Heat and water exchange of the snowpack and permafrost during the snowmelt season in a larch forest in eastern Siberia

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Abstract

To clarify the features of the heat and water balances of the snowpack and their influence on the permafrost during the snowmelt season, observations of the snow water equivalent, snowmelt rates, water vapor flux at the snow surface, and meteorological elements were made in a larch forest in the middle reaches of the Lena River basin. The snow temperature reached 0 ºC only at the snow surface in the pre-melt period, and reached 0 ºC in all layers of the snowpack in the melt period. The heat balance components were calculated using the bulk method. The heat available to the snowpack included the net all-wave radiation and the sensible heat flux. The net all-wave radiation contributed more than 60% of the available heat in both periods. The main consumption heat was the latent heat flux in the pre-melt period and the heat for melt in the melt period, which accounted for 67 and 72% of the consumption heat, respectively. The runoff ratio of meltwater from the snowpack was estimated from the snow water equivalent and surface snowmelt rates; 44 and 81% of the meltwater in the snowpack flowed out to the permafrost in the pre-melt and melt periods, respectively. The contribution of evaporation to snow ablation was as much as 37% in the pre-melt period and 6% in the melt period. In the pre-melt period, the meltwater was thought to flow down through snow fingers. The meltwater infiltrated the frozen permafrost and raised the temperature of the frozen soil by releasing the fusion heat of refreezing in both periods.

Keyword: Siberian larch forest, snowmelt, heat balance analysis, snow finger, permafrost

1. Introduction

Siberia is a typical high-latitude area in the Eurasian Continent. The Lena River basin is divided into two main zones: taiga and tundra. The taiga contains boreal forest. Snowmelt processes and the timing of the snow disappearance can affect the timing of the thaw. In boreal forests, the forest canopy has a marked effect on snowmelt. The characteristics of the snowmelt processes in a forest are determined by the heat balance in the snowpack, which is affected by the forest canopy. Heat balance models reflecting forest canopy structure have been applied to boreal forest.

The meltwater discharge includes water movement in the snowpack. Flow paths are often formed in the snowpack. The meltwater discharged from the snowpack flows on the ground surface or infiltrates the ground. The infiltration of meltwater into frozen ground in permafrost or frost regions has been noted. For example, a rise in the temperature of frozen ground caused by the infiltration of meltwater has been reported. The water or ice content of the ground affects the snowmelt stream runoff.

To connect the snowmelt processes in the snowpack to the timing of the disappearance of snow, the snowmelt runoff in streams, the permafrost thaw, and the moisture content in the active layer, it is necessary to grasp the heat and water exchanges in the snowpack, and their influence on the permafrost under the snowpack. Taking these factors into account is important for making good estimates or for improving the heat balance models used in snowmelt or runoff models.

The purpose of this study was to clarify the features of the heat and water balances in the snowpack and permafrost, during the period from pre-melt to the disappearance of the snowpack, for the taiga forest in the middle reaches of the Lena River basin, using observation data.

2. Observations

The study site is located about 20 km north of Yakutsk City (62º15'18"N, 129º37'08"E) in the middle of the Lena River basin, in eastern Siberia. The altitude is 220 m a.s.l. The topography is essentially flat. The dominant species around the site is larch (*Larix gmelinii*). A 32-m-high observation tower was installed in the forest in August 1996. The water and heat fluxes and the profile of meteorological elements have been observed since 17 August 1997 (Ohta et al., 2001). For the 50 x 50-m quadrate in which the tower is centered, the mean stand height and density were 18 m and 840 trees per hectare, respectively. The site was covered with snow from mid September 1997 until mid May 1998.

