ADEOS-II/GLI Snow/Ice Products and the Scientific Implications

Teruo Aoki*1, Masahiro Hori*2 and Knut Stamnes*3

Abstract

The algorithm principles, calibration and validation (Cal/Val) experiments, and retrieval results of ADEOS-II/GLI snow/ice products are reported. The GLI snow/ice products are snow surface temperature, two types of snow grain sizes for topmost and shallow snow layers, and mass fraction of snow impurities. The snow grain size and snow impurities as satellite standard products are unique, but very important because snow surface albedo essentially depends on those parameters. From the analyses of GLI snow/ice products, the new findings on spatial distributions of clean snow, drastic spatial and seasonal evolution of snow grain size, and the possibility of detecting spatial distributions of vertical inhomogeneity in the top several centimeters of snow cover in the northern hemisphere were obtained. These snow parameters are expected to be used as an indicator of climate change by long-period monitoring. From the Cal/Val experiments in Alaska and eastern Hokkaido, Japan from 2001 to 2005 using MODIS and GLI data, it was found that snow surface temperature and grain size for shallow layer agreed well with in-situ measured values, while the accuracies of mass fractions of snow impurities and grain size at topmost layer were not so good compared with those for the former two products. The Cal/Val experiments also revealed some scientific results which are spectral or broadband snow albedos depending on snow grain size and snow impurities, relationship between snow surface temperature and snow grain size, and spectral and directional features of emissivity depending on snow types.

Keywords: ADEOS-II, GLI, cryosphere, snow grain size, and snow impurities

1. Introduction

Since the cryosphere is the most sensitive area for global warming on the earth, the understanding of its variation is very important. Although it has been discussed about the snow/ice extent estimated by means of satellite remote sensing as an index of global warming, the qualitative variation of snow/ice should be detected and understood for accurate simulation of future cryosphere. Because snow physical parameters of snow grain size and impurities (insoluble solid particles with light absorption) are essentially determine the snow albedo in case of sufficiently deep snowpack (Fig. 1)\(^1\). Absorptive snow impurity such as soot potentially reduces the albedo and is thus a possible trigger of warming in the Arctic. Since snow grain size on ice sheet is very sensitive to the surface temperature, it could be an indicator of warming and a temperature history. We have developed the remote sensing algorithms to retrieve these snow physical parameters and have made the global maps from April to October in 2004 with ADEOS-II/GLI data. For the validation of the products, in-situ measurements were performed on the snowfields in Hokkaido, Japan and Alaska synchronized with GLI and Terra/Aqua/MODIS overpasses. The final results of GLI snow/ice products were published as a series of three papers: Part I: Scientific basis\(^3\), Part II: Validation results\(^3\), and Part III: Retrieved results\(^4\).

2. ADEOS-II/GLI Snow/Ice products

The target satellite-derived snow parameters of GLI (Table 1) are snow surface temperature (\(T_s\)) retrieved from the channels 35 (\(\lambda = 10.8 \mu m\)) and 36 (\(\lambda = 12.0 \mu m\)), snow grain radius (\(R_{a,0}\)) from the channels 5 (\(\lambda = 0.460 \mu m\)) and 19 (\(\lambda = 0.865 \mu m\)), snow grain radius (\(R_{a,4}\)) from the channel 28 (\(\lambda = 1.64 \mu m\)), and a mass fraction of soot contained in the snow (\(C_s\)) which is retrieved together with \(R_{a,8}\). Since a light absorption at \(\lambda = 1.64 \mu m\) is stronger than that for \(\lambda = 0.865 \mu m\), \(R_{a,8}\) is expected to be retrieved near the snow surface than \(R_{a,8}\). The detailed descriptions of the algorithms for these snow parameters are presented in GLI snow/ice products Part I\(^1\).

GLI observes the earth completely for 4 days and the composite global maps of snow products are made from
clear-sky images by making cloud discrimination. In the followed ground discrimination process, surface types are classified into snow on sea ice, bare sea ice, open sea, ground snow, and snow-free ground. Retrieved monthly results of \( T_s \), \( C_s \), \( R_{s,0.9} \), and \( R_{s,1.5} \) are shown in Figs. 2a-d, respectively. In the high latitudinal areas, \( R_{s,0.9} \) and \( C_s \) generally take lower values (Figs. 2b-c), where \( T_s \) is low (Fig. 2a). In summer \( R_{s,0.9} \) in Greenland increases up to a size range of granular snow (\( R_{s,0.9} > 250 \mu \text{m} \)) (Fig. 2c), while the value of \( C_s \) keeps low (Fig. 2b). The values of \( R_{s,1.5} \) indicated drastic spatial and seasonal evolution of the snow cover over the northern hemisphere with radius ranging from 50 \( \mu \text{m} \) to over 1000 \( \mu \text{m} \) synchronized with variations in \( T_s \) (Fig. 3).

