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Effect of snow interception on the energy balance above deciduous and coniferous forests during a snowy winter

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Abstract We discuss how snow intercepted by deciduous and coniferous forests affects their water and energy balances. Intensive micrometeorological observations above and below the canopy were carried out in deciduous (DF) and coniferous (CF) forests in the winter of 1996–97 in Sapporo, Hokkaido Island, Japan. Compared with the DF, large amounts of intercepted snow on the canopy of the CF caused a relatively large latent heat flux, which depended on the aerodynamic and canopy resistance. When the intercepted snow on the canopy disappeared from the CF, the sensible and latent heat fluxes were the same at the two sites. Canopy resistance determined the latent heat flux above the DF because the aerodynamic resistance was insignificantly small. The canopy resistance for the DF was correlated with the snow surface temperature. Differences in the amounts of intercepted snow and in the canopy and aerodynamic resistance affected the partition of the input radiative energy above the two canopies. Furthermore, the site of effective energy exchange differed in the CF and DF because the effective energy exchange in the DF occurred at the forest floor.

Keywords aerodynamic and canopy resistance; coniferous forest; deciduous forest; energy balance; snow interception

INTRODUCTION

In northern Japan, most mountain drainage basins are covered by forests and have a seasonal snowpack. During thaws, melt water is an important water resource, and it is necessary to estimate the net snow water equivalent under the forest canopy in mountainous regions. Some snowfall is intercepted by the forest canopy and evaporates or melts. Snow interception depends on the tree species and affects the water and energy balances in mountain watersheds.

Many studies have examined snow interception above the forest canopy; most were carried out in Japan, Canada and Sweden (Nakai *et al*., 1993, 1999; Hedstrom & Pomeroy, 1998; Lundberg *et al*., 1998; Lundberg & Halldin, 2001). All of these studies reported that snow interception was important in partitioning the radiative energy above the forest canopy. However, the dependence of the amount of snow intercepted on tree species and the influence of snow interception on the energy and water balances are poorly understood. This paper discusses how intercepted snow above deciduous and coniferous forests affects the water and energy balances.

METHODOLOGY

Site description

Intensive micrometeorological observations above and below the canopy were carried out in a deciduous (DF) and a coniferous (CF) forest in the winter of 1996–97 near Sapporo, on Hokkaido Island, Japan (Fig. 1). The energy balances were determined from the observations. Table 1 shows details of the forest at each site. The DF was composed mainly of ash (*Fraxinus* spp.) and oak (*Quercus* spp.) trees, and had a plant area index (*PAI*) of 0.9. The CF consisted of Yezo spruce (*Picea jezoensis*), Akaezo spruce (*Picea glehnii*), and Todo fir (*Abies sachalinensis*), and the *PAI* was 5. The sensible heat fluxes above both DF and CF were measured using the eddy covariance technique, while the latent heat fluxes were evaluated using the band-pass eddy covariance method for the CF and the energy balance method for the DF.

Measurements

We conducted an intensive field campaign during the winter of 1996–97 in the Hitsujigaoka Experimental Forest, at the Hokkaido Center of the Forestry and Forest Products Research Institute. We observed energy balance components and meteorological values above and within the CF and DF canopies. Details of our observations are reported in Nakai *et al*. (1999) for site CF, and in Ohta *et al*. (1999) for site DF. In this paper, temperature is expressed in °C.

Theory

The energy balance above a forest canopy is described as follows:

$$R_n = (1 - \alpha)\, I\!\downarrow + L\!\downarrow - L\!\uparrow = H + lE + G + S \qquad (1)$$

where R_n is the net all-wave radiation (W m^{-2}), $I\!\downarrow$ is the global solar radiation (W m^{-2}), α is the albedo, $L\!\downarrow$ and $L\!\uparrow$ are the atmospheric and upward longwave radiation (W m^{-2}), respectively, H is the sensible heat flux (W m^{-2}), lE is the latent heat flux (W m^{-2}), G is the energy storage within the snowpack (W m^{-2}), and S is the energy storage within the forest canopy. Here, we used the eddy covariance method for the sensible heat flux:

