EXPERIMENTAL STUDY ON THE SPECTRAL REFLECTANCE OF SNOW

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ABSTRACT: The spectral reflectance of snow was measured experimentally. Prior to taking the measurements for snow, the spectral reflectance of glass beads of known size distributions was measured for five groups of beads with different diameters: 150-230μm, 500-710μm, 800-1,200μm, 3mm and 6mm. The results with the glass beads showed no remarkable dependency on incident light angle, but showed a remarkable size dependency; the smaller the grain size the larger the reflectance.

Three different types of snow, artificially made new snow, artificial snow that was compacted with age, and natural granular snow, were used for the measurements. The spectral reflectance of the three types of snow showed a less consistent dependency on size than the glass beads, but in general, the smaller the diameter the larger the reflectance.

A one-time sequential experiment showed that the spectral reflectance of snow decreased when snow metamorphosed or aged from new snow to granular snow under the influence of intermittent lighting and freezing. This was due to the growth of snow grains, which was revealed by measuring grain size on microscopic photographs taken by the aniline method.

KEYWORDS: Snow reflective properties, snow optics, snow physics, snow, snow cover.

1. INTRODUCTION

Sometimes we need to know the physical properties of snow in a very remote location, and in such cases a powerful remote sensing technique is needed. To obtain the necessary information about snow remotely requires a fundamental knowledge of the physical properties of snow and of the magnetic response to the snow beforehand. The spectral property of snow is one piece of fundamental information of which our knowledge remains inadequate.

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Recently, some authors have published information on the spectral reflectance of snow. For example, Wiscombe and Warren (1980) presented a method for calculating the spectral albedo of snow with an adjustable parameter for the effective grain size. Nakamura and Ikarashi (1993) measured the spectral albedo of natural snow packed 0.9m deep, a block of compacted snow, and a block of granular snow. Aoki et al. (1995 and 1998) constructed a multiple scattering model for the atmosphere-snow system and compared the theoretical results with the observed results using the effective grain size. However, none of these authors considered the distribution of the size of snow grains. The grain size distribution should be considered because packed snow has a complex texture. The purpose of this paper is to measure the spectral reflectance of snow with reference to the snow grain size distribution experimentally. Most of the measurements were made with artificially produced snow .

2. EXPERIMENTAL

A spectroradiometer (MSR-7000, OPTO Research Corporation) was used to measure the spectral reflectance of snow. This instrument can focus on an area 4cm in diameter and measure wavelengths ranging from 280 nm (0.28μm) to 2,500 nm (2.5μm). Three different light sources were used for the measurements. The artificial snow was produced using a new big machine at the Shinjo Branch, NIED that produces dendrite snow crystals. We also metamorphosed or 'aged' the fresh new snow to obtain compacted snow. We define the spectral reflectance, α, as the ratio of the reflection from the snow surface to that from a white plate of barium sulfate powder. The reflection from the white plate is nearly 100%. Therefore, our definition of spectral reflectance is the same as the normal definition of reflectance. In this paper, we use the word reflectance because the paper treats this phenomenon experimentally. In astronomy, reflectance is the same as albedo.

Prior to making measurements of snow, the spectral reflectance of five groups of glass beads of different diameters was measured (150-230μm, 500-710μm, 800-1,200μm, 3mm and 6mm). Approximately 8,000 cm^3 of glass beads in a cylinder 20cm in diameter with a height of 25cm were used for each measurement. The light source used for the measurement was a 500W halogen lamp. The light was placed 30cm from the surface of the glass beads at incident angles of 30, 45, and 60 degrees. All the measurements of the reflectance of the glass beads were carried out in dry air conditions, so the beads were not wet.

Three different types of snow, artificially made new snow, artificial snow that was compacted with age, and natural granular snow, were used for the measurements. The compacted snow was made by aging artificial snow in a cold room at –20°C for about one month.

To determine the distribution of grain sizes, microscopic photographs of each type of snow sample were taken before and after the reflectance measurements using the aniline method (Kinoshita and Wakahama, 1959). The sample thickness for the microscopic photograph was 0.2 to 0.3mm and snow grain size was measured in an area of 20 to 50 mm^2. The thickness of each branch was measured at locations every 0.1mm along the length of the branches in the photographs. A 100W lamp (SOLAX) producing wavelengths mainly between 370 and 780 nm with a color temperature of 5,500K was used in this experiment. It was positioned 90cm from the snow surface at an incident angle of about 45 degrees. This lamp radiated the weakest radiation of the three light sources used.

