

Validation and Algorithms Comparative Study for Microwave Remote Sensing of Snow Depth over China

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Abstract. In this study, five different snow algorithms (Chang algorithm, GSFC 96 algorithm, AMSR-E SWE algorithm, Improved Tibetan Plateau algorithm and Savoie algorithm) were selected to validate the accuracy of snow algorithms over China. These algorithms were compared for the accuracy of snow depth algorithms with AMSR-E brightness temperature data and ground measurements on February 10-12, 2010. Results showed that the GSFC 96 algorithm was more suitable in Xinjiang with the RMSE range from 6.85cm to 7.48 cm; in Inner Mongolia and Northeast China. Improved Tibetan Plateau algorithm is superior to the other four algorithms with the RMSE of 5.46cm~6.11cm and 6.21cm~7.83cm respectively; due to the lack of ground measurements, we couldn't get valid statistical results over the Tibetan Plateau. However, the mean relative error (MRE) of the selected algorithms was ranging from 37.95% to 189.13% in four study areas, which showed that the accuracy of the five snow depth algorithms is limited over China.

1. Introduction

Snow is an important part of Cryosphere which exerts profound impact on global climate change and energy balance. Along with the Scanning Multi-frequency Microwave Radiometer (SMMR), Special Sensor Microwave/Imager (SSM/I) and Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) have been successfully launched, it is convenient to use passive microwave detect snow information at large scale ^[1]. Dry snow is a strong scatter medium at higher frequency (e.g., 37GHz), and snow radiation can be greatly weakened by scattering which can be used to detect the presence of snow ^[2]. Lower frequency (e.g., 18/19GHz) can reflect the state of the background field. Therefore, the existing experience/semi-empirical snow algorithms mainly employ the 19GHz and 37GHz gradient to derive snow depth or snow water equivalent.

There are many global snow algorithms at present, but the accuracy of global snow algorithms is still limited. In North America, 15% difference existed between GSFC 96 algorithm and snow depth climatology (SDC) in February, but with Chang algorithm the difference is greater than 50% ^[3]. In Eurasia, only 1.3% difference existed between GSFC 96 algorithm and SDC, whereas the difference increased to 20% with Chang algorithm ^[3]. Chang et al. had inter-compared SMMR, NOAA/NESDIS and USAFGWC snow maps, found that the greatest difference among these three products were in central Asia and western China ^[4]. In Eurasia, Chang algorithm had large RMSE (e.g., 70.7mm~71.6mm), AMSR-E SWE algorithm had an RMSE of 57.5 mm over Finland, winter periods 2005-2008^[5]. Same test work had been taken in Canada from AMSR-E for the 2005/06 through 2007/08 winter seasons, the RMSE of AMSR-E SWE algorithm ranges from 28mm to 65mm ^[5].

In order to evaluate the accuracy of the snow depth algorithms over China, we selected five



different snow algorithms to validate the accuracy of snow depth algorithms in four regions with brightness temperature data and ground measurements during February 10-12, 2010, and compared accuracy of five snow inversion algorithms.

2. Passive microwave snow depth algorithms

The snow algorithms selected in this study consist of: Chang algorithm^[6], GSFC 96 algorithm^[3], AMSR-E SWE algorithm^[7], Improved Tibetan Plateau algorithm^[8] and Savoie algorithm^[9], these algorithms were shown specifically in table 1.

Table 1. Passive microwave snow depth algorithms

Snow Depth Algorithm	Algorithm formula
Chang Algorithm	$SD = 2.0 \times (TB_{18H} - 37H) - 8.0$
GSFC 96 Algorithm	$SD = (0.78 \times (TB_{18H} - 37H)) / (1 - ff)$
AMSR-E SWE Algorithm	$SD = (ff \times (SD_f)) + ((1 - ff) \times (SD_o))$
Improved Tibetan Plateau Algorithm	$SD = 0.868 \times (TB_{19H} - 37H) - 2.130$
Savoie Algorithm	$SD = 1.59 \times ((TB_{adj}(19H) - 6.0) - (TB_{adj}(37H) - 1.0))$

SD_f , SD_o , $TB_{adj}(19H)$ and $TB_{adj}(37H)$ were calculated as follows:

$$SD_f = \frac{(TB_{19V} - TB_{36V})}{(1 - 0.6fd) \log_{10}(TB_{36V} - TB_{36H})} \quad (1)$$

$$SD_o = \frac{TB_{10V} - TB_{36V}}{\log_{10}(TB_{36V} - TB_{36H})} + \frac{TB_{10V} - TB_{19V}}{\log_{10}(TB_{19V} - TB_{18H})} \quad (2)$$

$$TB_{adj}(19H) = 10.61837 + 0.940172 \times TB_{sat}(19H) + 1.217340 \times z \quad (3)$$

$$TB_{adj}(37H) = 17.52656 + 0.9089241 \times TB_{sat}(37H) + 1.526162 \times z \quad (4)$$

where SD is snow depth, measured in centimeter; $(TB_{18H}/19H - TB_{37H})$ is the difference between 18/19GHz and 37GHz at horizontal polarization; ff is fractional forest cover; SD_f is snow depth from the forested component of the IFOV, SD_o is snow depth from the non-forested component of the IFOV; TB_{adj} is adjusted brightness temperatures, TB_{sat} is satellite-observed brightness temperatures, measured in Kelvin; z is elevation, measured in kilometer.