$$H = C_P\, \rho\, \overline{w'T'} \qquad (2)$$

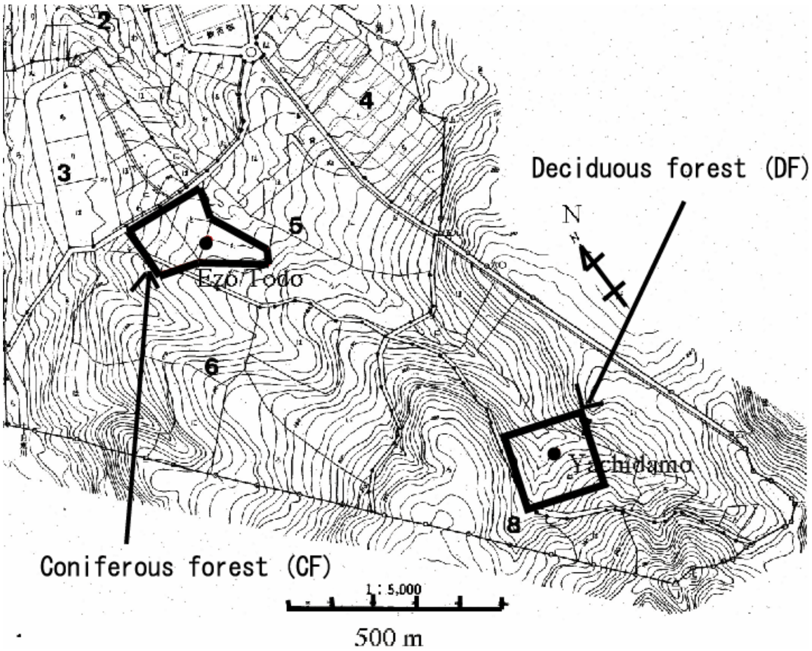

Fig. 1 Location of the observation sites. Dots denote the observation towers in the CF and DF. The contour interval is 1 m.

Table 1 Details of the CF and DF.

Site	Forest type	Dominant tree	Mean tree height (m)	Stand density (stem/ha)	Sky view factor	Plant area index
CF	Coniferous with leaves	*Abies sachalinensis*	6.4	2400	0.1	6.0
DF	Hardwood with free leaves	*Fraxinus mandshurica*	20.0	800	0.5	0.87

where C_P is the specific heat constant of air (J kg^{-1} K^{-1}), ρ is the density of air (kg m^{-3}), and $\overline{w'T'}$ is the covariance of the fluctuation of the vertical wind speed and air temperature (m s^{-1} K). To evaluate the latent heat flux, we used the band-path eddy covariance method at site CF and the energy balance method at site DF. Therefore, the latent heat fluxes at sites CF and DF can be written as:

$$B_{bp} = \frac{\overline{w'T'}_{bp}}{\overline{w'q'}_{bp}} \quad \text{and} \tag{3}$$

$$lE = \frac{H}{C_P \times B_{bp}} \quad \text{for site CF, and} \tag{4}$$

$$lE = Rn - H - G - S \quad \text{for site DF, and} \tag{5}$$

$$B = \frac{H}{lE} \quad \text{for sites CF and DF} \tag{6}$$

where B_{bp} is the band-path Bowen ratio, B is the Bowen ratio, G was estimated using the model of Kondo & Yamazaki (1990), and S was estimated using the profiles of air temperature and relative humidity within the canopy. In order to evaluate the potential evaporation and evaporation efficiency, we used the Penman-Monteith equation as follows:

$$lE = \frac{\Delta(Rn - G - S) + (q_{SAT}(T_Z) - q(T_Z))/r_a}{\Delta + (l/C_P)\times(r_a + r_c)/r_a} \quad (7)$$

$$\beta = \frac{r_a}{r_a + r_C} \quad (8)$$

$$r_a = \frac{1}{C_H \cdot U_Z} \quad (9)$$

where Δ is the change in the saturation-specific humidity with temperature, q_{SAT} is the saturation-specific humidity for the air temperature at the reference height above the canopy (kg kg^{-1}), q is the specific humidity for the air temperature at the reference height above the canopy (kg kg^{-1}), β is the evaporation efficiency above the canopy, r_a and r_c are the aerodynamic and canopy resistance above the canopy (s m^{-1}), respectively, C_H is the bulk coefficient for the sensible heat flux above the canopy, and U_Z is the wind speed at the reference height above the canopy (m s^{-1}). Here, we used C_H = 0.017 for the CF after Nakai *et al*. (1999), and C_H = 0.29 for the DF after Ohta *et al*. (1999).

