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SPECTRAL ALBEDO OBSERVATION ON THE SNOW FIELD AT BARROW, ALASKA

Teruo AOKI[1], Tadao AOKI[1], Masashi FUKABORI[1], Yoshihiro TACHIBANA[2], Yuji ZAIZEN[1], Fumihiko NISHIO[3] and Tomohiko OISHI[4]

[1]*Meteorological Research Institute, 1–1, Nagamine, Tsukuba 305-0052*
[2]*Research Institute of Civilization, Tokai University, 1117, Kitakaname, Hiratsuka 259-1292*
[3]*Hokkaido University of Education, Shiroyama 1-chome, Kushiro 085-8580*
[4]*Tokai University, Orido 3-chome, Shimizu, 424-8610*

Abstract: Spectral albedo observation at the visible and near infrared wavelengths was carried out on the snow field at Barrow, Alaska in April, 1997. The data are compared with the theoretical calculations made by a multiple scattering radiative transfer model for the atmosphere-snow system using the snow physical parameters observed by snow pit work. It is found that the optically effective snow grain size is on the order of branch size for new snow consisting of dendrites, but is not of the crystal size. The observed spectral albedo was lower than theoretically calculated for "pure snow" in the visible and a part of the near infrared; such reduction is explained by the internal mixture of soot and external mixture of dust for snow particles. The theoretical spectral albedo calculated for a two-layer snow model that contains impurities agrees very well with the observations at all wavelengths.

1. Introduction

The cryosphere is a very sensitive region for climate change and has large feedback effects for the climate system. Snow and ice albedos in the visible region are very high and this makes the cryosphere act as a cold source on the global scale. However, soot in the Arctic snowpack originating from the Arctic haze reduces the albedo by up to 0.035 (WARREN and CLARKE, 1986). Such a reduction of snow albedo acts to accelerate the snow melting and reduces the albedo further. On the other hand, the near infrared albedo decreases with increase of the snow grain size (WISCOMBE and WARREN, 1980). In general, the snow grain size increases with snow age due to sintering that depends on the snow temperature. Thus, we may say that the snow grain size reflects the history of the snow.

There are possibilities of remote sensing for snow impurities by observation of the visible albedo, and the snow grain size using the near infrared albedo (WARREN, 1982). One of the most suitable optical sensors for such observations may be the GLI (Global Imager) in ADEOS-II (Advanced Earth Observing Satellite-II) that will be launched in 1999. GLI has 36 channels from the visible to infrared regions with 250 m or 1 km spatial resolution, 1600 km swath and global coverage in 4 days (NAKAJIMA *et al.*, 1994). We will estimate the snow impurities and snow grain size with GLI data. The basis of these studies is a multiple scattering radiative transfer model for the atmosphere-snow system that simulates the spectral albedos at the snow surface and the top of the atmosphere. To validate this model, field observations for the spectral albedo and snow physical parameters have been done on the snow field at Barrow, Alaska, from April 14 to 27, 1997. Under a clear sky, even a gentle slope of the snow surface affects the snow albedo (GRENFELL and WARREN, 1994). As a simpler case in which it is unnecessary to consider such an effect, the relation between the spectral albedo and snow physical parameters under overcast condition on April 21 after new snowfall is discussed in this study.

2. Observation

The observation site was a snow field on tundra 5 km of northeast of Barrow town as shown in Fig. 1. The snow depth was 60 cm and the surface was covered by new snow of 1 cm depth that fell on the day before the observation (Fig. 2). The grain shape of surface new snow was dendrites with crystal size (radius) of 1–2 mm and branch size (radius) of 20–50 μm. The second layer was fine-grained old snow with the grain radius of 100–150 μm and the third layer was faceted crystals with the grain radius of 250–400 μm. The lowest two layers were depth hoar with the grain radius of 1–3 mm. These grain sizes were estimated using a portable microscope. Snow impurities were filtered within a day by 25-mm Nuclepore filters with the pore size of 0.2 μm after melting the snow samples of the surface and 5–10 cm depth snow layers. The concentrations of impurities were estimated by direct weight measurements of the Nuclepore filters, before and after filtering, with a balance. The sky condition was overcast with altocumulus. Air and snow surface temperatures were -14.2°C and -11.0°C, respectively at 1200 LT.

