The Effect of Boreal Forest Canopy on Snow Covered Terrain Broadband Albedo

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Abstract

The effect of snow-covered forest floor on the total albedo is studied using unsupervised classification of wide angle orthogonal airborne images and albedo model simulations. The snow is darker at the forest floor than at the open areas both in clear sky and cloudy conditions. The reflectance decreases with decreasing snow pixel fraction. The effect is linear in the case of cloudy images, but in the clear sky cases the decreasing is steeper for small snow pixel fractions. The total reflectance of the image, however, decreases essentially linearly with decreasing fraction of snow pixels. An albedo model was used to simulate various components of the forest scattering. The multiple scattering between the snow-covered forest floor and the canopy is not negligible in the red band and actually dominates the forest floor related scattering in the near infrared (NIR) and broadband, when the leaf area index (LAI) is in the range 1 - 2, depending on the sun zenith angle. If this multiple scattering is not taken into account, also the ratio of the midday black-sky (i.e. direct) and white-sky (i.e. diffuse) broadband albedo values may deviate largely from the actual value, especially for LAI values smaller than 3. The effect is largest at high latitudes, where the midday sun elevation is low and the canopy small and sparse.

Keywords: albedo, boreal forest, snow, remote sensing

1 Introduction

Surface albedo is the fraction of incoming solar radiation reflected hemispherically by the surface. The black-sky albedo represents the theoretical case of purely direct incoming radiation and the white-sky albedo refers to a case of complete cloud cover, when the total irradiance equals the diffuse irradiance (*Schaepman-Strub et al.*, 2006). The black-sky albedo is one of the essential climate variables (ECV). Surface albedo serves as an indicator of climate change, and change of the albedo will also affect the climate (*GCOS*, 2016). The boreal zone land cover has a very significant influence on the northern hemisphere albedo and is an important component of the northern hemisphere carbon budget (*Bonan et al.*, 1992; *Randerson et al.*, 2006). The boreal forest zone is sensitive to changes in local and global climate (*Parry et al.*, 2007). If the length of the snow-covered season gets shorter and snow melts earlier in spring due to climate change. On the other hand, if the northern forest edge moves further north due to the climate change, the winter and spring time albedo will decrease markedly, which also will enhance the climate change.

In snow free conditions the coniferous forest broadband albedo is of the order of 10% (Betts and Ball, 1997). The pure snow broadband albedo is in midwinter about 83% (Warren, 1982). In snow-covered conditions the albedo of forested areas varies with the LAI of the forest and the snow properties (albedo). In a case of crown snowload even the structure of the canopy changes and snow dominates completely the forest albedo. Canopy snow-cover is observed to substantially influence the albedo, increasing it by about 20% as compared to snow free conditions (Kuusinen et al., 2012). Yet, the snow remains on the tree branches mainly in midwinter, when the solar irradiance is low and the weather is cold. From the point of view of climate the case of snow on forest floor but not on the tree branches is more important (Kuusinen et al., 2012). Without snow on the forest floor the midday albedo is the smallest (Briegleb et al., 1986). When there is snow on the forest floor, but not on the trees, there is a local maximum for the total albedo at midday. The effect is amplified by the typically linear diurnal decrease of the snow albedo during the melting season, so that afternoon albedo values are altogether smaller than the morning values corresponding to the same sun zenith angle value.

The evaluation of CMIP5 (Coupled Model Intercomparison Project Phase 5) models suggest that inaccurate canopy treatment explains, in part, an observed positive bias in winter albedo over boreal forest regions of the Northern Hemisphere (*Wang et al.*, 2016). Albedo modelling differs mainly from the point of view of treating multiple scattering related to the canopy and snow interaction. In this study we use a photon recollision probability based model (*Manninen and Stenberg*, 2009) that takes into account all four components of the scattering: 1) only forest floor scattering, 2) only canopy scattering, 3) multiple scattering from the forest floor and canopy with last hit from the floor and 4) multiple scattering from the forest floor and canopy with last hit from the canopy. Model calculations are made to simulate various effects of snow at the forest floor on the total forest albedo.

