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ESTIMATION AND DISCUSSION OF LONG-TERM SNOW DEPTH BASED ON SSM/I SATELLITE DATA

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SYNOPSIS

This paper proposes a new method of estimating long-term interannual snow depth variation based on SSM/I (The special sensor microwave / imager) satellite data by using a snow retrieval algorithm. The snow retrieval algorithm considers the effects of land-surface hydrological conditions under the snow layer and snow-particle grain size on brightness temperatures in the microwave region by using the multi-frequency channels of AMSR (The Advanced Microwave Scanning Radiometer) and AMSR-E (The Advanced Microwave Scanning Radiometer - Earth Observing System).

In this research, this algorithm, which corresponds to AMSR-E (AMSR) was improved so that it could be applied to SSM/I data which have been observed since 1987. And, snow depth for 12 years (from 1988 to 1999) was estimated by this improved algorithm on the global scale, and the variation of snow depth was investigated at a long-term global scale. The above mentioned algorithm corresponding to AMSR-E (AMSR) was improved so that it could be applied to SSM/I data which are observed since 1987. And, snow depth for 12 years (from 1988 to 1999) was estimated by this improved algorithm on the global scale, and the variation of snow

depth was investigated at a long-term global scale. The typical heavy-snow in Central Siberia plateau, Alaska, and Canada was estimated. Also, the increasing tendency which reaches maximum in March was clearly confirmed in central Siberia. Next, snow depth for 12 years (from 1988 to 1999) was averaged in January, February and March, and the deviation of each year was calculated. The vibration in a cycle of one year or two years occurred in Central Siberia plateau and North Siberia lowlands in 1992 and afterwards especially. Next, 4 points (Sejmchan, Isim, Njuba, Anady') were extracted from these 7 points by Raino *et.al.*; 2006(4). A comparison between the in situ snow depth and the estimated snow depth by our algorithm was performed at these 4 points in the period from 1988 to 1999. As a result, the average the root mean square error (RMSE) was 10.3 cm, the average RSD was 8.0 and the average of absolute error was 8.8cm. When a spatial deviation with the wide range spatial resolution of SSM/I and the point data of a point are taken into consideration, the estimated snow depth agrees relatively well with the in situ data.

INTRODUCTION

The land surface has various coverings, such as vegetation, snow, and soil. In addition, spatial and temporal heterogeneity of the land surface is considerably larger than that for the ocean. Such variation makes it difficult to quantitatively assess variations in land-surface hydrology. A global-scale observation system for land-surface hydrological conditions allows us to improve predictions of the long-term global water cycle variables and short-term local water resources. 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 in such cold regions. In the past, we developed an algorithm for the estimation of snow depth based on brightness temperature in multi-frequency channels of AMSR and AMSR-E (Tsutsui *et. al.*; 2007(1)). In this work, the algorithm corresponding to AMSR, AMSR-E was improved so that it could be applied to the Special Sensor Microwave Imager（SSM/I）data which are continuing being observed from 1987. And, snow depth for 12 years (from 1988 to 1999) was estimated by this improved algorithm on a global scale, and the variation of snow depth was investigated on a long-term global scale.

CHARACTERISTICS OF THE SNOW RETRIEVAL ALGORITHM BY USING THE MULTI-FREQUENCY CHANNELS OF AMSR AND AMSR-E

In this section, we describe several characteristics of our snow retrieval algorithm based on brightness temperature in multi-frequency channels of AMSR and AMSR-E will be described.

Classification of the snowy region into four groups

In Figure 1, 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) was distributed over a single lookup table. As shown in Figure 1, a part of brightness temperature distribution for 18.7/36.5GHz is not shown in the table.

