The effects of *Picea schrenkiana* forest litter on snow surface albedo

Heng Lu, Wenshou Wei, Mingzhe Liu, Xi Han and Wen Hong

ABSTRACT

In this paper, we analyze the characteristics of the snow albedo of different underlying surfaces based on measurements of shortwave radiation and observations of forest litter on snow surfaces, both in an open, unforested environment and in areas with differing forest canopy openness. The fractional litter coverage was obtained through the binarization of digital photos of forest litter distributed on snow surfaces. The effects of *Picea schrenkiana* forest litter on snow albedo were then quantitatively analyzed to establish an empirical formula for the calculation of forest snow albedo. According to the results, forest litter is the dominant factor determining forest snow albedo. Differences caused by vegetation in the proportion of visible radiation vis-à-vis near-infrared radiation and snow grain size (r) are of minor importance. Forest snow albedo values exponentially decrease with the increase in fractional litter coverage. During snow accumulation period, snow albedo can be calculated using a combination of the new snow albedo and the number of days after fresh snowfall. In snowmelt period, snow albedo can be calculated using a combination of the number of days after the snowmelt began, the number of days after fresh snowfall and the accumulated wind speed after such fresh snowfall.

Key words | forest litter, forest snow albedo, simulated snow albedo

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LIST OF SYMBOLS

r	the snow grain size (mm)
ρ_s	the new snow density (g cm^{-3})
$\alpha_{v\theta}$	the visible radiation albedo
$\alpha_{nir\theta}$	the NIR radiation albedo
$frac_v$	the fractions of visible radiations
$frac_{nir}$	the fractions of NIR radiations
θ	the solar zenith angle
$lc_{(80\%)}$	the fractional litter coverage (%) on snow surface beneath 80% forest canopy openness
$lc_{(20\%)}$	the fractional litter coverage (%) on snow surface beneath 20% forest canopy openness
D_{sm}	the days after snowmelt
W_{ac}	the accumulated wind speed after snowfall
α (α_n)	the snow albedo
Δt	the time step after snowfall
lc	the fractional litter coverage (%)
n	the number of days after fresh snowfall (rainfall was estimated as a continuous day, not a new snowfall event)

doi: 10.2166/nh.2014.113

INTRODUCTION

Snowmelt runoff is very important in arid areas in sustaining the ecological environment and aiding industrial and agricultural production. Snow accumulation and ablation are influenced not only by meteorological factors such as air temperature and humidity, but also by the underlying surfaces, such as vegetation type and canopy openness (Link & Marks 1999). The radiation budget is the most important factor in forest snow accumulation and ablation (Federer 1968; Sicart *et al.* 2004). Shortwave radiation and sub-forest snow albedo measurements, and analyses of their characteristics, are crucial for snowmelt runoff forecasts, water resource and land use management, flash flood warnings, etc. (Ellis & Pomeroy 2007; Winkler *et al.* 2010, 2014; Pugh & Small 2012).

Snow albedo is affected by *r*, snow depth, the solar zenith angle (θ) and the ratio of direct radiation to diffuse radiation (Warren & Wiscombe 1980). For example, snow albedo decreases with an increase in *r*. This decrease is reflected in near-infrared radiation (NIR) rather than visible radiation readings (Melloh *et al.* 2001). Nakamura *et al.* (2001) found that snow albedo was not affected by snow texture >3 cm below the surface. Snow albedo values fell beneath a forest canopy, as did the proportions of incoming diffuse radiation vis-à-vis direct radiation, and visible radiation vis-à-vis NIR (Winkler *et al.* 2010). Snow albedo also decreased with an increase in impurities in the snow layer and on the snow surface (Adhikary *et al.* 1997). For example, forest litter within the snowpack or on the snow surface absorbs shortwave radiation (Melloh *et al.* 2001). Dunne & Leopold (1978) demonstrated that the snow albedo dropped to 0.5 ~ 0.6 only when dust and vegetation litter were concentrated on a snow surface. Barry *et al.* (1990) showed that forest litter could reduce the albedos of new snow and old snow beneath balsam fir forest to 0.7 and 0.3, respectively, in the Lac Laflamme Basin of Quebec City, Quebec, Canada. A report by the US Army Corps of Engineers (1956) suggested that snow 15 to 20 days old beneath forest would approach a mean daily albedo c. 0.4 during the snowmelt period. Although the influence of vegetation litter on snow albedo has been studied for a long time (Barry *et al.* 1990; Hardy *et al.* 1997), its influence has seldom been quantified (Liston 1995; Buttle & Buttle 1998). Using a snowpack energy balance model, Hardy *et al.* (1998, 2000) studied the influence of forest litter deposition speed on the snowpack energy balance. In this forest litter model, only the forest litter rate was considered. However, forest litter amount varies with forest type. The effects of forest litter have only been quantified for red spruce, balsam fir, white birch, lodgepole pine, and Engelmann spruce forests (Hardy *et al.* 2000; Melloh *et al.* 2001, 2002; Winkler *et al.* 2010). The effect of forest litter on snow albedo beneath *Picea schrenkiana* forest has not yet been quantified. The objectives of this study are quantitatively to analyze the effect of forest litter on forest snow albedo and establish an empirical formula to calculate *Picea schrenkiana* forest snow albedo using the relative factors (wind speed, new snow albedo and number of days after snowmelt, number of days and accumulated wind speed after fresh snowfall). The results can also then be used to study snow accumulation and ablation.

