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Investigation of the relation between physical and radiometrical properties of snow covers

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ABSTRACT: The extension of the snow cover and the distribution of different snow types can be considered an indicator of global changes and a key parameter in the global radiance balance of the Earth. Moreover, in the mountainous region the possibility to monitor the snow characteristics using remote sensing images can support hydrological studies. The reflectance of snow is determined in part by the size and shape of snow crystals, especially in the short wave infrared (SWIR) wavelength region; for this reasons it is possible to use remote sensed images to map differences in the snow cover. The Specific Surface Area (SSA) of snow is a crucial variable for understanding snow chemistry and air snow exchanges of chemical species, that can also be related to snow reflectance. This study shows how field spectral measurement and SSA data of snow samples can be used as input data for classifying Landsat TM SWIR images in order to obtain a distribution maps of different snow types. This method can be a very useful tool to monitor the snow metamorphism, air-snow exchanges and climate.

1 INTRODUCTION

The extent of the snow cover is a key parameter for global change studies as well as for hydrological balance calculation in alpine regions; snow cover extent monitoring can be performed using remote sensed images and field data. (Painter *et al.* 2003; Painter *et al.* 1998; Dozier 1989). Remote images, collected in the wavelength range 400–2500 nm, can be used in order to provide reliable cartography of snow surfaces, but some physical characteristics of the snow must be taken into account. Snow is a highly unstable target and structural changes of grain size and shape may occur quite rapidly due to climate and atmospheric variations. Even if the spectral contrast between snow and ice is such that these surfaces can be easily mapped, the same contrast between different snow surfaces can be very subtle. Snow reflectance is due to its light scattering properties, that are a function of the size and shape of snow grains and to the absorption by the ice medium and to the presence of impurities (Warren 1982). In the visible range, ice is a very weak absorber, and its reflectance is not very sensitive to its physical properties but is largely dependent on its impurity content such as soot particles. In the short wave infrared (SWIR), i.e. in the wavelength range 1.5–2.5 μm, ice is a strong absorber and its albedo is very strongly determined by the size and shape of snow grains, while being insensitive to impurities (Sergent *et al.* 1998, Wiscombe & Warren 1980). The description of the effect of crystal size and shape on snow optical properties is an enormous task (e.g. Wiscombe & Warren 1980), and an approximation has been proposed (Neshyba *et al.* 2003): snow crystals are considered as spheres of equivalent surface to volume ratio (S/V). The benefit of this approach is that the equivalent-sphere size of snow crystals is the main physical variable that affects snow scattering properties, shape being often secondary.

To understand snow cover variability it also necessary to understand chemistry and air–snow exchanges of chemical species (Dominé & Shepson 2002); this can be done measuring the specific surface area (SSA) of snow. The specific surface area (SSA) of snow is defined as the surface area of snow crystals that is accessible to gases per unit mass and it is proved that during snow metamorphism as grain size increases, the SSA decreases (Dominé & Shepson 2002).

Since it has been shown that the scattering fraction of snow reflectance could be modeled in an acceptable manner by spheres of equal S/V, there is a clear link between reflectance and SSA = S/ (V·ρ). In the SWIR region, impurities have little effect, and reflectance is determined by scattering where the relation with SSA is much simpler than that in the visible. By measuring simultaneously the SSA and the reflectance of snow at Ny-Ålesund (Svlabard, Norvey), Dominé *et al.* (2006) found that SSA is the main physical factor responsible for the reflectance variations in the SWIR.

Following this consideration, in this paper we present a preliminary study in which Landsat infrared images of the Brøggen peninsula (Svalbard-) were processed, taking into account field spectroradiometrical data and laboratory SSA measurements in order to obtain a distribution map of different SSA value in the studied area.

2 FIELD AND LABORATORY DATA

Field data were acquired near Ny-Ålesund, between 21st April and 7th May 2001 The measurements were performed under clear sky conditions, with occasionally a few scattered clouds far from the sun (Casacchia *et al.* 2001).