RESULTS AND DISCUSSION

Climate conditions and radiation balance above the two canopies

According to the observations by Nakai *et al*. (1993), the percentage of gross precipitation intercepted as snow in the DF was 1%, and in the CF was more than 40%. From 15 to 21 February 1997, about 61.5 mm snow fell continuously. From 22 February 1997 until the end of the intensive observation period on 27 February 1997, no snowfall was observed. On 22 February 1997, the CF canopy was completely covered with snow and the DF forest canopy was snow free. The intercepted snow on the CF canopy disappeared on 25 February 1997, while that on the DF canopy disappeared on 22 February 1997.

Figure 2 shows the temporal change in the hydro-climactic conditions above the CF and DF canopies. Since the CF and DF were about 950 m apart, there was no difference in the precipitation or global solar radiation above the two canopies. Furthermore, there were no differences in air temperature or wind speed above the two canopies. The water vapour pressure above the canopy was slightly higher at the CF site than at the DF site.

Ohta *et al*. (1999) found no significant difference in the net radiation between CF and DF under snow-free conditions. Here, we first compare the effect of snow interception on the net radiation at the CF and DF sites. Figure 3 shows the temporal variation in the net radiation, upward longwave radiation, and albedo above the CF and DF canopies. During the snowfall event on 21 February 1997, intercepted snow in the CF caused the albedo above the canopy to increase more than in the DF. The albedo above the CF quickly decreased as the intercepted snow disappeared. The albedo above the DF was essentially constant, ranging from 0.20 to 0.25. By contrast, the maximum albedo when there was intercepted snow on the CF was 0.3, and the albedo above the CF when the canopy was snow free was around 0.1. Nevertheless, the difference in the net radiation above the two forest canopies was insignificant, because the upward longwave radiation above the canopy was larger in the DF than in the CF.

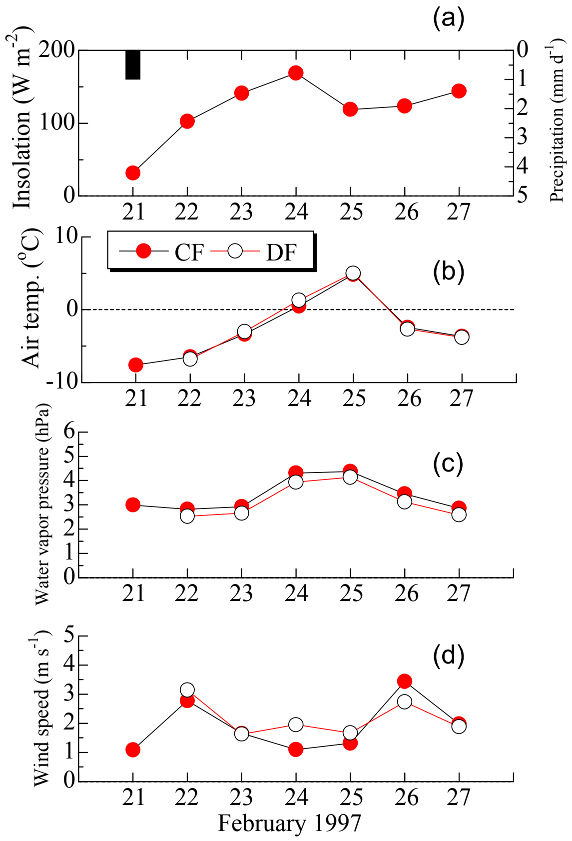

Fig. 2 Temporal variation in the daily hydrometeorological conditions above the canopies during the intensive observation period from 21 to 27 February 1997. (a) Global solar radiation and precipitation, (b) air temperature, (c) water vapour pressure, and (d) wind speed.

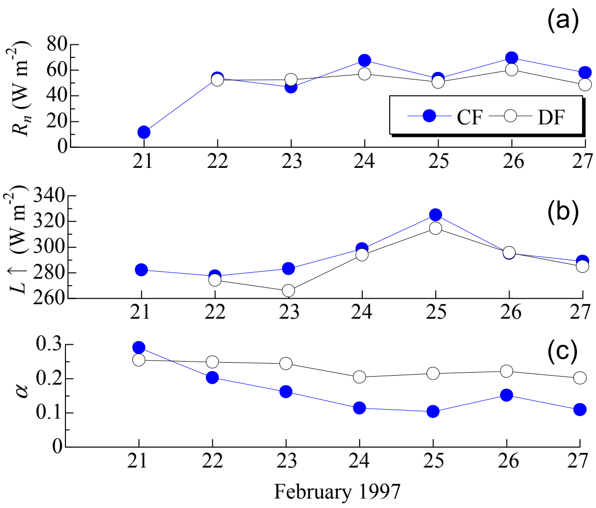

Fig. 3 Temporal variation in the daily radiation balance components above the CF and DF during the intensive observation period from 22 to 27 February 1997. (a) Net radiation, (b) upward longwave radiation, and (c) albedo.

