Snow Characterization by Optical Properties

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ABSTRACT: Snow optics offers an opportunity to measure physical properties of a vertical snow profile or a snow surface by unbiased, high-resolution and time-saving scientific methods. Thus, optical measurements could play an important role in various areas of interest to the snow science community, snow sports industry and recreational snow enthusiasts. Snowpack stability strongly depends on the distribution of ice mass inside the snow cover, hence on density and snow microstructure. Grain size, density and soot content impact energy transfer within the snowpack, since fine-grained snow reflects more incident radiation, while higher density and soot content imply a stronger absorption of radiation within the same snow volume. Furthermore, snow grain size and density contribute significantly to the gliding characteristics of a ski as those properties determine the contact area and thus friction at the ski-snow surface interface. We will give a summary of the theory behind measuring optical snow properties and stress major points of interest. Current methods for quantifying grain size will be presented. We also demonstrate the possibility to deduce snow density from optical measurements.

KEYWORDS: optical properties, reflectance, transmittance, grain size, density

1 INTRODUCTION

Snow microstructure near the snow surface determines the radiation balance between atmosphere and ground due to its impact on reflection of solar radiation (Wiscombe and Warren, 1980; Kuipers Munneke et al., 2009). It also has a great effect on mechanical interactions at the snow surface like ski gliding characteristics (Theile et al., 2009; Fauve et al., 2004; Colbeck, 1992). Furthermore, the distribution of snow properties in the entire snow cover plays a major role in avalanche formation (Schweizer et al., 2003). Important snow properties are traditionally estimated by manual tests. Methods and interpretation of the results are strongly dependent on the observer's experience level and thus subjective (Painter et al., 2007; Pielmeier and Schneebeli, 2003). Plus, they are biased in the sense that two measurements of equally skilled observers will generally not produce the same distribution of density, grain size and shape and other snow characteristics, which are usually recorded in a detailed snow profile in the field.

Micro-computed tomography (micro-ct) offers a means for a quantitative and objective analysis of snow samples in a cold laboratory (Schneebeli and Sokratov, 2004; Kerbrat et al., 2008). However, tested samples are limited in size to a few mm^3, and measurement and processing times are several hours and more. For in-situ analysis in the field micro-ct is not a viable option, either.

Snow methane adsorption can be used to measure snow specific surface area (SSA, ratio of ice surface area to ice volume in snow) at 77 K in a laboratory (Legagneux et al., 2002; Domine et al., 2007). This method is not applicable in the field due to its time requirements and the need for liquid nitrogen.

In recent years, several methods have been explored to derive snow properties from optical measurements. They all share a common measurement principle: For a sufficiently thick snow block diffuse reflectance at near-infrared (NIR) wavelengths is determined by specific surface area, which is equivalent to an optical grain size (Zhou et al., 2003; Grenfell and Warren, 1999; Wiscombe and Warren, 1980). This relation will be clarified in the next section. The methods are: Near-infrared photography (Matzl and Schneebeli, 2006), InfraSnow (Hug and Trunz, 2006; Frost, 2008), contact spectroscopy (Painter et al., 2007) and an integrating sphere setup (Gallet et al., 2009). Optical measurements should not only be limited to determine SSA/grain size. For a known SSA, it should be possible to deduce snow density from NIR transmittance measurements. Warren et al. (2006) and Beaglehole et al. (1998) already measured light transmittance in snow. However, they were not interested in determining snow

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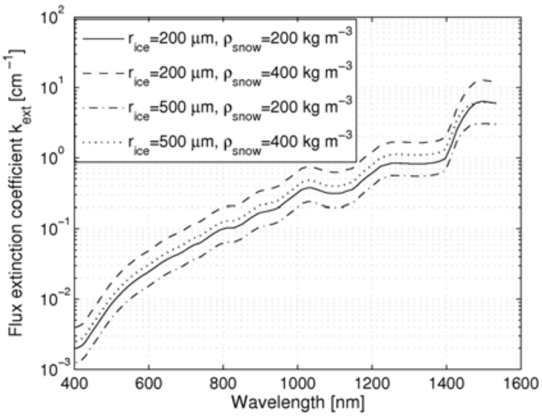

Figure 1. Flux extinction coefficients for two snow grain radii and two densities each, according to Equation 1. The denser the snow and the smaller the grains the greater the flux extinction.

density. Warren et al. derived ice absorption coefficients for visible light, and Beaglehole et al. focused on a general qualitative study of scattering parameters.