STUDY AREA AND STUDY METHODS

Study site

The study was conducted at the Tianshan Station for Snow Cover and Avalanche Research, Chinese Academy of Sciences (TS-CAS) at an altitude of 1,776 m above sea level (43 °16′N, 84 °24′E). The station lies in the upper branch of the Künes River in the central zone of the western Tianshan Mountains, China. Under the influence of the continental climate, the multi-year mean air temperature in the study area is 1.3 °C, and the monthly average air temperature in January is −14.4 °C. The multi-year mean precipitation is 867.3 mm, of which seasonal snowfall as solid precipitation accounts for >30%. The snow season at TS-CAS lasts from late October to early April and mean annual maximum snow depth is 0.78 m. Hu *et al.* (1997) found that subalpine meadow was distributed on sunny slopes and that coniferous forest was distributed on shady ones. Zhang *et al.* (2010) investigated woody plants and shrubs (DBH ≥ 1 cm) in 150 quadrates of 20 m × 20 m area on shady slopes. According to the results of their investigations, the plant community had one dominant species: *Picea Schrenkiana*. *Picea Schrenkiana* comprised 89.4% of the stems in the forest and averaged 30–40 m in height. *Betula tianschanica* comprised 8.2% of the total stems, and other species each accounted for <1%. Tree canopy coverage was 0.6 ~ 0.9; the shrub layer was therefore underdeveloped due to light limitation. Representative shrub species beneath the forest canopy include *Aegopodium alpestre, Cicerbita azurea, Dryopteris filix-mas*, etc. (Huang *et al.* 1989).

Study methods

This study was conducted at three sites: an open environment on a sunny slope (the meteorological station); and beneath *Picea schrenkiana* forest canopy of 20 and 80% openness on a shady slope. The underlying surface in the sunny slope open environment was grassland. Forest canopy openness was determined using hemispherical photographs. These hemispherical photographs were taken before snowfall in winter and were analyzed using Gap Light Analyzer (Version 2.0) software. The software was used to compute canopy openness, effective leaf area index, and the transmitted amounts of above- and below-canopy direct, diffuse and total solar radiation incident on a horizontal or arbitrarily inclined receiving surface (Frazer *et al.* 1999). The snow albedo, wind speed, fractional litter coverage, r, snow depth and snowmelt rate were measured at all three sites. Snow albedo was calculated using incoming and reflected shortwave radiation values. These, along with wind speed, were measured using automatic weather stations (model TRM-ZS2, JinZhou SunShine Meteorological Science Co., Ltd). The degree of error in radiation values was <5%. The margin of error for wind speed was 0.3 m/s. The distance between the three observation sites did not exceed 200 m.

Forest litter photographs on snow surface beneath forest canopy of 20 and 80% openness on shady slopes were taken using digital cameras from February 24, 2012 to April 15, 2013 under conditions of no direct sunshine or precipitation. The same sites were selected for the continuous photographing of forest litter on snow surfaces beneath different forest canopy openness. All photographs were scaled for comparison, that is, to be of area no less than 1 m^2. The distance from the automatic stations to the photographic sites did not exceed 2 m. A total of 27 and 31 photographs were taken beneath 20 and 80% forest canopy openness, respectively. There was no forest litter on the open snow surface during the whole observed period. Forest litter photographs were analyzed using Digimizer binarization software (Version 3.7.1, MedCalc Software, Belgium). Forest litter on snow surfaces was automatically identified and the litter pixels were automatically estimated (Figure 1). The fractional litter coverage was expressed as the ratio of litter pixels to photographic pixels. Forest litter on snow surfaces beneath the forest canopy was mainly of *Picea Schrenkiana* needles, branches, and bark.

r was obtained using image analysis of snow samples. Snow samples were collected from snow surfaces every 5 ~ 10 days for immediate observation. Observations were conducted under subfreezing temperatures and out of direct sunlight. Snow grains were placed on a glass sheet and observed with a 0.1 mm division ruler under a stereomicroscope (model XTL-165-LB, Phoenix Optica Co., Ltd, Shangrao). The images were recorded with a digital camera (E510, Olympus Electronics Co., Ltd, Shenzhen) installed on the microscope. Digimizer software was used to analyze the projective area, circumference and length of the snow grains photographed. The r of new snow was calculated (Anderson 1976) as:

$$r = 0.08 + 55\rho_s^4 \qquad (1)$$

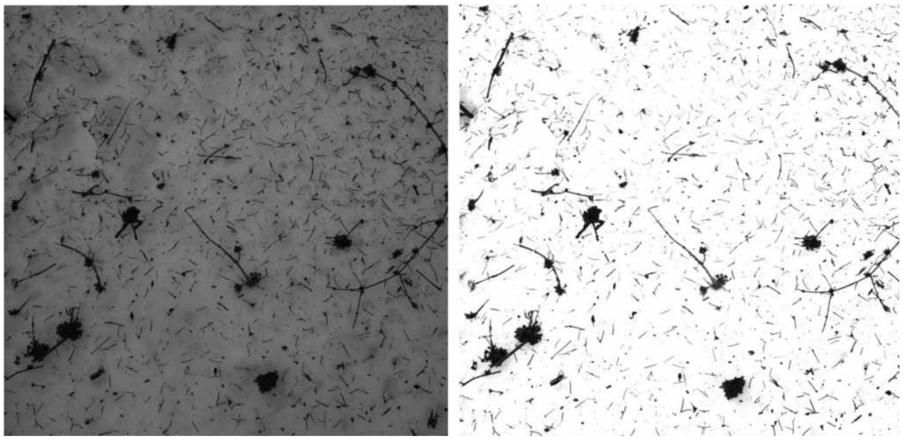

Figure 1 | The binarization result of snow surface photograph beneath 20% forest canopy openness on March 28, 2013.

