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Citation: AIP Conference Proceedings 1531, 176 (2013); doi: 10.1063/1.4804735
View online: https://doi.org/10.1063/1.4804735
View Table of Contents: http://aip.scitation.org/toc/apc/1531/1
Published by the American Institute of Physics

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Numerical Simulation of Spectral Albedos of Glacier Surfaces Covered with Glacial Microbes in Northwestern Greenland

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Abstract. To clarify the effect of light absorbing impurities including glacial microbes spectral albedo measurements using a spectrometer for spectral domains of the ultraviolet, visible and near-infrared have been carried out on ablation area in Qaanaaq Glacier in northwestern Greenland in July 2011. The almost glacier surfaces in the ablation area were covered with cryoconite (biogenic dust) on thin ice grain layer above bare ice. There were also snow-covered surfaces including red snow (snow algae). The measured spectral albedos had a remarkable contrast between red snow surface and cryoconite-covered ice surface in the spectral domain from the ultraviolet to the visible, where red snow albedo increased rapidly with the wavelength, while the cryoconite albedo was relatively flat to the wavelength. We simulated the spectral albedos of these surfaces with a radiative transfer model for the atmosphere-snow system. The single scattering properties are calculated with Mie theory by assuming red snow gains to be spherical and with geometric optics by assuming ice grains of cryoconite surface to be non-spherical Voronoi aggregates. We calculated the effect of glacial microbes as snow (ice) impurities using a mineral dust model by changing the imaginary part of refractive index so as to fit the theoretically calculated spectral albedo to the measurement. Finally the imaginary part of refractive indices for red snow and cryoconite at the wavelengths less than 1.0 \( \mu m \) were retrieved. It was found that cryoconite has uniformly higher light absorption compared to mineral dust and red snow has strong light absorption at the wavelengths less than 0.6 \( \mu m \).

Keywords: Spectral albedo, Glacier surface, Glacial microbes, Greenland, Radiative transfer model.

PACS: 92.70.Ha, 92.60.Vb and 93.30.Kh

INTRODUCTION

Snow and ice in the Arctic are presently undergoing drastic changes. The mass balance loss from the Greenland Ice Sheet increased significantly after the mid-1990s [1]. A gravity survey by the satellite-borne Gravity Recovery and Climate Experiment (GRACE) confirmed that the rate of ice loss accelerated during from 2002 to 2006 [2], mainly as a result of high rates of ice loss in southern Greenland [3]. One of the possible reasons of snow/ice surface melting is the increase of light absorbing impurities in snow/ice and snow grain size growth. This is because the surface albedo of snow (ice) is strongly controlled by mass concentration of light absorbing impurities including glacial microbes and snow (ice) grain size [4]. Recently the dark region appears every year during the summer season in the western Greenland ice sheet, which makes meltwater unlikely as the only source for the low albedos [5]. To clarify the effect of light absorbing impurities on albedo reduction and its impact on snow/ice melting in the Arctic, we have developed physically based snow albedo model (PBSAM) that calculates broadband albedos as a function of snow grain size, mass concentrations of black carbon (BC) and dust concentrations in snowpack, solar zenith angle and snow water equivalent (snow layer structure) [6]. This model has been incorporated into the Earth System Model (ESM) of the Meteorological Research Institute [7]. When PBSAM is used in the ESM, snow microphysics parameters, including snow grain size, affected by snow metamorphism processes are calculated with a snow metamorphism model [8] coupled with PBSAM. Furthermore, the effect of glacial microbes on albedo reduction is needed to be included explicitly into the PBSAM, in which the different types of light absorbing snow impurities are treated by snow impurity factor (SIF) calculated from mass absorption coefficients and mass concentrations for those different impurities. Hence we need to know the mass absorption coefficients and the related optical parameters such as refractive index of glacial microbes. For this purpose spectral albedo measurements have been carried out on ablation area in Qaanaaq Glacier in northwestern Greenland in July 2011.
GLACIER SURFACE CONDITION AND SPECTRAL ALBEDO MEASUREMENTS

Spectral albedo measurements have been performed in ablation area of Qaanaaq Glacier (77°30’N, 167°10’W) (Figure 1). The glacier surfaces were mostly covered with cryoconite on ice grain layer with a radius of 5 to 10 mm and thickness of several cm above bare ice. There were also cryoconite holes (a water filled cylindrical melt-holes with cryoconite on the bottom), red snow and rivulets in some parts of the glacier surfaces. We measured the spectral albedos for red snow at Site-1 (h=565 m a.s.l) on 29 June 2011 and for cryoconite surface at Site-2 (h=506 m a.s.l) on 31 June 2011.

The depth of red snow at Site-1 was 10 cm on bare ice (Figure 2a) and the snow grain size (radius) measured by snow pit work was 1 mm. The mass concentration of red snow was 1975 ppmw for surface layer (1-2 cm) and 48 ppmw for subsurface layer. Snow densities in the two snow layers were 550 and 460 kg m⁻³, respectively. The major mass contents of red snow were mineral dust and the others were organic matters, in which the organic carbon concentrations measured with the Lab OC-EC Aerosol Analyzer [9] were 80.8 and 3.2 ppmw for the two snow layers, respectively. The cryoconite surface we measured at Site-2 (Figure 2b) consisted of ice grains with a radius of 5 to 10 mm and thickness of 3 cm above bare ice. The mass concentration of cryoconite in surface layer (1-2 cm) was 1127 ppmw, in which the organic carbon concentration was 28.8 ppmw, and the subsurface layer looked clean (concentration not measured). The density of whole ice grain layer was 660 kg m⁻³.