2 THEORY OVERVIEW

While light transfer in snow has to be analyzed with a multiple-scattering theory, understanding a single scattering event is vital for a later discussion of multiple-scattering effects. In light scattering theory every interaction between an incident light beam and scattering medium results in scattered and absorbed light. Light whose path is not altered by the interaction is called transmitted. All light that has been absorbed or scattered out of the direction of incidence (scattering angle other than 0°) is called extinct. This is described by the extinction coefficient (μ_{ext}), which is simply the sum of scattering and absorption coefficient (μ_{scat} and μ_{abs} , respectively). The ratio of μ_{scat} to μ_{ext} is the single scattering albedo ω, i.e. the scattered fraction of all light extinction for one interaction event. Another important single-scattering parameter is the asymmetry parameter g, which is the mean cosine of the scattering angle (g close to one implies strong forward-scattering and values close to –1 strong backward scattering).

It has been shown that a real 3D snow structure is best modelled as a collection of spheres with the same specific surface area (Grenfell and Warren, 1999). The radius of those spheres is the equivalent grain radius of this snow. For spherical scattering particles, Mie theory can be applied to derive all single-scattering parameters. This is possible since grain centers (scattering events) are far apart from each other and thus, near-field effects can be neglected (Wiscombe and Warren, 1980). Additionally, all types of natural snow are not composed of only one specific grain shape, but contain a variety of shapes (Picard et al., 2009).

The actual deviations from a spherical grain shape should then not play an important role for multiple scattering in snow, since effects of non-sphericity should average out over multiple scattering events.

Within the single-scattering theory, light wavelength λ, snow equivalent grain radius r_{ice} , density ρ_{snow} and soot content determine the optical behavior of snow. The influence of soot content decreases at NIR wavelengths while the influence of grain size rapidly increases (Wiscombe and Warren, 1980; Warren and Wiscombe, 1980). An extension to multiple-scattering theory for real snow leads to a modification of the single-scattering parameters but does not change the fundamental dependencies. The flux extinction coefficient k_{ext} of diffuse incident light far from any boundaries (far from top, bottom and sides of a snow block) can then be written as a combination of the single-scattering parameters extinction coefficient, albedo and asymmetry parameter (Bohren, 1987; Warren et al., 2006):

$$k_{ext} = \mu_{ext} [(1 - \omega)(1 - \omega g)]^{1/2} , \qquad (1)$$

with

$$\mu_{ext} = f(r_{ice},\lambda)\ (\rho_{snow} / \rho_{ice})\ r_{ice} \qquad (2)$$

and $f(r_{ice},\lambda)$ being a function of grain size and wavelength, calculated by Mie theory; $\rho_{ice} \sim 917$ kg / m^3 is the density of ice.

Transmittance T of a diffuse flux inside a snow block over a distance d is

$$T = \exp(- k_{ext}\ d) . \qquad (3)$$

Reflectance and transmittance of a snow block at a known NIR wavelength then depend only on grain size and snow density via the flux extinction coefficient (Figure 1). The dependence of diffuse reflectance on snow density vanishes for sufficiently thick homogeneous snow blocks. However, this snow depth where the semi-infinite limit of diffuse reflectance is reached does depend on snow density (Figure 2).

The denser the snow the faster the semi-infinite limit is reached. In the visible and NIR spectrum the semi-infinite depth for natural snow is on the order of 1 cm to about 50 cm. Grain size is then the only unknown parameter of the employed scattering model, and measurements of semi-infinite diffuse reflectance can directly yield the optically equivalent grain radius.

Once grain size is measured, snow density is the sole remaining unknown parameter of NIR light scattering measurements and can then be determined uniquely. This can be done by fitting the modelled diffuse transmittance of a snow slab from radiative transfer models like DISORT (Stamnes et al., 1988) or the asymptotic flux extinction coefficient k_{ext} (by Equation 3) to the measured diffuse transmittance.

