic diagram of the automatic meteorological measurement system used in the present study.

Figure 2 provides a schematic diagram of the meteorological measurement system assembled in the understory. Moss surface temperature was measured using an infrared radiometer (Everest 4000-4GL) at an angle of 45° to the vertical at 0.85 m height above the soil surface. Soil temperature was measured using a thermometer (PT-100, Hakusan, Tokyo, Japan) at depths of 0.05, 0.15, 0.25, 0.35, 0.45, and 0.55 m below the soil surface. The ground heat flux was measured using two heat flux plates (Eiko-81F, Tokyo, Japan) at the moss and soil surface. For measuring ground heat flux at the moss surface, we installed half the heat flux plate into the moss layer at a depth of 1 cm and the other half under a small stone. We recorded air temperature, relative humidity, wind speed, incident and reflected short-wave radiation, net all-wave radiation, air pressure, wind direction, and surface temperature using data loggers (CR-10X, Campbell, Utah, USA and Datamark 3300, Hakusan, Tokyo, Japan) at 10 min intervals.

2.3 Theory

Water balance on the forest floor beneath the larch canopy

The water balance in a leafless forest can be expressed as:

$$\int P(t)dt + dSWE = \int D(t)dt + \int E(t)dt + dS \quad (1),$$

where P is the throughfall precipitation beneath the canopy (mm h^{-1}), $dSWE$ is the change in snow water equivalent (mm), D is discharge (mm), E is evaporation from the understory (mm h^{-1}), dS is the soil moisture change (mm) during the observation period, dt is the observation period (d), and t is the given day. In this study we ignored the evaporation of water intercepted by the canopy because the canopy was leafless during the observation period and had a PAI of 0.4. Therefore, we assumed that precipitation in this open site was equivalent to throughfall precipitation.

Energy balance on the forest floor beneath the larch canopy

The energy balance on the forest floor beneath the larch canopy can be expressed as:

$$R_N = H + lE + G \tag{2},$$

where R_N is the net all-wave radiation beneath the canopy (W m^{-2}), H is the sensible heat flux beneath the canopy (W m^{-2}), lE is the latent heat flux beneath the canopy (W m^{-2}), and G is the ground heat flux at the moss layer (W m^{-2}). The sensible (H) and latent (lE) heat fluxes beneath the canopy are described using the eddy covariance method:

$$H = C_P \cdot \rho \cdot \overline{w'T'} \tag{3}$$

and

$$lE = l \cdot \rho \cdot \overline{w'q'} \tag{4},$$

where C_P is the specific heat of air (kg kg^{-1}), ρ is the air density (kg m^{-3}), $\overline{w'T'}$ is the covariance in vertical wind speed and air temperature (m s^{-1} K), l is the latent heat of water vaporization (J kg^{-1} K^{-1}), and $\overline{w'q'}$ is the covariance in vertical wind speed and specific humidity (m s^{-1}).

Energy balance closure is an important measure of the quality of turbulent flux data (Baldocchi *et al.*, 1997; Anthoni *et al.*, 2002). Figure 3 shows the relationship between hourly net all-wave radiation and an hourly summation of energy balance components (sensible and latent heat fluxes + ground heat flux) for measurements made during May 2002. The slope of the linear regression for the relationship is 0.93, with an intercept at 5.3 W m^{-2}. The strong correlation (r^2 = 0.95) indicates that the hourly energy balance can be described with reasonable accuracy by summing each individual energy balance made within that hour .

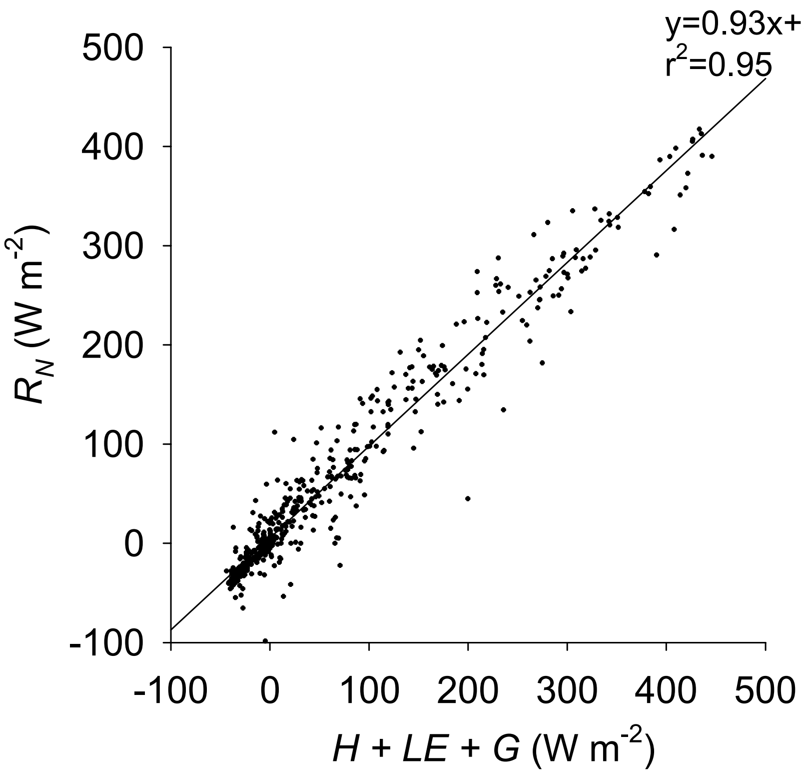

Figure 3. Relationship between hourly net all-wave radiation (R_N) on the moss and hourly summation of energy balance components (sensible [H] and latent [lE] heat fluxes on the moss plus ground heat flux [G]), as recorded during May 2002.