The preliminary analyses and an interpretation for the retrievals of snow parameters were reported by Hori et al. (2001)\(^5\) and the details were discussed in GLI snow/ice products Part III\(^6\). The important conclusions found from these studies are as follows. (1) The snow cover around the northern Canadian Arctic tundra and Archipelago regions and the Greenland ice sheet in April to June was found to be very clean with \( C_s \) of around 0.05 ppmw or less. (2) Retrieved \( R_{s,0.9} \) seemed erroneous over thin snow covers, but indicated drastic spatial and seasonal evolution of the snow cover over the northern hemisphere with radius ranging from 50 \( \mu \text{m} \) to over 1000 \( \mu \text{m} \) synchronized with variations in \( T_s \). (3) The spatial variability of \( R_{s,1.5} \) was partly different from that of the grain size in the shallow layer suggesting the possibility of detecting vertical inhomogeneity of the top several centimeters of the snow cover.

Snow grain size at topmost layer on ice sheet is considered to be very sensitive to a history of surface temperature. We applied the modified algorithm of \( R_{s,1.5} \) for Antarctica, in which the altitude of target on ice sheet is considered in atmospheric correction and the lower limit of look-up-table is extended, using a radiative transfer model\(^6\) to MODIS data in east Antarctica during the period from October 2000 to March 2004\(^7\). The result is shown in Fig. 4, where the values of \( R_{s,1.5} \) are relatively small in high altitude plateau areas compared to coastal zones, and the absolute \( R_{s,1.5} \) values vary seasonally (large in summer, and small in autumn and spring). Such a latitudinal dependence and seasonal variation in \( R_{s,1.5} \) mean this parameter could be used an indicator of climate change by long-period monitoring.

![Fig. 1 Theoretically calculated spectral snow albedos](image)

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<table>
<thead>
<tr>
<th>Products</th>
<th>Symbols</th>
<th>Used channels (wavelength)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud masking on surfaces</td>
<td>-</td>
<td>3.7, 6.7, 8.6, 10.8, and 12.0 ( \mu \text{m} )</td>
</tr>
<tr>
<td>including snow/ice</td>
<td></td>
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<tr>
<td>Surface classification</td>
<td>-</td>
<td>0.545, 0.678, 0.865, 1.05, and 10.8 ( \mu \text{m} )</td>
</tr>
<tr>
<td>(Snow/ice extent)</td>
<td></td>
<td></td>
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<tr>
<td>Snow surface temperature</td>
<td>( T_s )</td>
<td>10.8 and 12.0 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Snow grain radius in shallow layer</td>
<td>( R_{s,0.9} )</td>
<td>0.460 and 0.865 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Snow grain radius in top layer</td>
<td>( R_{s,1.5} )</td>
<td>1.64 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Mass fraction of soot</td>
<td>( C_s )</td>
<td>0.460 and 0.865 ( \mu \text{m} )</td>
</tr>
</tbody>
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* Mainly used channels. The other channels also are used secondarily.
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Fig. 2 16-day averaged distributions of (a) \( T_s \), (b) \( C_s \), (c) \( R_{obs} \), and (d) \( R_{src} \) retrieved from GLI data in the northern hemisphere from April 7 to October 15, 2004 (Hori et al., 2007).

3. Cal/Val activities and results

For calibration of the sensor and the validation of snow/ice products of GLI, several field campaigns (Cal/Val experiments) were performed for various types of snow conditions with satellite overpasses in Alaska and eastern Hokkaido, Japan from 2001 to 2005, which is presented in GLI snow/ice products Part II and is also reported in the next paragraph in this review. Calibration result is described in Nieke et al.
(2004)\textsuperscript{13}, where the spectral variations of sensitivities of shortwave channels of GLI sensor are investigated by cross calibration with the other sensors. In these Cal/Val experiments and laboratory measurements, various studies on optical properties of snow/ice were performed for spectral albedo, directional reflectance\textsuperscript{10, 13}, and directional emissivity\textsuperscript{14}. The detailed results are omitted in this review. Field campaign experiments using Airborne Multi-spectral Scanner\textsuperscript{15} and Airborne Visible/Infrared Imaging Spectrometer\textsuperscript{16} were also made to test algorithm performance. They found that the
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Fig. 3 Two-dimensional histogram between $T_s$ and $R_{oes}$. Red and dark blue colors indicate high and low frequencies, respectively (Hori et al., 2007)\textsuperscript{1}.

Fig. 4 Seasonal variation of $R_{oes}$ distributions retrieved from MODIS data in east Antarctica during the period from October 2003 to March 2004 (Motoyoshi, 2008)\textsuperscript{2}.
channel at shorter wavelength conveys the information of snow grain size for relatively deeper layers than the channel at longer wavelength due to a difference in light absorption.

