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Albedo over the boreal forest

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Abstract. Using the Boreal Ecosystem-Atmosphere Study mesonet data, we show the annual cycle of albedo for 1994 and 1995 at 10 sites; two over grass, one over an aspen forest, and an average of seven over coniferous forests. Representative daily average albedo values in summer are 0.2 over grass, 0.15 for aspen, and 0.083 for the conifer sites. In winter the corresponding mean albedo for snow-covered grass, aspen, and conifer sites with snow under the canopy are 0.75, 0.21, and 0.13. The jack pine sites have a higher mean winter albedo of 0.15 than the predominantly spruce sites for which mean albedo is only 0.11. Forest albedo increases at all sites in winter (with snow on the ground under the canopy) as the ratio of diffuse to total solar flux increases. The albedo of the conifer sites in winter rarely reaches 0.3.

1. Introduction

A key component of the surface energy balance over land is the albedo α, defined as the ratio of the reflected solar radiation ($S\uparrow$) to the incoming solar radiation ($S\downarrow$)

$$\alpha = (S\downarrow / S\uparrow) \tag{1}$$

The surface albedo can have a large impact on the net radiation R_n

$$\begin{aligned} R_n &= S\downarrow - S\uparrow + L\downarrow - L\uparrow \\ &= S\downarrow(1-\alpha) + L\downarrow - L\uparrow \end{aligned} \tag{2}$$

where $L\downarrow$ and $L\uparrow$ are the downwelling and upwelling longwave fluxes at the surface. The net longwave is typically negative, because the effective thermal radiative temperature of the atmosphere viewed from the surface is cooler than the surface temperature. The net solar radiation is positive during the daytime, and unless α is large (such as over a snow surface) and $S\downarrow$ small (as in midwinter at high latitudes), R_n is generally positive in the daytime. Positive daytime R_n drives the surface fluxes which in turn are the surface forcing of the atmosphere boundary layer [*Betts et al.*, 1996; *Eltahir*, 1996].

During BOREAS (Boreal Ecosystem-Atmosphere Study), 10 mesonet stations were located in Saskatchewan and Manitoba across the boreal forest [*Shewchuk*, this issue]. Table 1 lists their locations, elevation, the type of vegetation, and the station numbers we have assigned to them. Two sites in the south and southwest were over grass; one was over a stand of old aspen in the Prince Albert National Park; and three were over jack pine sites: two at BOREAS flux tower sites in the southern and northern study areas (SSA and NSA, respectively) and one at Lynn Lake, the most northerly site. The remaining four were over mixed spruce and poplar stands (mostly conifer). Instruments mounted on towers extending above the forest measured atmospheric variables and radiation fluxes. This note summarizes the albedo measurements calculated from upward and downward facing Eppley pyranometers located typically about 5 m above the forest canopy for eight sites and at 2 m over grass for two. In addition to the shortwave measurements, five of the sites (sites 1, 3, 4, 6, and 9), marked with an asterisk in Table 1, had measurements of incoming diffuse radiation and longwave radiation.

One of the objectives of BOREAS was to use measurements to help improve global forecast models, and this analysis has this in mind. Many global forecast models (unlike many climate models, discussed below) have a single model surface and do not treat albedo well over conifer forests in winter; that is, they do not treat the shading of the snow on the ground by the forest canopy. In some models, forest albedo in winter is too often as high as 60–80%. The National Center for Environmental Prediction (NCEP) model fixes albedo over snow (south of 70°N) at 0.6 following *Miyakoda and Sirutis* [1986]; while in the European Centre for Medium-Range Weather Forecasts (ECMWF) model, albedo was as high as 0.8 after fresh snow [*ECMWF*, 1991], prior to revisions made to the winter forest albedo in December 1996. In nature, however, snowfall does not stay long on the canopy, particularly if the solar radiation $S\downarrow$ is large, or if the wind is strong, and the deep snow between dense canopies reflects relatively little solar radiation, because of canopy shading. During the April 1996 field campaign the daily forecast temperature maxima over the BOREAS sites were often low by 10 K in the ECMWF model (P. Sellers, personal communication, 1996) simply because the albedo calculated in the model was as high as 80%.

The effect of canopy shading on the albedo of forests in winter and its climatological significance has been known for some time [*McFadden and Ragotzkie*, 1967; *Federer*, 1968, 1971; *Robinson and Kukla*, 1984, 1985]. *Robinson and Kukla* [1984], from aircraft data over southeastern New York State, showed that the difference between snow-covered and snow-free albedo was 0.72 for a peaty field but only 0.1 over a mixed forest. On a global scale, *Robinson and Kukla* [1985], from an analysis of polar orbiting satellite data, showed that the northern boreal forests stand out on a global map as regions of low maximum albedo in winter; they quote a mean value of 0.36 for the maximum winter albedo of the boreal forest. In a study using an energy balance climate model, *Otterman et al.* [1984] showed that the low winter albedo of the high-latitude forests increase the surface temperature at 65°N by 5 K.

There has been considerable work on the development of detailed snow cover models for climate simulations [e.g., *Loth et al.*, 1993], as the issue of the impact of snow cover on winter

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Table 1. BOREAS Mesonet Stations

Station	Name	Long, W	Lat, N	Elevation, m	Vegetation
1*	Saskatoon, SK	−106.60	52.16	480	grassland
2	Meadow Lake, SK	−108.52	54.12	480	grassland
3*	SSA-old aspen	−106.20	53.63	587	aspen
4*	SSA-OJP	−104.69	53.92	511	jack pine
5	The Pas, MB	−101.05	53.97	268	spruce/poplar
6*	Flin Flon, MB	−101.69	54.67	305	spruce/poplar
7	La Ronge, SK	−105.29	55.13	281	spruce/poplar
8	Thompson, MB	−97.87	55.80	221	spruce/poplar
9†	NSA-OJP	−98.62	55.93	282	jack pine
10	Lynn Lake, MB	−101.09	56.89	366	jack pine

SK, Saskatchewan; OJP, old jack pine; MB, Manitoba; SSA, southern study area; NSA, northern study area.

*Denotes that incoming long-wave ($L\downarrow$) and diffuse radiation ($D\downarrow$) were also measured at these sites.