where r is the new snow grain size (mm); ρ_s is the new snow density (g/cm^{-3}); $\rho_s \approx 0.03$ g/cm^{-3}.

The two-band albedo model (Marks & Dozier 1992) was used to calculate snow albedo vis-à-vis different r and θ values in both the open environment and beneath the forest canopy, as follows:

$$a = frac_{\mathrm{v}}\alpha_{\mathrm{v}\theta} + frac_{\mathrm{nir}}\alpha_{\mathrm{nir}\theta} \tag{2}$$

where $\alpha_{\mathrm{v}\theta}$ and $\alpha_{\mathrm{nir}\theta}$ are the visible radiation and NIR albedo, respectively; $frac_{\mathrm{v}}$ and $frac_{\mathrm{nir}}$ are the fractions of visible and NIR radiation. In the open environment, $frac_{\mathrm{v}}$ and $frac_{\mathrm{nir}}$ are 0.56 and 0.44, respectively, for cloud-cover precipitation events, and 0.5 and 0.5, respectively, for clear and partly clear conditions. In the forest, $frac_{\mathrm{v}}$ and $frac_{\mathrm{nir}}$ are 0.45 and 0.55, respectively, for cloud-cover precipitation events and 0.43 and 0.57, respectively, for clear and partly clear conditions (Melloh *et al.* 2002). $\alpha_{\mathrm{v}\theta}$ and $\alpha_{\mathrm{v}\theta}$ were calculated as:

$$\alpha_{\mathrm{v}\theta} = \left(\alpha_{\mathrm{vmax}} - \alpha_{\mathrm{v}0}r^{1/2}\right) + \left(\alpha_{\mathrm{v},\theta}r^{1/2}\right)(1-\cos\theta) \tag{3}$$

$$\alpha_{\mathrm{v}\theta} = \left(\alpha_{\mathrm{nirmax}}\exp\left(\alpha_{\mathrm{nir}0}r^{1/2}\right)\right) + \left(\alpha_{\mathrm{nir},\theta}r^{1/2} + b_{\mathrm{nir}\theta}\right) \times (1-\cos\theta) \tag{4}$$

where r (μm) is the radius of an ice sphere with optical properties equivalent to those of actual snow grains; $\alpha_{\mathrm{vmax}} = 1.0$; $\alpha_{\mathrm{nirmax}} = 0.85477$; $\alpha_{\mathrm{v}0} = 2.0 \times 10^{-3}$; $\alpha_{\mathrm{v},\theta} = 1.375 \times 10^{-3}$; $\alpha_{\mathrm{nir}0} = -2.123 \times 10^{-2}$; $\alpha_{\mathrm{nir},\theta} = 2.0 \times 10^{-3}$; $b_{\mathrm{nir}\theta} = 0.1$; and θ is the solar zenith angle.

The snowmelt was observed with a lysimeter. A galvanized iron box of dimensions 1 m × 1 m × 0.04 m was placed in all three sites prior to the first winter snowfall. The snowmelt rate was measured using a tipping bucket rain gauge (L3 model, JinZhou SunShine Meteorological Science Co., Ltd). The start of the snowmelt period was taken as the day when discharged water was first observed through the snow lysimeter. According to the snowmelt results obtained with the snow lysimeter, the snowmelt period for the open environment lasted from February 26, 2013 to March 28, 2013, from March 13, 2013 to April 16, 2013 beneath 20% forest canopy openness, and from March 20, 2013 to April 26, 2013 beneath 80% forest canopy openness.

RESULTS

Variations in daily average snow albedo for different underlying surfaces

Figure 2 shows the variations in daily average snow albedo for the sunny slope, open environment, and for the shady slope, 20 and 80% forest canopy openness sites. The variations in daily average snow albedo showed the same trends for the three different underlying surfaces. In addition, snow albedo decreased with time. In particular, daily average snow albedo values fell dramatically after March 9, 2013. Conversely, snow albedo increased in response to fresh snowfall. For example, snow albedo increased significantly to 0.74 and 0.76 in the open environment and beneath 80% canopy openness, respectively, after a snowfall event lasting from April 1 to April 4, 2013 (when the new snow depth was 25 cm). The snow albedo reading for 80% forest canopy openness represented the maximum for the set observation period. Snow albedo values for the 20% forest canopy openness site were higher than for the open environment before March 7, 2013, but lower afterwards. Differences in snow albedo between the different underlying surfaces were caused mainly by snowmelt rate, r, snow depth, the ratio of direct radiation to diffuse radiation, dirtiness, etc. The observed snow albedo for the open environment being the least of the three sites could be interpreted in at least three ways. First, dust became concentrated on the snow surface during the snowmelt period and so the snow surface in the open environment was dirtier than that of forest snow. Second, the snow liquid water