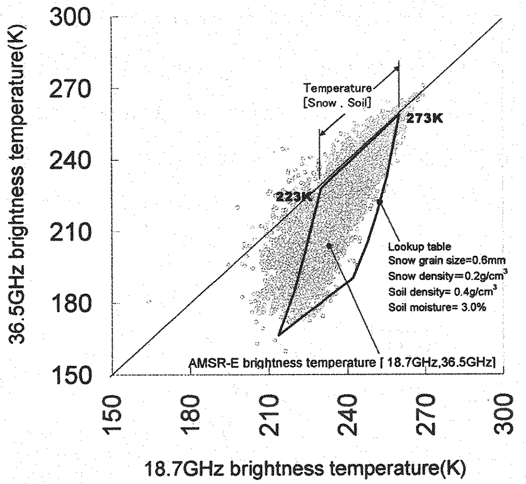

Fig.1 Daily values of AMSR-E brightness temperature recorded at the 70 GTS ground-based stations in the northern hemisphere. The lookup table is also shown.

The algorithm which we propose forms a lookup table based on the 18.7/36.5 GHz brightness temperature calculated using the microwave radiative transfer model. The snow depth (and snow temperature) is estimated by inputting the satellite observation brightness temperature (18.7/36.5 GHz) into the lookup table. Therefore, the conditions relating to a given brightness temperature (18.7/36.5 GHz) in the lookup table are indispensable when estimating snow depth. Consequently, we applied the following technique to store the scattered distribution of brightness temperatures (18.7/36.5 GHz) in the lookup table.

As shown in the following formula, the brightness temperature from the snow surface (T_b) is represented as the output from soil emission (T_{bsoil}) dissipated by snow ($e^{-\tau_{snow}}$).

$$T_b = T_{bsoil} \cdot e^{-\tau_{snow}} \quad (1)$$

That is, the absolute amount of the brightness temperature from the snow surface and the horizontal position on the lookup table are mainly determined by the strength of soil emission. The soil emission is determined by a permittivity, a moisture, temperature and the density of soil. In this study, the soil emission is the only variable of the soil density. Because soil permittivity is constant, the soil moisture was assumed to be 3.0%, and so we assumed that the soil temperature was equal to snow. Therefore, soil emission becomes the variable of a soil density. That is, the error based on moisture and permittivity is included in this soil density. Thus, we renamed this soil density the "virtual" soil density. Figure 2 is obtained by increasing the virtual soil density from 0.2 to 0.8 g/cm^3 in 0.2 g/cm^3 steps, and by calculating the lookup table. The distribution of brightness temperature (18.7/36.5 GHz) scattered by soil emission at the four different soil densities can be stored in the lookup table. Furthermore, the following emission level was arbitrarily established using 6.925 GHz with a wavelength that penetrates snowpack and which is able to detect soil. It is also possible to select the lookup table that is able to cover the distribution of brightness temperature (18.7/36.5 GHz) by selecting an emission level for the 6.925 GHz brightness temperature.