Finally, one could perform transmittance or reflectance measurements at visible wavelengths to extend the optical characterization of the tested snow block to include impurity effects like soot content: As the absorption coefficient of soot particles is many orders of magnitude larger than absorption in ice for visible light (Aoki et al., 2000; Warren, 1982), both reflectance and transmittance change drastically with already small amounts of soot present in snow.

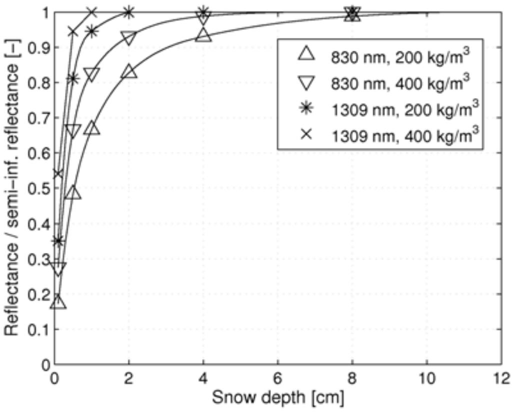

Figure 2. Semi-infinite snow depth is reached once reflectance equals semi-infinite reflectance. An increase in density merely causes a corresponding linear decrease in semi-infinite snow depth.

3 EXPERIMENTAL METHODS

3.1 Grain size measurements

Current optical methods for snow characterization in the laboratory and in the field exclusively focus on measuring SSA, i.e. equivalent grain size as described in Section 2.

Gallet et al. (2009), developed an integrating sphere setup with collimated incident laser diode light to measure the diffuse reflectance of small snow samples (~ 20 cm^3 volume). They suggest two light sources: One at 1310 nm to probe high-density snow with low SSA and one at 1550 nm for low-density, high-SSA snow types. They report a measurement precision of about 10% for both cases. Wavelengths were chosen according to snow reflectance-to-SSA correlation considerations (Domine et al., 2006) and availability. This method has been shown to also deliver good results in the field once the equipment is set up at the test site.

Another method is proposed by Painter et al. (2007), using a stable halogen light at a fixed incident angle and a spectrometer to record reflectance spectra. They deduced optical snow grain size from the ice absorption feature near 1000 nm (Nolin and Dozier, 2000). Ambient stray light (solar radiation) effects are minimized by attaching spectrometer sensor and light source to a rigid spacer. This also keeps distance and position of the sensor and light source constant relative to the snow. Spatial resolution of their method is as high as 3 cm on a smooth snow profile wall. They estimate their measurement accuracy to be 100 µm, which is about the grain size of fresh to freshly decomposed snow. For older snow types, 100 µm can correspond to a measurement variation of as low as under 10%.

Matzl and Schneebeli (2006) took pictures of snow pit walls with a digital camera equipped with a visible light blocking filter to only detect NIR light from 840 nm to 940 nm. They calibrated recorded reflectances with stereological SSA measurements of casted samples of various snow samples. With a correct normalization of measured intensities in the field, the images then yield SSA/grain size data with a spatial resolution of a few mms. Measurement accuracy for this method is given at 15% if diffuse lighting is guaranteed (either by a cloud-covered sky or by draping a diffusing cover over the snow pit).

These three methods focus on snow pit analysis as field application. In contrast to this, measuring snow grain size near the surface, where mechanical interactions take place, is the purpose of the InfraSnow device. It is a portable, hand-held instrument essentially consisting of an internal light source of 950 nm wavelength, integrating sphere detector and microcontroller for immediate grain size calculations from reflectance measurements (Hug and Trunz, 2006; Frost, 2008). It has a measuring footprint of 3.5 cm in diameter. A good accuracy of about 25% was achieved for a number of grain size measurements, compared to micro-ct reference measurements. However, significant deviations of more than 50% were also encountered due to specularly reflected light at the snow surface and possible stray light effects on a rough snow surface. While inherent properties of snow (like small-scale heterogeneities) and the above-mentioned effects at the snow surface can complicate an interpretation of the measurement results, the InfraSnow shows a very high reproducibility and accuracy (less than 1% variation in reflectance) on smooth diffusely reflecting surfaces like a Spectralon reflectance standard.