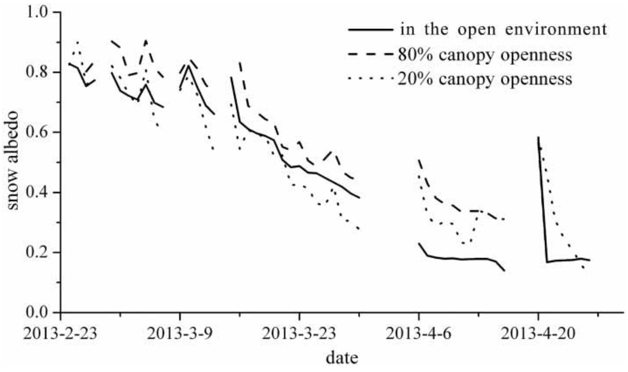

Figure 2 | The daily average of snow albedo in the open environment and beneath forest canopy.

content in the open environment was higher than that beneath the forest canopy sites and was beneficial to the growth of *r*, especially under wet snow conditions. Third, the higher snow liquid water content in the open environment was beneficial to the absorption of NIR radiation. Even though liquid water in the snowpack refreezes, the albedo still decreases (Berger 1979). The snow albedo beneath 20% canopy openness was less than that beneath 80% canopy openness principally because of forest litter.

The effect of *r* on albedo

The difference in *r* between open environment and forest snow was caused by different energy budgets and snow liquid water contents. Furthermore, the NIR fraction increased in a forested environment. Melloh *et al.* (2002) found that *r* beneath a forest canopy was only slightly smaller than in an open environment. According to our observations, *r* ranged from 0.08 to 3 mm. The greatest difference between forest canopy and open environment *r* was c. 1 mm. The distance between the three observation sites did not exceed 200 m, and the minimum θ at any of the sites was 28.79 °. Figure 3 shows the variations in snow albedo (modeled using Equation (2)) in the open environment and beneath the forest canopy in relation to *r* and θ. The results suggest that at the same θ, the effect of *r* on snow albedo was slight. For example, on clear or partly clear days, when $\theta = 40$ °, snow albedo ranged from 0.894 to 0.932 in the open environment and from 0.892 to 0.924 for both sites beneath the forest canopy. The difference