In the larch forest, the decrease in the snow surface, evaporation from the snow surface, density profile of the snowpack, snow temperature profile, and water equivalent of the snowpack were measured manually from 16 April to 13 May 1998. The evaporation from the snow surface was measured using two small cylindrical lysimeters. The lowering of the snow surface was measured by the snow-wire method. We considered the amount of lowering of the snow surface to be the sum of snowmelt and evaporation. The snow density profile was measured using a 100 cc box-type snow sampler, which was 3 cm high. The temperature profile of the snowpack in a cross-section was measured with a thermister thermometer inserting. The measuring points on the cross-section were at the surface of the snowpack, every 10 cm from the snow surface, and at the bottom of the snowpack. Measurements were usually made at 5:00, 8:00, 10:00, 11:00, 13:00, 14:00, 15:00, 16:00, 18:00, and 20:00 (lowering only). The snow surface density was measured every day between 14:00 and 16:00. The snow density profile at 3-cm intervals was measured around 10:00 and 15:00 every two days. The snow water equivalent was measured with a cylinder-type sampler from 8:00 to 9:00 every few days. The internal diameter and length of the sampler were 7 cm and 1 m, respectively. The times mentioned above are Yakutsk Standard Time.

The atmospheric downward long-wave radiation (MS-201, Eiko) was measured 32.0 m above the ground. Global solar radiation (CM-6F, Kipp & Zonen), reflected solar radiation (CM-6F, Kipp & Zonen), net all-wave radiation (Q7, REBS), air temperature (HMP-35D, Vaisala), relative humidity (HMP-35D, Vaisala), wind speed (AC-750, Makino), infrared snow surface temperature (4000-4GL, Everest), ground temperature (TS101, Hakusan Kougyou), and ground heat flux (MF-81, Eiko) were measured above the forest floor. A ventilated shelter covered the air temperature and relative humidity sensors. The radiation meters, ventilated shelter, wind speed, and infrared radiation thermometer for measuring the snow surface temperature were installed 1.2, 1.8, 1.9, and 1.9 m above the ground, respectively. The ground temperature was measured at seven depths (0, 10, 20, 40, 60, 80, and 120 cm). The ground heat flux was measured at a depth of 5 cm. All the elements, except radiation items, were measured every five minutes. These data were stored in a data logger (DATA MARK LS-3300, Hakusan Kougyou) every five minutes. For the radiation items, the average of measurements made every minute was recorded every five minutes.

3. Heat balance equations

To evaluate the heat balance components of the snowpack, we used the following heat balance equations under the condition of no precipitation and ignoring the vapor exchange at the bottom of the snowpack:

$$Q_M = Rn + H + lE + Q_B - \Delta Q_T \tag{1}$$

$$Q_M = \Delta Q_S + Q_D \tag{2}$$

where Q_M is the heat of snowmelt, Rn is the net all-wave radiation, H is the sensible heat flux, lE is the latent heat flux for exchanging water vapor at the snow surface, Q_B is the conductive heat flux at the bottom of the snowpack, ΔQ_T is the stored heat that changes the temperature of the snowpack, ΔQ_S is the fusion heat for the snowmelt stored in the snowpack, and Q_D is the fusion heat for the snowmelt flowing out from the snowpack as meltwater.

The daily values of each term in Eq. (1) were obtained as follows. The observed one-hour average value was used for Rn, while H and lE were given by the following bulk equations:

$$H = c_p \rho C_H U (T_a - T_s) \tag{3}$$

$$lE = l \rho C_E U (q_a - q_s) \tag{4}$$

where C_H and C_E are the bulk coefficient for the sensible and latent heat fluxes, respectively, c_p is the specific heat of air, U is the wind speed above the snow surface, ρ is the air density, T_a is the air temperature above the snow surface, T_s is the snow surface temperature, l is latent heat for the evaporation or condensation of water vapor, and q_a and q_s are the specific humidity of air and the snow surface, respectively. For U, T_a, T_s, and q_a, observed one-hour averages were used. The bulk coefficient for the sensible heat flux was assumed to equal that of the latent heat flux. The bulk coefficient for the latent heat was obtained from the relationship between the evaporation rates obtained using the lysimeters and the value of $\rho U (qa - qs)$ given by observed data.