Emission level 1 : $243K \leqq T_{b06}$

Emission level 2 : $231K \leqq T_{b06} < 243K$

Emission level 3 : $219K \leqq T_{b06} < 231K$

Emission level 4 : $T_{b06} < 219K$

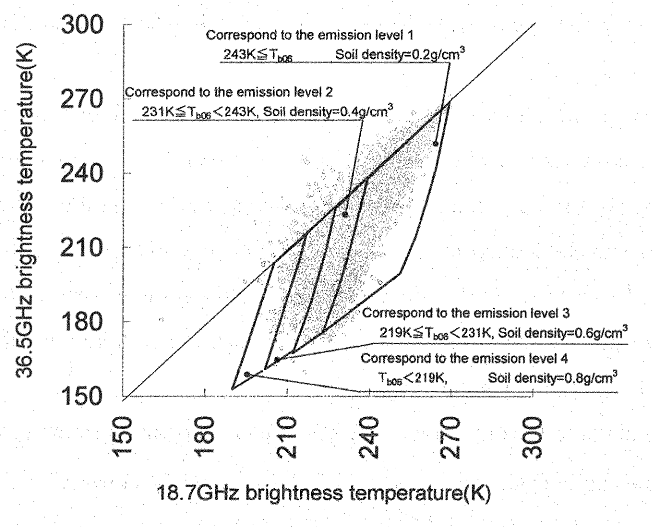

Fig.2 Position of the lookup table corresponding to the emission level

Construction of the lookup tables

For each ground-emission level, the lookup table is generated that represents the relationship between the brightness temperatures at 18.7 and 36.5 GHz and snow depth and physical temperature, corresponding to each grain size and constant snow density (0.2 g/cm^3). First, brightness temperature at 18.7 and 36.5 GHz is calculated by inputting snow depth and snow temperature into the microwave radiative transfer model. Then, the snow depth is varied from 1 to 200 cm, and the snow temperature changes from 223 K (-50℃) to 273 K (0℃). That is, one 18.7GHz brightness temperature and one 36.5GHz brightness temperature are calculated from one snow depth and one snow temperature by using the microwave radiative transfer model. Therefore, a data set size is 200cm x 50K. This is referred to as forward data. Second, the result of the calculation is reversed to obtain the snow depth and temperature by inputting the observed brightness temperature with a 1 K interval. That is, 18.7/36.5GHz brightness temperatures are set from the minimum value to the maximum value at 1K interval, and snow depth and snow temperature are interpolated by using the forward data. Therefore, a data set size is (maximum of 18.7GHz TB - minimum of 18.7GHz TB) × (maximum of 36.5GHz TB - minimum of 36.5GHz TB). This is known as the lookup table. As shown in Figure 3, the snow depth and snow temperature are estimated by inputting satellite-derived 18.7 and 36.5 GHz brightness temperature data into the lookup table.

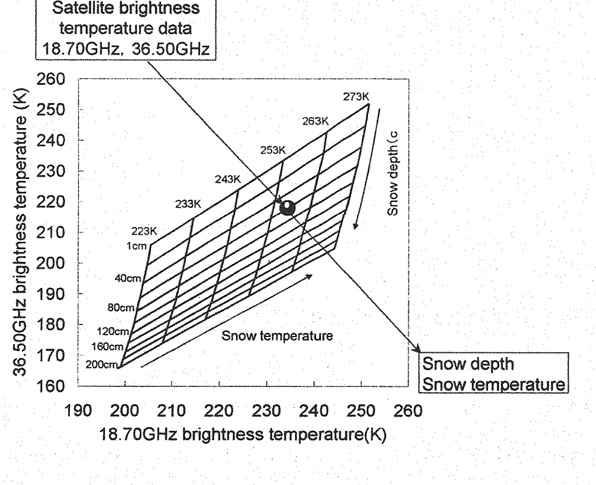

Fig.3 Estimation of snow depth using the lookup table

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

The old algorithm for estimating snow depth assumed snow grains of a fixed size(Koike and

Suhama;1993(2), Chang *et. al.*; 1991(3)); accordingly, the difference between the assumed grain size and the actual grain size of snow resulted in a reduction in the accuracy of the snow depth estimates. This effect is pronounced in the case of deep snow. Consequently, we devised a technique using high-frequency microwave satellite data (the brightness temperature for around 90GHz) to estimate changes in the size of snow particles from satellite observation data, independent of regional characteristics. An actual snow grain grows over time. Therefore, we had to estimate the optimum snow grain size to be equal to the actual snow grain size with the changes by using microwave data. It was 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 4. The optimal grain size of snow is selected by comparing the observed and calculated brightness temperatures at 89 GHz.