†$L\downarrow$ and $D\downarrow$ instruments were separately located at the NSA fen site at −98.42°W, 55.914°N.

climate has been of concern for some time [*Barnett et al.*, 1989; *Cohen and Rind*, 1991]. A few papers have specifically addressed the impact of the low boreal forest albedo on winter climate [*Thomas and Rowntree*, 1992; *Bonan et al.*, 1992, 1995]. *Thomas and Rowntree* [1992] in particular show that removing the boreal forests and increasing the surface albedo reduced the surface temperature in those regions. *Bonan et al.* [1992, 1995] showed the impact of the large difference in winter albedo between the northern forests and the bare ground (and tundra) on the net radiation balance and surface temperature, using both off-line experiments and climate model experiments. In the 15-year climate runs, the largest differences were seen in April, when net radiation over bare snow-covered ground was reduced more than 50 W m^{-2} at 50°N, and the corresponding surface air temperature at 60°N was 8 K cooler with climatologically prescribed sea surface temperatures and still colder (−12 K) with an interactive ocean model.

The data we have analyzed are for the first two years of BOREAS: 1994 and 1995 (measurements continued in 1996). We examine the mesonet data as a guide to first-order model improvements; other more detailed investigations of snow on conifer canopies are in progress [*Pomeroy and Dion*, 1996]. We discuss errors in winter due to snow on the upward facing pyranometer, show the annual cycle of daily average albedo for grass, aspen, and conifer sites for 1994 and 1995, present a table of mean values for different sites both with and without snow, and show the relation between albedo and incoming solar and diffuse radiation for selected sites.

2. Albedo Measurements

2.1. Instrumentation

The BOREAS mesonet sites typically sampled data every 5 s and the data loggers generated a 15-min average. The accuracy quoted by the manufacturer for the Eppley pyranometers is 5% [*Shewchuk*, this issue], which would give an accuracy of about 1% in albedo for low albedos below 20%. However, the measurement accuracy also depends on the alignment of the radiometers. The radiometers were mounted on the top of tilting towers: they were serviced regularly, generally every 3–7 days and aligned using jigs in a horizontal position, before being tilted into a vertical position. Although this was done with care [*Shewchuk*, this issue], some unknown errors due to alignment may result. A different issue is the representivity of the reflected radiation for the forest as a whole. The forest towers were carefully sited, but they extended only a few meters (typically 5 m) above the canopy, so the effective field of view of the downward looking pyranometer is small. To get some improvement in representivity, we generated daily mean values by averaging the 15-min data. Daily average albedo ($\bar{\alpha}$) was calculated from the daily average reflected ($\bar{S}\uparrow$) and incoming solar radiation ($\bar{S}\downarrow$) for each site.

In winter, snow or ice on the upward facing pyranometer will bias $S\downarrow$ low. This is important because the forest albedo in winter is a key issue, as discussed in section 1. We would like to know whether snow remaining on the canopy gives the forest a high albedo on occasions. Three factors might be important: one is the melting of snow on the canopy by the incoming solar radiation, the second is the effect of wind in shaking the snow off the canopy, and the third is a rise of the air temperature above freezing. The winter air temperatures at the BOREAS sites are generally well below freezing, so we shall not discuss this last factor. Unfortunately, the conditions of low wind and low insolation under which snow might remain on the canopy are also the conditions when snow (and ice) may remain on the upward looking pyranometer. This too gives an apparently high albedo, by biasing $\bar{S}\downarrow$ low (while $\bar{S}\uparrow$ is unaffected), as discussed in the next section.

In BOREAS, snow depth was measured by an ultrasound gauge [*Shewchuk*, this issue] in a clearing between the canopy. We have at each site only a single measurement, so estimation of the patchiness of snow is not possible. Snow depths reach half a meter each winter, so major snowfalls are readily seen. However, drifting of snow may also cause changes in snow depth, and small snowfalls of a few millimeters, which might affect albedo of the canopy, are hard to detect in this instrument record. A separate instrument, a Belfort precipitation gauge [*Shewchuk*, this issue] containing antifreeze, measures precipitation amount and thus gave an independent estimate of snowfall.

2.2. Winter Albedo Errors

There are problems with low and presumably incorrect $\bar{S}\downarrow$ data in winter at some of the forest sites, almost entirely in December and January, when solar radiation levels are very low. The probable cause is snow or ice on the upward looking radiometer. We looked critically at high winter values of albedo and examined the 15-min time series of the different radiation measurements, particularly the upward looking instruments, for consistency. Five sites have only $\bar{S}\downarrow$ and $\overline{PAR}$

(incoming photosynthetically active radiation), while the five with an asterisk in Table 1 have also $\bar{L}\downarrow$ (incoming longwave) and $\bar{D}\downarrow$ (incoming diffuse radiation).

We rejected winter $\bar{S}\downarrow$ data based primarily on two criteria:

$$\bar{D}\downarrow/\bar{S}\downarrow > 1.1 \tag{3}$$

because (3) implies more snow on the pyranometer measuring $\bar{S}\downarrow$ than on that measuring $\bar{D}\downarrow$, and

$$\overline{PAR}\downarrow/\bar{S}\downarrow > 0.6 \tag{4}$$

because typically $\overline{PAR}\downarrow/\bar{S}\downarrow \approx 0.4$, since (4) again implies more snow on the $\bar{S}\downarrow$ instrument. These filters typically eliminated blocks of suspect data (at primarily, the conifer sites 4, 9, and 10 after heavy snowfalls) in midwinter (December and January), when the recorded (but believed to be too low) $\bar{S}\downarrow \lesssim 20$ W m^{-2}. We then reexamined the daily time series of α and filtered a few additional isolated days of high albedo, which narrowly missed our criteria but were inside sequential days of bad data. One further check was considered. Snow on the $L\downarrow$ sensor gives $L\uparrow - L\downarrow \approx 0$, but this was relatively rare (we calculated $\bar{L}\uparrow$ from a downward looking infrared thermometer). Note that we cannot be certain that data that passes filters (3) and (4) in midwinter is correct, as there might be snow evenly distributed on all the sensors.