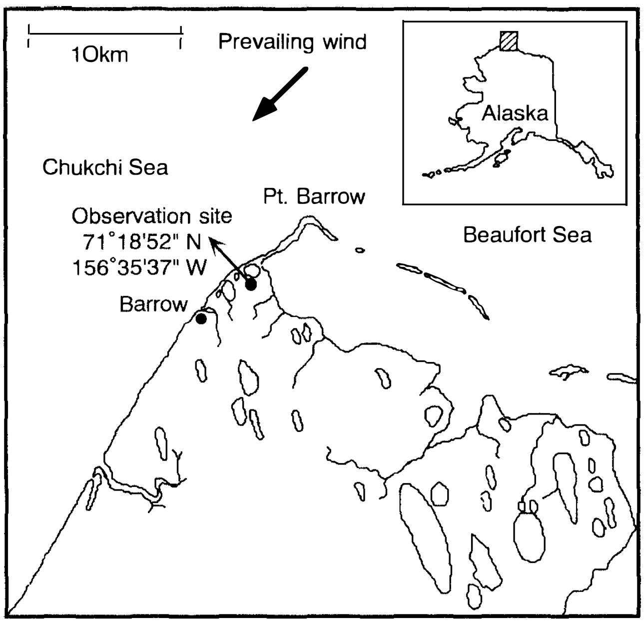

Fig. 1. Location map of the observation site around Barrow.

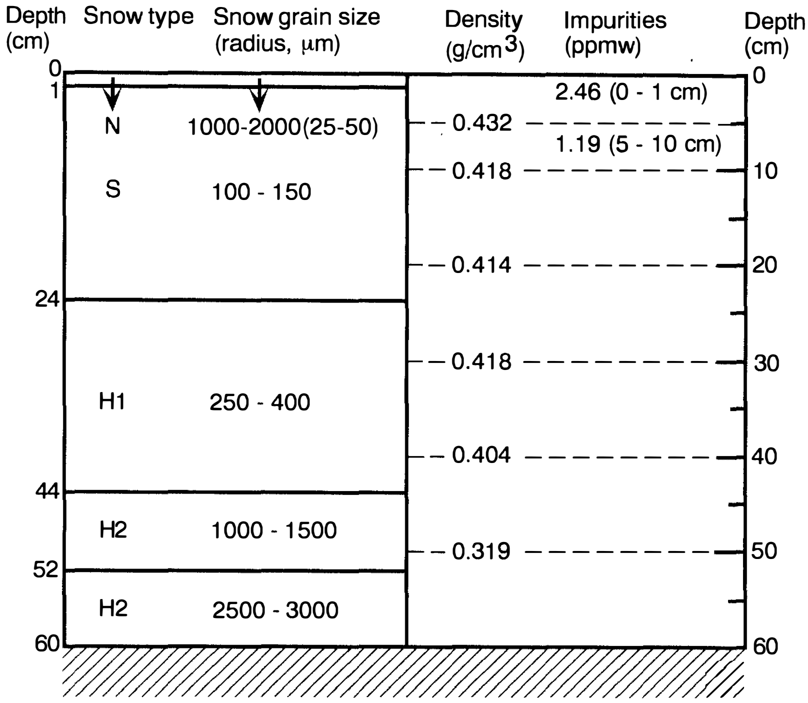

Fig. 2. Vertical profile of the snowpack used for the spectral albedo observations. Snow types are indicated by N for new snow, S for fine-grained old snow, H1 for faceted crystals and H2 for depth hoar. Snow grain sizes were estimated by the portable microscope. The values in parentheses in the surface layer indicate the branch size of the dendrites. Snow impurities were filtered within a day by 25-mm Nuclepore filters with pore size of 0.2 μm and the concentrations were estimated by direct weighting of Nuclepore filters with a balance.

