Annals of Glaciology 26 1998

Hemispherical–directional reflectance measurements of natural snow in the 0.9–1.45 μm spectral range: comparison with adding–doubling modelling

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ABSTRACT. The authors present the results of snow hemispherical–directional reflectance measurements on natural snow in the 0.9–1.45 μm spectral range. The measurements were made in a cold laboratory on snow collected in the field. Some of the samples have been subjected to controlled metamorphism in the laboratory before measurements were made. In the first part, the adding–doubling model, experimental assumptions and methodology are described. In the second part, experimental results are discussed and compared with theoretical values for different typical snow types and for different stages of snow evolution when subjected to temperature-gradient and wetness metamorphisms.

INTRODUCTION

Snow reflectance is an important climatic parameter and is of great interest in the fields of glaciology, climatology, meteorology and avalanche forecasting. Large snow-covered areas, such as the polar ice sheets, play an important role in the Earth–atmosphere global change (Grenfell and others, 1994). Moreover, snow-cover evolution is strongly dependent on its heat exchange with the atmosphere and especially on solar radiation, which is its main energy source. Thus, knowledge of the optical properties of snow is fundamental to energy-balance calculations, particularly for physical modelling of snow-cover evolution. In order to improve avalanche forecasting tools, the Centre d'Études de la Neige has developed an appropriate model (Brun and others, 1989). Theoretical models of the optical parameters of snow exist but they have been based generally on a spherical representation of snow grains which is quite unrealistic. In addition, available experimental data are incomplete and do not adequately describe the physical features of snow such as grain-size, shape or impurity content. So, it was necessary to make experimental measurements in order to obtain optical-parameter values for natural snow. Therefore, we performed cold-laboratory measurements of snow reflectances for different natural snow types. For each snow sample investigated, an objective size factor was measured and a chemical analysis of the carbon-soot content was also made. Measurements have been conducted over the last 6 years on natural snow collected in the Alps surrounding Grenoble. In the first campaign, we obtained reflectances in the 0.4–1 μm spectral range (Sergent and others, 1993) and, in the second one, in the 0.9–1.45 μm spectral range.

The polar ice sheets are not easily accessible for in-situ measurements and the use of remote sensing may be best for monitoring such large areas. Inversion methods for reflectance measurements are needed to recover the physical features of the snow cover. Field and laboratory measurements contribute to snow-reflectance-modelling validation by improving knowledge of the dependence of snow reflectance on the physical and optical properties of the snow. Our purpose has been to develop a reflectance model based on radiative-transfer theory and on the physical and optical features of snow, and to compare the results with observations. Snow grains are assumed to be isolated spherical or hexagonal ice particles. Single scattering is based on Mie scattering and on ray-tracing theory. Multiple scattering is calculated by using adding–doubling modelling (De Haan and others, 1987). The physical features used for modelling are snow grain-size and shape, the ice-refractive index and the carbon-soot content. The model calculates spectral reflectances and the polarization of reflected radiation. This paper presents some results from the second laboratory reflectance-measurements campaign in the 0.9–1.45 μm spectral range. These data are compared with the adding–doubling modelling and the results are discussed.

SNOW-REFLECTANCE MODELLING

The models commonly used to retrieve snow reflectance are based on radiative-transfer theory and have been reviewed by Warren (1982). In these, snow grains are represented by spheres and their single-scattering parameters are deduced from Mie theory assuming independent scattering. Once single-scattering parameters are computed, multiple scattering which occurs in the entire snowpack can be simulated by various methods: the two-stream approximation (Dunkle and Bevans, 1956; Giddings and LaChapelle, 1961; Bohren, 1987), the Delta–Eddington method (Wiscombe and Warren, 1980; Choudhury and Chang, 1981), the discrete-ordinate method (Stamnes and others, 1988) or the adding–doubling method. We used the adding–doubling code of the Department of Astronomy of the Free University of Amster-

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https://doi.org/10.3189/1998AoG26-1-59-63 Published online by Cambridge University Press

dam for our study. As with the discrete-ordinate method, it is a numerical method which determines bidirectional reflectance (needed for interpretation of remote-sensing data) and the polarization of reflected radiation which can also help with the discrimination of snow/clouds (Goloub and others, 1992). Bidirectional reflectance is defined as the ratio of the radiance scattered by a surface in a given direction to the collimated power incident on unit area of the surface (Hapke, 1993). Bidirectional reflectance and polarization are not fundamental to the present study but may be necessary for other snow-reflectance applications.

