Abstract

In the past, many of the relationships between Arctic oscillations and snow cover in the Eurasian Continent were discussed assuming a decadal cycle. However, the possibility of an annual rotation of the relationship was not discussed. The target of our study is the investigation of an annual variation of snow quantity in the Northern Hemisphere.

In 2007, we developed a snow depth retrieval algorithm for AMSR and AMSR-E. In this paper, that algorithm was adjusted to make it applicable to the Special Sensor Microwave Imager (SSM/I) data which have been collected continuously since 1987. Then, snow depth in the Northern Hemisphere by using our improved algorithm is estimated, and the interannual variation of the long-term distribution of snow depth in the Northern Hemisphere is discussed. Next, the relevance of our estimations of March snow depth and Arctic oscillation (AO) is confirmed. Then the estimation accuracy of snow depth as compared with a few in situ observations, concluding that its accuracy is comparatively good is discussed. Furthermore, the interannual fluctuation of the distribution of snow depth is discussed. Our result shows a tendency toward a converse fluctuation between the Siberia and the Alaska/Canada snow depths in January and February, which has been confirmed from 1995 to 1999.

Keywords: SSM/I, AMSR-E, Snow, Microwave radiative transfer model, remote sensing

1. Introduction

Land surfaces have various coverings, such as vegetation, snow and soil. In addition, the spatial and temporal heterogeneity of land surfaces is greater than that of the oceans. To monitor snow conditions quantitatively, globally, and operationally, satellite remote sensing is the only viable method because it is impossible to install and operate in situ observation instruments with a uniformly high observation density over land within cold regions.

We developed a snow depth retrieval algorithm for AMSR and AMSR-E (Tsutsui et al., 2007). In this paper, that algorithm is adjusted to make it applicable to the Special Sensor Microwave Imager (SSM/I) data which have been collected continuously since 1987.

We present the theory of our earlier algorithm for AMSR (AMSR) in detail at the beginning of this paper in order to understand the adjustment process. We then describe the adjustment process involved in making it applicable to SSM/I. We then estimate snow depth, based on our improved algorithm, and discuss the interannual variation of the long-term distribution of snow depth in the Northern Hemisphere as a target of this paper. We then discuss the estimation accuracy of snow depth as compared with in situ observations. Furthermore, we discuss the interannual fluctuation of the distribution of snow depth.

2. The current snow retrieval algorithm for AMSR-E (AMSR)

In this section, we outline two microwave radiative transfer models: the 4-Stream fast model developed by Liu (1998) and the dense media radiative transfer model (DMRT) proposed by Tsang (1992). The latter model (Tsang (1992)) is able to estimate the scattering effect. A conventional microwave transfer assumes that scattering for spherical snow particles is mutually independent. Accordingly, radiation from the soil is scattered in many directions by snow grains (Figure 1) and the degree of attenuation by scattering is overestimated.

In contrast, DMRT assumes that snow particles are mutually dependent. As shown in Figure 2, once radiation from the soil is scattered by an arbitrary snow particle, the scattering spreads to many other particles. This scattering process is known as multiple scattering theory, and it expresses a realiz-
Our radiative transfer model calculates the characteristic parameters $K_e$ and single scattering albedo ($\omega_s$) of snow. The calculation uses DMRT and is based on several snow parameters: permittivity, fractional volume (density), grain size, and frequency. The brightness temperature from the snow surface is calculated by inputting the characteristic parameters ($K_e$ and $\omega_s$), snow depth and temperature calculated using DMRT, and soil parameters (moisture, density, and permittivity) into the 4-stream fast radiation transfer model.