Figure 1 illustrates these filters by showing the first 120 days of 1994, until snow melt at the SSA old jack pine site 4. Snow depth, shown as a light solid line (right-hand scale in centimeters), rises from 150 to 250 mm during January and remains deep till snowmelt in April. The measured incoming $\bar{S}\downarrow$ (right-hand scale, shown with thick dashes) is very low in January (≈20 W m^{-2}), indicating either a very cloudy period (clear sky daily mean $\bar{S}\downarrow \approx 60$ W m^{-2}), or bad data, affected by snow on the $S\downarrow$ radiometer. The values we rejected are marked with a cross and include most of the January data. The calculated albedo (thick solid on left-hand scale) is low for most of February and March (0.15–0.2) except for one day. The values we have rejected on the basis of tests 3 and 4 are again marked with a cross. These include most of the high values in January and an isolated snow event in February. The highest remaining value in January (day 8) does correspond to recent snow, but it passed our simple filters. On day 33 (February 2), albedo, calculated from the 15-min data plunges (not shown), as $\bar{S}\downarrow$ rises during the daylight hours, but we believe that this was snow melting off the $\bar{S}\downarrow$ radiometer, rather than off the canopy.

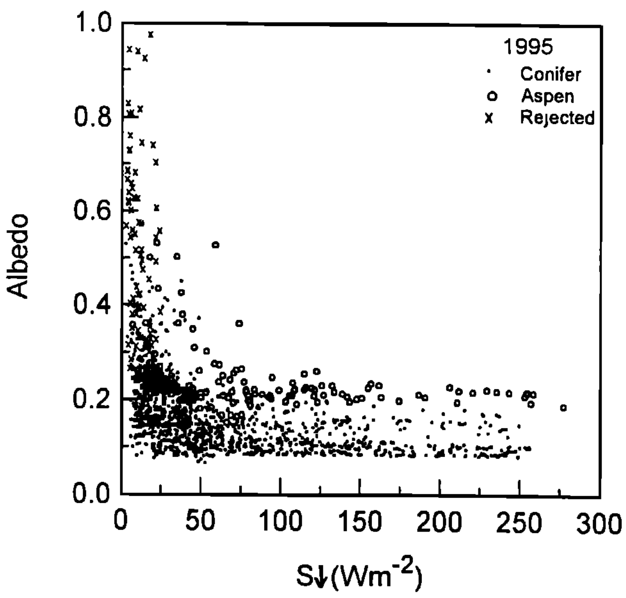

Figure 2. Albedo against $S\downarrow$ for all forest sites in 1995 (Julian days <110 and >304). Rejected data (crosses) are included.

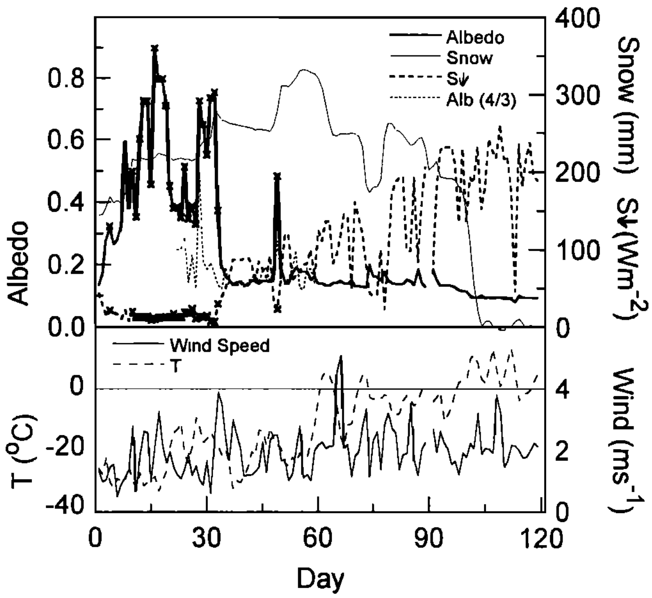

Figure 1. Albedo, snow depth and $S\downarrow$ (top panel) and wind speed, air temperature for southern study area old jack pine site for beginning of 1994.

An independent check on the validity of our filters is based on the fact that daily average values of $\bar{S}\downarrow$ are generally quite well correlated (not shown) between the old aspen site 3 and the old jack pine site 4, which are about 100 km apart (when the sensors are snow-free). The fine dotted line (with legend Alb (4/3)) is an albedo (from days 22 to 59) for site 4 calculated using $\bar{S}\uparrow$ from site 4 and $\bar{S}\downarrow$ from site 3, which started collecting data on January 20: the data from day 22 passed our filters.

$$\mathrm{Alb}(4/3) = \bar{S}\uparrow(4)/\bar{S}\downarrow(3) \tag{5}$$

Alb(4/3) is lower than the albedos we have rejected (meaning $\bar{S}\downarrow$ at site 3 is higher, even for two snow events on day 28 and 49, and it agrees reasonably well with $\bar{\alpha}$ from site 4 for those days where we have not rejected the site 4 $\bar{S}\downarrow$ data. We conclude that we were correct in rejecting most of the high albedo data in January.

The bottom panel shows daily mean windspeed (on right hand scale), mostly <3 ms^{-1} in January, and daily mean temperatures, which are well below zero (dashed on left-hand scale) in January and February. The melting of the snow pack in March and April on days where mean temperature rises above freezing is clearly visible.

2.3. Dependence of Winter Albedo on $\bar{S}\downarrow$ and Wind Speed

Figure 2 is a scatterplot of the calculated winter albedo for all the forest sites (for Julian days <110 and >304 in 1995). The crosses, which include all the high albedo values >0.6, are the data which we rejected, as discussed in section 2.2: they

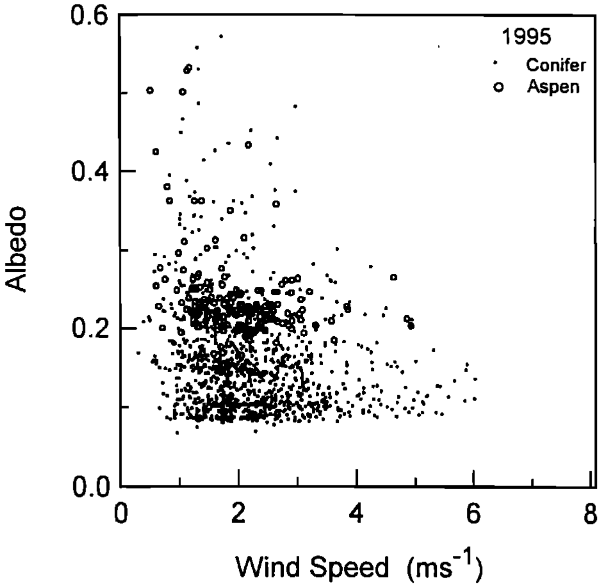

Figure 3. As Figure 2 for albedo against daily average wind speed but without rejected data.

correspond to low $\bar{S}\downarrow$ measurements, caused, we believe, by snow or ice on the upward facing pyranometer. The open circles are for the aspen site which, with a more open leafless canopy in winter, generally has higher albedos. The dots are for all the conifer sites 4–10; these have generally lower albedos. The days with $0.4 < \bar{\alpha} < 0.6$, which passed our filters 3 and 4, are all in December and January and still have very low values of $\bar{S}\downarrow$ $<$20 W m^{-2}. We consider these also suspect, and as a result, we can say nothing about the occasions in midwinter, when snow may stay on the canopy because of the low incoming solar radiation, because in just these conditions, snow also appears to remain often on the upward facing pyranometer.