The spectral snow albedo was observed by a grating type spectrometer, "FieldSpec FR", made by ASD Inc. (USA). It is necessary to observe the downward and upward flux to obtain the albedo. The downward flux was observed by directing the optical fiber of the spectrometer toward the surface of a standard white reflection plate that is set horizontally above the snow surface (Fig. 3). This method has the merit that the so-called "cosine property" of reflection is very good compared with the case of using a cosine collector. The upward flux was observed by directing the optical fiber toward the underside of the standard white reflection plate. Another advantage is that it is unnecessary to know the reflectance of the standard white reflection plate. The scanning spectral range of the spectrometer is 0.35–2.5 μm with the spectral resolution of 3 nm for the wavelength (λ) of 0.35–1.0 μm and 10 nm for λ=1.0–2.5 μm. The scanning time is one second with the sampling interval of 1 nm for the full spectral range. Detectors are one dimensional Si photodiode CCDs for λ=0.35–1.0 μm and two different types of InGaAs photodiode for λ=1.0–1.8 μm and λ=1.8–2.5 μm. The spectral snow albedo is the average of five spectral albedos obtained from five pairs of measurements for the downward and snow reflected solar fluxes. It takes several minutes to obtain these quantities. To calculate the albedo, we used the raw digitized out-

Fig. 3. A photo of the measurements of the downward solar flux on the snow surface with the spectrometer.

put count from the detector in which there is less error than the value calibrated with a standard lamp.

3. Radiative Transfer Model

The observed spectral snow albedo is compared with the theoretical calculations by a multiple scattering model for the atmosphere-snow system. In the snow layer(s), snow grains are assumed to be mutually independent ice particles and radiative transfer is treated the same as the usual multiple scattering model in the atmosphere containing aerosols or cloud particles. Radiative transfer processes are based on the Mie theory for single scattering and the "doubling and adding" method for multiple scattering omitting polarization (for details see AOKI *et al.*, 1997). According to AOKI *et al.* (1999), the effect of gaseous absorption on the spectral snow albedo is less than 0.01 at the solar zenith angle $\theta_0=64°$, at which our observation was made, so that we neglected gaseous absorption. Since the effect of cloud on spectral albedo cannot be ignored (WISCOMBE and WARREN, 1980), we assumed an ice cloud layer of 4–5 km height in the Rayleigh atmosphere. The optical depth of cloud is 10 at $\lambda=0.5$ μm and Deirmendjian's cloud model (DEIRMENDJIAN, 1964) with the effective radius 15 μm is employed for the size distribution. Since the effect of aerosols on the snow albedo is smaller than that of cloud (AOKI *et al.*, 1999), the aerosols were not considered in the model atmosphere.

4. Results and Discussion

4.1. *Snow grain size*

The observed spectral albedo is compared with the theoretical calculations for a

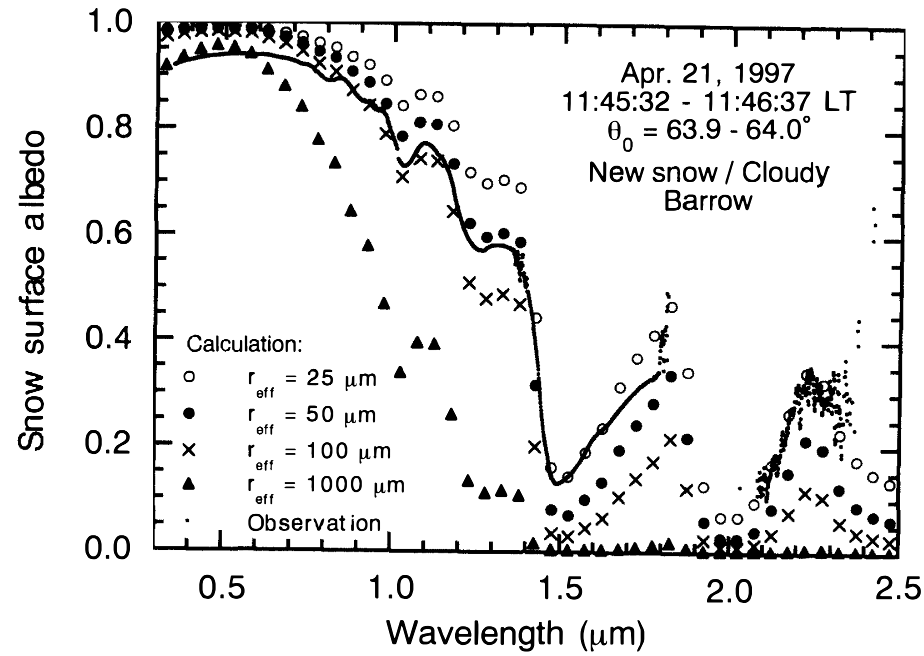

Fig. 4. Observed spectral snow albedo on April 21, 1997 at Barrow and theoretical results for the effective snow grain radii (r_{eff}) of 25, 50, 100 and 1000 μm, and the semi-infinite geometric depth. Solar zenith angle (θ_0) was 63.9–64.0° during the observations and that for theoretical calculation is 64.0°.

