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Measuring the Vertical Albedo Profile of a Subarctic Boreal Forest Canopy

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The validation of airborne and satellite-derived albedo measurements suffers from the fact that the surface albedo of forest is difficult to measure in-situ over large areas. The goal of this study is to examine whether or not the estimation of the surface albedo of a forest stand from ground level measurements is possible. In addition, knowledge about the vertical behavior of albedo, and therefore transmitted solar radiation, is important in the modeling of interactions of sunlight with the forest canopy. Such modeling is useful for forest growth estimations among other things. To achieve these goals, an albedometer set-up capable of vertical albedo profiling has been used to obtain data from a boreal forest stand in Northern Finland during periods in summer 2006 and winter 2007. The results show a strong relationship between the data and fitted power-law regression curves. Power-law regression fits best likely because of the radiation transmission characteristics of boreal forest.

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1 Background

Interactions of sunlight and the forest canopy are a vibrant area of research in forestry and related fields. Together, the reflection, absorption and transmission of sunlight in the canopy and understory comprise the radiation budget of the forest. Understanding the radiation budget of boreal forest is an important and topical issue given the pressing need to be able to better monitor the effects of climate change in the vulnerable northern latitudes (e.g. Bonan et al. 1995, Holland and Bitz 2003). One of the dominating parameters of the radiation budget is the surface broadband albedo. It is defined as the ratio between upwelling (reflected) and downwelling (incident) radiative fluxes at Earth's surface (Liang 2000). Surface albedo controls the amount of solar radiation absorbed by the forest and thereby also indirectly affects several forest biophysical variables (Sellers et al. 1995).

Monitoring of boreal forests requires observations on a broad scale both temporally and spatially (Boyd and Danson 2005, Rautiainen 2005, Heiskanen 2008). For surface albedo, there exist dedicated instruments for in situ observations (called albedometers and pyranometers), but it is often unpractical to extend in situ measurements into large spatial or temporal datasets. Optical remote sensing of surface albedo from space is the most convenient way to accomplish both requirements. However, care must be taken to account for the potential sources of error in optical remote sensing (Myneni et al. 1995, van Leeuwen and Roujean 2002). The most important sources of error are the limited knowledge on the anisotropical behaviour of target surfaces, cloud contamination and other atmospheric effects, limited angular sampling, and instrument calibration issues.

At present there are several surface albedo products derived from satellites, such as MODIS albedo (Schaaf et al. 2002), AVHRR global albedo dataset (Strugnell et al. 2001), and several surface albedo products derived from Meteosat by EUMETSAT and related Climate-SAF and Land-SAF projects (Pinty et al. 2000, Schulz et al. 2008, Geiger et al. 2005). Validation of remotely sensed surface albedo requires co-operation of theoretical modeling and analysis with in situ measurements to create accurate retrieval algorithms. There have been many studies of fitting empirical in situ surface albedo data to models and satellite retrievals (Myneni et al. 1992, DeAbreu et al. 1994, Lafleur et al. 1997, Privette et al. 1997, Lucht et al. 2000, Zhou et al. 2003, Oleson et al. 2003, Privette et al. 2004), but relatively few have focused on boreal forest areas (Betts and Ball 1997, Eugster et al. 2000, Wang 2005).

A special problem in the validation of satellite-derived surface albedo in forests results from the difficulty of getting surface albedo data from the forest top level in a wide area. Although some long term in situ measurement locations feature fixed masts high enough to place the instruments over the canopy, fixed location measurements generally take place in managed forests. Forest stands in such areas tend to differ from forest stands in the wilderness, and do not therefore represent boreal forests as a whole. In addition, the forest structure, density and understory vegetation affect the albedo. This situation limits the representability of the data, as the effect of the understory on the general reflectance of the forest can be quite high (Peltoniemi et al. 2005b) and have a large variation. Airborne measurements provide better spatial coverage than mast measurements, but they are sensitive to the flight altitude due to the atmospheric attenuation of radiation.