2 Material

A set of wide angle orthogonal images were acquired in Sodankylä, Finnish Lapland, during the SNORTEX (SNOw Reflectance Transition EXperiment) campaign (*Roujean et al.*, 2010; *Manninen and Roujean*, 2014) in snow-covered conditions in 2008–2010. The areal coverage varied in the range $67.26^{\circ}N - 67.93^{\circ}N$, $24.91^{\circ}E - 27.28^{\circ}E$ (Fig. 1). The flight altitude was in the range 130 m - 1200 m (*Manninen*, 2014). A normal Canon pocket camera A640 with a $0.7 \times$ wide angle conversion lens WC-D58N was attached to the helicopter landing gear so that it was looking orthogonally downwards (*Manninen et al.*, 2009; *Manninen et al.*, 2011). The angle from the image centre was about 41° at the corners of the rectangular images and 35° and 28° at the middle of the image edges (Fig. 2). The images were taken every three seconds and the 3-D GPS coordinates were registered for each image frame. The images were stored in standard jpg format directly to a laptop used for operating the camera. During the flight the last image was repeatedly sent to the screen of the laptop to enable choice of

optimal route and altitude. A subset of 95 images retrieved in both, the completely clear sky (40) and the completely diffuse sky conditions (55) was chosen to this study. The basis for the choice was to achieve a large variation of snow pixel fraction, forest type and leaf area index.



Fig. 1. Area of SNORTEX airborne data acquisition in Northern Finland.



Fig. 2. View angle variation of the camera utilized for the airborne photos.

3 Methods

3.1 Unsupervised classification

Unsupervised classification (ISOCLASS) was carried out using ER Mapper software. This is a K-means or migrating means type of classifier. The K-mean clustering (MacQueen, 1967) is an iterative process, where every data point is set in one of the clusters, which amount is represented by variable K. At the start of the process each of the data points are assigned to the closest, initially chosen cluster center. The cluster centers are updated to be the mean of the data points in the cluster. Then the data points are assigned again. This is carried out until there are no changes in the clusters. Altogether eight classes were allowed and the minimum distance between class means was 3.2, the maximum standard deviation was 4.5, the minimum members in a class was 0.01% and the iteration ended when the fraction of unchanged classifications reached 98%. From the eight classes, three corresponded to the canopy and five to snow pixels. For cloudy images the eight class classification produced good results for all processed images (Section 4.1), but for clear sky images the structure of the shadows caused problems for unsupervised classification for a number of images. Therefore, the number of clear sky cases is smaller than that of cloudy cases. Increasing the number of classes might have improved the clear sky results, but in many cases even that would not solve the problem of mixing shaded snow pixels with canopy pixels. Also, in some cases the utilized wide view angle of the optics caused additional difficulties for the classification of the clear sky images, because the reflectance of the snow varies also with varying view angle. For the cloudy images the snow reflectance dependency on a view angle was obvious as well, but it did not complicate the discrimination of canopy and snow pixels. Altogether, the accuracy of the fraction of snow pixels and related reflectance value is less reliable for clear sky cases than for cloudy cases.

The relative darkening of the snow r_s was calculated as a function of the fraction of forest floor snow pixels using the formula

$$r_s = \frac{\langle R_s \rangle - R_{s0}}{\langle R_s \rangle} \tag{1}$$

where R_s is the mean reflectance of the snow and R_{s0} is the mean reflectance of the brightest snow class.