In the field survey the following data were recorded:

- snow data, particularly referred to grain shape and size in the first 10 cm of the snowpack;
- reflectance curves in the 350–2500 nm wavelength range;
- climatic data such as air Temperature, cloud cover, wind speed;
- other ancillary data such as GPS coordinates and description of the investigated sites.

Measurements of the snow reflectance were carried out by a portable spectroradiometer (FieldSpec, Analytical Spectral Devices, Boulder, CO, USA), that allows the acquisition of reflectance data in the 350–2500 nm spectral range by three separate spectrometers, that operate in the ranges 350–1050 nm, 900–1850 nm and 1700–2500 nm, with 1 nm resolution.

Fieldspec automatically calculates the reflectance value as the ratio between the incident solar radiation reflected from the surface target and the incident radiation reflected by a reference white Spectralon panel, to be regarded as a Lambertian reflector. For this research work a bare fiber optics with a FOV of 25° was used, thus resulting a surface area of about 4 cm^2 when the instrument is about 10 cm above the target. Special care was taken that the radiometer was nadir viewing over the surveyed surface. All measurements were carried out between 12:00 and 15:00 local time, when the solar zenith angle was between 64 and 68°

The absolute reflectance was obtained by multiplying this reflectance factor by the reflectance spectrum of the panel. In our measurements the estimated error of absolute reflectance was about 2% (Casacchia *et al.* 2002). Twenty to thirty measurements were carried out for every target, and each measurement represented an integration of 50 acquisition cycles.

Snow Surface Area (SSA i.e. the surface area of the actual sample, expressed in cm^2 per sample) was measured using a volumetric method with BET analysis (Legagneux *et al.* 2002). Briefly, the principle of the method is to determine the number of CH_4 molecules that can be adsorbed on the snow surface. In practice, the adsorption isotherm of CH_4 on the snow has to be recorded. A BET analysis is then used to obtain the SA from the isotherm. The snow mass was determined by weighing, and the SSA was derived as the ratio of SA over mass. Legagneux et al. (2004) observed that CH_4 adsorption on the stainless steel walls of the container used for SSA measurement produced an artifact of 5 to 20%, depending on the SA of the sample. This has been corrected for this experiment. The method has a 6% reproducibility and a 12% accuracy, as detailed in Legagneux et al. (2002). The snow samples studied and the data obtained are summed in Table 1.

Figure 1 shows the spectral reflectance of 3 snow samples, and illustrates that the SWIR reflectance is related to SSA, while no obvious relationship appears in the visible. To perform a first rough test of the relationship between SSA and spectral reflectance, a linear correlation between these variables was sought at all wavelengths.

The correlation coefficient, R^2, is greater than 0.9 for all the wavelength where the signal is adequate. In order to compare the SSA values with reflectance data deriving from the images, the correlation coefficients were also calculated taking in to account mean reflectance values computed in the wavelength ranges corresponding to Landsat Thematic Mapper bands. As expected from the plot in Figure 2 the correlation in the TM visible bands is very low while it is greater than 0.98 in the ranges of TM4 and TM5; increasing to 0.99 at TM7 range. Given the number of data points, all these values indicate correlations significant at levels $p < 0.01$.

This result clearly suggests that it may be possible to determine snow SSA from its reflectance at a single wavelength, or even over an optical band of limited width.

Table 1. SSA and field reflectance ([a] replicated measurements) sampled in the TM wavelength range.

Type of measurement	Snow type	Sample N°	SSA cm^2/g	Density g/cm^3	Reflectance		
					TM4	TM5	TM7
Surface snow	Fresh dendritic snow	1	683	0.013	0.824	0.2030	0.1708
Surface snow	Needles and dendrites	2	447	0.16	0.878	0.1427	0.1128
Surface snow	Surface wind crust	3	304	0.34	0.853	0.1055	0.0816
Snow in glass	Deep faceted crystals	4	145	0.22	0.809	0.0347	0.0259
Snow in glass	Deep faceted crystals	5[a]	145	0.21	0.767	0.0372	0.0272
			145		0.779	0.0306	0.0190
Snow in glass	Deep faceted crystals	6	120	0.27	0.852	0.0313	0.0231
Snow in glass	Rounded crystals, a few facets	7	124	0.33	0.859	0.0362	0.0257
Snow in glass	Deep faceted crystals	8	89	0.32	0.789	0.0158	0.0103
Snow in glass	Depth hoar	9[a]	102	0.25	0.822	0.0211	0.0135
			102		0.799	0.0209	0.0136
			102		0.790	0.0268	0.0184
			TM band (nm)		760 – 900	1550 – 1750	2080 – 2350