3. Data

The data include brightness temperature data, ground-measured snow depth records and other auxiliary data. As snowfalls happened on February 10-12, 2010 in China, remote sensing brightness temperature data and ground-measured snow depth records acquired in this period were used.

Passive microwave remote sensing brightness temperature data contain 10.65 GHz, 18.7 GHz, 23.8 GHz, 36.5 GHz and 89.0 GHz horizontal and vertical polarization channels. The auxiliary data consist of: the 1/120th degree (1 km) MODIS/Terra Land Cover Type 96-Day L3 Global (MOD12Q1) data set, the 1/120th degree 500 m MODIS Vegetation Continuous Fields (GLCF_MODIS_VCF) data set, the possibility of snow mask and The Land/ocean/ice mask data file and GTOPO30 data.

4. Results and analysis

It is meaningful to discuss the regional applicability of snow depth algorithms in stable seasonal snow areas like Xinjiang, Qinghai-Tibet, Inner Mongolia, and Northeast China. The Mean Relative Error (MRE) of five snow algorithms was shown in table 2.

4.1. Xinjiang

As Figure 1 shows, there is no obvious linear relationship in the interval between 5cm and 15cm, in the interval between 15cm and 50cm, GSFC 96 algorithm and Improved Tibetan Plateau algorithm underestimated snow depth. Chang algorithm, AMSR-E SWE algorithm and Savoie algorithm underestimated or overestimated snow depth. In the interval greater than 50cm, all snow depth

algorithms underestimated the snow depth. Due to the snow grain size in Xinjiang is very large, when snow depth deeper than 40cm, the brightness temperature signals (37 GHz) tend to be saturating^[10].

Table 2. The MRE statistics of snow algorithms in each study area

Date	Study Area	N	Chang Algorithm	GSFC 96 Algorithm	AMSR-E SWE Algorithm	Improved Tibetan Plateau Algorithm	Savoie Algorithm
Feb. 10, 2010	Xinjiang	71	53.50	50.14	44.37	50.97	43.97
	Qinghai-Tibet	2	107.55	56.60	116.98	64.15	81.13
	Inner Mongolia	29	79.77	55.04	63.81	50.00	61.46
	Northeast China	90	165.67	70.38	132.16	44.72	107.36
Feb. 11, 2010	Xinjiang	50	49.26	50.04	37.95	50.83	38.38
	Qinghai-Tibet ^a	--	--	--	--	--	--
	Inner Mongolia	22	81.75	49.40	58.68	38.46	56.64
	Northeast China	105	183.19	74.75	143.46	48.81	119.66
Feb. 12, 2010	Xinjiang	60	52.50	44.83	44.94	45.56	40.99
	Qinghai-Tibet	2	118.00	64.00	136.00	70.00	90.00
	Inner Mongolia	28	81.41	51.64	58.26	44.02	60.26
	Northeast China	16	189.13	90.68	174.48	52.04	127.42