This study seeks to examine whether or not the forest surface albedo can be estimated from the ground level (beneath the canopy) measurements. If a relationship can be found that describes the dependence of forest albedo from the albedo beneath the canopy, future surface albedo measurements at the forest floor could be transformed into the forest surface albedo. This would ensure correspondence to satellite or airborne albedo measurements once atmospheric effects have been accounted for.

2 Methods and the Dataset

The location chosen for this study was the Arctic Research Centre of the Finnish Meteorological Institute located near Sodankylä in Northern Finland (67.368 °N, 26.633 °E). The centre offers excellent facilities and most importantly several fixed masts in research forest stands at the centre. The one employed in this study was an 18-meter high metal mast, shown in Fig. 1. It is located at 67.362 °N, 26.534 °E, and it was constructed for the NorSEN project. The mast reaches clearly above the canopy height at ca. 11–12 meters, with the maximum reachable height for the albedometer assembly being 14 m. It is the only mast at the site, or elsewhere in Northern Finland, which features a winch system to freely lower and raise instruments within a forest stand.

The mast is located at the edge of a Scots pine *(Pinus sylvestris* L.*)* forest stand. The understory at the site is varied, consisting of various lichen and moss species. The albedometer assembly was placed so that it faces the forest stand away from the mast. A 50 cm × 50 cm black cover was installed between the albedometer and the mast to remove the possibly harmful effects of

Fig. 1. The NorSEN mast at FMI-ARC with the vertical rail and CM-14 albedometer attached.

sunlight glinting from the metallic mast into the albedometer. The cover cuts out ca. 24% of the total viewing angle of 4π radians so that 12% of the upper and 12% of the lower hemisphere are covered. Its effect must be considered when analyzing clear weather (i.e. black-sky albedo) measurements. During fully cloudy weather, the illumination can be considered to be fully diffuse (i.e. white-sky albedo) and the cover's symmetric effect on the measurement can be considered negligible because it cut out equal proportions of the downwelling and the upwelling radiation.

Even though the measurement height of the albedometer assembly can be freely chosen between 0–14 meters, it was decided to standardize the measurements to the heights of 3, 5, 7, 9, 11, and 13 meters. They cover the forest from the understory level observed at 3 m to the canopy viewpoint at 13 m. The albedometer used in this study was the CM-14, manufactured and calibrated by Kipp & Zonen. It measures the broadband albedo in the wavelength range from 305 to 2800 nm. The set-up was carefully installed and balanced into horizontal plane. There may remain some small bias due to imperfect horizontal aligning, but the bias is expected to be small.

The measurements detailed in this paper took place during early and late summer of 2006, as well as winter 2007. Since the albedometer assembly was a prototype instrument, the amount of acquired data was fairly modest. Other limiting factors were illumination geometry and cloudiness conditions. High Sun Zenith Angle (SZA) values occur for most of the day during winter, making albedo retrievals unreliable for all times excepting midday (van Leeuwen and Roujean 2002). Varying cloudiness also significantly alter the direct and diffuse radiation components and therefore albedo as well, rendering the data very difficult to analyze (Wang 2005). The orientation of the albedometer assembly (roughly due east) was also such that the afternoon sun is covered by the mast cover plate, rendering measurements impossible. Also, when measuring a single forest stand canopy, one needs to limit the range of sun azimuth angles to preserve comparability between measurements. This is due to the fact that the shadowing effects of tree trunks and branches may vary during the day, so harmonisation of measurement times to similar sun azimuth angles helps prevent shadowing errors. Also, early morning and late evening suffer more from shadowing (longer shadows), so removing such measurements is pertinent. Despite these limiting factors, a total of 6 vertical albedo profiles for the summer and 2 for the winter were collected.

3 Results

3.1 Results of Summer 2006

The results from the summer measurements are shown in Fig. 2. Along with the data points, power law curves fitted to the data are shown. It is readily apparent that the albedo of the stand at canopy level (13 m) is similar for most measurement sets, as expected. There is a large deviation between the measurements at understory level (3 m). This may result from a variety of factors.

