Evaluating the diffuse attenuation coefficient of dry snow by using an artificial light source

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A novel and non-destructive method is proposed for measuring the diffuse attenuation coefficient \( K_d \) of snow which helps to solve the problem of snow cover disturbance whilst making the measurements. The method is based on the measurement of backscattered upwelling light from an artificial light source above the snow cover. A Monte Carlo model of this measurement system was developed and model runs were made with different sized snow grains. The model produced results that show that the \( K_d \) obtained from the new method is higher than the \( K_d \) that would be obtained using vertical profiles of downwelling irradiance. The coincidence is better for larger grain sizes. A pilot study of the new measurement system was made in Kilpisjärvi in northern Finland in early January 2003. The measurement results for dry snow show that in the visible wavelengths the attenuation coefficients obtained are in reasonable agreement with those obtained using more traditional methods for snow with similar properties. However, in the near infrared the values are much lower.

Introduction

Solar radiation is one of the most important terms in the heat budget of snow. The albedo and the diffuse attenuation coefficient \( K_d \) are the properties of the snow that describe the way in which radiation is available within the snow at each depth. The theory behind the attenuation of light in snow is reasonably well understood (Warren 1982) but due to snow being a mixture of air and ice grains, the attenuation of light in snow is very hard to measure without disturbing the snowcover. Several approaches to this measurement problem exist that disturb the snow to a lesser or a greater extent. The crudest method is to measure the irradiance in the snow from the side of a snow-pit but this method produces the largest disturbance. To reduce its effect, the pit can be covered with snow before the measurements take place. Another way is to set the instruments up before the snowcover forms so the snow can form on top of them. This method needs a lot of time (Perovich 2007) and the snow above the measurement setup is not necessarily in the same state as the surrounding snow cover. A good and widely used way of measuring \( K_d \) is to first measure the attenuation of upwelling radiation by pushing a probe into the snow from above and then deducing the value of \( K_d \) from the obtained profile (Kärkäs et al. 2002,
This method assumes that the upwelling radiance profile is related to the
downwelling irradiance profile at all depths in a well known way. This assumption is accept-
able because after a few centimetres the light
distribution within small grained snow becomes
diffuse. In addition to the diffuse attenuation
coefficient of upwelling light, the value of \(K_d\)
can be deduced from the transmittance, the ratio
of transmitted to incident light, of snow samples
(Beaglehole et al. 1998). The transmittance then
needs to be related to \(K_d\) in some way.

For sea or lake ice, the value of \(K_d\) can
be calculated from under-ice measurements of
irradiance. The instrument can be placed under
the ice and snow without disturbing the snow
(Rasmus et al. 2002). The effect of the ice and
the thin layer of water between the ice and the
instrument can be subtracted from the measured
signal to leave only the effect of the snow cover itself. Recent measurements of the attenuation
coefficient of snow above sea ice have been
made by Hamre et al. (2004). These were made
by measuring the attenuation of light in the snow
covered sea-ice system and fitting a radiative transfer model to the measurements. Haines et al. (1997) used upwelling light from an artificial
light source below the ice to measure the value
of \(K_d\) in sea ice.

All of the above methods make the measure-
ment of \(K_d\) and the construction of time-series of
the same snow very difficult. Only the under-ice
methods are totally non-destructive as far as the
snow being measured directly at the measure-
ment location is concerned. In this study a novel,
totally non-destructive, method for measuring
the \(K_d\) based on the backscattered upwelling light
from an artificial light source above the snow
surface is presented. The method is non-destruc-
tive because the measurement head does not
need to be inserted into the snow. The upwelling
light from the snow depends on the physical
properties of the snow.

Here, a presentation of radiative transfer in
snow is followed by the introduction of a new
measurement concept, and finally its feasibility
is studied using a two dimensional Monte-Carlo
radiative transfer model to simulate the system.
Comparisons between \(K_d\) and the variable value
obtained using the new system are then made.