For the one-time sequential experiment, the spectral reflectance of artificial snow was measured after a sample had been metamorphosed by illuminating it intermittently. The successive measurements were carried out in a cold room at about –15°C. After an initial reflectance measurement, the sample was illuminated for 23 minutes at 500W/m^2 (1st radiation). A fixed light source in the cold room was used and it was the strongest of the three lamps used in this experiment. The incident angle was approximately zero. The reflectance was measured 35 minutes later. Snow sample to make a thin section was taken one hour and 45 minutes after the initial illumination. The reflectance was measured again after the snow sample was taken. This procedure was repeated for a 2nd and 3rd radiation with illumination at 475 to 482W/m^2 for 17 minutes and at 480W/m^2 for 13 minutes, respectively. Successive measurements were made at the same location on the snow surface.

To examine the dependency of the reflectance of new snow on the incident angle, the reflectance was measured at incident angles of 30, 45, and 60 degrees. A halogen lamp was used for this experiment.

3. RESULTS

1) Glass beads

Figure 1 shows the dependency of the spectral reflectance on the size of the glass beads. For this experiment, a halogen lamp was used with

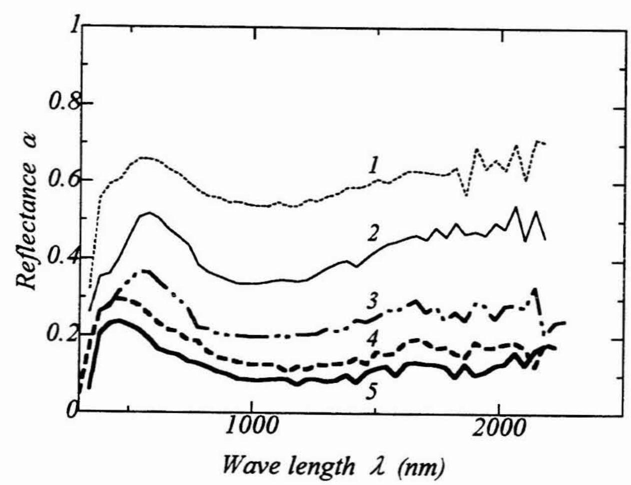

Figure 1. Dependency of the spectral reflectance on the size of glass beads. The numbers indicate the glass bead diamaters. 1: 150-230 μ m, 2: 500-710 μ m, 3: 800-1,200 μ m, 4: 3mm, 5: 6mm.

the incident angle at 60 degrees. All the raw curves are smoothed for every 30nm of wavelength to eliminate noise. The spectroradiometer generated more noise at wavelengths from 1,100 to 2,500 nm than in the range from 280 to 1,100 nm. Therefore, the curves in this range show larger fluctuations than in the shorter wavelength region. As seen in this figure, the reflectance of the glass beads showed a remarkable size dependency, the smaller the grain size the larger the reflectance. The maximum reflectance for the 150-230 μ m glass beads was about 0.66 at a wavelength of about 580 nm. As the wavelength increased, the reflectance at first increased gradually and then decreased gradually until the reflectance was nearly the same as that at the shorter wavelengths. This trend was also observed with the larger glass beads. The minimum reflectance for the five groups was observed with the 6mm glass beads, which had a maximum reflectance value of about 0.27. The results with the glass beads showed no consistent dependency on the incident light angle, which was set at 30, 45, and 60 degrees.

2) Spectral reflectance of three different types of snow

Figure 2 shows the spectral reflectance of three different types of snow: artificially produced new snow, artificial snow that was metamorphosed from the new snow, and natural granular snow. The reflectance at wavelengths from 745 to 895 nm was eliminated because of the

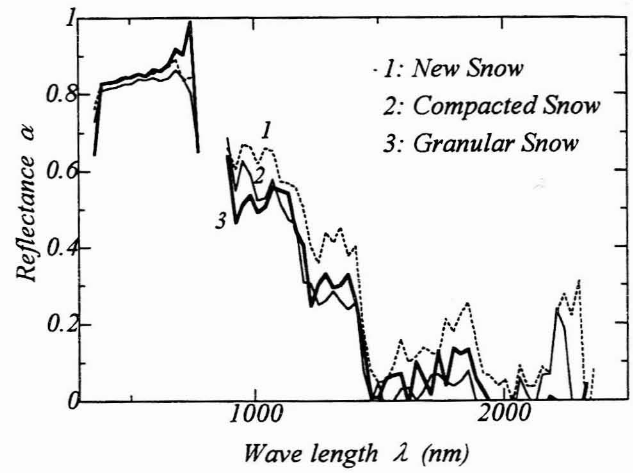

Figure 2. Spectral reflectance of the three different types of snow.