The observed one-hour average of the ground heat flux was used as Q_B. The daily value of ΔQ_T was obtained using the following equation:

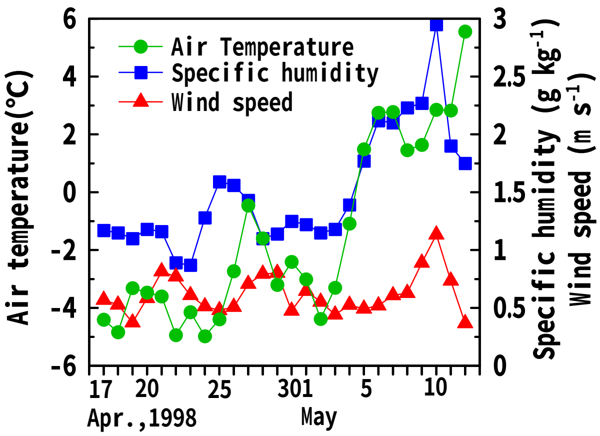
$$\Delta Q_T = \sum_{i=1}^{n} C_{PS} \rho_{Si} \Delta T_i \Delta Z_{Si} \tag{5}$$

where n is the number of vertical divisions of the snowpack, the subscript i is the number assigned to a layer, C_{PS} is the specific heat of ice, ρ_{Si} is the density of snow, ΔT_i is the difference in snow temperatures at the median point within the period from 18:00 on one day to the previous day, and ΔZ_{Si} is the snow thickness of a layer. The snowpack was divided into layers 10 cm thick. ΔT_i was obtained from the snow temperature measured at every 10 cm depth. ΔQ_S and Q_D in Eq. (2) were obtained by partitioning the daily value of Q_M. The daily runoff ratio was determined from the observed snow surface lowering, snow surface evaporation, and water equivalent of the snowpack from the snow density profile.

4. Results

The snow depth was about 50 cm at the beginning of our manual measurements. On May 12, snow covered less than 50% of the area and the maximum snow depth in the quadrate was about 20 cm. Our period of analysis was from 17 April to 12 May.

Figure 1 shows the daily mean values of air temperature, specific humidity, and wind speed above the forest floor. The mean air temperature and mean specific humidity increased after May 5. The mean air temperature changed from below 0 to 1 ºC on that day. The mean wind speed was very low, below 1.2 m s^{-1}.



ig. 1: Daily mean air temperature, humidty and wind eed above the forest foloor

Figure 2 shows the daily mean values of the observed radiation above the forest. The global solar radiation increased slightly before May 5. The downward long-wave radiation increased after May 5. This was partially due to the increase in the downward long-wave radiation above the forest. The increases in air temperature and specific humidity shown in Figure 1 could have caused the increase in the downward long-wave radiation above the forest. The daily net all-wave radiation in the forest was positive during the period. The net all-wave radiation increased more before May 5 than after that date. This was caused by both the increase in absorbed solar radiation due to the lowered albedo and the increase in the downward long-wave radiation in the forest.

Figure 3 shows the daily snowmelt and surface evaporation rates. The snowmelt occurred during our study period and increased rapidly, beginning May 5. Minimal condensation of water vapor occurred on the surface at night, while the evaporation of water vapor dominated the daily values. In the study period, the water equivalent of the snowmelt and evaporation was 90.4 and 9.8 mm, respectively.

All layers of the snowpack reached 0 ºC for the first time on 5 May. Before this date, the snow temperature reached 0 ºC only at the surface of the snowpack, and was below 0 ºC below the snow surface.

In this paper, we call the period after May 5 the melt period, and the period before that date the pre-melt period.

The snow density tended to increase with time of day. This tendency was strongest between 40 and 50 cm, and decreased with the distance from the ground. The density above 20 cm above the ground increased to around 260 kg m^{-3} in our study period. The density of the layers above a height of 20 cm did not vary much with time of day. The snow density at our site was from 150 to 260 kg m^{-3}.