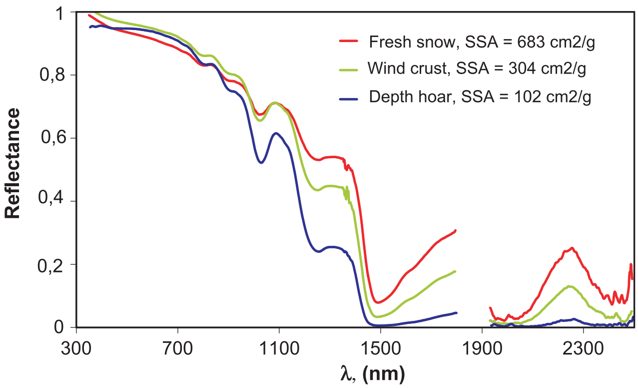

Figure 1. Spectral reflectance of 3 snow samples (1, 3 and 9 in Table 1), illustrating the effect of snow SSA on reflectance in the IR, and the lack of effect in the visible. Data for wavelengths between 1800 and 1935 nm are not shown because of a poor S/N ratio.

Therefore it was possible to express the relation between reflectance in band TM5 and TM7 as follows:

$$\text{TM5} \quad y = 3054.2 * x + 30.083 \quad R^2 = 0.986 \tag{1}$$

$$\text{TM7} \quad y = 3620.1 * x + 47.125 \quad R^2 = 0.990 \tag{2}$$

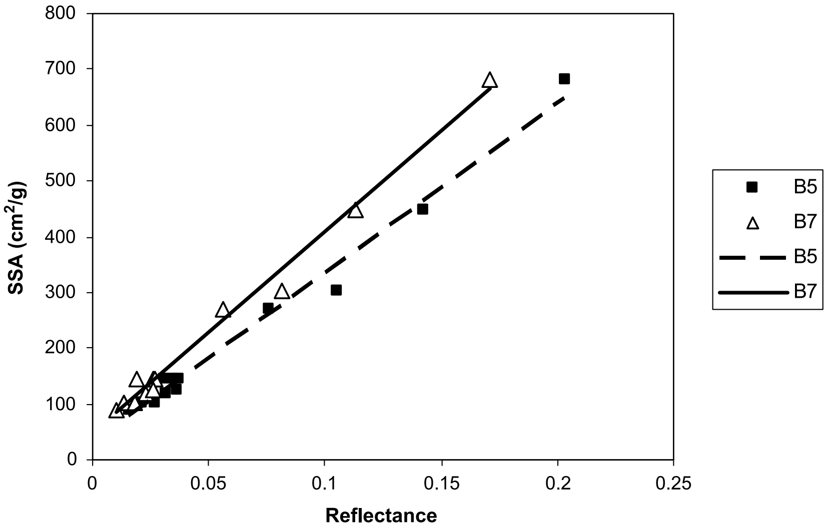

Figure 2. correlation between SSA and filed reflectance measured at Ny-Ålesund, arranged in the TM spectral range.

3 IMAGE PROCESSING

A Landsat Thematic Mapper image of 26th April 1998 was acquired, and radiometric calibration using ENVI routine (ENVI-4.3manual) was performed in order to obtain reflectance value from DN values. The reflectance values, derived from the images, were compared with spectroradiometric data collected in the same areas during the snow surveys. The good agreement between images-reflectance values and field-reflectance values, suggests that further atmospheric and geometric corrections are not necessary.