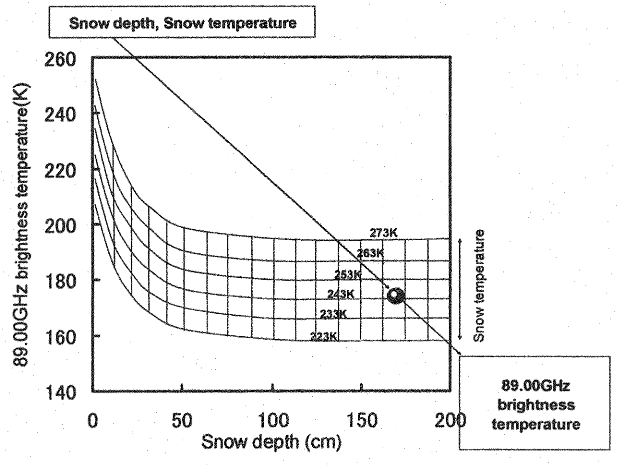

Fig.4 Estimation of the brightness temperature at 89GHz

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

In this paper, we used SSM/I to estimate the long-term changes of snow depth in the Northern Hemisphere. However, 6GHz channel brightness temperature was not observed by SSM/I. In Figure 5, daily data of AMSR-E brightness temperature of 6GHz/19GHz corresponding to the GTS ground-based stations in the northern hemisphere were plotted in a scatter diagram. Then, the technique of using the brightness temperature for 19GHz instead of the brightness temperature for 6GHz in the algorithm was introduced based on the relationship between 6GHz and 19GHz identified from Figure 5.

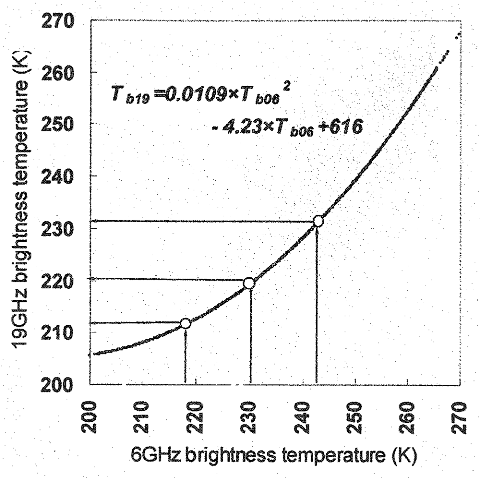

Fig. 5 Relationships between daily 6GHz channel brightness temperature data and 19GHz which are corresponding to the GTS ground-based stations in the Northern Hemisphere

Each classification, which is based on the 6GHz channel brightness temperature, is converted to a new classification which is based on the 19GHz channel brightness temperature, by using the relation shown in Figure 5.

Emission level 1 : $231K \leqq T_{b19}$

Emission level 2 : $220K \leqq T_{b19} < 231K$

Emission level 3 : $212K \leqq T_{b19} < 220K$

Emission level 4 : $T_{b19} < 212K$

In this way, long-term snow depth in the Northern Hemisphere can be estimated by using the 19GHz channel brightness temperature which is the minimum channel equipped on SSM/I.

RESULT AND DISCUSSION

The long-term snow depth in the Northern Hemisphere from 1988 to 1999 was estimated. In addition, snow depth during the months of January, February, and March of each year was examined. Experimental methods reveal that the snow depth in Central Siberia plateau, Alaska and Canada are comparatively deep and that the snow depth in Siberia in March is deeper than the snow depth in January and February. As shown in Figure 6, the typical heavy-snow in Central Siberia plateau, Alaska, and Canada were estimated. Furthermore, the increasing tendency which reaches maximum in March was confirmed clearly in central Siberia. However, the over-estimated snow depth is shown in central Siberia from 1989 to 1991.