The snow layer was divided into the portions above and below about 20 cm from the ground. The crystals were

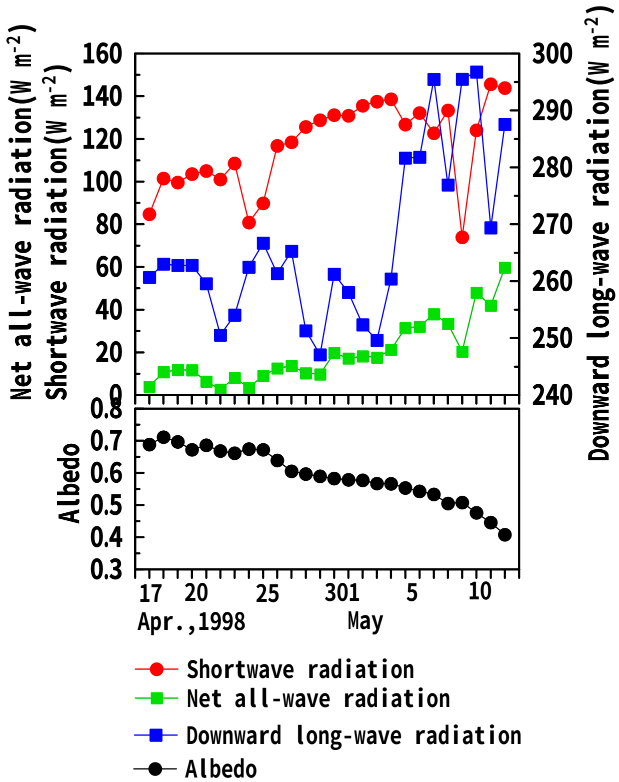


Fig.2:Radiations in the forest

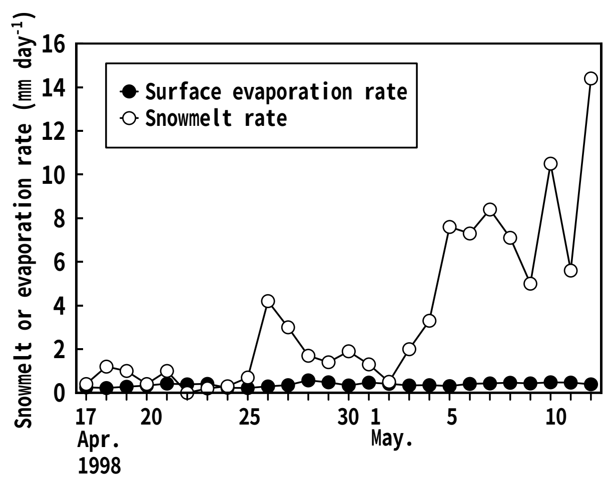


Fig. 3: Snowmelt and evaporation rates

0.5-2.0 mm in size in the upper layer, and 2.0-4.0 mm in the lower layer. The snow in the upper layer changed from compact to granular snow with time. The snow in the lower layer changed from dry to wet hoar on May 5.

In addition, the snowpack at our site was also characterized by snow fingers. We found numerous snow fingers, from 2 to 6 cm in diameter, in the snowpack at our site on 8 May. The fingers were clearly visible about 5 cm below the snow surface and extended to the ground. A

Table 1 Heat balance components of the snowpack

Period	Available heat Wm^{-2} (%)		Consumed heat Wm^{-2} (%)					
	Rn	H	lE	Q_M	ΔQ_S	Q_D	Q_B	Q_T
Pre-melt	11.6	7.6	12.9	5.4	2.6	2.8	0.6	0.3
	(60.4)	(39.5)	(67.1)	(28.3)	(13.6)	(14.7)	(2.9)	(1.7)
Melt	37.6	14.3	13.0	37.2	5.2	32.0	0.9	0.8
	(72.5)	(27.5)	(25.0)	(71.8)	(10.0)	(61.7)	(1.7)	(1.6)

Pre-melt period: Apr. 17 - May 4 1998, Melt period: May 5-12 1998

snow finger is a water pathway.