Then results from a measurement implementa-
tion of the method for dry snow are shown for a
pilot study from Kilpisjärvi in the northwestern
tip of Finland. Comparisons with the measured
\(K_d\) value and values obtained by other authors
using different methods are made.

### Radiative transfer of light in snow

Radiance is the amount of radiative energy inci-
dent per unit time in a unit spectral bandwidth,
per unit area of surface from a solid angle:

\[
L_\lambda(z,\theta,\phi) = \int_l L(z,\theta,\phi) \cos\theta \sin\theta \, d\theta \, d\phi.
\]  

(1)

where \(\theta\) and \(\phi\) are the declination and azimuth
angles describing the direction of the radiation.
The subscript indicates that the quantity has a
wavelength dependence. The subscript will be
left out from this point on but the wavelength
dependence is still implied in all quantities.

\(L\) can be integrated over all directions in a
hemisphere to produce fluxes of radiation. These
fluxes are called irradiances. If \(L\) is integrated
over the upper hemisphere the product is the
downwelling irradiance (\(E_d\)):

\[
E_d(z,\theta,\phi) = \int_0^{\frac{\pi}{2}} \int_0^{2\pi} L(z,\theta,\phi) \cos\theta \sin\theta \, d\theta \, d\phi.
\]  

(2)

Similarly if the integration is made over the
lower hemisphere, the result is the upwelling
irradiance (\(E_u\)):

\[
E_u(z,\theta,\phi) = -\int_0^{\frac{\pi}{2}} \int_0^{\frac{\pi}{2}} L(z,\theta,\phi) \cos\theta \sin\theta \, d\theta \, d\phi.
\]  

(3)

The distribution of radiation within a medium
is described by the radiative transfer equation. In
this equation the radiation in a beam of radiation
decays due to absorption and scattering from the
beam and increases due to emission or scattering
into the beam. The equation can be written in a
simplified form as:

\[
\frac{\partial L(z)}{\partial s} = -cL(z) + \int_0^\Omega \beta L(z') \, d\Omega',
\]  

(4)

where \(c\) is the beam attenuation coefficient, \(\Omega\)
is a solid angle and \(\beta\) is the volume scattering
function. The second term on the right-hand side
in Eq. 4 is a source term related to scattering.
into the beam of radiation. The beam attenuation coefficient is the sum of the absorption and scattering coefficients. The solution to Eq. 4 depends on the boundary conditions and the scattering source term. The boundary conditions depend on the system under consideration but for the top surface it is usually the illumination.

In a horizontally homogeneous snowpack and for a diffuse radiation field, which begins a few centimetres below the surface (Warren 1982), the radiative transfer equation can be reduced to predict exponential decay if the scattering source term is assumed to also decay exponentially. The $K_d$ of light for the downwelling irradiance ($E_d$) can then be calculated. It is:

$$K_d(z) = -\frac{1}{dz} \ln E_d(z),$$

(5)

where $\lambda$ is the wavelength and $z$ is the depth. If the value of $K_d$ is known, then the vertical light profile within the snow can be calculated and used in thermodynamic modelling. If a profile of vertical radiation measurements is available then it can be used to calculate $K_d$ using Eq. 5. Similarly the diffuse attenuation coefficient for upwelling irradiance ($K_u$) can be obtained by using $E_u$ in place of $E_d$ in Eq. 5.