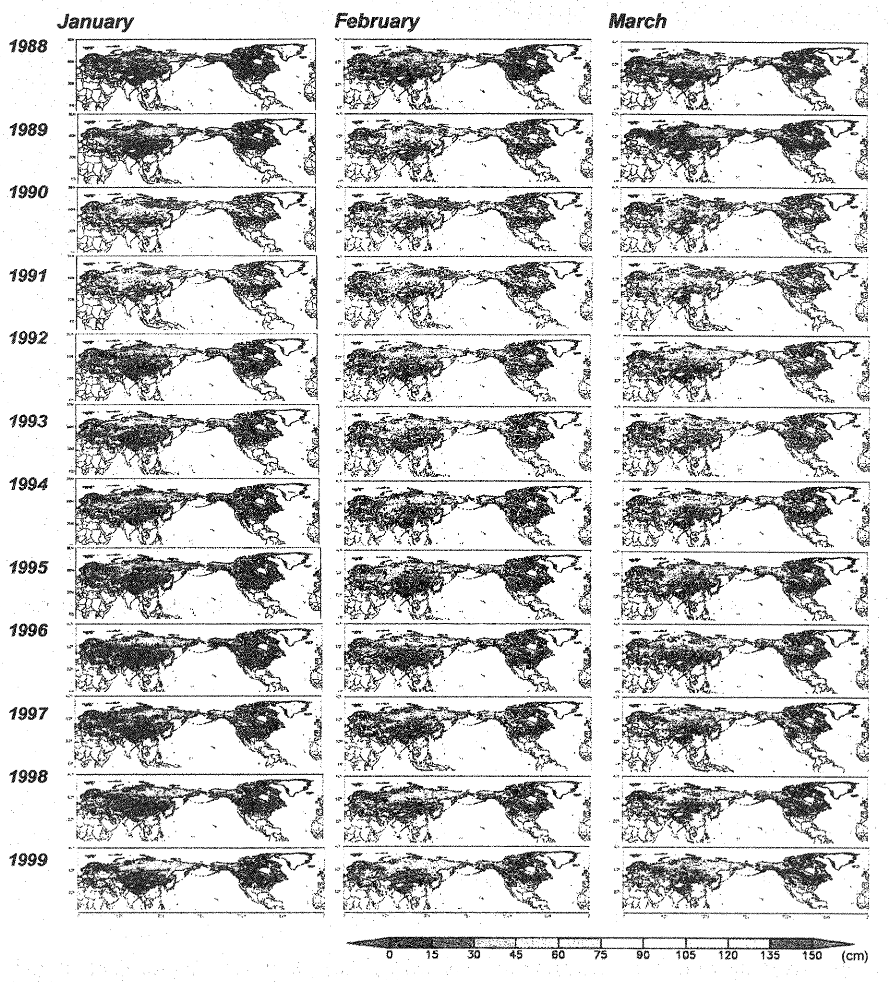

Fig. 6 Estimation of snow depth from 1988 to 1999 in Northern Hemisphere.

Secondly, snow depth over a period of 12 years (from 1988 to 1999) was averaged at January, February and March, and the deviation of each year was calculated. As shown in Figure 7, the vibration in a cycle of one year or two years had occurred in Central Siberia plateau and North Siberia lowlands in 1992 and especially after this year. However, the overestimation of the snow depth over 3 years from 1989 to 1991 was confirmed again as shown in Figure 6.