Using the relation between reflectance and SSA for band TM5 and TM7 (Figure 2 and equation 1 and 2) the reflectance value of TM5 and TM7 images were sliced in 7 classes corresponding to 7 SSA ranges (0–700 cm2/g) (Table 2).

In both cases a good agreement with the field observations were observed according also to image spectral classification presented in a previous paper (Salvatori *et al.* 2005).

The map obtained for band TM7 is presented in Figure 3; the colors correspond to different values of SSA. As in Figure 1, fresh snow is presented in red, wind crust in green, while blue represents the snow with faceted crystals. This type of snow is mainly located along the glacier where at that time of the year (early spring) the snow was submitted to metamorphic processes. Sun face surface (white) were not classify as well as shaded areas (black). Also in this case a good correlation between images data and snow surveys are found. Analogue considerations can be obtained using TM5 image.

Table 2. Reflectance values from Landsat TM5 and TM7 and corresponding SSA values. This values were also used to classify the images.

SSA (cm^2/g)	100	200	300	400	500	600	700
Reflectance TM5	0.0223	0.0556	0.0884	0.1211	0.1539	0.1866	0.2193
Reflectance TM7	0.0145	0.0418	0.0692	0.0966	0.1239	0.1513	0.1787

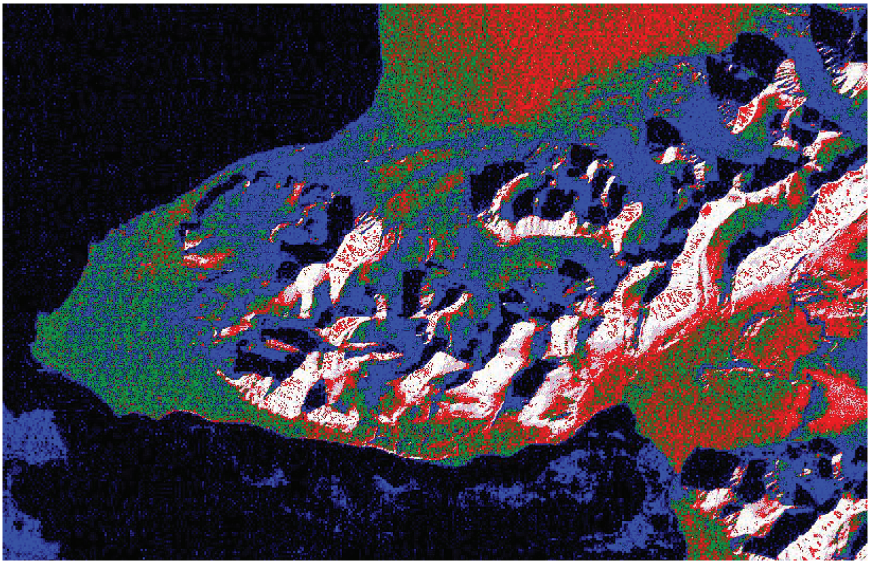

Figure 3. A Landsat 5 TM7 image classified according to equation 2. Color corresponds to different snow type according to reflectance curves of Figure 1.

4 CONCLUSIONS

The results of the classification procedures adopted in this study demonstrate that it is possible to discriminate snow cover with different values of SSA using Landsat infrared images. This was made possible by a good knowledge of the spectral and structural features of the snow targets achieved at the ground. This study also underline that the range of Landsat infrared bands can be used to describe the distributions of the different types of snow since at these wavelengths absorption is very high and the size of the particles is the main factor on the diffusion of light. Given the relations between SSA and snow reflectance in the SWIR wavelengths, it is possible to process remote sensed images in order to describe the spatial distribution of physical characteristic of the snow cover. Applying this methodology it is then possible to obtain SSA maps directly by images, improving the snow metamorphism studies as well as the climate and hydrology studies. This procedure was tested in an area where climatic conditions are fairly similar in every season, and where snow characteristics are spatially constant, thus minimizing the variety of snow types present in a Landsat image. This technique can be exported to other sites at different latitudes and markedly improved if remote sensing data include also the 900–1300 nm wavelength interval and if the temporal resolution is increased.

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