The two most important phenomena that define the ultraviolet (UV), visible (VIS) and near infrared (NIR) radiation distributions within the snowpack are absorption and scattering. For snow, emission does not generally play a major role at these wavelengths of natural light. The absorption coefficient of ice has a minimum in the blue wavelengths and increases as the wavelength both increases and decreases from that waveband value. The increase with wavelength is five orders of magnitude across the solar spectrum from 500 to 2000 nm and two orders of magnitude within the VIS and near UV wavelengths (Warren et al. 2006). Because of this increase, the probability of absorption of photons in the snowpack after multiple-scattering events increases substantially with wavelength. The mean path-length between scattering events of photons at 2000 nm is only 0.1 mm, and so most of the photons that escape from the top of the snowpack at these wavelengths do so after only one scattering event. Whilst this is true in the mean, some photons do propagate onwards into the snowpack after the first scattering event. Across the visible spectrum, the absorption coefficient does vary, but it is so small everywhere that almost no absorption occurs during the transit of light through individual snow grains and so the exiting light consists mostly of photons scattered numerous times in the snow.

Photons enter the snowpack and are scattered around until they are either absorbed or they emerge from the snowpack. Snow grains scatter light in a very strongly anisotropic way with most of the scattering occurring in forward directions. The amount of forward-scattered light becomes larger when the grain size increases. In addition to this, photons that go through coarse-grained snow have to pass through a larger volume of ice between scattering events, and so they have a larger probability of being absorbed. In visible wavelengths, the absorption coefficient of ice is very small, and so this effect becomes much less important.

Forward scattered photons penetrate deep into the snow when they arrive with high incidence angles (e.g. when the solar elevation is high). Many scattering events are required for these photons to eventually escape the snowpack from the top surface. The emerging photons are therefore distributed more uniformly with angle into the upward hemisphere than is the case for lower incidence angles.

**New method for measuring $K_d$**

If the illumination comes from a cone of light (see Figs. 1 and 2) then the boundary conditions of the system become more complicated. The illumination is the top boundary condition up to $x = x_S$ after which there is no light coming from above. The radiation flux passing horizontally through $x_S$ is a boundary condition for the solution beyond $x_S$. The other boundaries are radiating boundaries at the bottom and at the top after $x = x_S$. The snow can be considered infinite in the $x$-direction.

The light entering into the snow after $x = x_S$ would decay as it passes further into the snowpack. A certain portion of it would be absorbed, but the rest would continue until it exits the snowpack at the top or bottom boundary. The radiation leaving the top boundary would there-
fore depend on the absorption and scattering properties of the snow and a certain coincidence between the attenuation coefficient of the horizontal profile of this upwelling light and $K_d$ would be expected. The presence of an open top boundary would mean that a photon in horizontal propagation has a larger probability of exiting the snow cover. This would lead to the decay coefficient for upwelling irradiance in the horizontal direction being larger than $K_d$.

This gives the motivation to define a new variable that describes the horizontal attenuation of upwelling irradiance at the surface. It will be called $K_x$ and will follow the formula for $K_d$ shown in Eq. 5:

$$K_x(x) \equiv -\frac{1}{dx} \ln E_x(x).$$

where $z$ is the depth. In this study, the definition of $K_x$ will be applied after $x = x_S$.

The horizontal profile of upwelling irradiance can be measured without disturbing the snow cover. This means that by measuring the value of $K_x$ and studying the relationships between it and $K_d$, the value of $K_d$ for snow can eventually be deduced in a non-destructive manner.

### Modelling

The system (shown in Figs. 1 and 2) requires a numerical solution to the radiative transfer equation due to the complicated nature of the boundary conditions. A Monte-Carlo numerical approach was chosen because it is capable of coping with them.

#### Monte-Carlo model

Monte-Carlo modelling refers to a technique initially developed by Metropolis and Ulam (1949) to simulate physical processes using a stochastic model. In the case of radiative transfer, it calculates the radiation field using a large number of simulated photons called scatterees that pass through, and interact with, a medium. As an example, the Monte-Carlo method is also rapidly becoming the main way of modelling light transfer in such media as tissue (Prahl et al. 1989). Light et al. (2003) used Monte Carlo modelling to study the light field within the sea ice. In this modelling study, snowpack is assumed to be semi-infinite in the vertical direction, infinite in the $x$-direction, homogeneous and consisting of spherical snow grains. The diameter of the grains is an input variable to the model.