Single-scattering modelling

When spherical or hemispherical–directional reflectances are investigated, approximation of spherical particles can be made but is no longer suitable for snow bidirectional applications in the middle infrared (Leroux and others, 1996). According to Hapke (1993), hemispherical–directional reflectance is the fraction of light scattered in a direction by a surface illuminated from above by hemispheric light. By integrating the scattered light in all directions of the upward hemisphere, we get the bihemispherical reflectance, also called, spherical reflectance. In fact, for large wavelengths, bidirectional reflectance is very sensitive to the single-scattering parameters especially the phase function, the behaviour of which is strongly linked to snow-grain shape. When spherical reflectance is considered, directional effects are smoothed by integrations over incident or reflected directions. In this paper, we compare model simulations with hemispherical–directional observations and assume a spherical shape for snow grains. Single-scattering parameters are derived from Mie computations. Independent scattering is assumed because in the solar spectrum the particles and the mean free paths between particles are large enough to be compared with the wavelength.

Because of the large anisotropy of the snow scattering, we had to modify the Mie theory for snowpack studies. For that reason, we truncated the forward peak of the phase function for a sphere using a delta approximation (Lenoble, 1993). In the near and middle infrared, because absorption of ice is dominant over absorption by soot components, we only consider the effect of snow grain-size and shape on reflectance. In our model, we incorporated the spectral-absorption coefficients of pure ice as tabulated by Warren (1984) and Kou and others (1993).

Adding–doubling modelling

The adding–doubling method was introduced by van de Hulst (1963) and extended to polarization by Hovenier (1971). It was largely adopted to determine the reflectance and transmission properties of plane parallel atmospheres.

If one considers two homogeneous plane parallel layers, one placed on top of the other and solar illumination reaching the top layer, the adding scheme states that the reflectance of the combined layer composed of two layers can be obtained from the same known properties of the separate layers. One starts with very thin layers where the single-scattering parameters are introduced. When the layers are identical, the adding method is called the doubling method. The code we used (De Haan and others, 1987) gives the bidirectional, the spherical and the hemispherical–directional reflectances. For comparison with measurements made in the laboratory, we are interested in the latter quantity.

EXPERIMENTAL APPARATUS AND METHODOLOGY

The experimental device (Fig. 1) was built to measure the hemispherical–directional reflectance of snow, considered as a semi infinite medium. Snow samples are under diffuse illumination from an integrating sphere and a quartz halogen light. A collimating lens collects the backscattered light from the snow sample in front of the snow sample (the viewing angle is $\theta = 0°$). The collected flux is transmitted through an optic fiber to the grating monochromator. Moreover, the snow samplers are large enough to be in accordance with the semi-infinite medium assumption. The diameter of 145 mm and the inner coating, made with a high-reflectance product (0.99 on the working spectral range) allow horizontal infinity of the snow. A length of 250 mm is more than the e-folding distance for flux extinction in the 0.9–1.45 μm spectral range (vs unpublished tables of Warren, at 0.9 μm, this distance is 16 mm for snow with a density of about 300 kg m^{-3}).

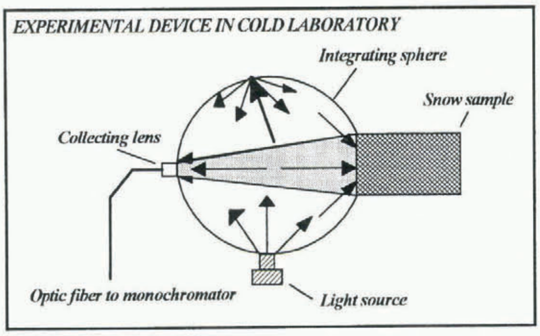

Fig. 1. Plan view of the experimental device located in the cold laboratory.