The dielectric constant of ice was taken as $\varepsilon_{\text{ice}} = 3.15 - i \cdot 0.001$, based on the work of Cumming et al. (1952) and other studies (Vant et al. (1974), Lamb (1946), Lamb and Tumey (1949)) and Tumey (1949). The dielectric constant of the background, except for ice in snow, was taken as $\varepsilon_b = 1.00 - i \cdot 0.000$ to target dry snow. There are few observation examples of snow density in the Northern Hemisphere cryosphere. However, we observed the snow density in Fraser (Colorado, USA) and based the snow density values on those observations. As shown in Figure 4 (1), the snow density at midwinter (from November to February) is around 0.2 g/cm$^3$. The fractional volume was set to 0.218 ($=0.2$ g/cm$^3$/0.9164 g/cm$^3$ (density of pure ice)). The dielectric constant of soil was calculated based on Dobson’s model (Dobson et al. (1985)). As in the case of snow density, there are few observation examples of soil moisture in the Northern Hemisphere cryosphere. However, we observed the soil moisture in Yakutsk (Republic of Sakha-Yakutia, Russia) and used those observations in our studies.
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Fig. 4 Result of snow density and soil moisture observation algorithm. As shown in Figure 4 (2), the soil moisture at midwinter (from November to February) is 1% to 5%. Therefore, we used the mean value of 3% for the snow density in our algorithm.

2.1 Classification of the snowy region into four groups

In Figure 5, daily data of AMSR-E brightness temperature corresponding to the 70 GTS (global telecommunication system) ground-based stations in the northern hemisphere (daily data: 2002.10–2003.3) are distributed over a single lookup table. It is apparent from this figure that the distribution of various satellite brightness-temperatures is not covered by a single lookup table.

Our proposed algorithm forms a lookup table based on the 18.7/36.5 GHz brightness temperature calculated using the microwave radiative transfer model. The snow depth is estimated by inputting the satellite observation brightness temperature into a lookup table. Therefore, the conditions that a brightness temperature is included in a lookup table are indispensable when estimating snow depth. We applied the following technique to store the scattered distribution of the brightness temperatures in a lookup table. As shown in the following formula, the brightness temperature from the snow surface \( T_s \) is represented as the output from soil emission \( T_{soil} \) dissipated by snow \( e^{-\frac{t_{soil}}{t_{snow}}} \).

\[
T_s = T_{soil} \cdot e^{-\frac{t_{soil}}{t_{snow}}} \tag{1}
\]

That is, the absolute brightness temperature from the snow surface and the horizontal position on the lookup table are mainly determined by the energy of soil emission. In this study, the soil emission became solely a variable of soil density because we assumed the soil moisture to be 3.0% and that snow temperature is equal to soil temperature. Figure 6 was obtained by increasing the soil density from 0.2 to 0.8 g/cm³ in 0.2 g/cm³ steps, and then calculating the lookup table. The distribution of brightness temperature scattered by soil emission at the four different soil densities can be stored in a lookup table. Furthermore, the following emission level was arbitrarily established using 6.925 GHz, a wavelength that
model. The snow depth is varied from 1 to 200 cm, and the
snow temperature changes from 223 K (−50°C) to 273 K
(0°C). Second, the result of the calculation is reversed to
obtain the snow depth and temperature by inputting the
observed brightness temperature with 1 K interval. As shown
in Figure 7, snow depths are estimated by inputting satellite-
derived 18.7 and 36.5 GHz brightness temperature data into
the lookup table.

2.3 Calculation of the brightness temperature at 89 GHz
and selection of optimal grain size

Previous snow retrieval algorithms assumed snow grains of
a fixed size; accordingly, the difference between the assumed
and actual size of a snow grain results in a reduction in the
accuracy of snow depth estimates. This effect is pronounced
for deep snow. We devised a technique using high-frequency
microwave satellite data to estimate changes in the size of
snow particles from satellite observation data, independent of
regional characteristics. It is possible because high-frequency
microwaves are sensitive to the dispersion effect related to
changes in snow grains.

In our algorithm, the brightness temperature at 89 GHz is
calculated by inputting data on snow depth, temperature, and
grain size derived from the lookup table at 18.7 and 36.5 GHz,
as shown in Figure 8. The optimal grain size of snow is
selected by comparing the observed and calculated brightness
temperatures at 89 GHz.