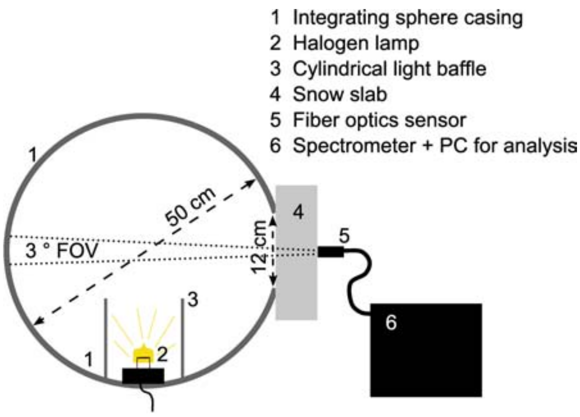

Figure 3. Integrating sphere measurement setup for diffuse transmittance measurements. Only diffuse light illuminates the snow slab. Used snow slab thickness ranges from 2 cm to 8 cm.

3.2 Density measurements

For our density measurements in the laboratory we use an integrating sphere with a halogen light bulb as diffuse light source, which illuminates an area of 12.5 cm diameter of a snow slab with a thickness between 2 and 8 cm (Figure 3). Transmittance spectra are recorded with an ASD VNIR spectrometer at 3° field of view (FOV).

Snow slabs are about 20 x 20 cm^2, so flux within the entire field of view should remain diffuse and boundary effects should not influence measurements for a snow slab thickness of at least 6 cm and less (Beaglehole et al., 1998).

We also measured transmittance values of a natural snowpack as described in Warren et al. (2006). This method involves measuring diffuse upward fluxes inside the snowpack from the top down in 1 cm increments at 25° FOV.

An analysis of both methods showed that measured extinction was substantially larger than extinction values which were calculated from Equations 1 to 3 with known specific surface area and density from micro-ct measurements. Figure 4 shows an exemplary result of our laboratory measurements at two NIR wavelengths, compared to theoretical calculations by the flux extinction coefficient and to DISORT simulations. A reason for the strong deviations between experimentally determined and calculated (Equation 3) transmittances could be that the semi-infinite approximation, i.e. independency from boundary effects, is not valid at the probed snow depths. This is surprising since according to previously mentioned studies, light transfer in snow should become diffuse within the top few cm in the NIR due to the strong scattering. At least for our measurements of upward diffuse fluxes in the field, this assumption should be a valid approximation.

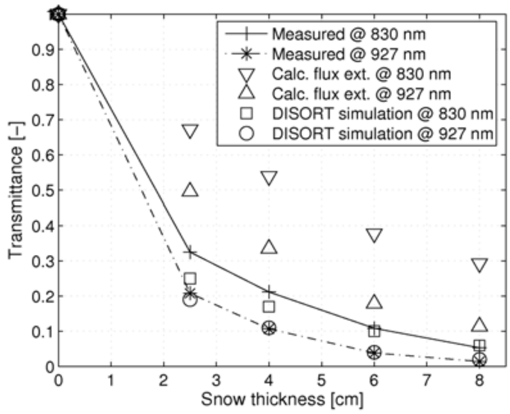

Figure 4. Measured and modelled transmittances at two NIR wavelengths. DISORT calculations fit the measured values considerably better than the transmittances calculated from Equation 3.

When calculating transmittance with the DISORT code, a significantly better agreement between measurements and calculations is evident. DISORT ignores boundary effects like limited lateral snow block extension, but, in contrast to the semi-infinite flux extinction, it does include the effects of a finite snow slab thickness in the analysis.

4 CONCLUSIONS

Scattering theory and current experimental methods provide a basis for quantitative snow characterization by optical properties. SSA/grain size has been derived successfully from diffuse reflectance measurements by various experimental setups in the laboratory and in the field. Transmittance measurements are scarce and we still lack an accurate interpretation to use them for snow density analyses. Nevertheless, with more-refined methods, which are less dependent on boundary effects and more easily implemented in scattering calculations, agreement between experimental results and model calculations improved greatly. We have presented one such case for a good match between measured diffuse NIR light transmittance for snow slabs and modelled transmittance with DISORT.

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