Therefore, the climactic conditions and net radiation above the two forests did not differ significantly, despite the large differences in forest type and density.

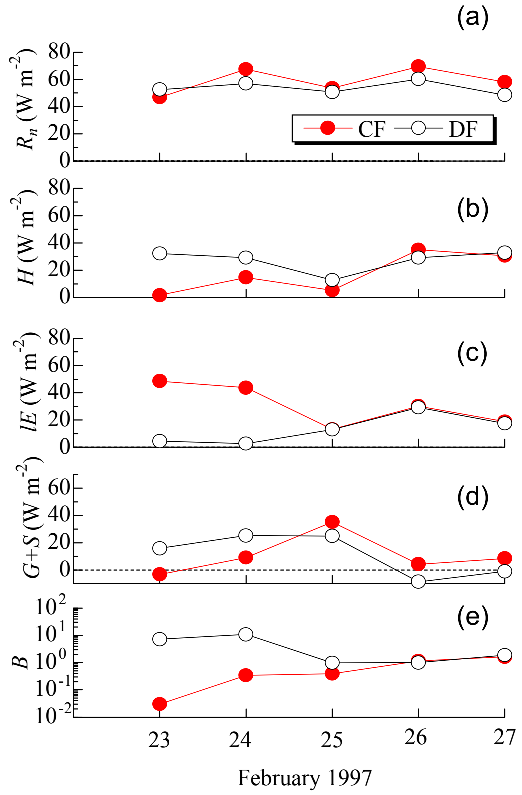

Fig. 4 Temporal variation in the daily energy balance components above the CF and DF from 23 to 27 February 1997. (a) Net radiation, (b) sensible heat flux, (c) latent heat flux, (d) energy storage term, and (e) Bowen ratio.

Energy balance and evaporation efficiency above the two canopies

Figure 4 shows the temporal changes in the daily energy balance above the two canopies from 23 to 27 February 1997. The latent heat flux was larger above the CF than above the DF, especially immediately following a snowfall. This demonstrates that the variation in the amount of snow on the canopy due to differences in the forest conditions affects the water and energy balances above the canopy. When the intercepted snow above the CF canopy disappeared on 25 February 2002, the sensible heat flux increased and the latent heat flux decreased. Therefore, the latent and sensible heat fluxes in the CF were nearly equivalent to those in the DF. The energy storage term (S + G) was larger for the DF than for the CF, but was maximal for the CF on the date that the intercepted snow disappeared. We assume that this implies that the energy contributed to the energy that caused the intercepted snow to melt. Due to the existence of intercepted snow above the CF, the Bowen ratio (B) above the DF was larger than above the CF.

Lundberg & Halldin (2001) showed that the most important parameters for intercepted snow evaporation are the aerodynamic properties of the forest, the sky view factor, and the specific humidity deficiency. Next, we show the effect of evaporation efficiency, and the aerodynamic and canopy resistance. Using equations (7) to (9), we estimated the evaporation efficiency, and aerodynamic and canopy resistance above the two canopies. Figure 5 shows the temporal variation in the daily

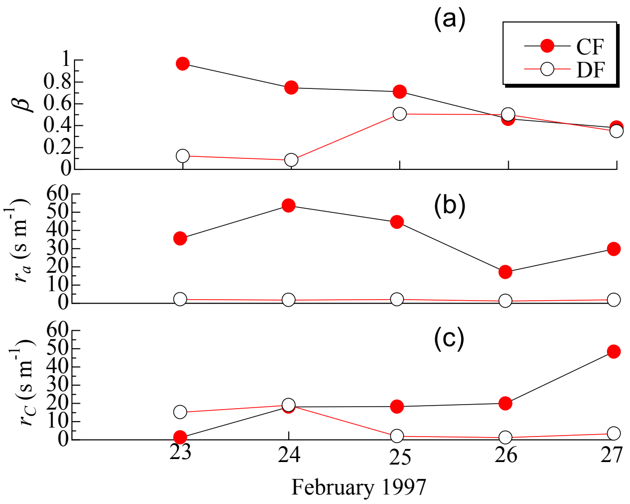

Fig. 5 Temporal variation in the daily evaporation efficiency and aerodynamic and canopy resistance above the CF and DF canopies. (a) Evaporation efficiency, (b) aerodynamic resistance, and (c) canopy resistance.