large amount of noise due to the weak radiation of the light source. The spectral reflectance of the three types of snow at wavelengths from 350 to 750nm increased gradually to an average value of about 0.8 to 0.85, and then decreased to about zero as the wavelength increased to 1,500nm with some wavy fluctuations. At wavelengths from 1,500 to 2,500nm, the reflectance ranged from zero to 0.3 depending on the type of snow. Of the three types, new snow had the highest reflectance, although the reflectance of both new snow and granular snow was quite similar in the range 350 to 750nm. The reflectance of compacted snow and granular snow were similar over the entire range of wavelengths. The grain size, shape, and size distribution for the three types of snow are shown in Figs. 3 to 8. Figure 3 shows a photograph of new snow, which was produced artificially by a special new machine at the Shinjo Branch of Snow and Ice Studies, NIED, and shows branches of dendritic snow crystals. Figure 4 shows the grain

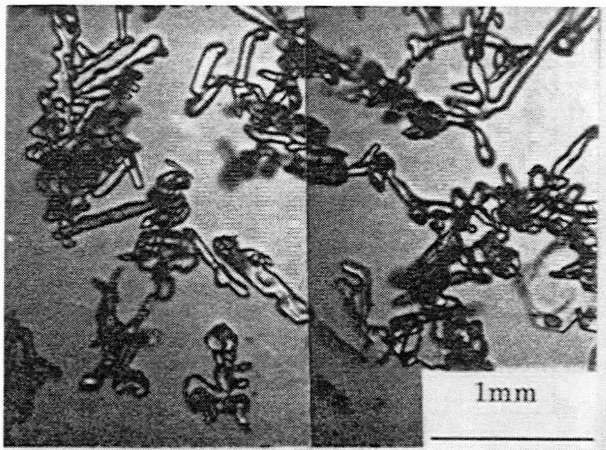

Figure 3. Thin section of artificially produced new snow made by the aniline method.

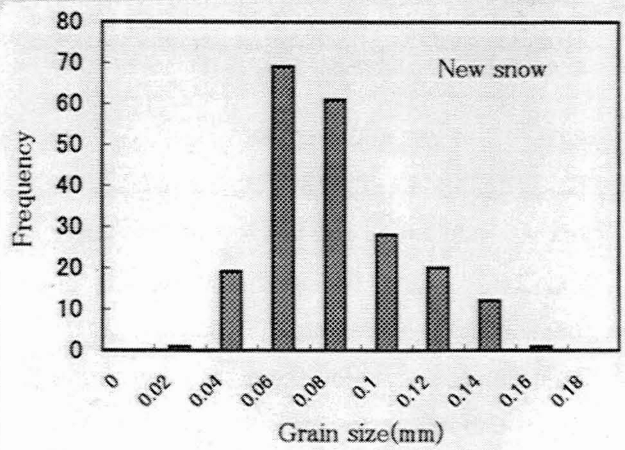

Figure 4. Grain size ditribution for the artificially produced new snow shown in Fig.3.

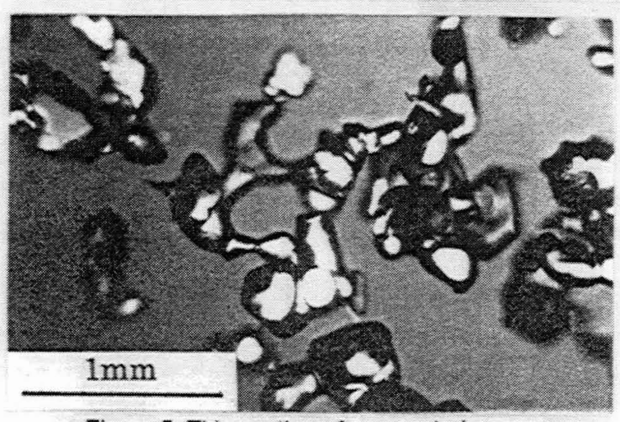

Figure 5. Thin section of compacted snow metamorphosed from new snow.