For the second measurement campaign, covering the 0.9–1.45 μm spectral range, the experimental device, formerly built to work in the 0.4–1 μm range, was slightly modified. The output of the monochromator was fitted with a photovoltaic detector (Ingaas) and the calibration of the whole device was carried out using a set of six reflectance standards (about 99, 80, 60, 40, 20 and 2%). The uncertainty of the measurements (which depends on the calibration errors) is smaller than 3% in the 0.9–1.35 μm spectral range and reaches 7% beyond the 1.35 μm wavelength.

Investigated snow samples were collected from a natural snowfield in appropriate homogeneous snow layers. Some of the snow samples were made directly from these types of snow and others were made from collected snow subjected to controlled metamorphism in a cold laboratory. For each snow sample, the measured physical features are snow density, mean convex radius of the snow grains and carbon-soot content. The mean convex radius of the snow grains was obtained from an image-analysis system. This parameter is defined as the inverse of the mean curvature of the grain contour. The curvature is computed in each pixel of the grain periphery. Each mean convex radius was obtained from a 40–60 snow-grain sample. The mean convex radius gives a rather good idea of the snow grain-size, especially for rounded grains, and is moreover an objective way of deter-

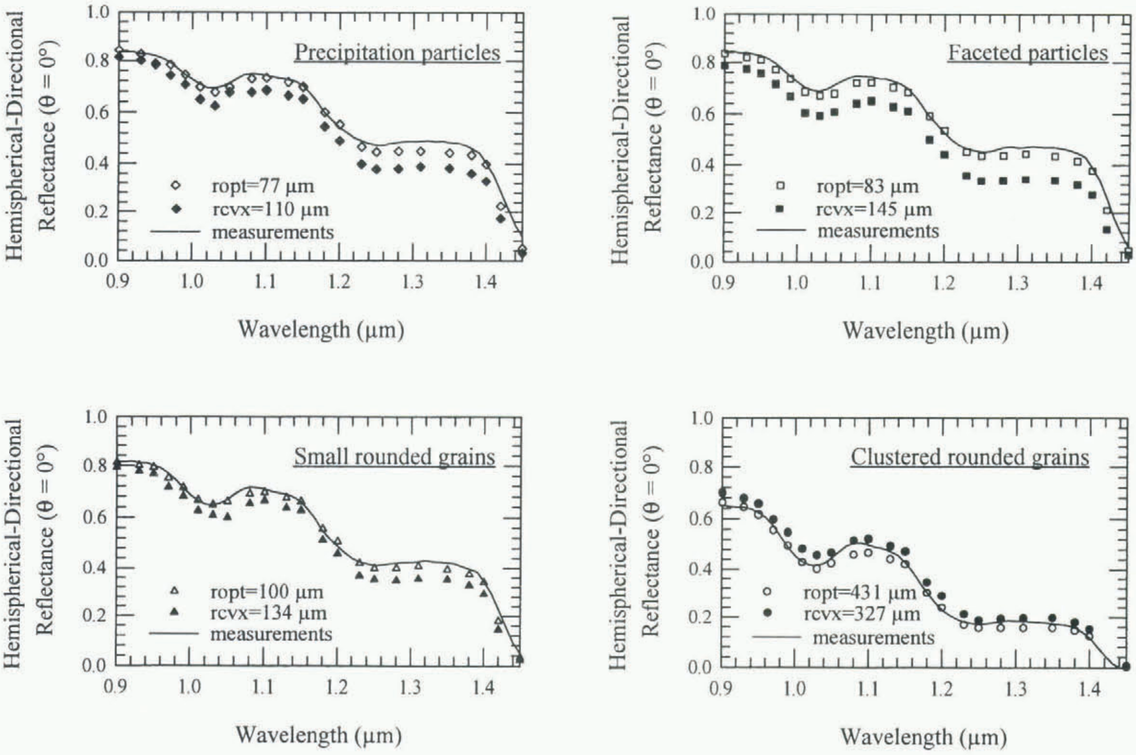

Fig. 2. Snow hemispherical–directional reflectance curves for four different snow types. Comparisons between measurements (solid lines) and adding–doubling model simulations (open and solid symbols). (rcvx) is for the mean convex radius and (ropt) for the optical radius.

mining the snow grain-size factor. The carbon-soot content of each snow sample was measured by Coulometric titration (Cachier and others, 1989) with the assistance of the Centre des Faibles Radioactivités of Gif-sur-Yvette.