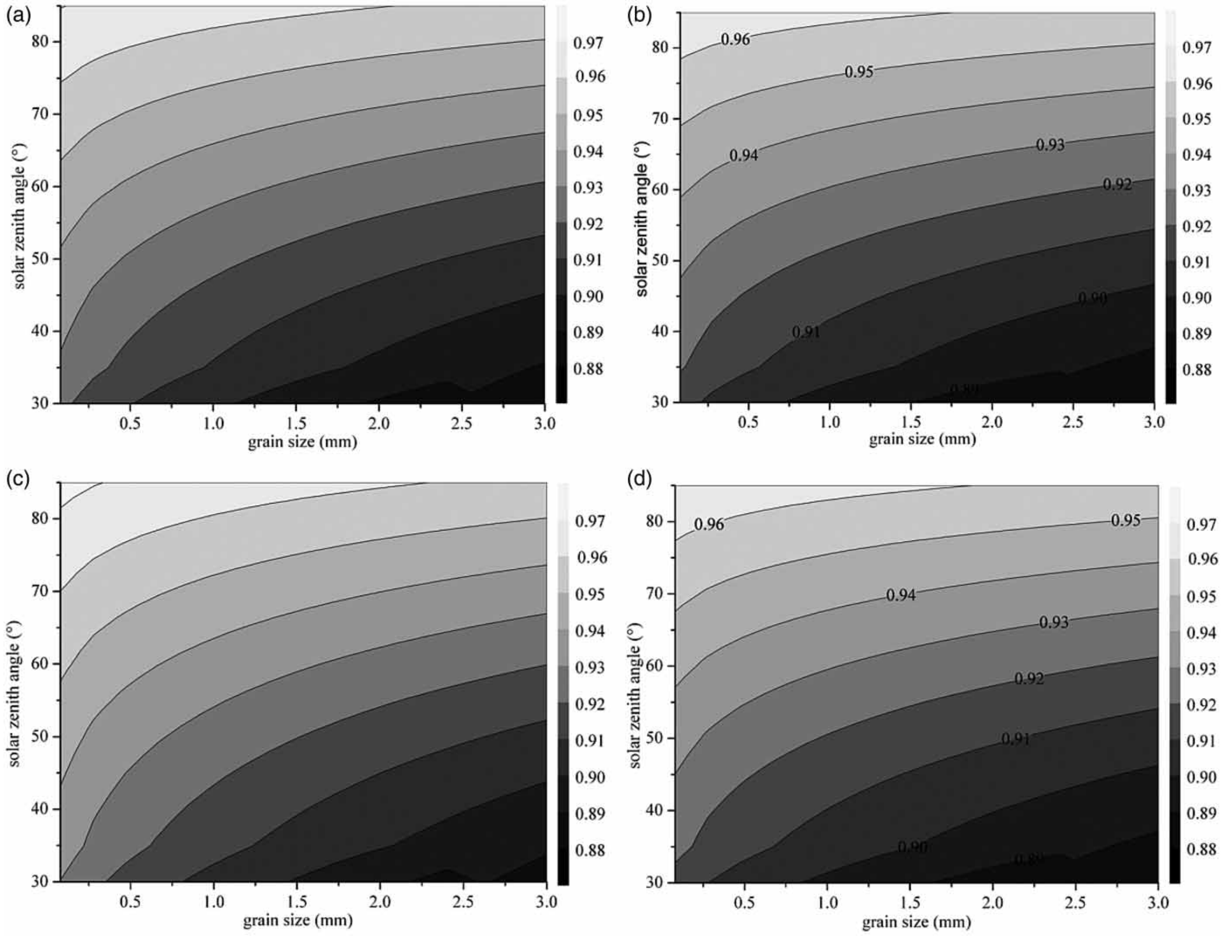

Figure 3 | The change of modeled snow albedo with snow grain size and solar zenith angle: (a) in open environment on clear or cloudy day, (b) beneath forest canopy on clear or cloudy day, (c) in open environment on cloudy days during precipitation events, (d) beneath forest canopy on cloudy days during precipitation events.

between snow albedo values in the open environment and beneath forest caused by *r* and the visible and NIR radiation fractions due to vegetation were no more than 0.06 and 0.02, respectively. During the snowmelt period, the average snow albedos in the open environment and beneath 20 and 80% forest canopy openness were 0.64, 0.44, and 0.46, respectively. The difference between snow albedo in the open environment and beneath the forest canopy was significantly greater than the difference caused by *r* and the visible and NIR radiation fractions.

The effect of forest litter on albedo beneath the forest canopy

Differences in snow albedo between the open environment and beneath the forest canopy are predominantly due to the large quantity of litter concentrated on the snow surface beneath the forest canopy. Forest litter not only reduces the snow albedo (Dunne & Leopold 1978; Barry *et al.* 1990; Hardy *et al.* 1997), but also affects snow surface roughness and *r* (Winkler *et al.* 2010). Our results show that the snow albedo beneath the forest canopy decreased correspondent to an increase in fractional litter coverage (Figures 4(a) and 4(b)). The snow albedo beneath 20 and 80% canopy openness showed a significantly negative correlation with fractional litter coverage. The correlation coefficients were −0.968 and −0.928, respectively (where $p = 0.01$).

Fractional litter coverage on the snow surface beneath 20% canopy openness was significantly higher than that beneath 80% forest canopy openness. Snow albedo beneath 20% canopy openness was less than that beneath 80% canopy openness because forest litter coverage was more significant at the former site. Further, decreases in snow albedo were beneficial to snowmelt. Dust particles on the snow surface and within the snow layers were partially flushed through the snowpack by snowmelt. However, only submicrometer-sized soot particles can be flushed through snowpack (Conway *et al.* 1996). Forest litter continuously accumulated on the snow surface at this site,

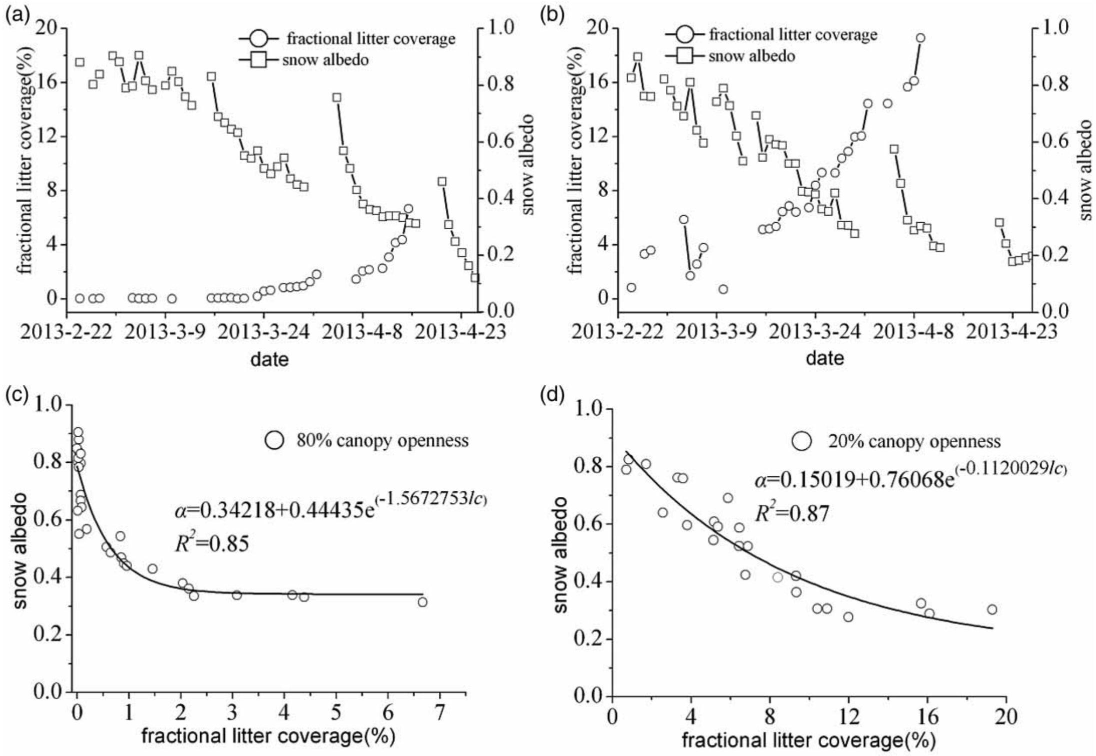

Figure 4 | The change of fractional litter coverage and snow albedo beneath different forest canopy openness on a shady slope: (a) and (c) beneath 80% forest canopy openness, (b) and (d) beneath 20% forest canopy openness.

reducing snow albedo values. Thus, snow albedo showed a positive relation with fractional litter coverage.