^a There is no ground measurements in Qinghai-Tibet on February 11, 2010

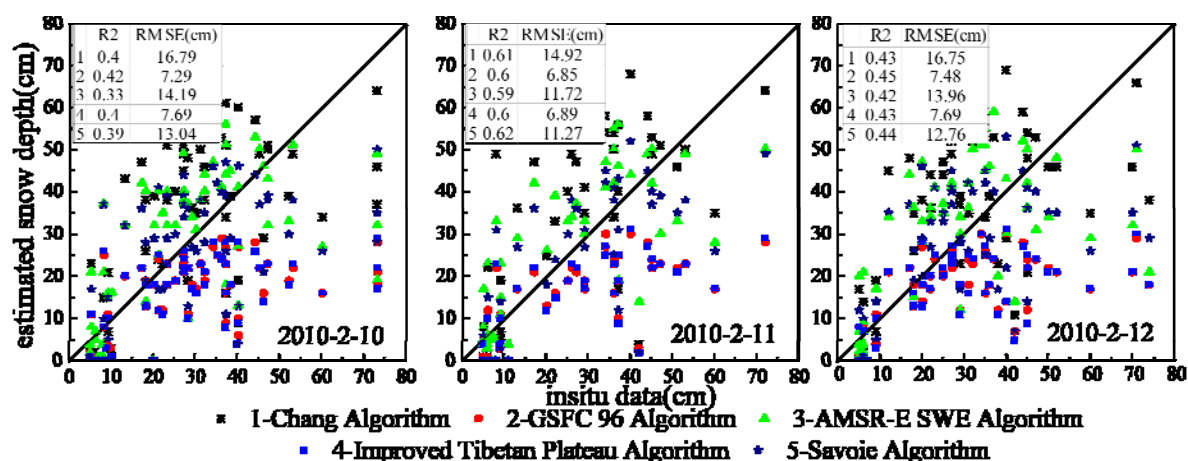


Figure 1. Scatter diagrams for algorithm validation in Xinjiang

4.2. Qinghai-Tibet

In Qinghai-Tibet, the MRE of GSFC 96 algorithm is 56.60% and 64%. It is superior to the Improved Tibetan Plateau algorithm with the MRE value of 64.15% and 70.00%. The MRE of Chang algorithm is up to 118%. Meteorological records showed that, the highest temperature of Qinghai-Tibet was up to 18 Celsius degree during this period, while the high temperature leads to snow melting, metamorphism, water content increasing and snow physical properties changing. For the lack of ground measurement, the reliability of the validation result is absent in this area.

4.3. Inner Mongolia

The figure 2 shows, in the interval between 5cm and 15cm, data points accumulated intensively and haven't presented a linear relationship. When ground-measured data is greater than 15cm, data points distribute vertically, except Improved Tibet Plateau algorithm, the snow depth algorithms have overestimated snow depth, especially Chang algorithm. Minimum RMSE and MRE for Improved Tibet Plateau algorithm are 5.46cm and 38.46%. Minimum RMSE and MRE are 11.65 cm and 79.77% with Chang algorithm.

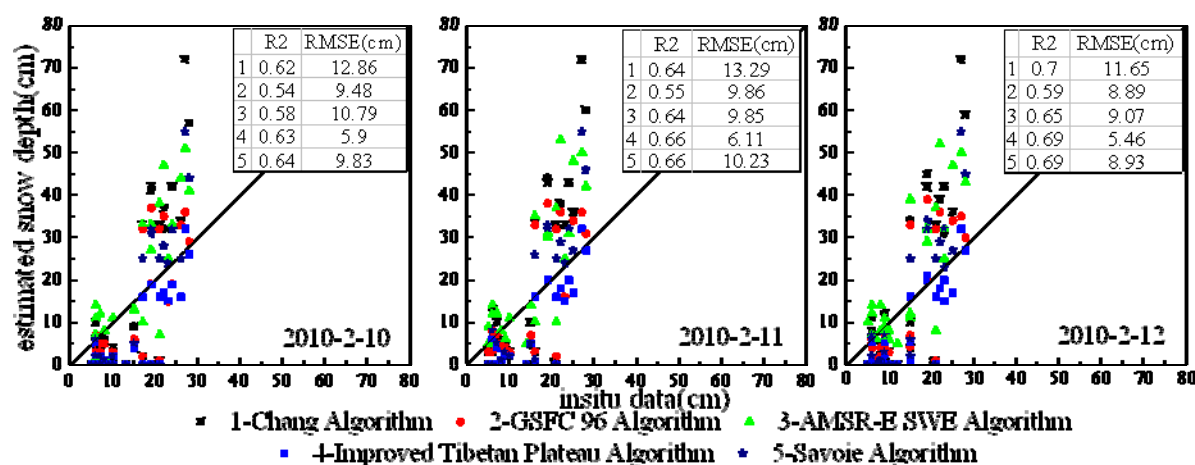


Figure 2. Scatter diagrams for algorithm validation in Inner Mongolia

4.4. Northeast China

Much of Northeast China is covered by vegetation which could affect microwave signal. Existing research showed that, if the influence of the forest is ignored, snow depth will be underestimated [3]. However, except Improved Tibet Plateau algorithm, the snow depth algorithms overestimated snow depth seriously. Therefore, there are some other impact factors in Northeast China. The validation results showed that, RMSE for Improved Tibet Plateau algorithm is ranging from 6.21cm to 7.83cm, the MRE is 44.72%~52.04%. Whereas RMSE is ranging from 14.66cm to 18.05cm, MRE is 165.67%~189.13% with Chang algorithm.