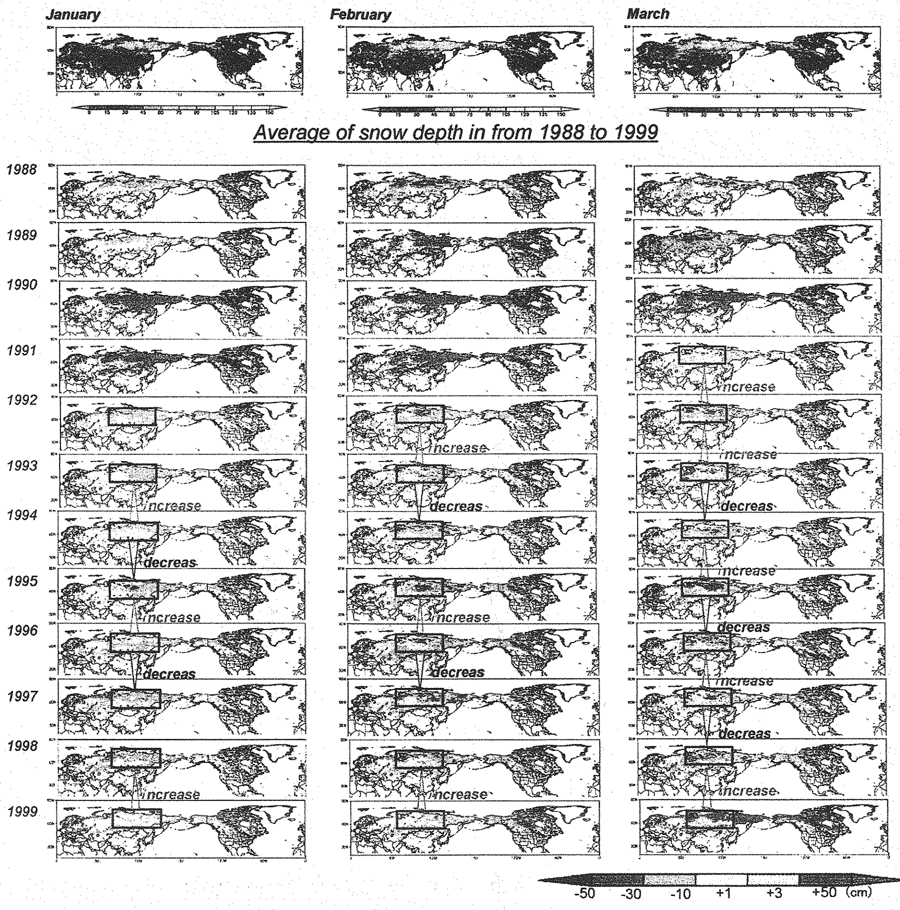

Fig. 7 Distribution of the deviation between the averaged snow depth and the annual snow depth. 12 years (from 1988 to 1999) snow depth was averaged at January, February and March, and then the deviation of each year was calculated.

The over-estimated snow depth from 1989 to 1991 is shown in Figure 6 and 7. We compared this with the satellite brightness temperature at 1989-1990 and 1992-1993. The estimation of snow depth over the period of 1989-1991 was unusually excessive, but for the period of 1992-1993 it was reasonable. The two regions were used to make a comparison of brightness temperature. One is latitude 60-75 degrees and longitude 90-150 degrees. This region has comparatively heavy 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 8, the TB difference between 1989/1990 and 1992/1993 at 19GHz 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 had an aberrant value in the period around 1990. We inferred that the overestimation of snow depth in around 1990 had occurred, because the change of snow particle size is estimated by an imperceptible change of the 90GHz brightness temperature in our algorithm.

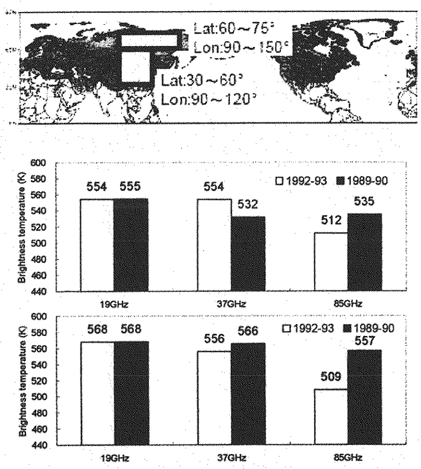

Fig. 8 Comparison between the satellite brightness temperature at 1989-1990 and 1992-1993. : Above diagram : Region of latitude 60-75 degree and longitude 90-150 degree. Below diagram : Region of latitude 30-60 degree and longitude 90-120 degree.

Raino *et.al.*;2006(4) investigated the trend of snow depth from 1936 to 2000 in North Eurasia. Simultaneously, they investigated the time series variation of snow depth at 7 points from 1936 to 2000 in the North Eurasia (see Fig. 9).