A point measurement of net all-wave radiation and ground heat flux beneath the canopy in this study would not represent the mean values beneath a larch canopy. Figure 4 shows the crown projection diagram with observation sites marked. Canopy coverage is sparse, with marked spatial variation in canopy coverage. Although we do not have the data necessary to verify the degree to which the net all-wave radiation and ground heat flux in the present study is spatially representative, we do refer to these energy balance components in the following discussion.

3. CONCLUSIONS

Net all-wave radiation below a leafless canopy in the southern mountainous taiga of eastern Siberia is partitioned into 39% latent heat flux and 39% sensible heat flux, while the daily Bowen ratio is about 1. Ground heat flux on the moss surface is important, as it comprises 22% of net all-wave radiation. The presence of the moss layer results in decreased soil temperature compared with that of bare soil. A large amount of the ground heat flux is absorbed by the moss layer. The absorbed energy within the moss layer results in increased moss temperature, increased sensible heat flux above the moss, and a low and constant soil heat flux under the moss layer. Finally, understory moss evaporation beneath the leafless canopy was 24 mm during the 1-month observation period, which represents 23% of the water flux into the larch forest. Thus, we assumed that the moss intercepted 23% of the water inflow into the forest floor; this value is comparable with the 22% of total evapotranspiration estimated above the larch canopy from April to October 2001 by Kubota *et al*. (2004).

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REFERENCES

Anthoni PM, Unsworth MH, Law BE, Irvine J, Baldocchi DD, Van Tuyl S, Moore D. 2002. Seasonal differences in carbon and water vapor exchange in young and old-growth ponderosa pine ecosystems. *Agricultural and Forest Meteorology* **111**: 203-222.

Baldocchi DD, Vogel CA. 1996. Energy and CO_2 flux densities above and below a temperate broad-leaved forest and a boreal pine forest. *Tree Physiology* **16**: 5-16.

Baldocchi DD, Vogel CA, Hall B. 1997. Seasonal variation of carbon dioxide exchange rates above and below a boreal jack pine forest. *Agricultural and Forest Meteorology* **83**: 147-170.

Campbell GS, Norman JM. 1998. *An Introduction to Environmental Biophysics*, 2nd ed. Springer-Verlag: Berlin; 315.

Kelliher FM, Hollinger DY, Schulze ED, Vygodskaya NN, Byers JN, Hunt JE, McSeveny TM, Milukova I, Sogatchev A, Varlargin A, Ziegler W, Arneth A, Bauer G. 1997. Evaporation from an eastern Siberian larch forest. *Agricultural and Forest Meteorology* **85**: 135-147.

Kelliher, F. M., J. Lloyd, A. Arneth, J. N. Byers, T. M. McSeveny, I. Milukova, S. Grigoriev, M. Panfyorov, A. Sogatchev, A. Varlargin, W. Ziegler, G. Bauer, and E. D. Schulze, 1998: Evaporation from a central Siberian pine forest. *Journal of Hydrology*, **205,** 279-296.

Kubota J, Suzuki K, Yamazaki Y, Ohata T, Vuglinsky V. 2004. Water and energy budget in the southern mountainous region of eastern Siberia. In *Proceedings of the 6th International Study Conference on GEWEX in Asia and GAME*, Matsumoto J, Higuchi A, Nakamura K, Yasunari T (eds). GAME Publ. no. 11; CD-ROM.

McFadden JP, Chapin FS, Hollinger DY. 1998. Subgrid-scale variability in the surface energy balance of arctic tundra. *Journal of Geophysical Research-Atmospheres* **103**: 28947-28961.

Ohta T, Hiyama T, Tanaka H, Kuwada T, Maximov TC, Ohata T, Fukushima Y. 2001. Seasonal variation in the energy and water exchanges above and below a larch forest in eastern Siberia. *Hydrological Processes* **15**: 1459-1476.

Powell TL, Starr G, Clark KL, Martin TA, Gholz HL. 2005. Ecosystem and understory water and energy exchange for a mature, naturally regenerated pine flatwoods forest in north Florida. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere* **35(7)**: 1568-1580.

Price AG, Dunham K, Carleton T, Band L. 1997. Variability of water fluxes through the black spruce (*Picea mariana*) canopy and feather moss (*Pleurozium schreberi*) carpet in the boreal forest of northern Manitoba. *Journal of Hydrology* **196**: 310-323.

Rapalee G, Steyaert LT, Hall FG. 2001. Moss and lichen cover mapping at local and regional scales in the boreal forest ecosystem of central Canada. *Journal of Geophysical Research-Atmospheres* **106**: 33551-33563.

Sato N. 2004. Water transport process of the air-vegetation-soil system in the Arctic tundra. Ph.D. diss., Hokkaido University, Sapporo, Japan.

Suzuki K, Kubota J, Ohata T, Vuglinsky V. 2006. Influence of snow ablation and frozen ground on spring runoff generation in the Mogot Experimental Watershed in the southern mountainous taiga of eastern Siberia. *Nordic Hydrology* **37**, 21-29.

Suzuki, K., Kubota, J., Yabuki, H., Ohata, T, Vuginsky, V. 2007. Moss beneath a leafless larch canopy: influence on water and energy balances in the southern mountainous taiga of eastern Siberia. Hydrological Processes, **21**, In press.

Zhuravin SA. 2004. Features of water balance for small mountainous watersheds in East Siberia: Kolyma Water Balance Station case study. In Northern Research Basins Water Balance (Proceedings of a workshop held at Victoria, Canada, March 2004), Kane D, Yang D (eds), IAHS Publ. no. 290; 28-40.