On 17 Apr., the first day of our study, the ground temperature profile was almost constant between –6 and –7 ºC. The ground temperature increased gradually in the pre-melt period and rapidly approached 0 ºC during the melt period.

The slope of the regression line of the relationship between the evaporation rates obtained from the lysimeters and the value of $\rho U (qa - qs)$ given by observed data had a value og 0.0039, which we adopted as the bulk coefficient.

Using Eq.(4), the evaporation rates were reproduced satisfactorily. The heat for snowmelt (Q_M) calculated using Eq. (1) also were good agreement with the observed value of the snow surface melt rates.

5. Heat and water balance analysis

The daily runoff ratio was determined from the difference between snowmelt rates at the surface layer (obtained from the snow surface lowering and snow surface evaporation) and the water equivalent of the snowpack from the snow density profile. The runoff ratio of the meltwater was 0.44, 0.81, and 0.71 in the pre-melt, melt, and all periods, respectively. The evaporation rate as a percentage of the ablation rate was 37%, 6% and 13% during the pre-melt, melt, and all periods, respectively. Evaporation contributed markedly to snow ablation in the pre-melt period. Only the snowpack surface reached 0 ºC in the pre-melt period. Despite the fact that the temperature below the snow surface was sub-zero, 44% of the meltwater reached the ground. We found complete snow fingers at our study site on 8 May. It is thought that the fingers were formed by the downward flow of meltwater.

Table 1 shows the heat balance of the snowpack during both periods. The main available forms of heat were the net all-wave radiation and the sensible heat flux. The main heats consumed were the latent heat flux of evaporation and the heat for snowmelt. The conductive heat flux at the bottom of the snowpack, and the heat required to change the snowpack temperature, were relatively small. In both periods, the net all-wave radiation dominated the available heat flux. In the melt period especially, the net all-wave radiation accounted for 72.5% of the available heat flux. In the pre-melt period, the latent heat flux for evaporation accounted for 67.1% of the consumed heat, dominating the consumed heat. By contrast, in the melt period, the heat for snowmelt was the major consumed heat, accounting for 71.8% of the consumed heat. There was little difference in the latent heat flux between the pre-melt and melt periods. As has been already noted, the increase in the heat for snowmelt from the pre-melt period to the melt period depended on the increase in net all-wave radiation. Therefore, the latent heat, as a percentage of the consumed heat, showed a relative decrease. Nevertheless, the latent heat was not negligible as a consumed heat in the melt period. The heat fluxes from the snowpack to the ground were the conductive heat at the bottom of the snowpack, and the fusion heat of the meltwater discharged from the snowpack. The value of the latter was much higher than that of the former (Table 1).

In the pre-melt period, 14.7% of the consumed heat, as the fusion heat for the snowmelt, was discharged from the snowpack with the meltwater (Table 1). We consider the fusion heat for snowmelt that is stored in the snowpack in the pre-melt period. The fusion heat for snowmelt stored in the snowpack accounted for 13.6% of the consumed heat (Table 1). In our study, the stored heat that changed the temperature of the snowpack (ΔQ_T) was calculated from Eq. (7), using the observed snow temperature profile. The calculated value of ΔQ_T was the stored heat in the snowpack excluding snow fingers, as the temperatures of snow fingers were not measured. We postulate that the meltwater stored in the snowpack froze again, releasing the heat of solidification, and formed a snow finger in which the temperature was around 0 ºC. The formation of a snow finger discharged the heat of fusion for snowmelt, which accounted for 14.7% of the consumed heat and decreased the heat stored in the snowpack. This prevented a rapid increase in the snowpack temperature, resulting in prolongation of the pre-melt period.

The heat required to increase the ground temperature was calculated in one-dimension from the time vaiations of the ground temperature profiles and was compared with the fusion heat of meltwater discharged from the snowpack and with the conductive heat at the ground surface. In the result, it was indicated that snowmelt water infiltrated to the ground was very important to rise the ground temperature in both period.