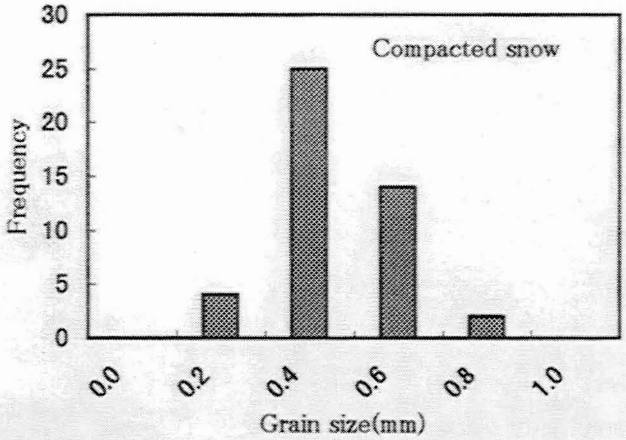

Figure 6. Grain size distribution for the compacted snow shown in Fig.5.

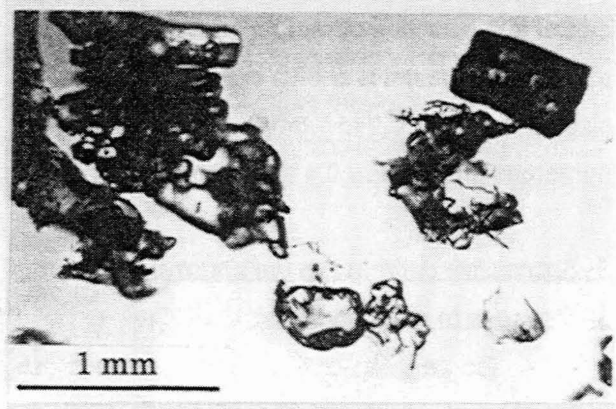

Figure 7. Thin section of natural granular snow.

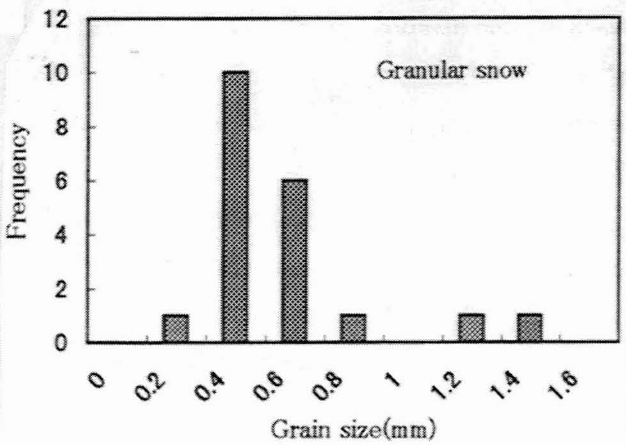

Figure 8. Grain size distribution for the natural granular snow shown in Fig.7.

size distribution of the new snow. In this figure, the grain size, d, ranged from 0.02 to 0.18mm $(0.02 \le d < 0.18mm)$ with the majority of the particles in the range from 0.06 to 0.1 mm $(0.06 \le d < 0.1mm)$. Figure 5 shows part of a thin section of compacted snow. The size distribution is shown in Figure 6. The snow grains were assumed to be elliptical and the grain size was defined by $\sqrt{ab}$, where a and b are the major and minor diameters of an ellipse. The size ranged from 0.2 to 1.0mm. The most numerous grains were 0.4 to 0.6mm in size. Figure 7 shows part of a thin section of natural granular snow, and the size distribution is shown in Figure 8. The size ranged from 0.2 to 1.6mm and the most numerous grains were 0.4 to 0.6mm.

<u>3) Successive decrease in the spectral reflectance of snow due to metamorphosis</u>

Figure 9 shows the successive decrease in the spectral reflectance of snow with metamorphosis caused by melting due to light radiation and freezing. Curve No.1 in Figure 9 shows the reflectance of new snow which microscopic photograph is shown in Figure 10. Branches of new snow are seen in this photograph. The grain size distribution before the snow was exposed to radiation is shown in Fig. 11 and ranges from 0.02 to 0.12mm with most grains in the range from 0.02 to 0.06mm. The snow density was 0.037g/cm^3.