3.2 Albedo model

An albedo model based on photon recollision probability was utilized to analyze the effect of the canopy on the forest floor scattering for clear sky cases (i.e. the blacksky albedo), because they correspond to illumination conditions of satellite retrievals (*Manninen and Stenberg*, 2009). The model belongs to a family of canopy models called PARAS (*Rautiainen and Stenberg*, 2006). The albedo equations were simplified according to the following assumptions. The surface reflectance was assumed to be half Lambertian and half forward scattering, i.e. k = 0.5, a spherical leaf distribution (G = 0.5) was assumed and the scattering characteristics of the canopy were assumed to be identical for photons entering it from above and from below, i.e. the upwards escaping $q = q_b$, where q is the fraction of incoming radiation scattered upwards (i.e. to the same hemisphere where it came from) by the canopy and q_b is the fraction of radiation reflected by the forest floor and scattered downwards (to the hemisphere it came from) by the canopy. The model divides the albedo in four components (*Manninen and Stenberg*, 2009): 1) only forest floor scattering α_{tt} , 2) only canopy scattering α_s , 3) multiple scattering from the forest floor and canopy with last hit from the floor α_{st} and 4) multiple scattering from the forest floor and canopy with last hit from the canopy α_{ss} . With the above mentioned simplifications those four components are reduced to the following Eqs.

$$\alpha_{tt} = \frac{1}{2} \alpha_b t_0 (t_0 + t_1)$$
(2)

$$\alpha_s = q \left(1 - t_0\right) \frac{\omega_L - p \omega_L}{1 - p \omega_L} \tag{3}$$

$$\alpha_{st} = \frac{1}{2} \left[\alpha_b (1-q) t_0 \left(2 - t_0 - t_1 \right) \right] \frac{\omega_L - p \omega_L}{1 - p \omega_L}$$
(4)

$$\alpha_{ss} = \left\{ \alpha_{b} \left[(1-q)(1-t_{0}) + \frac{1}{2}q\alpha_{b}t_{0}(2-t_{0}-t_{1}) \right] \frac{t_{1}(1-\omega_{L}+q\omega_{L}-qp\omega_{L}) + (1-q)(\omega_{L}-p\omega_{L})}{1-p\omega_{L}-q\alpha_{b}(1-t_{1})(\omega_{L}-p\omega_{L})} \right\} \\ \cdot \frac{\omega_{L}-p\omega_{L}}{1-p\omega_{L}}$$
(5)

where α_b is the surface albedo of the forest floor material, ω_L is the leaf single scattering albedo, the photon recollision probability *p* is related to *LAI* by (*Stenberg*, 2007; *Stenberg and Manninen*, 2015)

$$p = 1 - \frac{1 - e^{-0.5 \, LAI \, \beta} (1 - 0.5 \, LAI \, \beta) + (0.5 \, LAI \, \beta)^2 Ei(-0.5 \, LAI \, \beta)}{LAI} \tag{6}$$

and the fraction of direct radiation $t_0(\theta_s)$ corresponding to the sun zenith angle θ_s and diffuse radiation t_1 reaching the forest floor without hitting the canopy are (*Manninen and Stenberg*, 2009)

$$t_0(\theta_s) = \exp(-0.5 \, LAI \, \beta / \cos \theta_s) \tag{7}$$

$$t_1 = \exp(-0.5 \, LAI \, \beta)(1 - 0.5 \, LAI \, \beta) - (0.5 \, LAI \, \beta)^2 \text{Ei}(-0.5 \, LAI \, \beta) \tag{8}$$

where Ei denotes the Exponential integral.

The value of q for the red and NIR channels were estimated on the basis of numerical fit to (*Mõttus and Stenberg*, 2006) and they were

$$q_{Red} = 1 - 0.5 \exp(-0.0913 \, LAI - 0.0169 \, LAI^2) \tag{9}$$

$$q_{NIR} = 1 - 0.5 \exp(-0.0733 \, LAI - 0.0118 \, LAI^2) \tag{10}$$

The simplified diffuse albedo formulas corresponding to Eqs. 2–5 are:

$$\alpha_{difftt} = \frac{1}{2}\alpha_b(t_1^2 + t_2) \tag{11}$$

$$\alpha_{diffs} = q(1 - t_1) \frac{\omega_L - p\omega_L}{1 - p\omega_L} \tag{12}$$

$$\alpha_{diffst} = \frac{1}{2}\alpha_b(1-q)(2t_1 - t_2 - t_1^2)\frac{\omega_L - p\omega_L}{1 - p\omega_L}$$
(13)