The measurements of June 6th may owe some of their behavior (having generally largest albedo values beneath the canopy) to the understory Bidirectional Reflectance Distribution Function

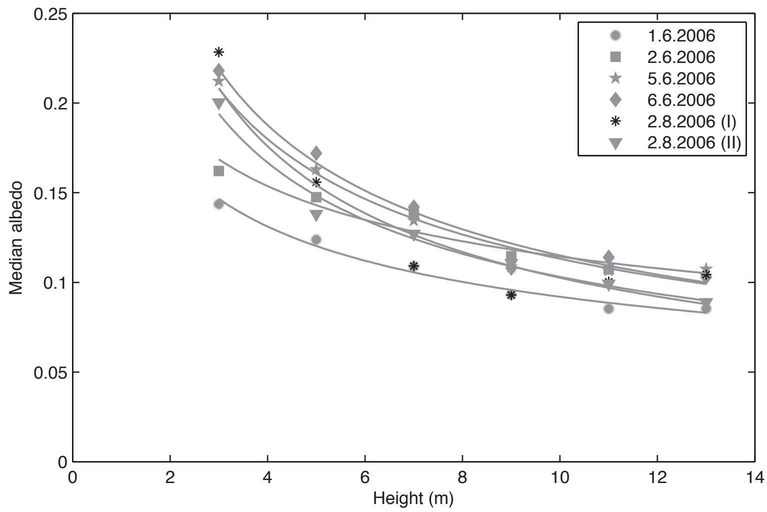

Fig. 2. Vertical white-sky albedo profiles from the summer 2006 measurements. Power law curves fitted to the data are included. Regression parameters and coefficients of determination for the fit are shown in Table 1.

(BRDF) contribution, since that was the only day on which the cloud cover was thin enough for the Sun to be seen through at times. Many understory species have anisotropic scattering characteristics, as explained below, which may affect the observed albedo gradient. However, the effect is expected to be minor since cloud cover was still voluminous even on June 6th. The results from June 1st are probably affected by a wet soil and understory following rains on the previous day, most likely lowering the albedo due to increased soil moisture (Eltahir 1998). In addition there is an increasing trend of the understory vegetation albedo at the end of May and beginning of June due to the start of the growth season. Most probably also the canopy top albedo of June 1st is reduced by the rainfall of the previous day, because the same effect can be seen in the canopy top albedo measured at the meteorological mast of Sodankylä.

It is known that the reflectance properties of some understory vegetation species have a strong directional dependence (Peltoniemi et al. 2005b). The understory could thus produce a different response to the incident solar radiation during different times of day. However, nearly all of the measurement data were taken during fully cloudy days, ensuring minimal contribution from the understory BRDF properties due to the hemispherical illumination of the scene.

The measured data, the power law regression parameters and the coefficients of determination for the fitted curves are shown in Table 1. The single values of albedo data are the median values of approximately 10–20 minutes of continuous albedo measurement at the given height. The use of median to characterize the albedo is appropriate since it tends to suppress any spikes

Table 1. The power law regression parameter values and coefficients of correlation for the 2006 and 2007 measurements at the Sodankylä site.

Date	Regression parameters for a power law fit	R^2 of power law fit
1.6.2006	$0.2243 * x^{-0.3871}$	0.98
2.6.2006	$0.2403 * x^{-0.3224}$	0.92
5.6.2006	$0.3627 * x^{-0.5058}$	0.96
6.6.2006	$0.3937 * x^{-0.5343}$	0.96
2.8.2006 (I)	$0.3977 * x^{-0.5885}$	0.86
2.8.2006 (II)	$0.3454 * x^{-0.5251}$	0.98
20.2.2007	$2.5750 * x^{-1.0238}$	0.86
21.2.2007	$4.0457 * x^{-1.1361}$	0.76

in the measurement series caused by a sudden break in the cloud cover or other harmful natural phenomena. A single profile is generally the result of approximately 2 to 3 hours of measurements, including downtime for height adjustments.