The model calculations start by selecting evenly distributed random numbers $P_n$ in the range [0,1] which are related to model parameters using the following equations. The initial
direction ($\theta_0$) from nadir taken by the scatteree is calculated from:

$$P_i = \frac{2}{\pi} \theta_0 + \frac{1}{2}. \quad (7)$$

The horizontal location of the scatteree on the surface of the snow is fixed by the initial angle and the height of the light source ($H$). No scatteree interactions in the air between the lamp and the surface are allowed to occur.

When the scatteree hits the surface of the snow it travels a distance less than one free length ($L$). $L$ is also the distance between interactions:

$$P_z = \frac{L}{2d}, \quad (8)$$

where $d$ is the diameter of the snow grain. In the parameterization used in this study the maximum free length is assumed to be equal to two times the diameter of the snow grains at nominal snow densities of 400 kg m$^{-3}$. This produces an attenuation coefficient of 500 m$^{-1}$ for grains with a diameter of 1000 µm because $L$ is the reciprocal of $c$ (i.e., $L = c^{-1}$). The free length also decreases with grain size. In dry snow with small grains, the snow is relatively compact and the free space between grains is assumed to be roughly equal to the grain diameter. This parameterization removes the necessity of an a priori assumption of $c$.

The fate of the scatteree at the point of interaction is then decided.

$$P_3 \geq \sigma \rightarrow \text{absorption}. \quad (9)$$

where $\sigma$ is the single scattering albedo which is the ratio of the scattering coefficient to $c$. In this study, $\sigma$ is taken to describe the distribution of scatteree interaction events between scattering and absorption. If it is close to one, then most of the events are scattering events and only a very small amount of interactions are absorption events. This is reflected in the fact that the random numbers are uniformly distributed. If $\sigma$ is close to one it is very improbable that absorption occurs. If absorption does occur, ie the value of $P_3$ is larger than $\sigma$, then the scatteree is terminated and the calculation restarts from Eq. 6 with the next scatteree.

The scattering or declination angle ($\theta$) away from the direction the scatteree is travelling in is then calculated from:

$$P_s = \int_0^\theta \tilde{p}(\theta') d\theta'. \quad (10)$$

where $\tilde{p}$ is the normalised phase function. The phase function determines the probability distribution of the directions into which a photon can be scattered. It is assumed to be symmetrical with regard to the azimuth angle but because this model setup is two-dimensional ($x$-$z$) the scattering direction has to be projected onto the $x$-$z$ plane according to the value of the azimuth angle. This leads to the total projected direction change in the $x$-$z$ plane ($\theta_c$) experienced by the scatteree.

$$\theta_c = \frac{1}{\pi} \arcsin\left(\frac{\theta}{\delta}\right) + \frac{1}{2}, \quad (11)$$

$\theta_c$ is added to the direction in which the scatteree was travelling to get a new propagation direction. Equation 11 is not valid for a scattering angle of 0°, but for this angle the projection does not need to be made.

In this study the Henyey-Greenstein phase function is used:

$$p(\cos\theta) = \sigma \frac{(1 - g^2)}{(1 + g^2 - 2g\cos\theta)^{\frac{3}{2}}}, \quad (12)$$

where $g$ is the asymmetry parameter which is the first moment of the Mie-scattering phase function when it is developed into a series of Legendre polynomials. Equation 12 is normalised to one and used in Eq. 10. In the original study by Henyey and Greenstein (1941) on diffuse radiation in the galaxy, the phase function is related to the spherical albedo. In this study, that has been changed to the single-scattering albedo because the incident light is not isotropic. The exact specifics of the reflectance distribution are not being studied so the use of the Henyey-Greenstein approximation to the phase function is plausible.