3. Applying the AMSR-E (AMSR) snow retrieval
algorithm to SSM/I data set

In our study, we use SSM/I for the estimation of the
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Fig. 10 Estimation of snow depth from 1988 to 1999 in Northern Hemisphere.

long-term changes of snow depth in the Northern hemisphere. However, 6GHz channel brightness temperature is not observed by SSM/I.

In Figure 9, daily data of AMSR-E brightness temperature of 6GHz/19GHz corresponding to the 70 GTS ground-based stations in the northern hemisphere (daily data: 2002.10-2003.3) were plotted in a scatter diagram. Then, the technique of using 19GHz TB (Tb19) instead of a 6GHz TB (Tb06) in the algorithm was introduced based on the relationship between Tb06 and Tb19 identified from Figure 9.

The classification based on Tb06 which was described in Section 2.1 is converted to a new classification which is based on Tb19 by using the relation shown in Figure 9.

Emission level 1 : \( 231K \leq \text{Tb19} \)

Emission level 2 : \( 220K \leq \text{Tb19} < 231K \)

Emission level 3 : \( 212K \leq \text{Tb19} < 220K \)

Emission level 4 : \( \text{Tb19} < 212K \)

In this way, Tb19 is used to estimate the long-term snow depth in the Northern Hemisphere.

4. Result and discussion

4.1 Relevance between snow depth in the Northern Hemisphere and Arctic oscillation (AO)

In this paper, the long-term snow depth in Northern Hemisphere from 1988 to 1999 was estimated. In addition, snow depth at January, February, and March of each year was examined. As shown in Figure 10, our estimates of the snow
depth in the typical heavy-snow regions (Siberia, Alaska and Canada) was adequate, and the estimations showed clearly the trend for snow depth gradually to become deep from January to March.

In general, snow cover decreases in the Eurasian Continent when the Arctic oscillation (AO) index in winter is positive. Occurrence of this feature before February is not reflected clearly in Figure 10. However, it can be seen after 1994 in March. In 1994, 1996, and 1998, the deeply estimated snow cover on the Eurasian Continent appears clearly, centered in Siberia. In contrast, the estimated snow cover in 1992, 1993, 1995, 1997, and 1999 is not so deep at the Eurasian Continent. On the other hand, the Arctic oscillation index in 1994, 1996 and 1998 is negative, and it in 1995, 1997 and 1999 it is positive (Thompson and Wallace; 1998). Thus the estimated snow accumulation is not deep during a positive Arctic oscillation (1992, 1993, 1995, 1997, and 1999). However, the estimated snow depth during a negative Arctic oscillation is deep in the Eurasian Continent (1994, 1996, and 1999).

In the past, many of the relationships between Arctic oscillations and snow cover in the Eurasian Continent were discussed assuming a decadal cycle. However, our results show the possibility of an annual rotation of the relationship.

4.2 High frequency data of the SSM/I brightness temperature with an aberrant value in the period around 1990

The over-estimated snow depth from 1989 to 1991 is shown in Figure 10. We compared this with the satellite brightness temperature at 1989–1990 and 1992–1993. The estimation of snow depth in 1989–1991 is unusually excessive, but for 1992–1993 it is reasonable. Two regions were used for comparison of brightness temperature. One is latitude 60–75 degrees and longitude 90–120 degrees. This region has comparatively heavy
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Interannual fluctuation of snow depth: The interannual fluctuation of snow depth was discriminated based on Figure 13., (a) Siberia, (b) Alaska and Canada.

Table 2  Interannual fluctuation of snow depth: The interannual fluctuation of snow depth was discriminated based on Figure 13., (a) Siberia, (b) Alaska and Canada.