RESULTS

In this section we compare laboratory hemispherical–directional reflectance measurements with model simulations for homogeneous snow samples in the 0.9–1.45 μm band. Initially, we focus on the effect of snow-grain type on reflectance, then, we study snow-grain metamorphism under temperature-gradient and wetness conditions.

Snow-type effect on the reflectance

The snow-cover stratigraphy (snow grain-size and type) is one of the parameters which govern the mechanical equilibrium of the snow cover (Brun and others, 1989). Our purpose was to check that the model could reproduce the snow reflectance behaviour vs different snow types.

The hemispherical–directional reflectance measurements and model results are shown in Figure 2 for four snow types: precipitation particles, faceted crystals, small rounded grains and clustered rounded grains (Fig. 3; Table 1).

As expected, snow reflectance decreases with wavelength and reaches its lowest values in the strong ice-absorption bands. Both model and observations are sensitive to snow-grain type. The larger the grain-size, the smaller the reflectance. Maximum reflectances were observed for precipitation and faceted particles (mean convex radius: 110 and 145 μm) and minimum values for clustered rounded grains (mean convex radius: 327 μm).

To validate the adding–doubling model, we first entered directly into the model the mean convex radius (rcvx) determined by digitizing the snow samples (previously detailed). The results are represented by solid symbols in Figure 2. Except for clustered rounded grains, where measurements and simulations are in a somewhat good agreement, the theoretical reflectance from adding–doubling is

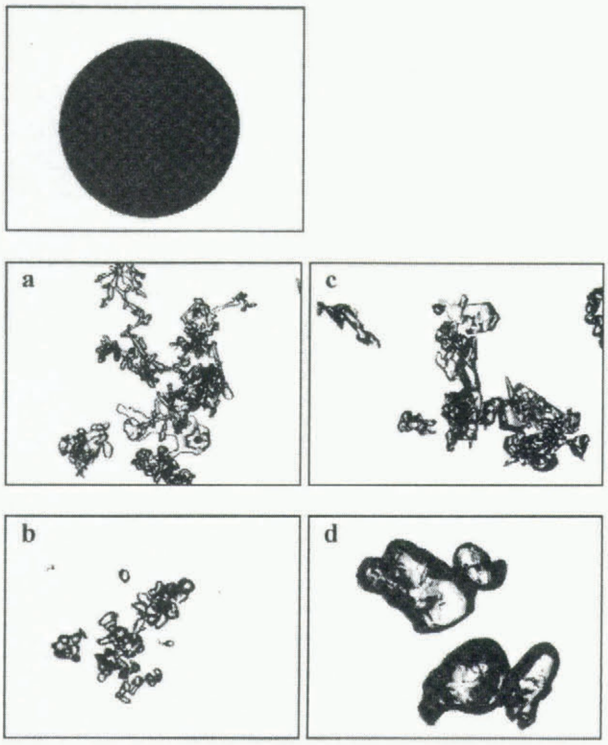

Fig. 3. Snow-grain pictures of the different snow types used in this investigation. (a) Fragmented precipitation particles; (b) small rounded particles; (c) faceted crystals; (d) clustered rounded grains. The scale is given by the upper ball (3 mm diameter) which is used for the mean convex radius computation.

https://doi.org/10.3189/1998AoG26-1-59-63 Published online by Cambridge University Press

smaller than the observations and does not match the measurement curves. In an effort to improve the agreement between measurements and theory, we introduced a new size parameter called the optical radius defined as the spherical radius which gives the same reflectance as the measured one in the 0.98–1 μm band. We selected the centred 0.99 μm wavelength to determine the optical radius, because it is present both in the 0.9–1.45 μm band and in the 0.4–1 μm band where previous data were collected by the authors (Sergent and others, 1993).