Snow albedo beneath the forest canopy exponentially decreased with increases in fractional litter coverage (Figures 4(c) and 4(d)). The fractional litter coverage can explain 87 and 85% of the variance in snow albedo beneath 20 and 80% forest canopy openness, respectively. Where the ground was not bare, snow albedo dropped to c. 0.3 due to forest litter. For example, the minimum snow albedos beneath 20 and 80% canopy openness were 0.28 and 0.31, respectively, but the minimum snow albedo in the open environment was 0.38. The influence of forest litter on snow albedo was more significant than that exerted by r, θ, and visible and NIR radiation fractions.

Variations on fractional litter coverage on forest snow

Litter production is influenced by climate, forest type, community structure, and human activity (Lawrence 2005; Olena & Nedret 2007; Scherer-Lorenzen *et al.* 2007). Thus, canopy openness is an important factor in litter production. During the snow accumulation period, forest litter on snow surfaces is composed principally of the needles, branches, and bark that has fallen onto the snow surface or has been carried by the wind from other places (adjacent forest canopy areas). Fractional litter coverage is influenced by the forest litter fall rate over the snow surface and by wind speed. Forest litter is mainly distributed in the interfaces between different snow layers. During the snowmelt period, in addition to the litter from needles, branches, and bark which has either fallen on the snow surface or been carried by the wind from other places, litter sources also include concentrated litter from lower snow layers exposed by snowmelt and compacted by further snowfall. Thus, the important factors in any calculation of fractional litter coverage include snow depth, litter fall rate, and wind speed. Litter carried by the wind from other places depends upon accumulated wind speed after fresh snowfall. Fractional litter coverage is significantly and positively correlated to snow depth, accumulated wind speed after fresh snowfall, and the number of days after fresh snowfall (Table 1) and can thus be fitted with these variables. However, snow depth is usually estimated as an output parameter in snow models. To some degree, snow depth can be replaced by the number of days after snowmelt begins during the snowmelt period. Fractional litter coverage can be calculated with multivariate linear regression equations as follows:

Table 1 | The correlation coefficients between the fractional litter coverage and other climate factors including snow depth, average and accumulated wind speed after fresh snowfall, and the number of days after fresh snowfall

	Snow depth	**Average wind speed**	**Accumulated wind speed**	**The number of days after fresh snowfall**
$lc_{(80\%)}$	0.971^{a}	0.149	0.511^{a}	0.734^{a}
$lc_{(20\%)}$	0.99^{a}	0.219	0.598^{a}	0.689^{a}

$^{a}p = 0.01$.

$$lc_{(80\%)} = 0.015 \times n + 0.027 \times W_{\mathrm{ac}} + 0.004, \tag{5}$$

$$lc_{(20\%)} = 0.990 \times n - 1.452 \times W_{\mathrm{ac}} + 1.563, \tag{6}$$

$$lc_{(80\%)} = 0.054 \times D_{\mathrm{sm}} + 0.117 \times n + 2.423 \times W_{\mathrm{ac}} - 1.622, \tag{7}$$

$$lc_{(20\%)} = 0.540 \times D_{\mathrm{sm}} - 0.002 \times n + 0.764 \times W_{\mathrm{ac}} + 2.831, \tag{8}$$

where $lc_{(20\%)}$ and $lc_{(80\%)}$ are fractional litter coverage (%) on a snow surface beneath 20 and 80% forest canopy openness, respectively; n is the number of days after fresh snowfall (rainfall was estimated as a continuous day, not a new snowfall event); D_{sm} is the number of days after snowmelt; W_{ac} is the accumulated wind speed after fresh snowfall. The R^2 of Equations (5)–(8) are 0.714, 0.743, 0.935, and 0.966, respectively. The results of Equations (5) and (6) give the litter coverage on a snow surface during the snow accumulation period. The results of Equations (7) and (8) give the fractional litter coverage on a snow surface during the snowmelt period. The path coefficients of D_{sm}, D_{sf}, and W_{ac} are 0.271, 0.261, and 0.742 in Equation (7) and 0.966, −0.003, and 0.046 in Equation (8), respectively. These results suggest that most of the forest litter on snow surfaces beneath 80% canopy openness was carried by the wind from other places (the adjacent forest canopy). However, fractional litter coverage beneath 20% canopy openness was mainly influenced by snow depth and most of the litter was from the forest above the snow surface. Figure 5 demonstrates how closely variations in fractional litter coverage on snow surfaces beneath a forest canopy can be simulated using regression equations.