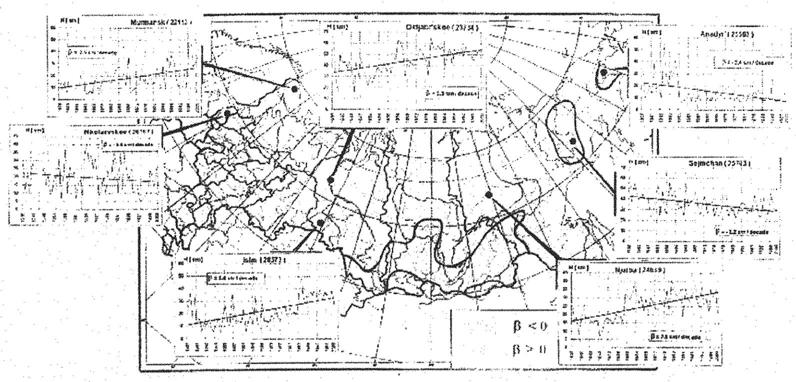

Fig. 9 Time series variation of in situ snow depth at seven spots in North Eurasia in from 1936 to 2000 (Raino *et. al.* ;2006)

Next, 4 points (Sejmchan, Isim, Njuba, Anady') were extracted from these 7 points. A comparison between the in situ snow depth and the estimated snow depth by our algorithm was made at these 4 points in the period from 1988 to 1999. However, the period from 1989 to 1991 was excluded because abnormalities were recognized on the satellite brightness temperature.

Estimated snow depth based from the SSM/I at 4 stations (Sejmchan, Isim, Njuba, Anady') over the period from 1988 to 1999 is shown in Figure 10. As shown in Table 1, we then calculated the Root mean square error (RMSE) based on the error between observed and estimated values and the residual standard deviation (RSD) for all of the verification periods. The average the root mean square error (RMSE) was 10.3 cm, the average RSD was 8.0 and the average of absolute error was 8.8cm. When spatial deviation with the wide range spatial resolution of SSM/I and the point data of a point are taken into consideration, the estimated snow depth agrees relatively well with the in situ data.

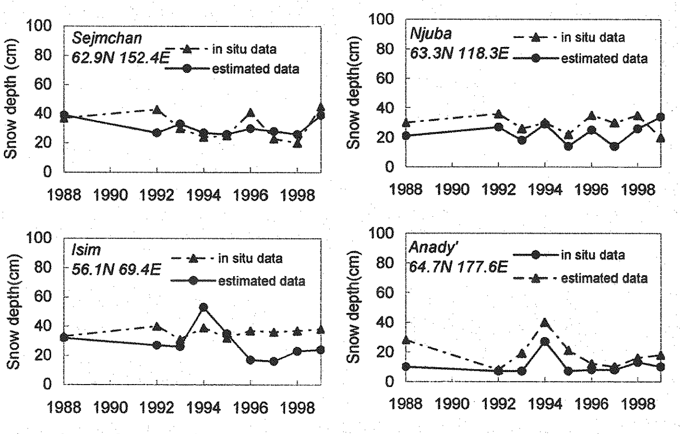

Fig. 10 Estimation of snow depth from SSM/I in the period from 1988 to 1999 at 4 stations (Sejmchan, Isim, Njuba, Anady').

Table.1 Evaluation of error between in situ snow depth and estimated snow depth from SSM/I in the period from 1988 to 1999 at 4 stations(Sejmchan, Isim, Njuba, Anady').

	RMSE	RSD	Average of absolute error
Sejmchan	7.4	7.3	5.9
Isim	13.3	10.8	11.6
Njuba	10.1	8.0	9.3
Anady'	10.1	5.8	8.3
Average	10.3	8.0	8.8

RMSE: Root mean square error (cm)
RSD: Residual standard deviation (cm)

In this paper, sufficient verification and modification of the algorithm could not be made, because of a lack of long-term in situ snow depth observation data. Hence, in further research, additional long-term in situ snow depth data needs to be collected in the North Eurasia, and the algorithm based on the in situ data needs to be improved.

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