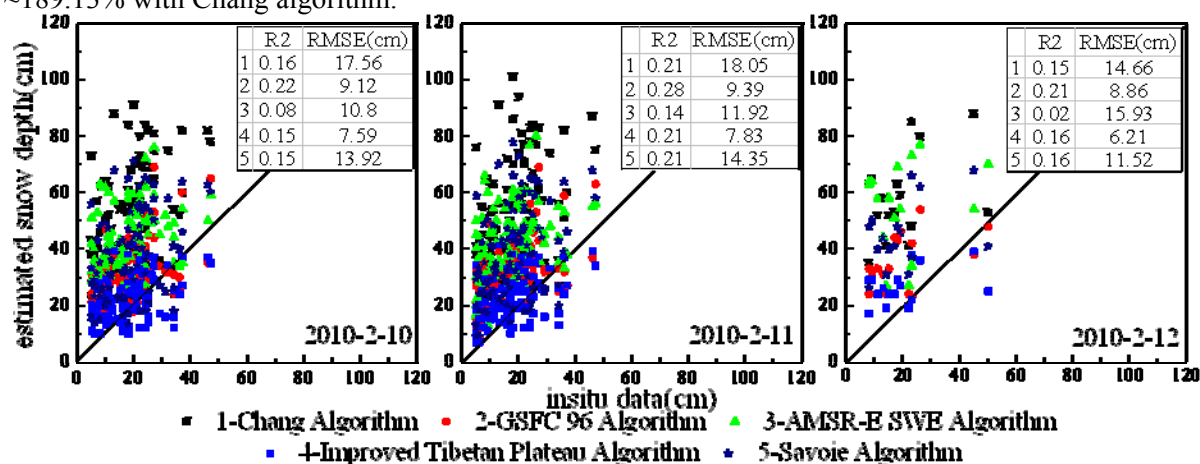


Figure 3. Scatter diagrams for algorithm validation in Northeast China

5. Discussion

For Chang algorithm, R^2 ranges from 0.62 to 0.70 in the Inner Mongolia, better than the other snow depth algorithms. But this algorithm overestimated snow depth in four study areas with the RMSE of 10.18cm~28cm, and the MRE is as high as 189.13% in Northeast China. Because the Chang algorithm assumed snow grain radius as a constant 0.3 mm, it is different from some regions in China such as Northeast China. The field snow investigation campaign in Northeast China during January 2010 shows that most of the measured snow particle size is far larger than 0.3 mm [11]. The applicability of Chang algorithm is limited in Inner Mongolia and Northeast China.

For GSFC 96 algorithm, R^2 is between 0.42~0.60, RMES is 6.85cm~7.48 cm in Xinjiang, and R^2 is 0.21~0.28 in Northeast China, which is better than the other snow depth algorithms. In consideration of the effects of variations in forest cover and snow grain size, introduced fractional forest cover parameter, with a grain size of 0.40mm the coefficient becomes 0.78, which is more appropriate for

the actual snow characteristic in Northeast China. However, GSFC 96 algorithm still overestimated the snow depth in Northeast China, and underestimates the snow depth in Xinjiang.

The AMSR-E SWE algorithm which is a prototype operation algorithm, has the minimum R^2 of 0.02 and the maximum RMSE of 15.93 cm in Northeast China. The AMSR-E SWE algorithm was developed in North America, northern Europe and Siberia, which are places with colder winter, longer snow duration, deeper snow, wider snow cover area and majority area covered by coniferous heavily. In China, most snow cover area in the middle latitude area, snow cover is thinner and uneven distribution, vegetation coverage is lower, terrain is more complex. Therefore, the applicability of AMSR-E SWE algorithm is much limited in China.

For Improved Tibetan Plateau algorithm, the RMSE ranges from 5.46cm to 6.11cm and the minimum MRE is 38.46% in the Inner Mongolia. In northeast China, the RMSE is significantly less than the other four algorithms with value of 6.21 cm~7.83cm. But in Qinghai-Tibet, the MRE are 64.15% and 70%, the result is not better than GSFC 96 algorithm. This is because that the coefficient was corrected by simple regression analysis between brightness temperature gradient and ground measured data for a short period, thus the result will not be applicable when time and snow state changes.

For Savoie algorithm, the R^2 is between 0.39 ~ 0.62, MRE is 38.38% ~ 43.97% in Xinjiang. The atmospheric influence was considered in this algorithm using digital elevation data to adjust brightness temperature. In China, the elevation is less than 3200 m in most areas excepting Qinghai-Tibet, where atmospheric correction is not necessary. Moreover, Savoie algorithm is based on the NSIDC (National Snow and Ice Data Center) microwave algorithm^[12], which is inherited from the original Chang algorithm. Therefore, the algorithm is not applicable in China.

6. Conclusions

According to this study, the existing passive microwave snow depth algorithms are overestimated or underestimated snow depth over China, its regional accuracy and applicability are limited. Therefore, for purpose of improving the regional accuracy and applicability of the passive microwave snow inversion algorithm, we should take full consideration to the influencing factors of passive microwave signal in specific study area, obtaining the underlying classification information and enhancing the acquisition of ground measurements.

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