single snow layer with the effective snow grain radii (r_{eff}) of 25, 50, 100 and 1000 μm. Figure 4 shows the observed and theoretical spectral albedos. In the absorption bands of the atmospheric water vapor and carbon dioxide such as the wavelength regions $1.8<\lambda<2.0$ μm and $\lambda > 2.4$ μm, the energy of downward solar flux is so weak compared to the detector sensitivity that the obtained spectral albedo highly fluctuates. Thus, observational data in which the downward or snow reflected solar flux is zero are not shown in Fig. 4. The observed albedo is lower than any theoretical results for $r_{eff}=25$–100 μm at the wavelengths $\lambda < 0.9$ μm and that for $r_{eff}=1000$ μm at the wavelengths $\lambda < 0.6$ μm. WARREN and WISCOMBE (1980) showed that snow impurities reduce the spectral albedo mainly in the visible region. This is because the difference of absorption coefficient between ice and impurities such as soot and dust becomes maximum in the visible region. The discrepancy between observed and calculated albedos for $\lambda < 0.9$ μm or $\lambda < 0.6$ μm in Fig. 4 seems to be due to the snow impurities as will be examined in the following sections. The theoretical spectral albedo for $r_{eff}=$ 25 μm agrees well with the observed one for $\lambda > 1.5$ μm. In this region, there is no significant effect of snow impurities on spectral albedo (WARREN and WISCOMBE, 1980). The grain shape of surface new snow on the observation site was dendrites with crystal size (radius) of 1–2 mm and branch size (radius) of 25–50 μm. The theoretical spectral albedo for $r_{eff}=1000$ μm is considerably different from the observed one at all of the near infrared wavelengths. We, therefore, conclude that the optically effective snow grain size is on the order of branch size for the snow of dendrites, but is not of the crystal size.

4.2. Snow impurities

The observed concentration of snow impurities was 2.46 ppmw for surface snow and 1.19 ppmw for 5–10 cm depth. These were the results of direct weight measurements of Nuclepore filters on which the impurities were stuck by passing the melted snow sample. We have not yet analyzed the constituents of impurities, but according to the microscopic observation of impurities on Nuclepore filters, mineral particles with size smaller than 50 μm and further small unknown particles were recognized. Theoretical spectral albedos were calculated for snow with $r_{eff}=25$ μm and three kinds of impurities, including soot-contaminated snow containing 2 ppmw internal mixture, soot-contaminated snow containing 2 ppmw external mixture and dust-contaminated snow containing 2 ppmw external mixture. For external mixture, the method by WARREN and WISCOMBE (1980) is used for the soot and dust whose effective radii are 0.1 μm and 1.0 μm, respectively. For the internal mixture, eqs. (13)–(14) in CHÝLEK *et al.* (1983) with the same soot size as the external mixture and soot density $\rho_s=1.0$ g/cm^3 (WARREN and WISCOMBE, 1980) are used. The refractive indices are assumed to be $m=1.8$–$0.5i$ for soot, and the compiled data by AFGL (1985) are used for dust.

Figure 5 shows the comparison of the observed spectral albedo with the theoretical results for three kinds of snow impurities. The amount of 2 ppmw dust is too low and the amount of 2 ppmw soot is too high even for internal and external mixtures to account for the observed spectral albedo at the wavelengths λ <0.9 μm. This suggests that a small amount of highly absorptive material such as soot, and large amount