Nonetheless we can draw some conclusions about the mean albedo of the conifer forest in winter. Whenever the average daily insolation $\bar{S}\downarrow$ $>$ 50 W m^{-2}, the albedo of the conifer sites rarely exceeds 0.2.

For the "winter" days shown in Figure 2, we only rejected 2% of the data for the aspen site 3, while for the conifer sites, we rejected 8%, almost all in December and January. Even in these midwinter months, the mean albedo for the 78% of the unrejected conifer data was 0.18. Since this midwinter sample may still contain some bad $\bar{S}\downarrow$ data, it is worth noting that in 90% of this sample, the conifer albedo was <0.3. We conclude that even in midwinter the conifer albedo is low, generally <0.3.

Figure 3 shows the corresponding figure for daily average albedo against daily average wind speed for the forest sites, with the rejected data removed. Assuming (which is unlikely, except perhaps for the aspen site) that the remaining days of higher albedo are correct, we see that all values of $\bar{\alpha} > 0.3$ correspond to days with low wind speed <3 m s^{-1}, which is consistent with the possibility that more snow may stay on the canopy in low winds, but clearly, this conclusion is very weak.

2.4. Seasonal Variation of Albedo for 1994 and 1995

Figure 4 plots daily albedo for grass (sites 1, 2), aspen (site 3), and an average albedo for the seven conifer sites. Gaps correspond to days without good data. The variation between the conifer (or mainly conifer) sites 4–10 is small, so to obtain a better representative large-scale estimate of the fraction of the incoming solar energy reflected by the primarily coniferous boreal forest, we show an average albedo calculated as

$$\langle\bar{\alpha}\rangle = \langle\bar{S}\uparrow\rangle/\langle\bar{S}\downarrow\rangle \qquad (6)$$

where the angle bracket denotes an average over the seven sites 4–10. This method of averaging also reduces the relative impact of any remaining days of snow-contaminated data, since these are all days of very low $\bar{S}\downarrow$ and $\bar{S}\uparrow$.

In Figure 4 the two grass sites have the highest albedo, both in summer ($\approx$0.2) and in winter ($\approx$0.7–0.8, whenever they are snow covered). The most southern site at Saskatoon (site 1) has more periods in fall and winter without snow. The aspen site has three albedo regimes: in summer when the canopy is in leaf $\bar{\alpha} \approx 0.16$, in winter $\bar{\alpha} \approx 0.21$, and in spring and fall there are transition periods with the lowest albedo $\approx$0.12, when there is no snow, and the canopy is bare. The conifer site-average has the lowest albedo in both summer and winter. The summer mean is 0.083, while when snow lies on the ground under the canopy, $\langle\bar{\alpha}\rangle \approx 0.15$ typically, with occasionally higher values. Both in summer and winter, the conifer sites have a significantly lower albedo than grass. In summer the difference between $\bar{\alpha} = 0.2$ for grassland and 0.083 for conifers is significant in the radiation balance. In winter the corresponding albedo difference is still larger: with $\bar{\alpha}$ as high as 0.7–0.8 over snow-covered grass and, typically, only 0.15 over the coniferous forests. Although the incoming solar energy is small in midwinter at these latitudes, in March and April, $\bar{S}\downarrow$ has become significant, while the ground snow cover typically has not melted. Consequently, as mentioned above, global forecast models that do not predict correctly the low albedo over the forest have large errors in surface temperature in spring.

Figure 5 shows the corresponding albedos for 1995, for which the year's record is complete. It is similar to 1994, although there are some differences in winter, presumably associated with snowfall events. In midsummer, albedos are lower

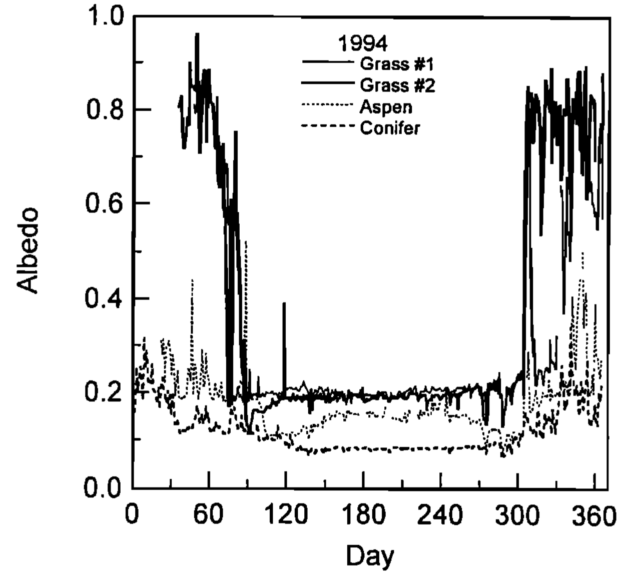

Figure 4. Daily average albedo for 10 BOREAS mesonet sites for 1994; showing two grass sites, the aspen site, and an average of the seven conifer sites.