Simulation of snow albedo beneath the forest canopy

Empiric formulae with exponential functions were usually used to simulate daily average snow albedo, using the number of days after fresh snowfall and the new snow albedo as input data. However, snow albedo beneath the forest canopy was mainly influenced by forest litter. Thus, forest snow albedo calculated using these empiric formulae was inaccurately rendered. As shown in Figure 4, forest snow albedo decreased exponentially with fractional litter coverage. Further, fractional litter coverage varied as a function vis-à-vis the number of days since snowmelt began, the number of days of fresh snowfall, and accumulated wind speed after fresh snowfall. Forest snow albedo therefore had to be calculated using these latter three variables. We used three commonly used empiric formulae in addition to the empiric formula established in this paper to calculate forest snow albedo and then selected the most appropriate formula for further calculations of forest snow albedo, thus:

Model 1 (DeBeer & Pomeroy 2009)

$$\alpha_n = (\alpha_{n-1} - 0.3)\mathrm{e}^{(-\Delta t/\tau)} + 0.3 \tag{9}$$

Model 2 (Andreadis *et al.* 2009)

$$\alpha_n = 0.85\lambda_m^{\kappa n}, \tag{10}$$

Model 3 (Petzold 1977)

$$\alpha_n = a_{n-1}(1 - 10^{(a-bn)}), \tag{11}$$

Model 4

$$\alpha_n = c + d \times e^{(f\times l_c)}, \tag{12}$$

where α_n is the snow albedo; n is the number of days after fresh snowfall; Δt is the timestep after fresh snowfall; $\tau = 10^6$ s; lc is the fractional litter coverage (%); λ_m is 0.92 for the snow accumulation period and 0.70 for the snowmelt period; κ is 0.85 for the snow accumulation period and 0.46 for the snowmelt period; a is 0.78 for the snow accumulation period and 1.05 for the snowmelt period; b is 0.069 for the snow accumulation period and 0.070 for the snowmelt period; c is 0.15 beneath 20% forest canopy openness and 0.34 beneath 80% forest canopy openness; d is 0.76 beneath 20% forest canopy openness and 0.44 beneath 80% forest canopy openness; and e is -0.11 beneath 20% forest canopy openness and -1.571 beneath 80% forest canopy openness.

As shown in Figure 6, snow albedo is better simulated by Model 1 and Model 3. Average errors and root mean square errors (RMSE) are less for Models 1 and 3 than for Model 2. When 0.85 is taken as the new snow albedo reading and fed into Model 2, the simulated results are very poor. Because snow albedo in the open environment is not affected by forest litter, the simulated results for the open environment using Model 1 and Model 3 were better than the simulated results for the sites beneath the forest

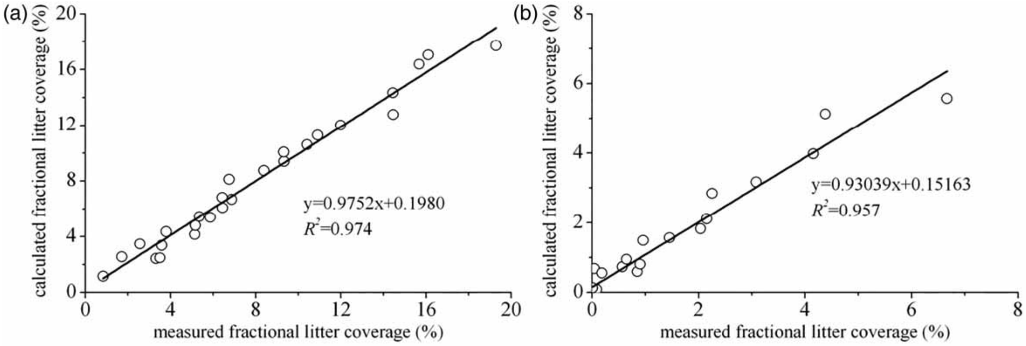

Figure 5 | The measured fractional litter coverage and calculated fractional litter coverage (the calculated fractional litter coverage using Equations (5)–(8)) on snow surface beneath forest canopy: (a) beneath 80% forest canopy openness, (b) beneath 20% forest canopy openness.