The retrieved satellite products were compared with in-situ measured snow parameters based on snow pit work and snow sampling obtained from these Cal/Val experiments. Figures 5a-d show the validation results for $T_s$, $C_s$, $R_{d,s}$, and $R_{d,a}$. The following results are obtained. (1) $T_s$ agreed well with in-situ measured values with a correlation coefficient ($R_1$) of 0.900 and a root-mean-square error (RMSE) of 1.1 K (Fig. 5a). (2) The values of $C_s$ were close to in-situ measured mass fractions of snow impurities for the relatively thick snow layer (0–7 cm or 0–10 cm) (Fig. 5b) rather than the shallower layer (0–2 cm: not shown in figure) among two different snow sampling layers, while the satellite-derived absolute values were lower than the in-situ measured ones ($R_2 = 0.506$ and RMSE = 5.0 ppmw). This discrepancy is due primarily to the difference in the composition of snow impurities assumed in the satellite algorithm (soot) and measured in-situ (mineral dust). (3) From the correlations between satellite-derived grain sizes ($R_{d,9}$ and $R_{d,4}$) and the in-situ measured snow grain size simply averaged over the snow layer from the surface to various snow depths with snow thicknesses of 0.5, 1, 2, 3, 4, 5, ... cm (see Aoki et al. 2007 for details), it is confirmed that $R_{d,9}$ and $R_{d,4}$ have the maximum correlations for snow layers of 0–5 cm and 0–0.5 cm, respectively. In these comparisons of satellite-derived snow grain sizes with depth-averaged in-situ measurements, $R_{d,9}$ has a better accuracy ($R_3 = 0.840$ and RMSE = 125 μm) (Fig. 5c) than $R_{d,4}$ ($R_4 = 0.524$ and RMSE = 123 μm) (Fig. 5d). The values of $R_{d,4}$ are underestimated as a whole. The possible reasons of this underestimate in $R_{d,4}$ are very short penetration depth at $\lambda = 6.0 \mu m$.
1.64 μm and sun crust at snow surface in case of wet snow.

4. Scientific implications

Snow pit works conducted as a part of routine field experiment for GLI sciences, indicates that snow grain size and concentration of snow impurities are crucially important factors determining broadband snow albedo needed to assess the long term impact on the radiation budget and thus climate change.

We have thus made radiation budget observations simultaneously with snow pit work during 8 winters in snow covered areas in Japan since 1999, in which snow grain size and snow impurities were measured. Using these data the effect of snow aging on broadband albedo can be investigated\(^{(17-19)}\). The dependence of albedos on elapsed time after snowfall by snow aging could be clearly classified by dry snow season and wet snow season rather than snow surface temperature. The effect of snow aging essentially attributes the increases of snow grain size and snow impurities after snowfall. The relationships between broadband albedos and these snow physical parameters were shown in Fig. 6. The measured albedos fall close to the ranges of theoretically calculated ones as functions of these snow parameters.

The mutual relationships among those snow parameters measured on the ground can be found from satellite data as well. Figures 7 and 8 show the relationships between snow surface temperature and snow grain size obtained from in-situ measured field data and MODIS data, respectively. An increase in snow grain size with snow surface temperature was clearly shown both from these data. These results provide useful information required to improve the treatment of land-surface processes in regional and global climate models.

5. Summary

We reported the retrieval results of ADEOS-II/GLI snow/ice products, the results of Cal/Val experiments for the algorithms and products, and the scientific implications of snow/ice products obtained from Cal/Val experiments. The GLI snow/ice products are snow surface temperature, snow grain radius for shallow layer of 0–5 cm, snow grain radius at topmost layer, and mass fraction of snow impurities as soot. Snow surface temperature and grain size for shallow layer agreed well with in-situ measured values, while the accuracies of mass fractions of snow impurities and grain size at topmost layer were not so good compared with those for the former two products. The global maps of those four snow parameters from April to October in 2004 were made with GLI data. From the analyses of these maps, we obtained the new findings on spatial distributions of clean snow, drastic spatial and seasonal evolution of snow grain size, and the possibility of detecting spatial distributions of vertical inhomogeneity in the top several centimeters of snow cover. These snow parameters are expected to be used an indicator of climate change by long-period monitoring. We also obtained other scientific findings on spectral or broadband snow albedos depending on snow grain size and snow impurities, relationship between snow surface temperature and snow grain size, and spectral and directional features of emissivity depending on snow types. These results could be used for improvement of land-surface processes in regional and global climate models.

Acknowledgments

This study has been carried out by PIs and CIs in GLI Cryosphere Team: Teruo Aoki (MRI/JMA), Masahiro Hori
Fig. 7 Relationship between snow surface temperature and snow grain radius measured in Kitami and Shinjyo, Japan during 4 winters of 1999–2003.

Fig. 8 Same as Fig. 7, but from MODIS data on June 18, 2000 in the north hemisphere. (Hori et al., 2001)\textsuperscript{3}.

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