$$\alpha_{diffss} = \begin{cases} \alpha_{b} \left[(1-q)(1-t_{1}) + \frac{1}{2}q\alpha_{b}(2t_{1}-t_{2}-t_{1}^{2}) \right] \cdot \\ \frac{t_{1}(1-\omega_{L}+q(\omega_{L}-p\omega_{L})) + (1-q)(\omega_{L}-p\omega_{L})}{1-p\omega_{L}-q\alpha_{b}(1-t_{1})(\omega_{L}-p\omega_{L})} \right\} \frac{\omega_{L}-p\omega_{L}}{1-p\omega_{L}} \end{cases}$$
(14)

where

$$t_2 = \exp(-LAI\,\beta)(1 - LAI\,\beta) - (LAI\,\beta)^2 \operatorname{Ei}(-LAI\,\beta)$$
(15)

A clumping factor of $\beta = 0.671$ was used (*Manninen and Stenberg*, 2009, Eqs. 1– 8). Two alternative values were used for the leaf single scattering albedo $\omega_{\rm L}$ in red and NIR channels to study their effect on the results. The used values were 0.1 and 0.7 (*Panferov et al.*, 2001) and 0.2 and 0.8 (*Lukeš et al.*, 2013), respectively. The latter values are based on a data set measured in Finland, but in summer conditions. It is not known, how much the leaf single scattering albedo varies between winter and summer, but some difference is expected due to the winter hardening of the coniferous species. The values of the forest floor snow albedo were taken to present the midwinter and hence to be 0.95 for the red channel, 0.9 for the NIR channel and 0.83 for the broadband case (*Warren*, 1982). The model calculations were carried out spectrally and the broadband albedo was then derived using a conversion formula (*Liang*, 2000). The white-sky albedo is obtained assuming completely isotropic illumination integrating the solar angle dependence away (*Manninen and Stenberg*, 2009).

4 Results and discussion

4.1 Unsupervised classification

Examples of classification of photos taken in cloudy conditions are shown in Figures 3 and 4. Obviously the brightness of the snow pixels of the forest floor depends on the density of the forest. Even in nadir viewing the snow looks darker in the denser forests. And very small canopy is sufficient to darken the snow. This is in line with the observations the shrubs decrease the albedo of tundra (*Sturm et al.*, 2005). Also a comparison of CMIP5 models suggested that the albedo for even a sparse forest in the presence of snow should be notably lower than for bare ground (*Wang et al.*, 2016). The reflectance of the snow pixels is systematically lower in the forest than in open areas (Fig. 4). No marked difference between Scots pine and Norway spruce forest characteristics is detected.



Fig. 3. Sparse Sub-Arctic Scots pine forest in diffuse illumination (top) and corresponding classification result (bottom). Yellow indicates the brightest snow class and darkest blue the darkest snow class. The canopy is masked black. The ratio of the darkest and brightest snow classes is 0.78.



Fig. 4. Sub-Arctic Scots pine and spruce forest in diffuse illumination (top) and corresponding classification result (bottom). Yellow indicates the brightest snow class and darkest blue the darkest snow class. The canopy is masked black. The ratio of the darkest and brightest snow classes is 0.49.

Classification results of clear sky conditions are shown in Figures 5 and 6. Although even the denser forest of Figure 5 is relatively sparse, the forest floor is practically completely shaded. The brightest snow class corresponds to only 6% of all pixels, whereas the forest floor snow-cover still constitutes 54% of all pixels. For the sparser forest of Figure 6 the fraction represented by the brightest snow pixels is 45% of all pixels, but the snow pixels of the forest floor represent 95% of all pixels. This shows, how

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dramatic the effect of even a small canopy has on the forest floor reflectance/albedo. The fraction of brightest snow pixels decreases roughly exponentially with increasing fraction of canopy pixels.