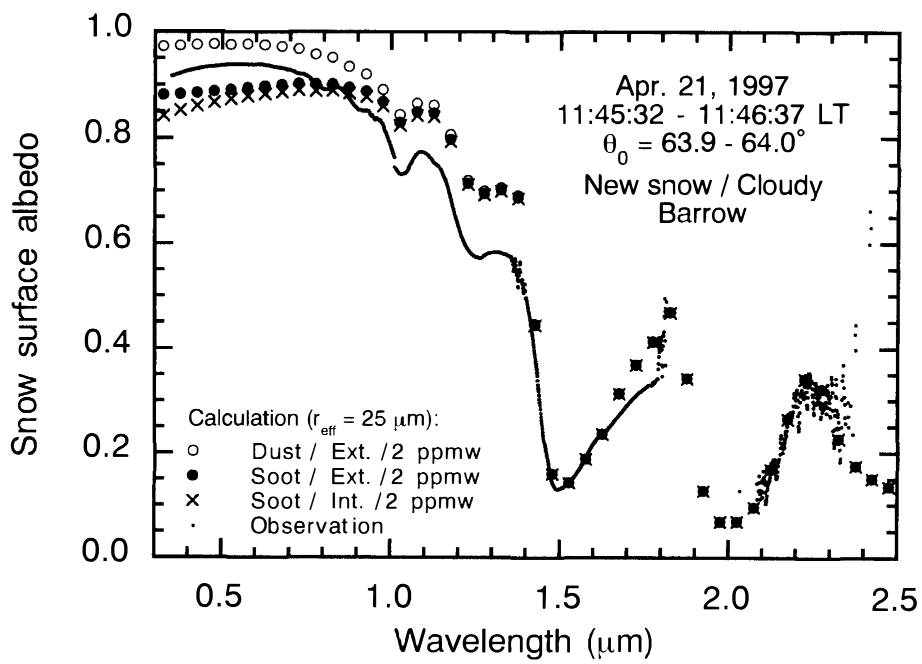

Fig. 5. Same as Fig. 4, except for theoretical results, which are calculated for $r_{eff}=25$ μm with soot-contaminated snow containing 2 ppmw internal mixture, soot-contaminated snow containing 2 ppmw external mixture and dust-contaminated snow containing 2 ppmw external mixture.

of weakly absorptive material such as dust, are simultaneously contained in the snow. The former contributes to the spectral albedo reduction in the visible and a part of the near infrared, and the latter contributes to raise the concentration of snow impurities measured by using Nuclepore filters. Therefore, we must consider a contaminated snow model with both soot and dust. However, impurities cannot account for the discrepancy between theoretical and observed albedos at the wavelengths $0.9<\lambda<1.35$ μm. This discrepancy and the spectral albedo reduction by snow impurities at $\lambda<0.9$ μm are further studied by calculating the spectral albedo for a two-layer snow model in the following section.

4.3. Snow layer structure

The observed geometric depth of the surface layer was 1 cm (Fig. 2), but we could not measure the density due to the very low density and thinness of the layer. It is known that the mean density of new snow consisting of spatial dendrites is 0.036–0.059 g/cm^3 except in a snowstorm, and the minimum is 0.02 g/cm^3 (KAJIKAWA, 1989). There was no snowstorm when new snow fell on the surface on April 20 at Barrow. So we assume the density of new snow to be 0.05 g/cm^3.

We calculated the theoretical spectral albedos for some combinations of snow layer structure and snow impurities and obtained the best fitting of theoretical spectral albedo to the observed one (Fig. 6). The theoretical calculations were carried out