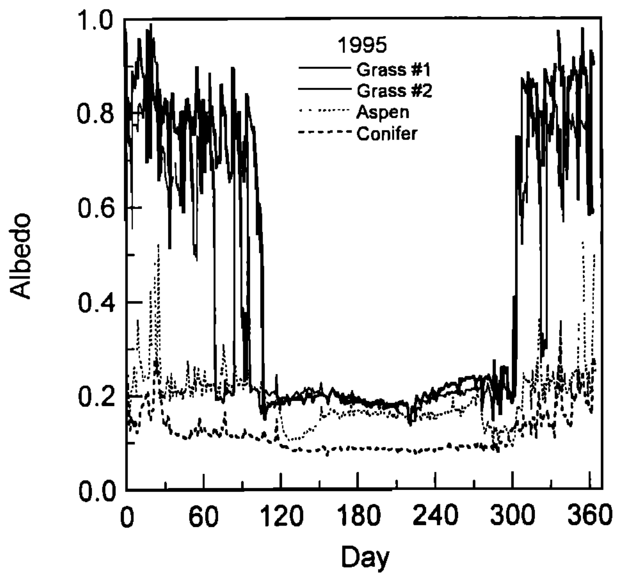

Figure 5. As Figure 1 for 1995.

in 1995 than 1994 at the two grass sites, perhaps because of lower rainfall in the preceding two months in 1995.

2.5. Mean Site Albedos With and Without Snow

Table 2 summarizes the albedo for the 10 sites, in groups with and without snow. We have excluded days where we rejected the $\bar{S}\downarrow$ data and also a few days clearly associated with transitions, such as the final melt period in spring. The albedo average is here calculated, not as an average of the albedos but as

$$\bar{\bar{\alpha}} = \bar{\bar{S}}\uparrow / \bar{\bar{S}}\downarrow$$

where the second overbar denotes an average over all days in the group. This method of averaging makes almost no difference to the summer mean, but we think it gives a slightly more representative and accurate mean measure of the forest albedo in winter, when radiation levels are low. In winter in particular, it gives a low weighting to the lowest $\bar{S}\downarrow$ days, when albedo values are often high, but we have the least confidence in the accuracy of the $\bar{S}\downarrow$ data. Table 2 also shows a count of the number of days in each average; and a standard deviation, calculated from the individual daily albedos to give an indication of their spread. Albedo at the two grass sites increases from nearly 0.20 in summer to 0.75 with snow on the ground. For the single aspen site we show three albedos: the lowest of 0.116 is with no snow and no leaves; in summer, when the aspen is in leaf, the mean is 0.156, while when the canopy is bare and there is snow on the ground, the mean is 0.21. The next group of three jack pine sites 4, 9, and 10 show some variation of summer albedo with the most northern site having the lowest albedo: the "no snow" mean is 0.086. In winter this group has a winter mean of 0.15; a smaller increase in albedo than the more open aspen site. The last group of four sites, described by *Shewchuk* [this issue] as spruce/poplar sites, have a low albedo in summer and the lowest albedos in winter. Their summer average is 0.081, and this increases only to 0.108 in winter. It appears that these towers were sited so that the downward radiometers see mostly spruce forest. Column 5 in Table 2 shows the increase in albedo (as a percent) associated with snow on the surface for each site and vegetation type. It is a convenient summary of the huge impact of canopy shading on winter albedo.

2.6. Distribution of Forest Albedos in Winter

Figure 6 shows the normalized frequency distributions of daily average albedo in winter by forest site. The data are from 1994 and 1995, and we show the total number of days in 0.02 albedo classes from 0.07(±0.01) to 0.39(±0.01), normalized by the total number of days for which we have accepted the data for that site (on the average, there are 330 days per site). The tail of the distribution for $\bar{\alpha} > 0.4$ is represented by a single point plotted at 0.45, because we have less confidence in these high albedo values, as discussed earlier (the highest 0.45 point is the most northern jack pine site 10). We have grouped the data by forest type. For the aspen site, the distribution is broadest with a peak at 0.21. The jack pine sites in the SSA (4) and NSA (9) have peaks at 0.15, while the most northern jack pine site 10, which has a low albedo in summer also has a lower winter peak. The spruce/poplar sites have generally the lowest albedo in winter, particularly sites 5, 7 and 8; their distributions peak even in winter in the range (0.09 ± 0.01), an extremely low albedo, considering there is snow on the ground under the canopy. Indeed, for spruce sites 7 and 8, almost half the days with snow under the canopy have $\bar{\alpha} < 0.1$.

Table 2. Mean Site Albedos With and Without Snow

Site	Type	No Snow (Count)	Snow (Count)	Percent Increase
1	grass	0.199 ± 0.015 (408)	0.72 ± 0.10 (182)	51.7%
2	grass	0.194 ± 0.021 (409)	0.77 ± 0.10 (267)	57.6%
	grass mean	0.197	0.75	54.7%
3	aspen (bare)	0.116 ± 0.011 (115)	0.214 ± 0.067	9.8%
	in leaf	0.156 ± 0.013 (245)		
4	jack pine	0.090 ± 0.005 (276)	0.155 ± 0.038 (264)	6.5%
9	jack pine	0.091 ± 0.006 (304)	0.167 ± 0.051 (226)	7.6%
10	jack pine	0.076 ± 0.007 (227)	0.129 ± 0.011 (365)	5.3%
	jack pine mean	0.086	0.150	6.5%
5	spruce/poplar	0.088 ± 0.008 (356)	0.115 ± 0.049 (348)	2.7%
6	spruce/poplar	0.085 ± 0.990 (243)	0.119 ± 0.052 (232)	3.4%
7	spruce/poplar	0.076 ± 0.004 (325)	0.100 ± 0.092 (360)	2.4%
8	spruce/poplar	0.076 ± 0.005 (231)	0.907 ± 0.076 (253)	2.1%
	spruce/poplar mean	0.081	0.108	2.7%

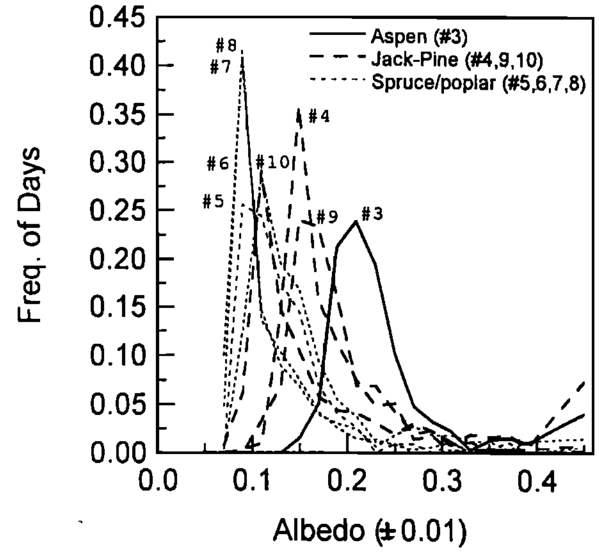

Figure 6. Normalized frequency distribution of forest site daily averaged albedos in winter (from 1994 and 1995 data).