Fig. 5. Dense Sub-Arctic Scots pine forest in direct illumination (top) and corresponding classification result (bottom). Yellow indicates the brightest snow class and darkest blue the darkest snow class. The canopy is masked black. The ratio of the darkest and brightest snow classes is 0.45.



Fig. 6. Sparse Sub-Arctic Scots pine forest in direct illumination (top) and corresponding classification result (bottom). Yellow indicates the brightest snow class and darkest blue the darkest snow class. The canopy is masked black. The ratio of the darkest and brightest snow classes is 0.74.

The effect of the darkening of snow with fraction of forest floor snow pixels is shown in Figure 7 for cloudy and clear sky cases separately. Obviously the average decrease of snow area reflectance decreases about the same amount in cloudy and clear sky conditions, when LAI is small. Then the decrease is essentially linearly related to the fraction of snow pixels. However, for dense forests the shadows in clear sky conditions are so dark that the relative snow pixel reflectance decreases more exponentially than linearly with decreasing fraction of snow pixels. Yet, the total forest reflectance, including also the canopy pixels, decreases practically linearly with decreasing fraction of snow pixels also in the clear sky conditions. If one assumes, that the snow has the same reflectance at the forest floor as in open areas, the fraction of snow pixels is underestimated for the same reflectance value (Fig. 8). Although the dynamic range of the snow reflectance is larger in the clear sky case the ratio of the darkest and brightest snow class reflectance values is very similar for the cloudy and clear sky situations (Fig. 9). The ratio varies in the range of 0.4–0.8 depending on the fraction of snow pixels. Naturally the ratio is smallest in densest forests.



Fig. 7. The relative decrease of snow reflectance as a function of the fraction of snow pixels for cloudy and clear sky cases.

The shadows at the forest floor obviously complicate the fractional snow cover estimation in clear sky conditions, which corresponds to the satellite image usage. If the total reflectance were only a direct mean of canopy and snow covered pixels reflectance values, a linear relationship between the total reflectance and the fraction of snow cover would be applicable (Fig. 7). However, the snow affects the total reflectance also indirectly via multiple scattering between the canopy and the forest floor (see Section 4.2) so that the total reflectance is higher than the mean of the canopy and snow reflectance values. Luckily the total reflectance and fraction of snow pixels are essentially linearly related (Fig. 8). If this relationship is determined empirically, for example by constructing a transmissivity map, it is possible to estimate successfully the fractional snow cover using a linear relationship with satellite based reflectance values (*Metsämäki et al.*, 2007).



Fig. 8. The fraction of snow pixels as a function of the total reflectance scaled with the reflectance of the brightest snow pixel per image (red). For comparison we show the corresponding relationship for the fraction of snow pixels and the total fictive scaled reflectance that is derived by replacing darker snow class mean reflectance values with the brightest snow class mean reflectance value (purple).



Fig. 9. The ratio of the darkest and brightest snow class reflectance mean values as a function of the fraction of snow pixels for cloudy and clear sky cases.

4.2 Effect of snow on total forest albedo

The albedo model was used first to estimate the three components of scattering with a contribution of the forest floor: 1) only transmission without canopy scattering, 2) scattering from both canopy and forest floor with last hit at the floor and 3) scattering from both canopy and forest floor with last scattering in the canopy before the photon escapes upwards. The first component consists of single scattering.

For the red wavelength range the single scattering dominates even in dense forests (LAI~5). However, neglecting multiple scattering components easily introduces an inaccuracy of 5-10% to the forest floor scattering for larger sun zenith angle values even for sparse forests (Fig. 10), depending on the leaf single scattering value used. For the NIR wavelength range and the broadband the multiple scattering dominates already at very small LAI values (1–2) depending on the sun zenith angle. Although the sun is typically quite low in winter in the boreal forest zone, the multiple scattering from the



Fig. 10. Modelled relative components of forest floor albedo as a function of LAI for red and NIR channels and the broadband for the sun zenith angle value 50° for two different spectral leaf single scattering albedo value pairs.

forest floor should be properly taken into account, when using the reflectance values in energy balance calculations etc. Also the interpretation of optical remote sensing data requires attention to the multiple scattering effect.