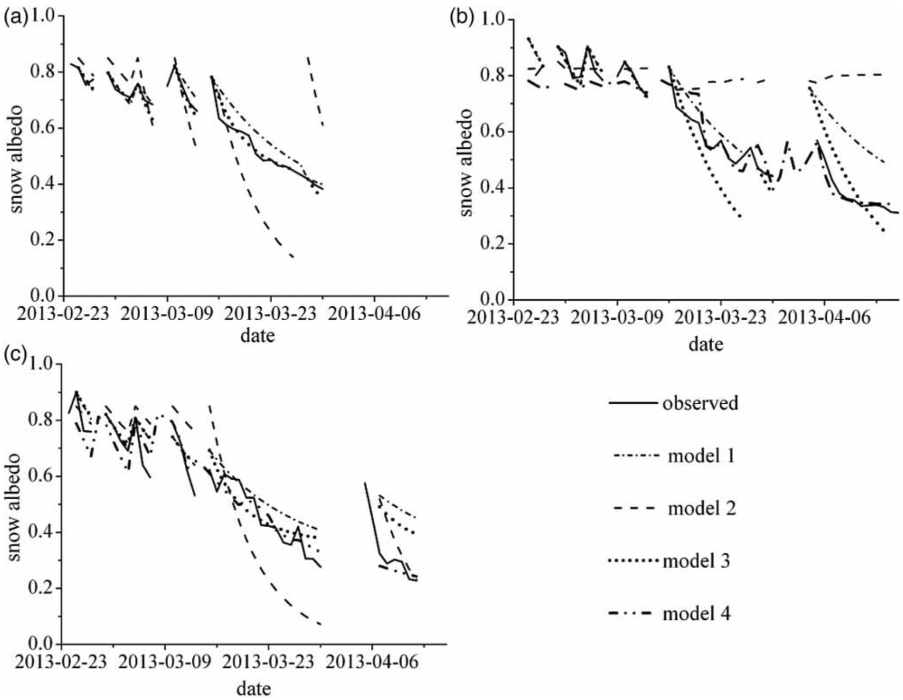

Figure 6 | The simulated value and measurement value of snow albedo using different models: (a) in open environment, (b) beneath 80% forest canopy openness, (c) beneath 20% forest canopy openness.

canopy. The simulated results for 80% canopy openness using Model 2 and Model 4 were very poor for the period of snow accumulation (prior to March 20, 2013). When new snow albedo was used as the input parameter in Models 1 and 3, the simulated results were consistent with the field measurements. Models 1, 2, and 3 could not accurately simulate forest snow albedo values for the snowmelt period, but Model 4's simulated results were consistent with field results (Figure 6(b)). The average errors and RMSE for Model 4 are less than for the other three models (Table 2). All four models could relatively closely simulate forest snow albedo beneath 20% canopy openness for the snow accumulation period (prior to March 13, 2013), although Model 4 gave values that were smaller than those measured in the field (Figure 6(c)). The simulated results of Models 1, 3, and 4 for the snowmelt period were consistent with field measurements, but the average errors and RMSE rendered by Model 4 were less than those given by the other models (Table 2). It is therefore clear that for the snowmelt period, forest snow albedo is best calculated using the number of days after snowmelt, the number of days after fresh snowfall, and accumulated speed wind as variables. However, the effect of forest litter on forest snow albedo may not be significant during the snow

Table 2 | The statistics of simulated results of snow albedo in different periods

	Snow accumulation period				**Snowmelt period**			
	80% canopy openness		**20% canopy openness**		**80% canopy openness**		**20% canopy openness**	
	Average error	**RMSE**	**Average error**	**RMSE**	**Average error**	**RMSE**	**Average error**	**RMSE**
Model 1	−0.025	0.015	0.039	0.022	−0.090	0.045	−0.105	0.026
Model 2	0.028	0.052	0.074	0.027	−0.292	0.083	0.032	0.038
Model 3	−0.009	0.011	0.044	0.023	0.062	0.038	−0.056	0.020
Model 4	−0.026	0.016	−0.022	0.017	−0.0007	0.009	0.016	0.016

accumulation period, and so Model 4 was not the best choice for calculating forest snow albedo. For periods of snow accumulation, forest snow albedo can best be simulated using the number of days after fresh snowfall and the albedo of new snow as variables (Models 1 and 3).

CONCLUSIONS

Snow albedo values in the open environment and beneath both forest canopy sites gradually decreased during the snowmelt period and showed the same trends in variability. Due to the influence of forest litter, snow albedo beneath 20% canopy openness was lower than snow albedo beneath 80% canopy openness and in the sunny slope, open environment.

Forest litter is the most important factor for snow albedo beneath the forest canopy. *r* and visible and NIR radiation fractions are not important factors in explaining differences in snow albedo values between the open environment and beneath the forest canopy. Snow albedo showed a positive relation with fractional litter coverage during the snowmelt period. Where the ground was not bare, the minimum snow albedo beneath the forest canopy was c. 0.3, but 0.38 in the open environment.

Fractional litter coverage on the snow surface was principally influenced by snow depth, litter falling rate, and the accumulated wind speed after fresh snowfall. It was best calculated using the number of days after snowmelt began, the number of days after fresh snowfall, and the accumulated wind speed as variables. Furthermore, snow albedo beneath the forest canopy exponentially decreased with increases in fractional litter coverage. Thus, forest snow albedo for the snowmelt period can best be simulated using the number of days after snowmelt, the number of days after fresh snowfall, and the accumulated wind speed as variables. This empiric formula can only be applied to the snowmelt period; simulated results for the snow accumulation period were poor. Forest snow albedo for the snow accumulation period can best be simulated using the number of days after fresh snowfall and the new snow albedo as variables.

Forest snow albedo can be better simulated using meteorological factors. Empiric formulae are especially useful for modeling forest snowmelt during the snowmelt period. In this study, we were only able to measure and analyze snow albedo and fractional litter coverage beneath 20 and 80% forest canopy opennesses. The relations between fractional litter coverage, forest canopy openness, and forest type need to be further studied and analyzed.

ACKNOWLEDGEMENTS

The research presented in this article was jointly funded by: National Key Technology Research and Development Program of the Ministry of Science and Technology of China (2012BAC23B01); National Natural Science Foundation of China (41271098, 41171066).

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First received 16 June 2014; accepted in revised form 14 September 2014. Available online 17 October 2014