Curve No. 2 shows the reflectance of snow 35 minutes after the 1st radiation. The snow

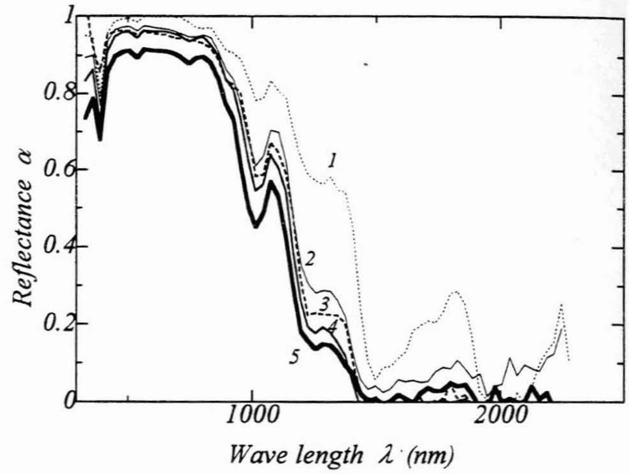

Figure 9. Successive decrease in the spectral reflectance of snow resulting from metamorphosis. 1: New snow before light radiation .2: Immediately after the 1st radiation. 3: Metamorphosed after the 1st radiation. 4: After the 2nd radiation. 5: After the 3rd radiation.

surface was wet and irregular as shown in Figure 12. The uneven snow surface resulted from the intense illumination and the snow depth decreased from 26.5 to 22cm, the depth at which the measurements were made. The snow temperature 5cm below the snow surface was about -5 to -6°C. In Figure 12, the dark areas 1 to 2cm in diameter are wetter than the white area. The surface was obviously wet to the touch and a

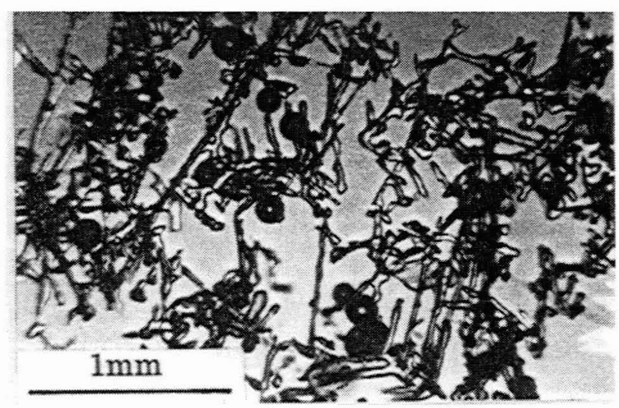

Figure 10. Thin section of artificially produced new snow.

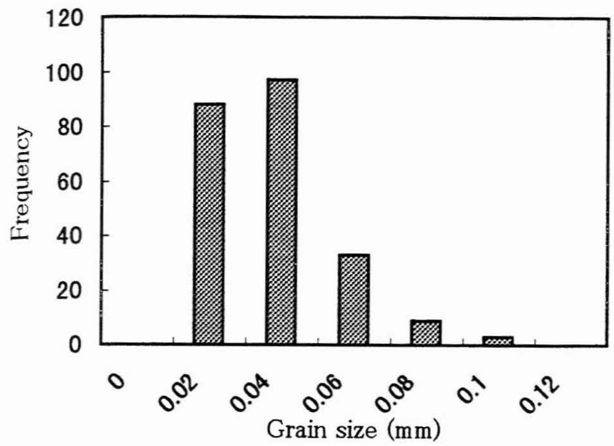

Figure 11.Grain size distribution for the artificially produced new snow shown in Fig.10.

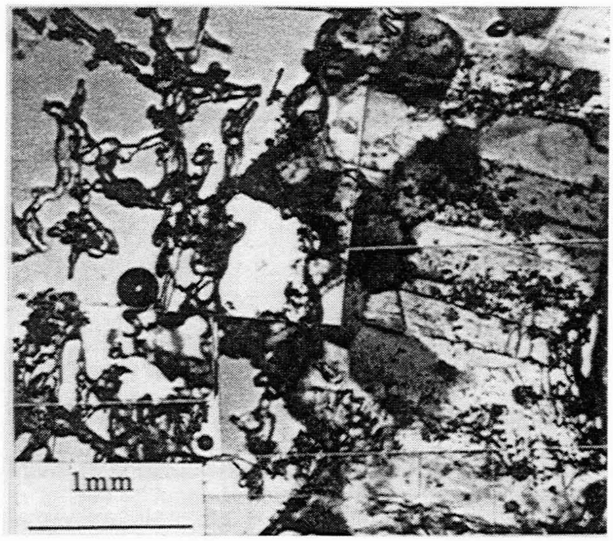

Figure 13. Thin section of the partially metamorphosed snow surface from Fig.12. The metamorphosis was produced by radiation and freezing (after the initial radiation).