The black-sky broadband albedo at midday was calculated as a function of LAI (0.2-8) using the albedo model for latitudes 45°, 55° and 65° (Fig. 11). The two sets of leaf single scattering albedo were used. The black-sky albedo decreases essentially exponentially from the open snow albedo and saturates to a value larger than the canopy albedo value, because the multiple scattering between the canopy and the forest floor is non-negligible. The albedo is naturally slightly higher for the higher leaf single scattering of the year causes that the albedo drops very steeply from the open snow area value because of the dark shadows on the forest floor. This is in line with the observations where small shrubs decreased the albedo of snow-covered area (*Sturm et al.*, 2005).

The ratio of the black-sky and white-sky albedo values at midday depend largely on the LAI and the latitude (i.e. the sun zenith angle value at midday), but the leaf single scattering albedo does not really matter much (Fig 12). For low sun elevation the blacksky albedo at midday is typically smaller than the white-sky albedo, whereas for higher midday sun elevation the black-sky is larger than the white-sky value. This ratio varies particularly for LAI values smaller than 3. This is the LAI range for which the multiple scattering contribution of the forest floor is largest (Fig. 10). Neglecting the multiple scattering components of the forest floor will then affect also the ratio of the black-sky and white-sky albedo values of midday. The effect of the multiple scattering between the forest floor and canopy is larger on the near infrared wavelength range than on the red wavelength range (Fig. 13). It is especially large in the north, where the sun elevation is low and the LAI small. If the multiple scattering is not taken into account in the climate model calculations, there is a risk of getting results biased with latitude.

4.3 Comparison with albedo estimation in climate models

In climate models the effect of snow on total albedo is taken into various by approaches (*Wang et al.*, 2016). One alternative is to take into account the fraction of open areas, gaps of canopy and snow on canopy separately like in the Canadian Land Surface Scheme (CLASS) (*Verseghy et al.*, 1993). Another approach is to calculate the forested area albedo using a two-stream approximation like in the Community Land Model version 4 (CLM 4) (*Oleson et al.*, 2010). The PARAS albedo model is compared to those two models in diffuse conditions and mid-winter snow (Fig. 14). Since the CLASS model uses observed canopy albedo values, it is applied to the variation range (0.1–0.2) of observed coniferous forest albedo values (*Breuer*, 2003). Obviously all three models produce essentially similar results, but CLM4 albedo decays more steeply with increasing LAI than the others. PARAS is about between the CLASS minimum and maximum values, as one would expect. However, CLASS does not include any multiple scattering (*Verseghy et al.*, 1993, *Wang et al.*, 2016). Depending on the sun zenith angle and LAI this may cause inaccuracy to the albedo estimation exceeding 20 % (Fig. 10).



Fig. 11. Modelled broadband black sky albedo of forest with snow on the forest floor as a function of LAI for various latitudes and Julian days for the two sets of leaf single scattering albedo values.



Fig. 12. Ratio of modelled broadband white and black sky albedo values of forest with snow on the forest floor as a function of LAI for various latitudes and Julian days for the two sets of leaf single scattering albedo values.



Fig. 13. Ratio of modelled red (left) and NIR (right) band black sky albedo values without the multiple scattering components of Eqs. 1–2 to the albedo containing all four components of Eqs. 1–4 as a function of LAI for various latitudes and Julian days.



Fig. 14. Comparison of the PARAS albedo model and the CLM4 and CLASS model white-sky albedo estimates as a function of LAI. The leaf single scattering albedo value ω_L was 0.2 for visible and 0.8 for NIR wavelength range. The respective upscatter parameter values used for CLM4 was 0.31 and 0.32. The CLASS model was estimated both for canopy albedo 0.1 (CLASS min) and 0.2 (CLASS max). The canopy was assumed to be snow-free. The snow albedo was 0.83.