2.7. Winter Albedo and Net Radiation Balance

The impact of the difference between winter albedo over grass and forest is large on the net radiation balance R_n. Figure 7 shows daily average R_n for March 1995 for all 10 BOREAS sites for all days with $S\downarrow > 120$ W m^{-2}; that is, we have excluded overcast days (the clear sky daily average $\bar{S}\downarrow$ at the beginning of March is $\approx$150 W m^{-2}). The solid symbols are the conifer sites, for which the mean snow depth is 44 cm, the crosses are the aspen site which has a similar snow depth (50 cm), but a more open canopy, and the open circles are for the two sites over grass, which have a lower snow depth in March. At site 2 the mean snow depth is 16 cm, while for site 1, it is only 3 cm, except for the period of March 11–25, when the snow melted, and the albedo was correspondingly low. The squares denote averages corresponding to the conifer data and the cluster of snow-covered grass data with $\bar{\alpha} > 0.5$. There is a clear separation: the grass sites, whenever snow covered, have a much higher albedo and a daily R_n averaging 50 W m^{-2} less than the forest sites (but the same average $\bar{S}\downarrow \approx 155$ W m^{-2}, not shown). These observations are comparable to the model differences cited by *Bonan et al.* [1995] for the difference in net radiation in spring over forest and snow-covered bare ground. They are also likely to be representative of the error in R_n introduced into a global forecast model in March with a model albedo of 0.75 instead of the observed 0.10 to 0.15.

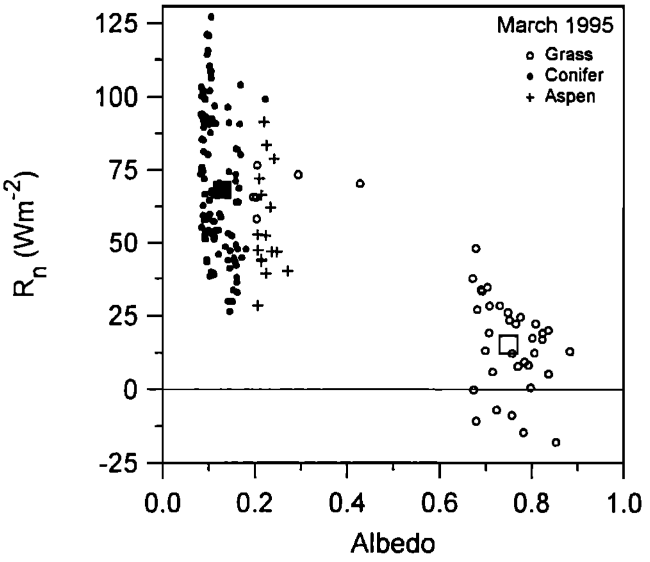

Figure 7. Daily average net radiation (R_n) against albedo for grass, aspen, and conifer sites for March 1995.

3. Albedo Dependence on Diffuse/Direct Solar Radiation

The daily albedo measurements show a dependence on the ratio of diffuse to incoming total solar radiation in both summer and winter. Incoming diffuse radiation ($\bar{D}\downarrow$) was measured (Table 1) by shadow-band radiometers at five BOREAS sites [*Shewchuk*, this issue]: the grass site at Saskatoon (see Table 1), the Old Aspen site, the SSA Old Jack Pine site, Flin Flon, and in the NSA (at the fen site). For the last two the diffuse and solar measurements were not collocated. The diffuse flux ratio, ($\bar{D}\downarrow/\bar{S}\downarrow$) is an indicator of whether a day was clear and cloud-free (when $\bar{D}\downarrow/\bar{S}\downarrow \approx 0.2$), or overcast, when $\bar{D}\downarrow/\bar{S}\downarrow$ may reach unity.

The graphs of daily average albedo against ($\bar{D}\downarrow/\bar{S}\downarrow$) are interesting. They include all the data from 1994 and 1995 which passed our filters 3 and 4. Figure 8 shows albedo plotted against ($\bar{D}\downarrow/\bar{S}\downarrow$) for the grass site at Saskatoon. The data are in three groups: the solid circles are bare grass, the open circles are snow-covered grass, and the crosses are transitional days with melting snow or morning frost. Two linear regression lines are plotted for the bare grass and snow.

$$\bar{\alpha} = A + B(\bar{D}\downarrow/\bar{S}\downarrow) \qquad (7)$$

The regression coefficients A and B and their standard deviation are given in Table 3 for this and the succeeding figures. In

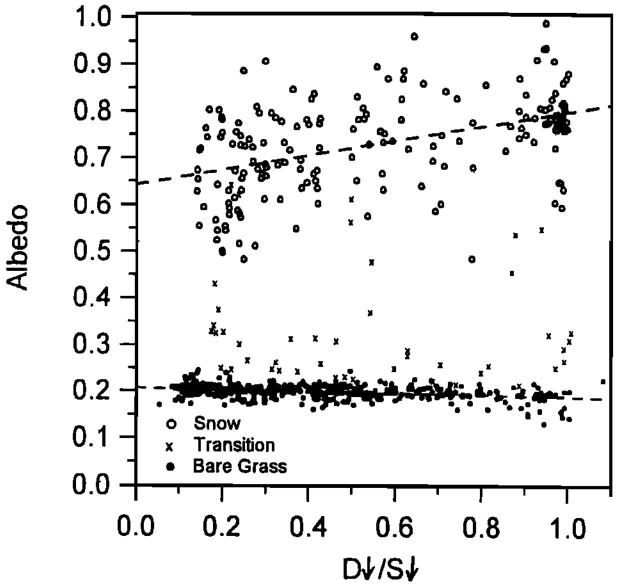

Figure 8. Albedo as a function of the ratio of incoming diffuse to solar flux ($\bar{D}\downarrow/\bar{S}\downarrow$) for the grass site at Saskatoon. Three classes are shown, together with linear regression lines for bare grass and snow.