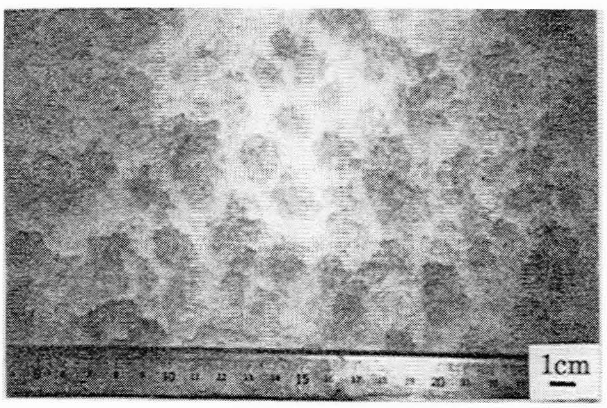

Figure 12. Metamorphosed snow surface melted by radiation. The dark area is much wetter than the surrounding white area (12:00).

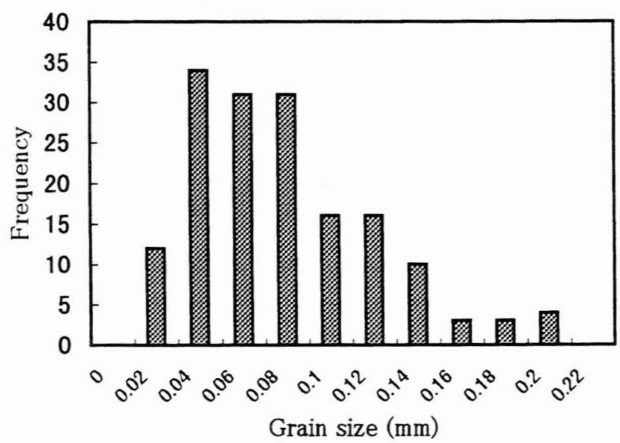

Figure 14. Grain size distribution for the metamorphosed snow shown in Fig.13.

small film of liquid water could be seen in the dark areas by the naked eye. Curve No. 2 was measured under these conditions. A thin section of the snow surface is shown in Figure 13. Snow sample to make the thin section was taken one hour and 45 minutes after the measurement of Curve No.2. By then, the water on the snow surface had frozen completely. The wettest portion, which appears black in Figure 12, is seen as large ice grains in Fig.13. Partially metamorphosed snow grains are also observed under the ice grains. The size distribution is shown in Figure 14. The grains range in size from

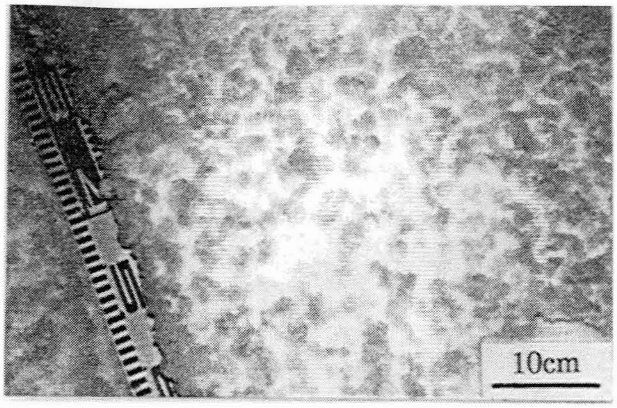

Figure 15. Rough metamorphosed snow surface produced by melting with further illumination (Immediately after the 3rd radiation at about 15:50).

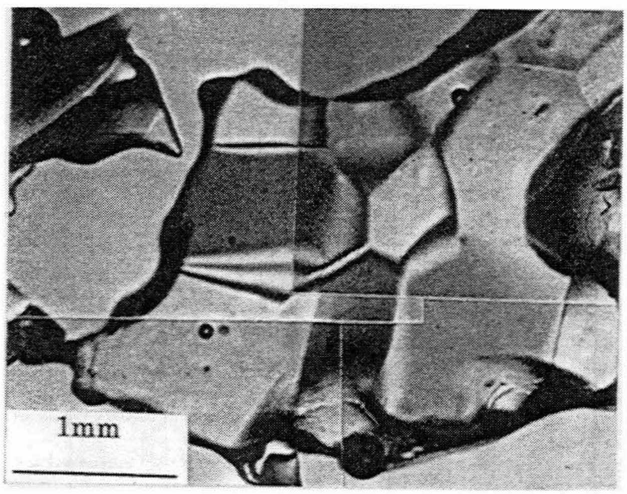

Figure 16. Thin section of the metamorphosed snow surface produced with further illumination (Immediately after the 3rd radiation).