5 Conclusions

The multiple scattering between the canopy and snow on the forest floor mostly dominates the total NIR and broadband albedo values of the boreal coniferous forests in winter and is not negligible for the red wavelength range. If this effect is not taken into account, also the ratio of the midday black-sky and white-sky broadband albedo values may deviate largely from the actual value, especially for LAI values smaller than 3. The effect is largest at high latitudes, where the midday sun elevation is low and the canopy small and sparse.

The reflectance/albedo of the forest floor is lower than that of the open areas, even when the canopy consists of very sparsely situated tiny trees or shrubs. In cloudy conditions the mean reflectance of snow pixels decreases linearly with their fraction of all pixels, but in clear sky cases the reflectance decreases more steeply for smaller snow pixel fractions. Yet, the total reflectance decreases also in the clear sky cases essentially linearly with the decreasing snow pixel fraction.

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References

- Betts, A.K. and J.H. Ball, 1997. Albedo over the boreal forest, Journal of Geophysical Research, **102**(D24), 28,901–28,909.
- Bonan, G.B., D. Pollard and S.L. Thompson, 1992. Effects of boreal forest vegetation on global climate, *Nature* **359**, 716–718.
- Breuer, L. and H. Frede, 2003. PlaPaDa an online plant parameter data drill for ecohydrological modelling approaches. <u>https://tinyurl.com/y72amlja</u>.
- Briegleb, B.P., P. Minnis, V. Ramanathan, and E. Harrison, 1986. Comparison of regional clear-sky albedos inferred from satellite observations and models comparisons, J. *Climate Appl. Meteor.*, 25, 214–226.
- GCOS, 2016. The Global Observing System for Climate: Implementation needs, Reference Number GCOS-200, WMO, 315 p.
- Kuusinen, N., P. Kolari, J. Levula, A. Porcar-Castell, P. Stenberg and F. Berninger, 2012. Seasonal variation in boreal pine forest albedo and effects of canopy snow on forest reflectance, Agricultural and Forest Meteorology, 164, 53–60.
- Liang, S., 2000. Narrowband to broadband conversions of land surface albedo. I. Algorithms, Remote Sensing of Environment, **76**, 213–238.
- Lukeš, P., P. Stenberg, M. Rautiainen, M. Mõttus and K.M. Vanhatalo, 2013. Optical properties of leaves and needles for boreal tree species in Europe, *Remote Sensing Letters*, 4(7), 667–676.
- MacQueen, J.B., 1967. Some methods for classification and analysis of multivariate observations. *Proceedings of the Fifth Symposium on Math, Statistics, and Probability* (281–297). Berkeley, C.A: University of California Press
- Manninen, T., L. Korhonen, P. Voipio, P. Lahtinen and P. Stenberg, 2009. Leaf Area Index (LAI) Estimation of Boreal Forest Using Wide Optics Airborne Winter Photos, *Remote Sensing*, 1(4), 1380–1394.
- Manninen, T. and P. Stenberg, 2009. Simulation of the effect of snow-covered forest floor on the total forest albedo, *Agricultural and Forest Meteorology*, **149**, 303–319.
- Manninen, T., L. Korhonen, P. Voipio, P. Lahtinen and P. Stenberg, 2011. Airborne estimation of boreal forest LAI in winter conditions: A test using summer and winter ground truth, *IEEE Transactions on Geoscience and Remote Sensing*, 50(1), 68–74, 10.1109/TGRS.2011.2173939.
- Manninen, T. and J.-L. Roujean (Eds.), 2014. SNORTEX, SNOW REFLECTANCE TRANSITION EXPERIMENT, *Finnish Meteorological Institute, Report* 2014:7, 68 p.
- Manninen, T., 2014. Summary Report of LAI data, Monimet project, LIFE12 ENV/FIN/000409, 25/09/2014, 14 p.
- Metsämäki, S., K. Böttcher, J. Pulliainen, K. Luojus, J. Cohen, M. Takala, O.-P. Mattila, G. Schwaizer, C. Derksen and S. Koponen, 2018. The accuracy of snow meltoff day derived from optical and microwave radiometer data — A study for Europe. Remote Sensing of Environment, 211, 1–12.