The model run starts with the calculation of the initial direction of the scatteree from the point source at height $H$ using Eq. 7. This is used together with $H$ to determine the initial $x$-location on the snow surface. For this study, $H$ is set to a value of 40 cm. The scatteree is then
added to the downwelling flux at the surface. The free length before the first interaction is then calculated using Eq. 8. The next step is to determine whether scattering or absorption occurs. If the scatteree is absorbed then the calculations continued from the beginning with a new scatteree. If the scatteree is scattered then the new propagation direction is calculated by adding the scattering angle obtained from Eqs. 10 and 11 to the old propagation direction. The calculations continue with the calculation of the free length before the next interaction event. At certain depths, the scatteree is added to the downwelling flux, or upwelling flux if it is travelling in the upward direction. If the scatteree exits the snow cover at the top surface, it is added to the upwelling flux at the surface and the calculation continues with a new scatteree. No backscattering from the atmosphere is assumed. In clear-sky cases this assumption is acceptable even though cloudcover considerably increases the chance of a photon being scattered back to the surface. However, the clouds are usually so far away that a photon originating from the artificial light source that exits the snow cover and is scattered from the clouds has very little chance of ending up in the study region again.

The model was run for grain sizes of 50, 200 and 1000 µm and for wavelengths between 300 and 1100 nm with a 100 nm spacing. The parameters \( g \) and \( \sigma \) were taken from the Mie calculations of Wiscombe and Warren (1980). The number of scatterees was set to \( 1 \times 10^5 \) and five runs were made for each combination of parameter values. For 200 µm, the calculations were repeated for \( 1 \times 10^7 \) scatterees but the results were not significantly improved. The half-angle of the lamp opening was set to 45° initially but a second set of model runs were made using an opening of 22.5°. For the second set of runs, Eq. 7 was modified to restrict the initial direction to a smaller range of angles:

\[
P_i = \frac{4}{\pi} \theta_o + \frac{1}{2}.
\]

After the model runs were made, the values of \( K_d \) were calculated by fitting a straight line to the profile of the natural logarithm of the downwelling flux using values up to a depth of ten cm. The value of \( K_u \) was similarly calculated from the upwelling flux values at the surface starting from the edge of the illumination. Only values further than 20 cm away from the centre of the light source in the horizontal direction were used to be sure that the area was not affected by direct downwelling light from the source of scatterees.

**Model results**

The modelling results show that the smallest grains have the highest values of \( K_d \), \( K_u \) and \( K_x \) and the largest differences between \( K_d \) and \( K_x \). The modelled mean \( K_d \), \( K_u \) and \( K_x \) values from the five runs together with the standard deviations (Fig. 3) show that the spectrum for \( K_x \) for 50 µm grains at the highest wavelengths has the highest standard deviation. Snow with grains of 50 µm size is usually not found in boreal regions or in the coastal zone of Antarctica (Kärkäs et al. 2002).

The ratio of \( K_x \) to \( K_d \) becomes closer to unity for larger grain sizes in the visible wavelengths (Fig. 4). In the near infrared, the ratio of \( K_x \) to \( K_d \) becomes almost one for large grains.

The values of the ratios of \( K_u \) to \( K_d \) are one for all grain sizes and all wavelengths (Fig. 4).
The consequence of this is that the deduction of \( K_d \) using upwelling radiation is capable of producing reasonable results.

The model runs for a half-angle lamp opening of 22.5° showed attenuation coefficients that were very similar to the 45° case. The ratios of attenuation coefficients at 22.5° to attenuation coefficients at 45° are close to unity at all wavelengths and all grain sizes (Fig. 5). The ratio is smallest for large grains at short wavelengths. For the smallest grain sizes the two different model runs produced almost identical results. The ratios become unity after 900 nm for all grain sizes.