0.02mm, which is the same as the minimum size of the new snow before radiation, to about 2mm (although this part is not shown in Figure 14) with grains of 0.04 to 0.1mm being the most numerous.

Curve No.3 in Figure 9 shows the reflectance of the snow one hour and 50 minutes after Curve No.2 was recorded. Curve No.4 was taken at the same location after the 2nd radiation. The snow depth was reduced to 18.5cm. Curve No.5 was measured after the 3rd radiation. As seen in Figure 15, the snow surface became much rougher and was more granular than that shown in Figure 12. The photograph of the thin section of the snow surface and the size distribution are shown in Figures 16 and 17, respectively. The

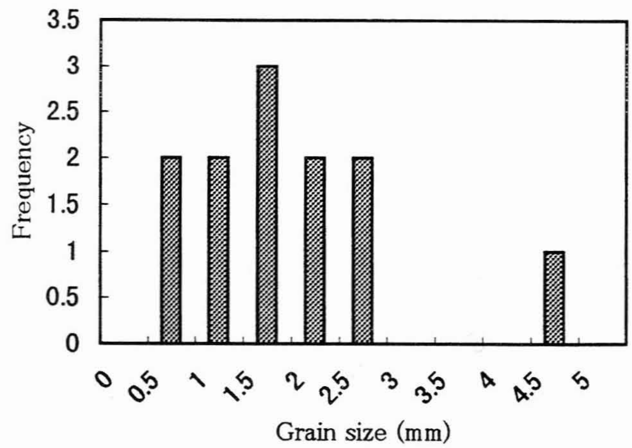

Figure 17. Grain size distribution for the metamorphosed snow shown in Fig.16.

size ranges from 0.5 to 5.0mm and the most numerous grains are 1.5 to 2.0mm. Figs.16 and 17 show that the ice grain sizes increased compared to the sizes seen in Figures 13 and 14.

4) Incident angle dependency.

Figure 18 shows the dependency of the reflectance of new snow on the incident angle. Curves No.1 to 3 show the spectral reflectance at incident angles of 30, 45, and 60 degrees, respectively. The reflectance had the minimum value at 30 degrees. At wavelengths from 1,500 to 2,500 nm, the reflectance was largest for 60 degrees, intermediate for 45 degrees and smallest

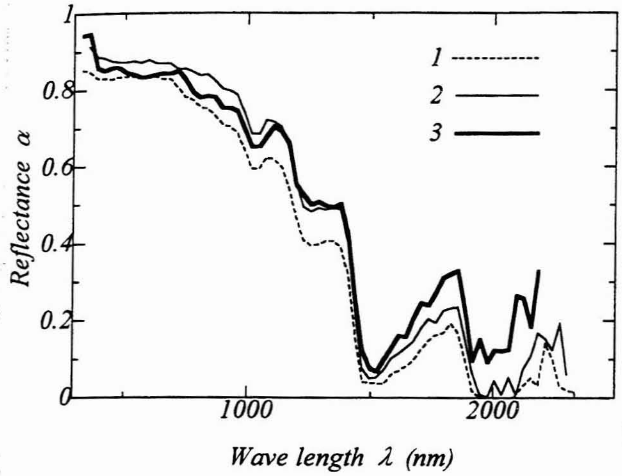

Figure 18. Dependency of the reflectance of new snow on the incident light angle. 1: 30° , 2: 45° , 3: 60° .