Table 1. Physical features of the different snow types investigated

Snow type	*Snow density* Mg m^{-3}	*Mean convex radius* μm	*Adding–doubling radius* μm	*Carbon-soot content* ppmw
Fragmented precipitation particles	0.114	110	77	0.077
Faceted particles	0.230	145	83	0.034
Small rounded grains	0.325	134	100	0.044
Clustered rounded grains	0.529	327	431	0.216

The theoretical curves with optical radius and the observed data for all the four snow types are in good agreement (Fig. 2). The difference between the model results and the measurements is very low in the near infrared (less than 2%) but becomes larger in the strong ice-absorption bands (5–10%). The discrepancy between measurements and model simulations is mainly due to the measurement uncertainty and the errors in the measured absorption coefficient of ice used in the modelling. In conclusion, the model should be able to take into account the dependence of the reflectance on the snow-cover stratigraphy.

Temperature-gradient and wetness metamorphism effects on reflectance

In Nature, snowpacks are subjected to more or less high temperature gradients and can contain a non-negligible quantity of liquid water depending on the prevailing meteorological conditions. These two variables play an important role in the evolution of snow grains.

In Figure 4 we plot observations and model simulations at different stages of metamorphism. First, we applied a temperature gradient to snow composed of fragmented precipitation particles and stellar dendrites (Fig. 5a). Under a temperature gradient of about 50° m^{-1}, snow changed first into faceted crystals (Fig. 5b) and then into depth-hoar crystals (Fig. 5c). At this time, part of the depth-hoar crystals was subjected to wetting in order to induce crystal rounding (Fig. 5d) without a significant size increase. One can observe that the temperature gradient that changes the fragmented precipitation particles into depth-hoar crystals does not produce a very strong decrease in snow reflectance. The size factor, mean convex radius (Table 2), increases from 110 μm up to 288 μm (about 3 times), while the optical radius is increased only from 77 μm to 149 μm (about 2 times). On the other hand, in Figure 5 we can see the important size measured by eye of depth-hoar grains (Fig. 5c) compared to that of the fragmented precipitation particles (Fig. 5a). So, we can say that the temperature-gradient metamorphism does not change the snow reflectance significantly, even when the depth-hoar grains become large. The wetting of the depth hoar, however, makes it become rounded and drastically changes its shape. In our experiment, we observed that the size determined by eye does not change very much (Fig. 5c and d). In the same way, the mean convex radius shows an increase of about 30% (from 288 to 367 μm). That seems relatively modest if we make a comparison with the strong increase of the optical radius (about 3 times from 149 to 452 μm) and the resulting strong decrease of the snow reflectance (Fig. 4). So, the snow-grain shape as well as the snow-grain size is important for snow