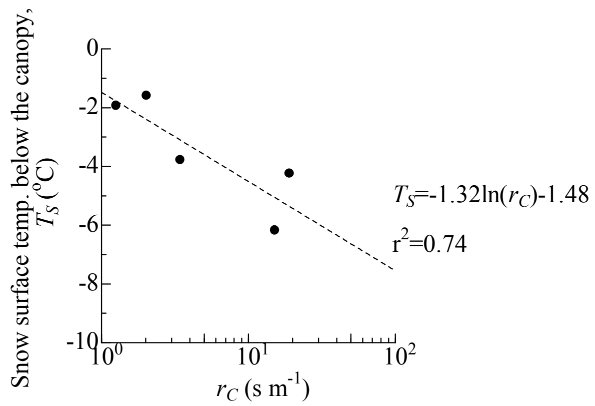

Fig. 6 Relationship between the daily snow surface temperature below the canopy, and the canopy resistance above the canopy, in the DF.

evaporation efficiency and the aerodynamic and canopy resistance above the two canopies from 23 to 27 February 1997. The daily evaporation efficiency in the CF decreased, while that in the DF increased due to the decreased canopy resistance. The daily evaporation efficiency above the CF depended on both the aerodynamic and canopy resistance, except for the period immediately following a snowfall event. This showed that the mechanism determining evaporation efficiency above the CF and the DF differed, and that the most important factor determining the daily evaporation efficiency above a CF canopy completely covered with snow is the aerodynamic resistance, as Lundberg & Halldin (2001) demonstrated.

Next, we explain why the canopy resistance above the DF canopy increased from 25 February 1997. Figure 6 shows the relationship between the daily snow surface temperature below the canopy and the canopy resistance above the canopy in the DF. The daily canopy resistance in the DF depended strongly on the daily snow surface temperature. When the daily snow surface temperature increased to about –1°C, the daily canopy resistance above the DF decreased to 1. This shows that the most important factor determining the daily canopy resistance of the DF was the snow surface temperature. This also indicates that the snowpack below the canopy was an important water source in the DF, whereas the intercepted snow was an important water source in the CF. These differences were caused by differences in DF and CF structure, since aerodynamic resistance depends on the roughness length and zero-plane displacement height above the forest.

All of our results indicate that the daily canopy resistance in the CF and DF differed. The amount of intercepted snow above the canopy had the greatest effect on canopy resistance in the CF, whereas snow surface temperature had the greatest effect in the DF.

CONCLUSIONS

We analysed the energy balance components and characteristics of evaporation above coniferous and deciduous forest canopies and found the following:

– There were no significant differences in the meteorological elements or net radiation above the coniferous and deciduous forest canopies. After a snowfall event, the albedo above the conifer forest canopy decreased until the intercepted snow on the canopy cover disappeared. The albedo above the deciduous forest canopy was constant and larger than that above the coniferous forest canopy, except during snowfall.
– The energy balance components above the two canopies differed, due to the effect of intercepted snow above the coniferous forest canopy. When snow covered the canopy, the latent heat flux above the coniferous forest canopy was high, whereas the main energy components at the deciduous forest site were the sensible heat flux and energy storage term. These differences in the energy balance caused differences in the Bowen ratio at the two sites. However, when the intercepted snow disappeared, the Bowen ratio at the two sites was similar.
– In the coniferous forest, the daily evaporation efficiency decreased when snowfall ceased, whereas it increased in the deciduous forest. In the coniferous forest, the factors with the greatest effect on evaporation efficiency were the aerodynamic and canopy resistance, because both values were of the same order, while in the deciduous forest efficiency depended strongly on the canopy resistance, and aerodynamic resistance was very small. Furthermore, the daily canopy resistance of the deciduous forest correlated with the daily snow surface temperature. When the daily snow surface temperature increased to about –1°C, the daily canopy resistance fell to nearly 1.

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