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snowfall, and snow depth estimates were excessive in 3 years (from 1989 to 1991). The other region is latitude 30–60 degrees and longitude 90-120 degrees. This region has comparatively light snowfall and snow depth estimates were similarly excessive in the same 3 years. As shown in Figure 11, the TB difference between 1989/1990 and 1992/1993 at 19 GHz band is almost negligible. However, a noticeable gap occurs at the high frequency band. At 85GHz the gap is 23K in the first region and there is a large gap of 48K in the second region. This confirms that the high frequency data of the SSM/I brightness temperature has an aberrant value in the period around 1990. We infer that the overestimation of snow depth in around 1990 occurred, because the change of snow particle size is estimated by an imperceptible change of the 90 GHz brightness temperature in our algorithm.

4.3 Examination of the estimated accuracy of snow depth

We also examined the estimated accuracy of snow depth. There are few actual long-term in situ observations of snow depth in the Northern Hemisphere cryosphere. However, Raino et al. (2006) investigated the trend of snow depth from 1936 to 2000 in the North Eurasia simultaneously at four stations: Sejmchan, Isim, Njuba, Anadyr. We compared these in situ snow depth measurements with our estimates at these four stations in the period from 1988 to 1999. However,
we excluded the period from 1989 to 1991 because we recognized abnormalities in the satellite brightness temperature data. Our estimated snow depth (annual average) based on SSM/I data at these four stations is shown in Figure 12. Table 1 shows the root mean square error (RMSE) and the residual standard deviation (RSD) between the observed and estimated values for all of the verification periods. The average the RMSE was 10.3 cm, the average RSD was 8.0 and the average of absolute error was 8.8 cm. This represents a relatively good agreement with the in situ data.

4.4 Interannual fluctuation of snow depth

The interannual fluctuation of snow depth is indistinct in Figure 10. Therefore, we averaged the snow depth for 8 years (from 1992 to 1999) for January, February and March, and calculated the deviation for each year (Figure 13). In addition, we excluded the periods from 1988 to 1991 from consideration because we recognized abnormalities in the satellite brightness temperature data. The interannual fluctuation of snow depth in Siberia and in Alaska and Canada indicated in Fig. 13 is shown in Table 2.

In Siberia, the estimated snow depth in January and February decreased after it increased from 1992 to 1993. The decrement continued until 1995. After that, it decreased again until 1998 although it increased temporarily in 1996, again in 1999. In contrast, the estimated snow depth in Alaska/Canada (January and February) fluctuated similarly to that in Siberia from 1992 to 1994. However, we confirmed a contrary fluctuation trend to that in Siberia after 1995. Moreover, we confirmed an annual fluctuation of estimated snow depth in Siberia for March. In contrast, the fluctuation of the estimated snow depth is very small in a one- to two-year cycle.

5. Conclusion

In this paper, the present algorithm has extended the capability of our previous algorithm for AMSR-E (AMSR) and enabled us to estimate snow depth based on SSM/I data in the Northern Hemisphere. We have been able to verify its accuracy by comparison with the relatively few available in situ observations of snow depth in the Northern Hemisphere.

We have illustrated its usefulness in several ways: We have used it to analyze the relationship between Arctic oscillation and snow cover in Eurasia and found that there is possibly an annual cycle rather than or in addition to the usually accepted. We showed a tendency toward a converse fluctuation between the Siberian and the Alaska/Canada snow depths in January and February, which has been confirmed from 1995 to 1999.

Acknowledgements

This paper was funded by the National Key Technology project “Data Integration and Analysis System” and the Japan Science and Technology Corporation, Core Research for Evolution Science and Technology (Development of Modeling and Satellite Remote Sensing of Atmosphere-land Interaction) and Special Coordination Funds for Promoting Science and Technology (Promotion of leading researches) as part of the Coordinated Enhanced Observing Period (CEOP) and AMSR/AMSR-E verification experiment of the Japan Aerospace Exploration Agency (JAXA). This study was carried out by using the data of National Snow and Ice Data Center (NSIDC). The authors express their great gratitude to them.

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