グリーンランド氷床の暗色化と衛星抽出積雪物理量

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Darkening of Greenland ice sheet and satellite-derived snow parameters

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The mass loss of the Greenland ice sheet (GrIS) has been occurring from the middle of the 1990s, corresponding to the acceleration of surface melting and outlet glacier flow. The acceleration of surface melting is related to an albedo reduction of the ice sheet during the summer season, which is called “Darkening of GrIS”. Surface albedo of snow depends on snow grain size (SGS) and the concentration of light absorbing snow impurities (LASI) such as black carbon (BC) and mineral dust. Furthermore, the albedo reduction rate, itself due to LASI, is enhanced by an increase of SGS. Thus, there is a positive snow-albedo feedback mechanism caused by LASI, which is accelerated by snow grain growth associated with temperature increase. The possible causes of albedo reduction over snow-covered areas on GrIS are snow grain growth and an increase of LASI. In coastal areas, expansions of bare ice extent would also be a possible cause of albedo reduction. In particular, the expansion and progress of a “dark region” covered with dust of mineral and biogenic origin, such as cryoconite, on bare ice could reduce the albedo remarkably. Hence, we retrieved SGS and LASI concentration in snow-covered areas over GrIS, and the extent of bare ice and dark regions in July for the coastal areas over GrIS from Moderate Resolution Imaging Spectroradiometer (MODIS) data. It is, however, generally difficult to detect the LASI concentration from space except for the case of high concentrations. The reason is due to the too small change in snow reflectance by LASI compared to the uncertainties of the retrieval algorithm and sensor sensitivity of satellite (Warren et al., 2013). Figure 1 depicts the theoretically calculated albedo reduction by LASI and snow grain growth derived from a physically based snow albedo model (PBSAM) (Aoki et al., 2011). The typical BC concentration previously measured in-situ over GrIS ranges from 0.55 to 20 ppbw (ng of BC in g of snow), for which the maximum albedo reduction by BC is 0.006 (0.026) for a snow grain radius of 50 μm (1000 μm) shown by a blue (red) solid line. When the relatively high concentration of dust (1000 ppbw) measured by Aoki et al. (2014) is contained with BC, the maximum albedo reduction by BC is 0.007 (0.032) for a snow grain radius of 50 μm (1000 μm) shown by blue (red) dashed line. On the other hand, the albedo reduction caused by a grain size increase from 50 to 1000 μm is 0.14, even for an impurity free case as shown by the green lines, which is much larger than the albedo reduction due to LASI over GrIS. Thus, snow grain growth would be closely related with the albedo reduction in snow-covered area of GrIS. Although the albedo reduction by LASI can be negligible for the case of small grains (blue lines in Fig. 1), it becomes obvious with snow grain growth. This combined effect cannot be ignored. So, we tried to retrieve the BC-equivalent concentration from satellite data in this study.

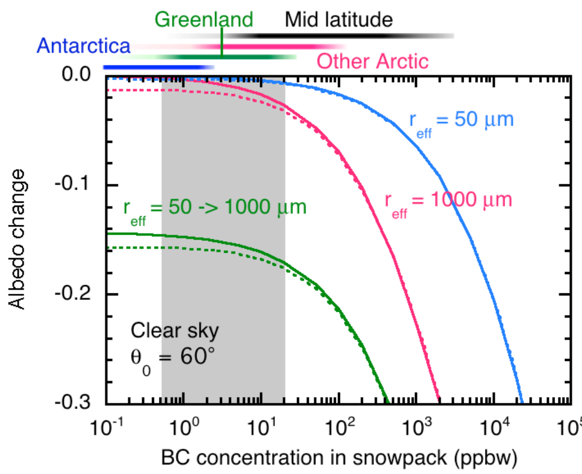

Fig. 1 Theoretically calculated albedo reduction by light absorbing snow impurities and snow grain growth as a function of BC concentration in snowpack under clear sky and solar zenith angle of 60°. The blue and red lines denote the case of effective snow grain radius of 50 and 1000 μm, respectively, and the green line is the case of the grain radius changed from 50 to 1000 μm. The solid and dashed lines show the cases of snow impurity composed by only “BC” and “BC+1000 ppbw of dust”, respectively. The upper color bars indicate the typical range of BC concentrations reported by the previous studies.

We used the algorithm for the retrievals of SGS and LASI concentration developed for Second Generation Global Imager (SGLI) of Global Change Observation Mission - Climate (GCOM-C), which is based on a look-up table (LUT) method for bidirectional reflectance distribution function at the top of the atmosphere as functions of SGS, BC concentration, and solar and satellite geometries (Aoki et al., 2007; Stamnes et al., 2007; Hori et al., 2007). The LUT was calculated with Advanced Radiative Transfer Model for the Atmosphere-Snow System (ARTMASS) (Aoki et al., 1999; 2000) using a snow shape model employing Voronoi columns and aggregates (Ishimoto et al., 2012). The algorithm uses a single-snow-layer or a two-snow-layer model composed from the topmost layer (5 mm of depth fixed) and the subsurface layer. The retrieved snow parameters are SGSs for the two snow layers (R_{s1} and R_{s2}) and BC-equivalent concentration (C_s) for the whole snow layer. The R_{s1} was retrieved first from the channel at the wavelength of 1.24 µm using a single-snow-layer algorithm, and the R_{s2} and C_s were retrieved by a two-snow-layer algorithm, in which the R_{s1} value is fixed, from the channel combination at the wavelengths of 0.55 µm and 0.86 µm. The validation for R_{s1} were conducted using the in-situ measured data of surface SGS synchronized with the Terra/Aqua MODIS overpasses at Summit (73°N, 38°W, 3,216 m a.s.l.) in 2011 and at SIGMA-A (78°N, 67°W, 1,490 m a.s.l.) in 2012. The results showed the excellent agreement for a wide range of SGS.

Using these algorithms, R_{s1}, $R_{s2,}$ and C_s over GrIS were retrieved with Terra/MODIS 5-km resolution resampled data from 2000 to 2014. R_{s1}, $R_{s2,}$ and C_s were monthly averaged from April to September and regional means for different elevation areas were calculated. The results showed that the R_{s1} and R_{s2} averaged in June, July, and August have an increasing interannual trend during the observed period; except the areas at an elevation higher than 3,000 m a.s.l. The trend for all snow-covered area over GrIS in June were 20 µm and 126 µm per decade for R_{s1} and R_{s2}, respectively but negative small values for the other months for both of R_{s1} and R_{s2} resulted. The trend of R_{s1} and R_{s2} averaged for high elevation areas beyond 3,000 m a.s.l. were slightly positive in June, July, and August and negative for the other months. These results indicate that the influence of temperature warming to snow grain growth by metamorphism is remarkable over the lower elevation areas during the summer season. The result of C_s shows no significant feature in spatial distribution and the trend is slightly positive or slightly negative depending on the season. However, the absolute C_s values were one order higher than the in-situ measurements reported by the previous studies. At the moment, it remains unclear whether a change in LASI contributes the albedo reduction or not.

Finally, we discriminated the bare ice extent and dark region extent by a normalized difference snow index together with a threshold method of the visible reflectances. The areal fraction of bare ice (dark region) to all of GrIS in July were 4.0% (0.16%) and 12.5% (1.2%) for 2000 and 2012, respectively, that is, the areas of bare ice (dark region) increased 2.9 and 7.6 times from 2000 to 2012. The fraction of the dark region in the bare ice in July have increased from 4 % in 2000 to 10% in 2012. These results suggest a remarkable contribution by the expansions of bare ice and dark region to the albedo reduction.

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