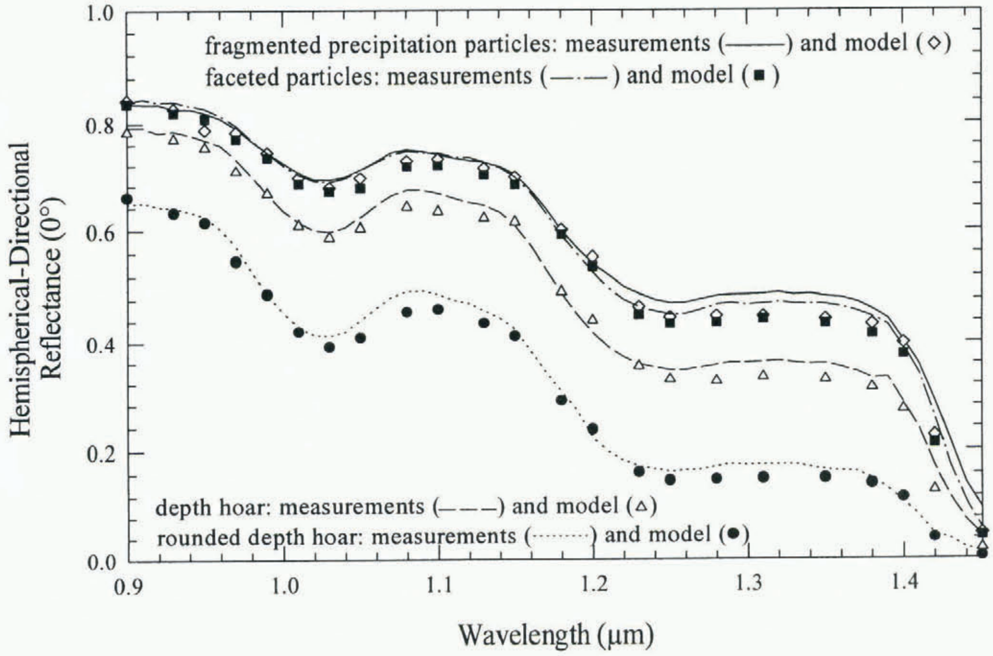

Fig. 4. Snow hemispherical–directional reflectance curves for snow grain at different stages of temperature-gradient metamorphism and for rounded depth hoar.

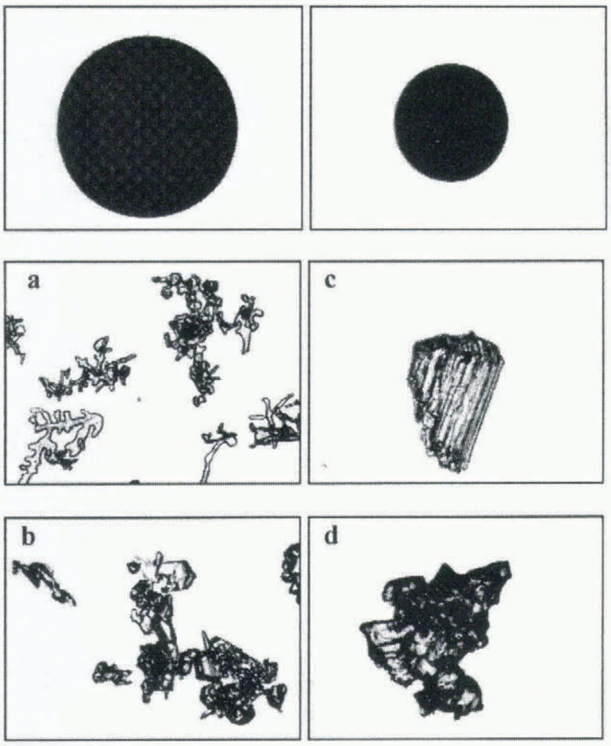

Fig. 5. Snow-grain pictures of the snow subjected to temperature-gradient and wetting metamorphism. (a) Fragmented precipitation particles; (b) faceted crystals; (c) depth hoar; (d) rounded depth hoar. For each column the scale is given by the upper ball (3 mm diameter) which is used for the mean convex radius computation.

Table 2. Physical features of investigated snow subjected to temperature-gradient and wetting metamorphisms

Snow type	*Snow density* $Mg\,m^{-3}$	*Mean convex radius* μm	*Adding–doubling radius* μm	*Carbon-soot content* ppmw
Fragmented precipitation particles	0.114	110	77	0.077
Faceted particles	0.230	145	83	0.034
Depth hoar	0.361	288	149	0.163
Rounded depth hoar	0.480	367	452	0.247

reflectance and therefore snow reflectance modelling has to take this parameter in account.

CONCLUSION

Snow-reflectance measurements were performed by the authors in the 0.9–1.45 μm range over different natural-snow types and snow samples subjected to a temperature-gradient and wet-snow metamorphism in a cold laboratory. The measured spectral data were found to be sensitive to snow grain-size and type and coincided with the minima and maxima of the absorption coefficient of ice.

Comparisons between our snow-reflectance model based on the Mie single scattering and the adding–doubling method show good agreement with hemispherical–directional reflectance measurements, provided that an adjustment is made at one part of the spectral range. The model is then suitable for simulating the spectral behaviour of measurements from an equivalent spherical representation (optical radius) of snow grains independent of the wavelength. It can also reproduce the hemispherical–directional reflectance dependence on certain snow grain-shape variations when metamorphism processes are applied. For instance, despite a small variation of the mean convex radius of snow grains during wetting metamorphism, the model, via the optical radius, predicts the large snow-reflectance decrease observed. In the future, an automatic relation between optical radius and mean convex radius will be developed.

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