The ratios of calculated upwelling to downwelling flux can be considered to be equal to the albedo, which is the ratio of \( E_u \) to \( E_d \). The albedo increases as the grain size decreases and decreases as the wavelength increases (Fig. 6). These variations are similar to variations in albedo observed in measurements of dry snow in e.g. Antarctica (Pirazzini 2004, Rasmus 2006). This is an indication that the model can be used to simulate the radiative transfer in the snow.

**Case study**

**Measurement setup**

A pilot study of this measurement setup was made on the snow above the ice of Kilpisjärvi, a lake in northern Finland (69°03′N, 20°50′E) in the late evening in the beginning of January 2003. The air temperature was −30 °C and there was darkness. The snow grains at the site were found to be approximately 1000 µm in length but they were not round, being more needle-like which is not ideal for comparisons with the model. The snow was assumed to be relatively dry.

The snow was illuminated from above using a halogen lamp at a height of 40 cm (Fig. 2). The lamp had a shade to limit the illumination into an angle of approximately 40°. This is five degrees less than in the model runs but due to the width of the real lamp it was not a genuine point source and some light was emitted outside the lamp opening. The lamp spectrum was continuous in the visible and near infrared wavelengths.
The irradiance measurements were made using a Li-Cor LI1800UW spectroradiometer. The LI1800UW is a good instrument for this kind of measurement because it scans the whole spectrum of radiation with one photodiode using a rotating bandpass filter and a rotating interference filter to split the irradiance into wavebands with a resolution of 6 nm. This makes it very sensitive to small radiation values. The integration time of the instrument was 40 s for the whole spectrum between 300 and 1100 nm. In this study the length of the integration time was not a problem because the light source was constant. It was actually a benefit because of the low light levels. A remote cosine corrector fitted to the end of a fibre-optic cable was used to make the measurements directly at the surface.

The downwelling irradiance was measured below the light source and then the upwelling irradiance was measured at 0, 25, 50 and 100 cm away from the centre of the light source. Two spectra of light were measured at each location. Only digital numbers (DN) were used in the calculations because only relative values of irradiance were of interest.

**Measurement results**

The downwelling and upwelling surface fluxes at point 0 (under the light source) together with the upwelling surface fluxes at three points going away from the light source show that the spectra are evenly spaced between 0 and 50 cm (Fig. 7). This indicates exponential decrease for the evenly spaced (in $x$) spectra. At 100 cm away from the light source the decrease is no longer the same because the change in $x$ is double to that of the previous steps. The instrument is already close to its digital resolution so this could be a reason for the change in $K_x$ values. Other sources of error include the spatial variations in the illumination due to the non-ideal shape of the lamp and the shape of the grains being non-spherical.

Equation 6 was used to calculate the values of $K_x$ for the different steps. They are almost independent of wavelength in the visible band and the near infrared (Fig. 8). The $K_d$ for the 0–25 cm step shows a slight increase towards the longer wavelengths following the shape of ice absorption.

**Discussion**

According to the Monte Carlo modelling results, the value of $K_x$ is larger than the $K_d$ for the chosen lamp geometry. The overestimation is largest for the smallest grains. This is because of the higher
probability for photon escape into the atmosphere whilst in horizontal propagation due to the constant presence of the open top snow surface.

Photons entering the snowpack at the edge of the illuminated area do so at a larger zenith angle. Therefore, as the large grains scatter them mainly in a forward direction they have a good chance of escaping the snowpack further away from the light source after a few scattering events. Photons are scattered more diffusely from small grains and so they are more likely to emerge from the snowpack closer to the light source. The results for the smallest grains show that the effect of making the lamp opening smaller is negligible. However for larger grains, making the opening smaller, and thus making the zenith angle of the incident photons smaller, has a dramatic effect at short wavelengths. The value of $K_d$ is almost halved. Photons approach the surface of the snow at a steep angle, penetrate deep into the snowpack and have a very small chance of escaping from the snowpack again.