3.2 Results of Winter 2007

The albedometer was used on two days in February 2007 to gather some preliminary data on the behavior of forest albedo during the winter season, when both ground and trees are covered by snow (see Fig. 3). Short daylight periods limited the time available for measurement, as each profile takes 2 to 3 hours to measure. The low sun zenith angles during winter present shadowing problems due to tree branches blocking direct sunlight from the instrument. Shadowing affects albedo, making the data unstable and unsuitable for analysis. Due to these conditions, only two profiles proved appropriate for analysis. Both are direct (black-sky) albedos owing to the fully clear weather conditions that prevailed during the time of the measurements. Fig. 4 shows the profiles with the power law fitted curves included. Because the February 20 measurements were carried out after midday and February 21 measurements before midday, it is natural that the illumination conditions are not identical in the two data sets. In addition, the target is highly anisotropic due to the strongly reflecting snow cover on the branches. Thus it is understandable that the measured albedo values of the inner parts of the canopy are not identical.

Since the measured albedo during the winter period was dominantly black-sky albedo, the geometry of the instrument set-up should be considered. As mentioned earlier, a 50 cm × 50 cm disk was used to shield the instrument from possible glares from the metal mast on which it was mounted. To achieve an accurate representation of the actual illumination conditions, one should also model the shadowing effect of the disk on the amount of radiation reaching the sensors. The task is made more difficult by the fact that only the reflected (upwelling) radiation is strongly affected. The incoming (downwelling) radiation is dominated by the Sun's direct radiation, which is always in the instrument's field of view during the measurement. However, since the black-sky measurements were all taken during winter, we chose to omit the correction at this time due to the scattering properties of snow. Snow is typically a strong forward scatterer of sunlight (Peltoniemi et al. 2005a), meaning that the reflected radiation reaching the sensor comes mostly from the direction of the Sun, the same as for incoming radiation. This effect ameliorates the shadowing error. The reader may note that the winter forest surface albedo values (over the canopy) of the profiles are in agreement with the results in Betts and Ball (1997) being around 0.2, though different forest composition limits comparability of results. This gives support to the assumption that the shielding disk's effect on these results is negligible. The effect should be considered for other measurement geometries, though.

Fig. 3. The conditions of winter 2007 were those of heavy snow on the trees, low temperatures around –15 degrees C, and clear weather.

The results from winter 2007 show that it is much more difficult to estimate the forest surface albedo from ground level measurements when there is snow on the tree branches. Because the snow cover changes often, the regression accuracy and parameters fluctuate as well.

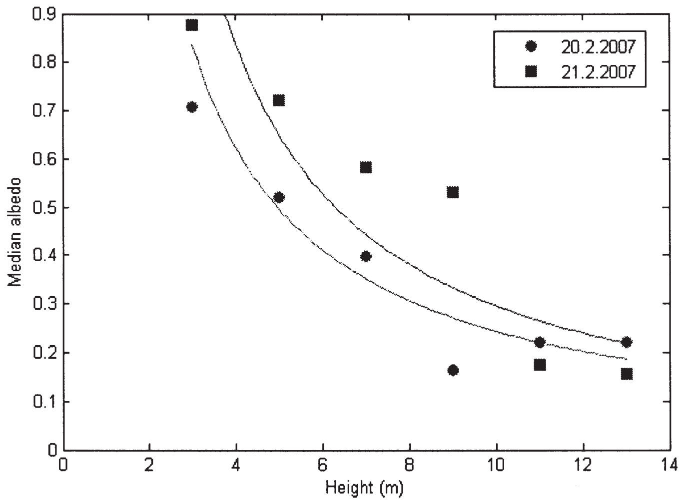

Fig. 4. Vertical black-sky albedo profiles from the February 2007 measurements. The median values of the measured time at each height are shown. Power law curves fitted to the data are included. Regression parameters and coefficients of determination for the fit are shown in Table 1.