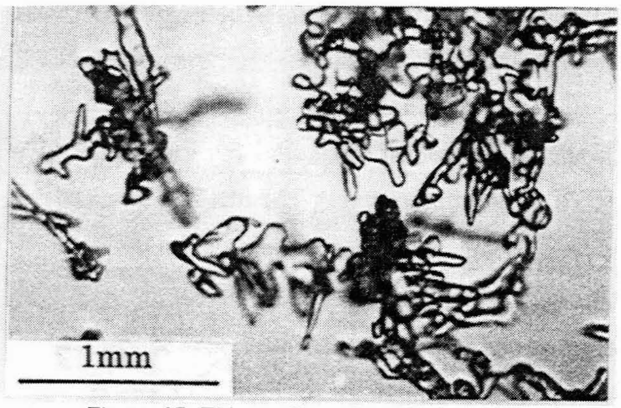

Figure 19. Thin section of new snow.

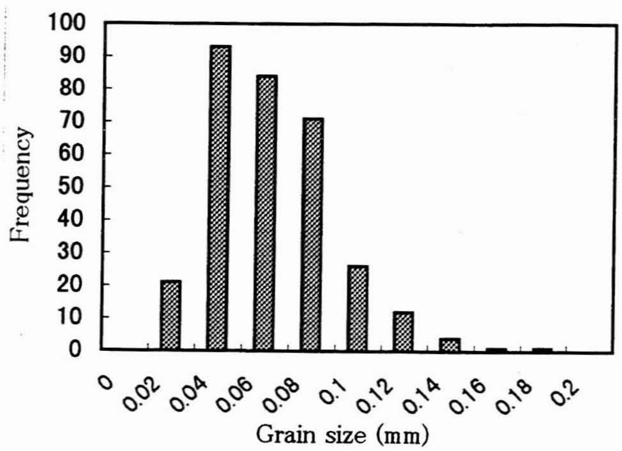

Figure 20. Grain size distribution for the new snow shown in Fig.19.

for 30 degrees. The thin section of the new snow and the size distribution are shown in Figs.19 and 20, respectively. The new snow is quite similar to the new snow shown in Fig.3.

4. CONCLUSIONS AND DISCUSSION

The glass beads showed a rather flat reflectance with a small peak around 600nm. This means that, unlike snow, the glass beads have no specific spectral absorption of light at the larger wavelengths. The reflectance showed size dependency at wavelengths from 300 to 2,500nm, i.e., the smaller the glass beads, the larger the reflectance. On the other hand, the snow had a higher reflectance at shorter wavelengths than at longer wavelengths. This means that snow has smaller absorption at the shorter wavelengths than at the longer ones. This tendency must be a native property of ice itself (Hobbs, 1974).

The new, compacted, and granular snow all had similar reflectances. Of these three snow types, new snow had the largest spectral reflectance at all wavelengths, although the reflectance for all three snow types was nearly the same (0.8 to 0.9) at wavelengths of 300 to 800nm. The compacted snow had the second largest reflectance and the granular snow the smallest reflectance. The difference in the reflectance between the compacted snow and the granular snow was small. This was probably due to the similar grain size distribution of the compacted snow and granular snow. The large amount of noise seen at wavelengths between 750 and 880nm observed in the measurement of all three types of snow was probably due to the light used for the measurement. The SOLAX lamp used for this measurement had the weakest light intensity, and would produce more noise than the other two light sources used.

The spectral reflectance of snow decreased successively with metamorphosis caused by melting due to light radiation and freezing. The successive decrease in the spectral reflectance corresponded to an increase in the grain size of the snow revealed by the measurements of the grain size from microscopic photographs of a thin section of snow.

The decrease in the spectral reflectance at wavelengths of about 380, 1,020 and 1,250nm must be a property of ice as these minimum values correspond to maximum values for the absorption curve of ice (Hobbs, 1974), although there are some differences in the corresponding wavelengths. In the successive measurements a clear size dependency was observed in the reflectance at wavelengths around 1,000 and 1,400nm. These wavelengths can be used to identify the snow type and can therefore be used for the remote sensing of snow in the future.

Incident angle dependency was observed in new snow at 30, 45 and 60 degrees. The experimental results showed that the larger the incident angle, the larger the reflectance. This relation was clearly observed at wavelength from about 1,470 to 2,500 nm. This relationship must be partly due to the properties of ice because the reflectance of ice remains constant at incident angles from 0 to nearly 50 degrees, after which the reflectance suddenly increases to 0.45 (Hobbs, 1974).

The general pattern of the spectral reflectance obtained in this experiment agrees well with the results obtained by Wiscombe and Barren (1980), Nakamura et al. (1993) and Aoki et al. (1995 and 1998). However, a detailed quantitative comparison should be made. A comparison between the effective grain size and the grain size distribution as determined in this paper must also be carried out.

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