Spectral albedos were measured by an albedo observation system (Figure 2) with a spectrometer FieldSpecrPro (ASD Inc., USA) for a spectral range λ = 0.35-2.5 µm of spectral resolutions of 3 nm at λ = 0.7 µm and 10 nm at λ = 1.4-2.1 µm. The instrument setup is the same as that by Aoki et al. (2000) [10]. Since the glacier surface is in general inclined, we measured downward and upward radiant flux densities on the plane parallel to the slope surface (Figure 2a) by pointing an optical fiber to white reference standard set parallel to the surface. The incident solar zenith angle relative to the slope is calculated from the geometry between sun and slope. In case of Site-2 the observed glacier surface was horizontal (not slope). The sky conditions at Site-1 and -2 were clear and overcast, respectively.

FIGURE 1. Location map and MODIS image of observation sites (white circle) on Qaanaaq Glacier in northwestern Greenland.

FIGURE 2. Surface conditions of (a) red snow at Site-1 and (b) cryoconite surface at Site-2. The devise on tripod is an albedo observation system by which spectral albedo was measured with a spectrometer connecting by an optical fiber (black cables). An albedo observation system was set parallel to the glacier surface.

OBSERVED RESULTS

Figure 3 shows measured spectral albedo for (a) red snow surface and (b) cryoconite surface. The measured spectral albedos have a remarkable contrast between red snow and cryoconite surface mainly for the ultraviolet to visible regions (λ<0.75 µm), where red snow albedo increased rapidly with the wavelength, while cryoconite surface albedo was relatively flat. The spectral albedo of cryoconite surface is lower than the reflectance of underlying bare ice at λ<0.75 µm. This is due mainly to the effect of light absorbing cryoconite particles. On the other hand, for λ>0.75 µm the cryoconite albedo was higher than the underlying bare ice reflectance. This is caused by the effect of light scattering by ice grains, on which the cryoconite covers, above bare ice. The relative high albedo in the near-infrared region has an opposite effect for the melting process of glacier surface in contrast to the effect of albedo reduction due to glacier microbes mainly in the visible region.
RADIATIVE TRANSFER MODELING OF GLACIER SURFACE ALBEDOS

We simulated the spectral albedos of red snow and cryoconite surface with a radiative transfer model for the atmosphere-snow system [10]. The single scattering properties of snow grains for red snow are calculated with Mie theory by assuming the snow gains to be spherical particles with a radius of 1 mm. The ice grains for cryoconite surface are assumed to be non-spherical particles of Voronoi aggregates [11] with a radius of 5 mm and the single scattering properties are calculated with geometric optics. Those grain sizes are based on in-situ measurements. For the effects of snow impurities of red snow and cryoconite, we simply employed mineral dust model [12] with in-situ measured mass concentrations, which are externally mixed with snow (ice) grains. Figure 4 shows the results of theoretically calculated spectral albedos for (a) red snow and (b) cryoconite surface using a two-snow (ice) layer model, in which the topmost (second) snow layer of red snow is assumed to be 1 cm (9 cm) in thickness with mass concentration of 1000 ppmw (100 ppmw) and snow density of 500 kg m$^{-3}$ (500 kg m$^{-3}$). The topmost (second) ice grain layer of cryoconite surface is assumed to be 1 cm (2 cm) in thickness with mass concentrations of 1000 ppmw (100 ppmw) and the density of ice grains of 500 kg m$^{-3}$ (500 kg m$^{-3}$) on bare ice. The spectral albedo of underlying bare ice is assumed to be the in-situ measured reflectance for bare ice. In Figure 4 the albedos measured for both red snow and cryoconite in the visible region are lower than the theoretically calculations using mineral dust model. This is because the light absorption of glacial microbes is in general stronger than that of mineral dust. We thus calculated the spectral albedos with more absorptive impurities as glacial microbes by increasing the imaginary part of refractive index of mineral dust. The results are shown by lower four dashed curves. The measured spectral albedos for more absorptive impurity cases in which the values of imaginary part of refractive index ($n$) of mineral dust model are increased by 2, 5, 10 and 20 times.

FIGURE 4. Comparison between theoretically calculated spectral albedos (curves) for (a) red snow and (b) cryoconite surface and the measurements (dots) with the values of imaginary part of refractive index ($n$) of mineral dust model are increased by 2, 5, 10 and 20 times.
albedos almost distribute in the range from the solid curve (original mineral dust) to the lowest curve (µx 20) for the spectral region from 0.45 µm to 1.0 µm. The measured albedos are higher than any theoretical curve at the wavelengths beyond 1.2 µm (red snow) or 1.4 µm (cryoconite). The possible reasons for this are difference in optical properties between mineral dust and glacial microbes, inappropriate snow (ice) grain shape model and liquid water effect among the snow (ice) grains. Using those theoretical albedos with different light absorbing impurities we retrieved the imaginary part of refractive indices for red snow and cryoconite at the wavelengths less than 1.0 µm (Figure 5). It was found that cryoconite has uniformly higher light absorption compared to mineral dust and red snow has strong light absorption at λ< 0.6 µm.

**CONCLUSION**

Spectral albedos of glacier surface covered with glacial microbes in northwestern Greenland were measured. Using a radiative transfer model for the atmosphere-snow system with spherical and nonspherical ice grain models, the spectral variations were simulated and the imaginary part of refractive indices for red snow and cryoconite were estimated. We found that the glacial microbes have unique and relatively strong light absorption properties compared to mineral dust. This is attribute to the albedo reduction of glacier surface and could cause to the recent rapid surface melting of ablation areas in Greenland.

**ACKNOWLEDGMENTS**

This work was supported by Japan Society for the Promotion of Science (JSPS), Grant-in-Aid for Scientific Research (S) 23221004 and the Global Change Observation Mission - Climate (GCOM-C) / the Second-generation GLocal Imager (SGLI) Mission, the Japan Aerospace Exploration Agency (JAXA).

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