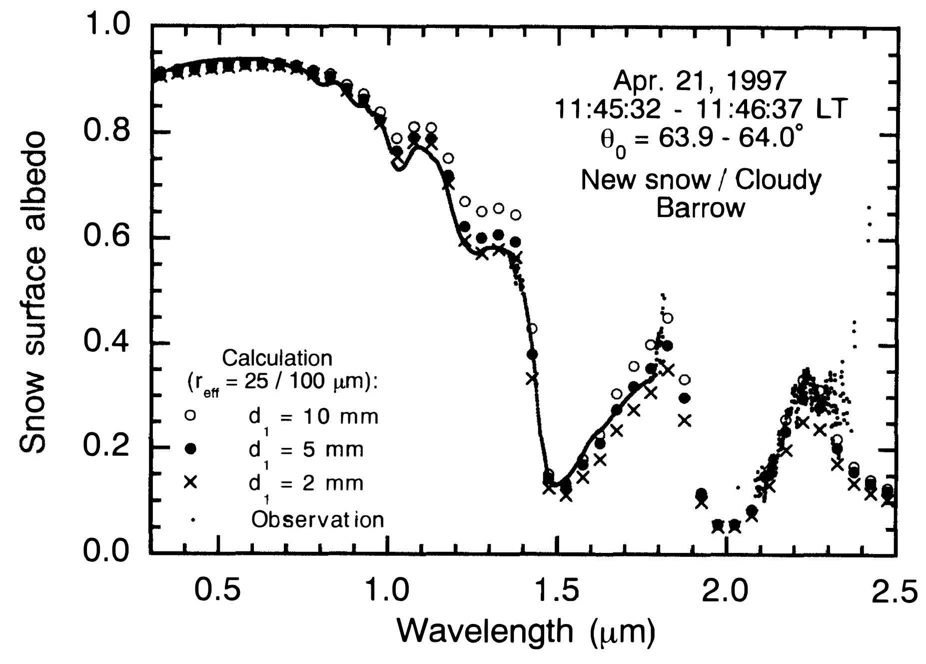

Fig. 6. Same as Fig. 4, except for theoretical results. The theoretical calculations are done for two-snow layer models with three geometric depths (d_1), 2, 5 and 10 mm, with density of 0.05 g/cm^3 and r_{eff} =25 μm in the first layer, and semi-infinite geometric depth with r_{eff} =100 μm in the second layer. The first snow layer is contaminated by 0.1 ppmw internal soot mixture and 2 ppmw external dust mixture. The second snow layer is contaminated by 0.1 ppmw internal soot mixture and 1 ppmw external dust mixture.

for two-layer snow models with three geometric depths (d_1), 2, 5 and 10 mm, with density of 0.05 g/cm^3 and r_{eff}=25 μm, in the first layer, and semi-infinite geometric depth with r_{eff}=100 μm in the second layer. The first snow layer is contaminated with 0.1 ppmw internal soot mixture and 2 ppmw external dust mixture. The second snow layer is contaminated by 0.1 ppmw internal soot mixture and 1 ppmw external dust mixture.

Good agreement is obtained for the model with geometric depth d_1=2 and 5 mm for the first layer at almost all wavelengths. In the case of d_1=10 mm, which is the value observed in this study, the theoretical spectral albedo is higher than the observed one by 0.05 to 0.1 at the wavelengths $1.0<\lambda<1.35$ μm. If we assume the value of snow density to be 0.02 g/cm^3, which is the minimum value of KAJIKAWA (1989), the geometric depths d_1=2 and 5 mm in Fig. 6, respectively, become to d_1=5 and 12.5 mm. These values are consistent with the observed geometric depth.

On the other hand, soot concentration of 0.1 ppmw with internal mixture in both snow layers leads to good agreement between theoretical and observed spectral albedos. The Arctic background concentration of snow impurities ranges from 0.005 to 0.045 ppmw (WARREN and CLARKE, 1986). Our value 0.1 ppmw is twice the highest value of WARREN and CLARKE (1986). Since our observation site was close to Barrow town, there is a possibility that the snow was polluted by locally emitted soot. Dust concentrations of 2 ppmw in the first layer and 1 ppmw in the second layer are consistent with the measured results obtained by using Nuclepore filters.

5. Summary

Spectral albedo observation was carried out on the snow field at Barrow, Alaska in April, 1997 and compared with the theoretical calculations made by a multiple scattering radiative transfer model for the atmosphere-snow system using the snow physical parameters observed by snow pit work. Optically effective snow grain size is on the order of branch size for new snow of dendrites, but is not of crystal size. Snow impurities reduce the albedo in the visible and a part of the near infrared. The observed albedo reduction in these regions is explained by the theoretical model for snow contaminated by an internal mixture of soot and external mixture of dust, where a small amount of highly absorptive material such as soot contributes to the albedo reduction in these regions and a large amount of weakly absorptive material such as dust contributes to the gross concentration of snow impurities. The soot concentration estimated by the comparison between the theoretically calculated and the observed spectral snow albedo is 0.1 ppmw. This value is higher than the Arctic background level of 0.005 to 0.045 ppmw observed by WARREN and CLARKE (1986). Since our observation site is close to Barrow town, there is a possibility that the snow was polluted by the local emission of soot. An optical method such as that by the CLARKE (1982a, b) may have to be introduced to clarify the concentration ratio of soot and dust for snow impurities on Nuclepore filters. Snow layer structure is important for the spectral albedo at the wavelengths $1.0<\lambda<1.35$ μm. We obtained good agreement between the theoretical and observed spectral albedos using a two-snow layer model based on the assumption that the density of new surface snow is 0.02 g/cm^3. This is the lowest density known for new snow.

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