- Mõttus, M. and P. Stenberg, 2008. A simple parametrization of canopy reflectance using photon recollision probability, *Remote Sensing of Environment*, **112**, 1545– 1551.
- Oleson, K.W., D.M. Lawrence, B. Gordon, M.G. Flanner, E. Kluzek, J. Peter and X. Zeng, 2010. Technical Description Of Version 4.0 of the Community Land Model (CLM), NCAR Tech. Note NCAR/TN-478 + STR, 257 pp., Natl. Cent. Atmos. Res., Boulder, Colo.
- Panferov, O., Y. Knyazikhin, R.B. Myneni, J. Szarzynski, S. Engwald, K.G. Schnitzler and G. Gravenhorst, 2001. The role of canopy structure in the spectral variation of transmission and absorption of solar radiation in vegetation canopies, *IEEE Transactions on Geoscience and Remote Sensing*, **39**, 241–253.
- Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, C.E. Hanson, 2007. IPCC: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press: Cambridge, London, UK, 976 p.
- Randerson, J.T., H. Liu, M.G. Flanner, S.D. Chambers, Y. Jin, P.G. Hess, G. Pfister, M.C. Mack, K.K. Treseder, L.R. Welp, F.S. Chapin, J.W. Harden, M.L. Goulden, E. Lyons, J.C. Neff, E.A.G. Schuur and C.S. Zender, 2006. The Impact of Boreal Forest Fire on Climate Warming, *Science* 314, 1130–1132.
- Rautiainen, M. and P. Stenberg, 2005. Application of photon recollision probability in coniferous canopy reflectance simulations, *Remote Sensing of Environment*, 96, 98–107. 10.1016/j.rse.2005.02.009.
- Roujean, J.-L., T. Manninen, T. Sukuvaara, J. Peltoniemi, S. Kaasalainen, O. Hautecoeur, P. Lahtinen, A. Riihelä, N. Siljamo, M. Lötjönen, T. Karjalainen, A. Kontu, H. Suokanerva, O. Aulamo, J. Lemmetyinen, J. Suomalainen, T. Hakala, H. Kaartinen, L. Thölix, O. Meinander and J. Karhu, 2010. SNORTEX: Remote sensing measurement of snowmelt in European boreal forest, *iLEAPS Newsletter*, 9, April 2010, 56–58.
- Schaepman-Strub, G., M.E. Schaepman, T.H. Painter, S. Dangel and J.V. Martonchik, 2006, "Reflectance quantities in optical remote sensing—definitions and case studies", *Remote Sensing of Environment*, **103**, 27–42.
- Stenberg, P., 2007. Simple analytical formula for calculating average photon recollision probability in vegetation canopies, *Remote Sensing of Environment*, **109**(2), 221– 224.
- Stenberg, P. and T. Manninen, 2015. The effect of clumping on canopy scattering and its directional properties: a model simulation using spectral invariants, *International Journal of Remote Sensing*, **36**(19–20), 5178–5191.
- Sturm, M., T. Douglas, C. Racine and G.E. Liston, 2005. Changing snow and shrub conditions affect albedo with global implications, *J. Geophys. Res.*, **110**(G01004), 13 p.
- Verseghy, D., N. McFarlane and M. Lazare, 1993. Class—A Canadian land surface scheme for GCMs. II: Vegetation model and coupled runs, *Int. J. Climatol.*, 13, 347–370.

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- Wang, L., J.N.S. Cole, P. Bartlett, D. Verseghy, C. Derksen, R. Brown and K. von Salzen, 2016. Investigating the spread in surface albedo for snow-covered forests in CMIP5 models, *Journal of Geophysical Research: Atmospheres*, 1104–1119, 10.1002/2015JD023824.
- Warren, S.G., 1982. Optical properties of snow, *Reviews of Geophysics and Space Physics*, **20**(1), 67–89.