Table 3. Regression Coefficients A, B for Albedo Dependence in $\bar{\alpha} = A + B$ $(\bar{D}\downarrow/\bar{S}\downarrow)$

		No Snow		Snow	
Site	Type	A	B	A	B
1	grass	0.206 ± 0.015	−0.018 ± 0.003	0.64 ± 0.09	0.16 ± 0.02
3	aspen (bare)	0.122 ± 0.010	−0.016 ± 0.004	0.182 ± 0.025	0.063 ± 0.006
3	aspen (leaf)	0.156 ± 0.013	0 ± 0.004		
4	jack pine	0.094 ± 0.005	−0.009 ± 0.001	0.140 ± 0.034	0.054 ± 0.007
6	spruce/poplar	0.093 ± 0.007	−0.018 ± 0.002	0.119 ± 0.036	0.023 ± 0.009
9	jack pine	0.094 ± 0.006	−0.006 ± 0.0015	0.139 ± 0.036	0.075 ± 0.009

summer, albedo decreases slightly with increasing $(\bar{D}\downarrow/\bar{S}\downarrow)$, while in winter albedo increases, although the scatter is large.

Figure 9 shows the Old Aspen site. We have partitioned the days into three groups, which separate clearly on the graphs. The lowest group (solid circles) are days in spring and fall (days 102–140 and 273–304 in 1994 and 122–145 and 278–304 in 1995), when there is no snow and the trees are not in leaf. These have the lowest albedo ≈ 0.12 and a weak decrease of albedo with increasing $(\bar{D}\downarrow/\bar{S}\downarrow)$. The regression coefficients are again in Table 3. The crosses are when the canopy is in leaf (Julian days 141 to 272 in 1994 and 146–277 in 1995), with a higher albedo ≈0.16, and no trend with increasing diffuse flux ratio. The open circles are from the winter (days <102 and >304 in 1994 and <122 and >304 in 1995), when there is snow on the ground (and no leaves on the canopy). We interpret the upper scattered points with $\bar{\alpha} > 0.3$ as the occasions when there may be fresh snow briefly on the canopy, and the broad band of points with albedo increasing with diffuse flux ratio from 0.18 to 0.24 as the general winter condition with snow on the ground and none on the canopy. We fitted three regression lines as shown to the three groups of data. We excluded all the data above the dotted line shown ($\alpha = 0.32$) in the linear regression fit to the winter snow-on-ground case. We see that with snow on the ground, albedo increases with increase diffuse flux ratio.

Figure 10 shows the corresponding graph for the SSA old jack pine (OJP) site for 1994. The separation is again by day into two main classes for this conifer site. Solid circles are for days without snow (days 101 to 304 in 1994 and 122–300 in 1995) and open circles for the winter, when snow was on the ground (there is no diffuse data before Day 50 in 1994). The clear separation is quite sharp: we have also distinguished a few days in spring (as crosses), when the final thaw of the snow-pack occurs. Without snow, albedo is low (≈0.09), with a slight decrease with increasing diffuse flux ratio. With snow under the canopy, an increasing trend of albedo with diffuse flux ratio can again be seen, although the scatter is large. There are no days at this site with $\bar{\alpha} > 0.3$. Figure 11 shows the corresponding very similar graph for the OJP site in the NSA. The dates with snow lying are different, but the pattern and regression lines are the same. We excluded the two isolated points with albedo close to 0.5 from the winter regression line calculation. For these jack pine sites, it is fairly easy to detect the presence of snow under the canopy from the albedo. Note also that the jack pine albedo is ≤0.2 most of the time in winter and only rarely reaches 0.3.

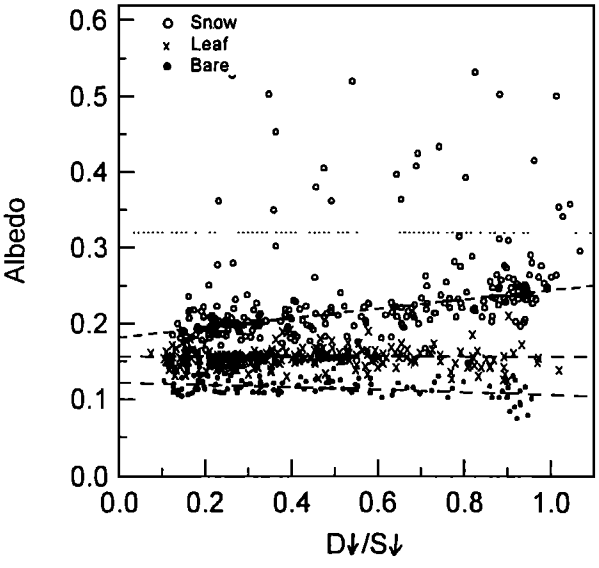

Figure 9. As Figure 8 for the southern study area (SSA) old aspen site. The three classes are bare (no snow, no leaves), in leaf, and with snow (and no leaves). The data above the dotted line were excluded from the snow regression line.

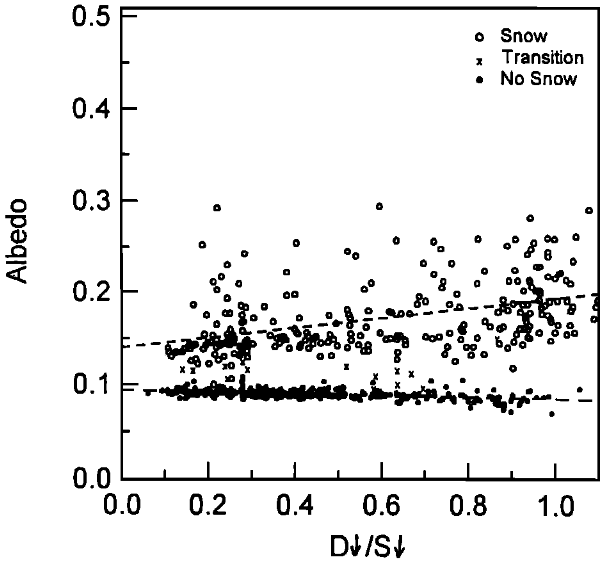

Figure 10. As Figure 8 for SSA old jack pine site. The three classes are with and without snow on the ground and the transition days during spring thaw.