The 200 µm modelled values of $K_x$ correspond to those measured by Beaglehole et al. (1998) for $K_d$. They deduced $K_d$ from transmission values and obtained values between 12 and 30 m⁻¹ at 400 nm and between 20 and 35 m⁻¹ at 700 nm for Antarctic snow.

The attenuation coefficient obtained for a mean snow grain size of 1000 µm measured in the coastal zone of Antarctica at 470 nm using a vertical profile of upwelling radiance was found to be 11 m⁻¹ (Kärkäs et al. 2002). The measurement results for the value of $K_x$ obtained in this study are approximately half of that value as are the modelled results for 1000 µm grains. The modelled $K_x$ values at 200 µm were however the same as in the measurements of Kärkäs et al. (2002). The grain size measurement in Kärkäs et al. (2002) was based on a small sample size and the grain size measurements are probably an overestimation of the real grain size.

The measurement results from the pilot study show a reasonable coincidence with the attenuation coefficient results of Warren et al. (2006) between wavelengths of 300 and 600 nm. They sampled Antarctic snow with a grain size of between 50 and 200 µm. The snow in the pilot study had larger grains which should produce a lower attenuation coefficient. The measured attenuation coefficient in this study seems to underestimate the value of $K_d$. Measurement results in this study could be affected by impurities within the snowpack whilst Warren et al. (2006) made their measurements in clean Antarctic snow. Even though the snow is visually devoid of impurities, they can be present in concentrations too small to be visible by the naked eye. Even these small concentrations can have had an effect on the results.

The measured $K_x$ values are much less than values of $K_d$ for snow obtained by Hamre et al. (2004). Their measurements were of snow above a sea-ice cover and the calculations were made by measuring the light transmitted through the whole snow–sea-ice system and removing the effect of sea ice. This is a totally different type of environment so the comparison is not trivial to make. For example, shallow snow on sea ice is subject to brine and heat from the sea ice below.

In the visible wavelengths, the measured values of $K_x$ are slightly lower than the values for new snow measured by Perovich (2007) but the spectral shape is not the same. In the near infrared wavelengths the measured values from this study are much lower.

This method of deducing $K_d$ from measurements of $K_x$ is totally non-destructive on dry
snow and so the same snow can be sampled repeatedly. This makes the construction of time-series of \( K_d \) of the same snow possible to construct. The measurements in this study are the first such measurements of the upwelling light of an artificial light source from snow. The measurement setup requires relative darkness, or very sensitive instruments, which can limit its usefulness on measurement campaigns to for example Antarctica during the Austral summer.

The model results show that the method presented could be a new way to calculate the \( K_d \) of snow. The measurements in this study represent a pilot study of the method but still show that the method produces values of \( K_s \) which are broadly similar to those of \( K_d \). More measurements, maybe with different illumination geometries, are required before a firmer conclusion can be made.

**Conclusions**

In this study a new, non-destructive method for measuring light attenuation in snow was proposed. The method requires a horizontal surface profile of upwelling irradiance from a conical artificial light source from which \( K_d \) can be deduced. Modelling results from a Monte Carlo radiative transfer model and measurement results for one dry snow location in Finland were presented. The model results show that \( K_d \) obtained from the new method is higher than \( K_d \) that would be obtained using vertical profiles of \( E_d \) at all wavelengths. The coincidence between the two different values of \( K_d \) becomes better for larger grain sizes. For large grain sizes, smaller values of \( K_d \) for upwelling and downwelling radiation are produced when the opening of the lamp is made smaller. The \( K_s \) value did not show any sensitivity to the opening angle of the lamp. In the visible wavelengths the results show that the measured \( K_s \) values obtained were in reasonable accordance with \( K_d \) values obtained by other authors for snow with similar properties. In the near infrared the measured results were too low but the method produces an overestimated value for the value of \( K_d \) in the visible wavelengths. More measurement results are required to make a firm conclusion of the validity of the method. The measurements in this study are the first measurements of the upwelling light produced by an artificial light source in snow.

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