3.3 Error Analysis

The error of the measurements was determined by examining the deviation of individual measured albedo values from the median. The average deviation for the summer measurements was ca. 0.01 albedo units (i.e. 1% absolute). Larger deviations occurred at the 3 meter level, ranging between 0.01 to 0.07 albedo units. These may result from sudden thinnings or reformings of the cloud cover. These would momentarily affect the measured albedo, although the magnitude of some spikes suggest that the measurement set-up may have also been disturbed by wind or other phenomena from time to time while close to the ground.

For the winter measurements, a similar approach in estimating the error of the measurements was adopted. As can be expected from black-sky albedo measurement conditions during winter, the deviations were higher. The average deviation from median was 0.064 albedo units, with higher deviations measured on February 20th and lower on February 21st. However, the high deviations can be expected because black-sky albedo reacts to shadowing, such as the shifting shadows of trees at the site. Also, snow is typically a strong forward scatterer of light, meaning that its measured albedo may change during the day as the geometry between the Sun and the albedometer changes.

To assess the accuracy of using the regression curves to obtain the forest surface albedo, the estimation was simulated with using the 3 and 5 meter observed albedos to fix a new power law curve, and compared the albedo obtained from the simulated curve to the actual observed albedo at 13 meters for each day. For the summer measurements, the differences between observed and simulated albedos at 13 m varied between 0.008 and 0.028 albedo units. The differences for the winter measurements were 0.122 for February 20th and 0.346 for February 21st. The simulation shows that while using the estimation with only two measurements from beneath the canopy does not lead to unacceptable errors during summer and white-sky conditions, a similar approach produces large errors during winter with black-sky conditions.

4 Discussion

This study is a demonstration of concept in showing that it is possible to estimate forest surface albedo from the ground level measurements. In this study we have measured the vertical albedo profiles of a boreal forest canopy. Profiles were obtained from diffuse (white-sky) albedo conditions during summer and direct (black-sky) albedo conditions during winter. The results show a strong and form-wise repeatable relationship between the obtained albedo data and a power-law regression curve fitted on the data in summer conditions. One is of course tempted to ask why the fit was chosen to be according to power law, since other choices would yield comparably good results.

Transmission of the direct radiation component entering the canopy will be attenuated exponentially. Also the diffuse component attenuates essentially exponentially (Nilson et al. 1977, Manninen and Stenberg 2008). However, the scattering of the radiation by the canopy is not negligible in the boreal forest. Therefore it is natural that the best fit regression curves were in most cases not exponential. Indeed, in most cases the power law fit matched the data best.

The reader may notice that the regression parameters of the fitted curves still vary between profiles. There are several factors at work here. Firstly, the albedo of a boreal forest stand changes naturally over time with the annual phenological cycles. Thus, albedos measured during early part of the summer will differ from those measured in August near the end of the growth season. Another factor is illumination. Even white-sky conditions will vary over time with increasing and decreasing radiation amounts.

Winter estimation is made difficult by the albedo effects of snow clinging to the trees. The time of winter measurements was deliberately picked as late February to illustrate this point. Winter measurements are also limited by short periods of sunlight and pronounced shadowing effects of tree trunks and branches.

Although the form of the relationship between the forest surface albedo and the ground level (understory) albedo is (in summer) simple and form-wise repeatable in similar weather conditions, one can not expect the obtained regression parameter values to be valid in all forests. Basically measurements at two different heights close to the forest floor are sufficient to determine the power law regression parameter values of individual forest plots. However, because the radiation propagation characteristics of different forest stands vary and there are practical challenges in getting a sufficiently large height difference for the two measurements to achieve reasonable accuracy for the regression, additional Leaf Area Index (LAI) measurements and canopy scattering modeling (Rautiainen and Stenberg 2005, Manninen and Stenberg 2008) would improve the forest top albedo results. Since LAI is integrally connected to the transmission of radiation through the forest canopy, the experimental albedo gradient results used in conjunction with collocated ground level LAI measurements and advanced scattering models should together enable reliable forest surface albedo estimations. The obtained data may also be used directly in the development of scattering models of radiation in the forest. The obtained results thus far are strong enough to support the idea that such an estimation of the forest surface albedo from ground observations is possible.

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