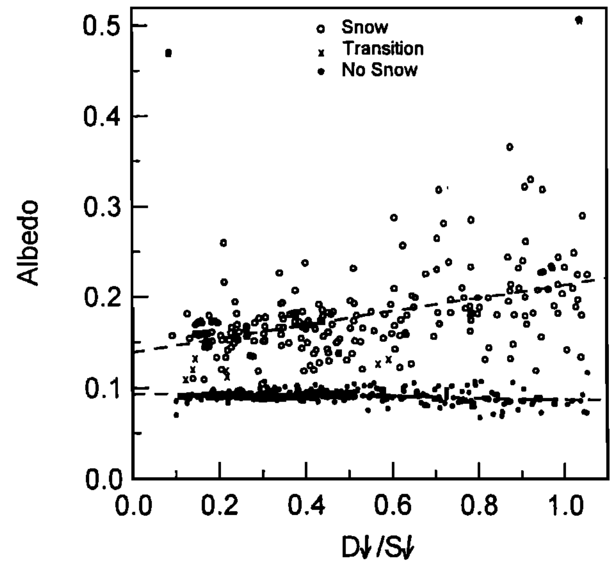

Figure 11. As Figure 10 for northern study area (NSA) old jack pine site. The two topmost points were not included in the snow regression line calculation.

Figure 12 shows a corresponding graph for the spruce/poplar site at Flin Flon. The scatter is a little larger than for the jack pine sites, and the separation between summer and winter is reduced for this largely spruce site, as seen in Tables 2 and 3. Summer albedo decreases with diffuse flux ratio, but the small increase in winter shown by the linear regression fit is arguably insignificant.

There are several possible explanations for the decrease with $(\bar{D}\downarrow/\bar{S}\downarrow)$ in albedo for all snow-free sites (except aspen in leaf), and the increase in winter with snow, which are shown in Figures 7–12. Different factors may indeed be responsible at different sites. At the snow-free conifer sites, diffuse radiation is thought to have greater penetration into the canopy and therefore might be absorbed more efficiently, thus reducing albedo. However, the different understories may also be important. At the jack pine sites, the lichen understory is whiter and more reflective when dry than wet, so perhaps the association of drier conditions with days of direct sunlight and rainfall and moister conditions with cloudy days may be playing a role. However, the grass site at Saskatoon shows a similar decrease of albedo with $(\bar{D}\downarrow/\bar{S}\downarrow)$. It is possible that the leaf physical and optical characteristics change with direct sunlight and drier conditions. In winter the increase of albedo with $(\bar{D}\downarrow/\bar{S}\downarrow)$ is seen at all sites (although marginal at Flin Flon), and several explanations are possible. Snow has a higher albedo to diffuse light, because of its different spectral properties [*Wiscombe and Warren*, 1980; *Warren*, 1982]. In comparison to the direct beam, the spectrum of diffuse radiation is shifted toward the visible (because of preferential absorption of the near infrared in clouds), where the albedo of snow is higher. Fresh snow has a higher albedo than aged snow and is likely to be associated preferentially with conditions of diffuse rather than direct solar radiation. For the forest sites, the rather high solar zenith angle in winter makes the canopy shading effect large, as mentioned earlier. However, the diffuse radiation has a smaller effective zenith angle and again will penetrate the canopy more effectively and therefore be reflected more off the underlying snow surface. Clearly, the dependencies shown in Figures 8–12 may have several explanations and deserve further study.

4. Conclusions

This paper analyzes the albedo calculated from the radiation flux measurements at the BOREAS mesonet sites. The measurements are ongoing, and we have analyzed the data from the first two years, 1994 and 1995. We show the annual cycle for both years, and we have then focused on the winter season, because current global forecast models (unlike many climate models) represent the forest albedo in winter very poorly. When snow is on the ground, the forecast models at NCEP and ECMWF too often have albedos as high as 0.6 to 0.8 for the boreal forest. This has a severe impact on the surface net radiation budget, especially in March and April, before snowmelt. In contrast, the mesonet data show very low albedos for the boreal forest in winter, typically in the range 0.1–0.2, and rarely as high as 0.3.

In summer the daily average albedo of the coniferous forest is very low: in the range 0.076 to 0.091. The aspen site has a seasonal variation with a summer value of ≈0.156, while the two sites over grass have a higher summer albedo, a little less than 0.2. The albedo difference between forest and grass, which is significant in summer is even larger in winter and spring, when there is snow on the ground. The BOREAS mesonet sites show that while over snow-covered grass albedo ≈0.75, the mean albedo in winter for the more open aspen site is 0.21, for the jack pine sites 0.15, and for the mainly spruce sites only 0.11. There are very few days in winter when we have good data that the forest albedo reaches 0.3. The forest albedo may occasionally be higher on occasions in midwinter when snow is on the canopy, and the daily insolation $\bar{S}\downarrow \le 50$ W m^{-2}, but under these conditions it appears that there is often snow on the upward facing pyranometer, and we have rejected most of these measurements.

The data show that with snow lying under the canopy, forest albedo increases on cloudy days. One possible reason is that

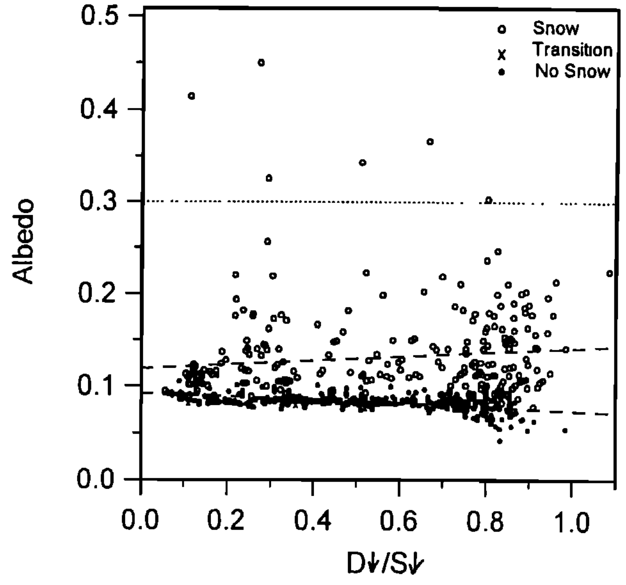

Figure 12. As Figure 11 for spruce/poplar site at Flin Flon. The points with albedo >0.3 were not included in the snow regression line calculation.

snow has a higher albedo for diffuse radiation, because of its different spectral properties, another for the forest sites is that the canopy shading is more important for the direct beam in winter, because the solar zenith angle is so high, higher than the effective zenith angle for diffuse radiation. In summer the data show a small decrease of albedo at both the grass and the coniferous sites with increasing ratio of diffuse to incoming solar radiation.

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