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Development of Snow Depth and Snow Water Equivalent Algorithm in Western China Using Passive Microwave Remote Sensing Data

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Abstract: In order to evaluate the accuracy of snow water equivalent (SWE) inversion algorithm for passive microwave sensor Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) in Western china, we compared SWE obtained from AMSR-E daily SWE product with the ground measurements from 15 meteorological stations in Tibetan plateau in 2003 and 35 meteorological stations in Xinjiang in January 2004. The results show AMSR-E overestimate SWE both in these two regions, and RMSE is 21mm and 31.8 mm in Tibetan plateau and Xinjiang, respectively.

Through incorporating snow fraction factor, a new empirical algorithm estimate snow depth and SWE have been developed in Xinjiang. This new algorithm appeared higher accuracy than AMSR-E does in Xinjiang. Due to complex topography, shallow patchy snow and frozen grounds covered at the Tibetan Plateau, this technique didn't show good results. In future we will focus on how to evaluate and eliminate the effects of these factors quantitatively on SWE retrieval.

Key words: Snow Water Equivalent (SWE); Snow depth; Passive microwave remote sensing; AMSR-E; Tibetan Plateau; Xinjiang.

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1 Introduction

The snow cover is key variable of hydrological cycle and climate change studies. Snow depth and snow water equivalent (SWE) are important parameters for snow cover. Hydrologic models, which use snow depth or SWE as an key input, are capable of forecasting stream flow in watersheds dominated by snow melt[1,2]. Base on the radiative transfer theory and Mie scattering theory and assumed snow cover consist of dry snow, a mean snow density of 0.3 g/cm^3 and snow grain size of 0.3 mm, Chang et al.[3] developed an empirical algorithm to estimate snow depth by using regression techniques in 1987. The Chang's algorithm describes the relationship between snow depth and difference of 18 GHz and 37 GHz horizontally polarized brightness temperature as linear (Eq. (1)). The algorithm using

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Scanning Multichannel Microwave Radiometer (SMMR) brightness temperatures as input parameters.

$$SD = 1.59 \times (T_{b18H} - T_{b37H}) \quad (1)$$

Where SD is snow depth (cm), T_{bxH} represents the horizontally polarized brightness temperature from SMMR at a frequency of x GHz (K). However, by compared the retrieval SWE using this algorithm with measurement value by meteorology stations Cao Meisheng et al.[4] found the algorithm overestimated the snow volume over western china.

By using Special Sensor Microwave Imager (SSM/I) brightness temperatures Chang adjusted Eq. (1) to Eq. (2) and substituted the channel 18 GHz of SMMR to 19 GHz of SSM/I in regional area-western china.

$$SD = 2.0 \times (T_{b19H} - T_{b37H}) - 8.0 \quad (2)$$

The Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) was launched in 2002, which has a better performance in configuration than the former microwave radiometers like SMMR or SSM/I. Foster, et al.[5] introduce a parameter fraction of forest cover to develop a SWE algorithm.

$$SWE = \frac{4.8 \times (T_{b19H} - T_{b37H})}{1 - f} \quad (3)$$

This algorithm was selected to estimate SWE algorithm for AMSR-E in global range. To evaluate this algorithm work on western china, we got SWE measurement from 36 meteorological stations in northern Xinjiang province where approximately bounded by the 80.25°N and 95.08°N longitudes and 39.02°N and 48.03°N and 15 meteorological stations at Tibet and Qinghai province where the range from 28.65°N to 48.8°N in latitude and from 99.9°N to 100.13°N compare with the AMSR-E estimated SWE from AMSR-E L3 SWE products.

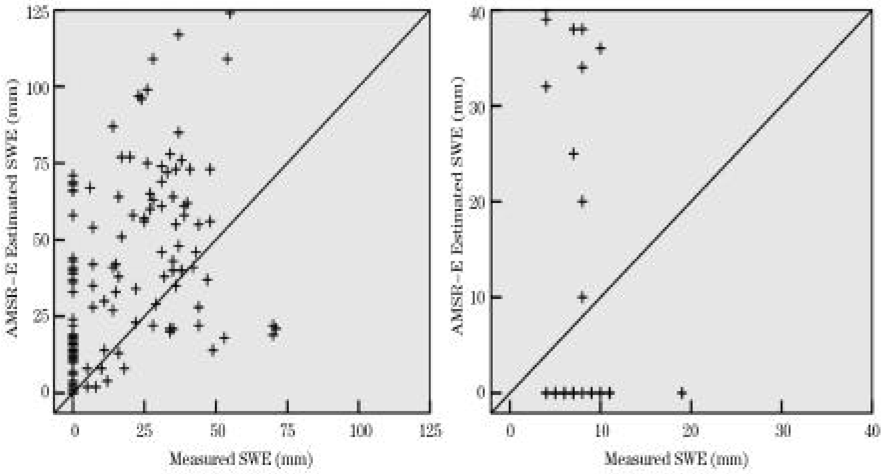

Fig.1 (a) Comparison of the SWE from AMSR-E L3 snow products with SWE measurements at 36 meteorological stations in northern Xinjiang province during the time period from January 1st to 31st 2004. The RMSE is 31.8 mm larger than common acceptable standard errors of 20 mm SWE; (b) Comparison of the SWE from AMSR-E L3 snow products with SWE measurements at 15 meteorological stations in Tibetan plateau during the time period 2003. Because SWE is not a routine observation item in most meteorology station. There are only 36 records of SWE in the dataset during 2003 in Tibetan plateau area. The RMSE is 21 mm

The Fig.1 (a,b) show the SWE algorithm of AMSR-E overestimated the SWE in western China. 35 meteorology stations locate in northern Xinjiang measured average of SWE is 14.6 mm and same location that AMSR-E estimated is 34.5 mm with an average percent error of 137%, max absolute error reach 81 mm RMSE is 31.8 mm lager than common acceptable value 20 mm[6]. AMSR-E SWE algorithm also overestimated the SWE in Tibetan plateau. The RMSE is 21 mm.

The primary goal of this study was to develop a new regional empirical snow depth and SWE algorithm for western China to determine if it could produce better results than the existing AMSR-E inversion algorithms.

2 Data sets

There were three types of data sets were employed in this study: (1) Satellite observation data. Two month daily AMSR-E brightness temperatures distributed by NSIDC (Ashcroft, P 2003) in Boulder, CO, USA [7] and MYD10C2 8-Day snow cover data [8] in NOV and DEC 2003 were used MYD10C2 products were selected for this study since the products is less effected by cloud. However, there are much shallow snow cover and patchy snow in Tibetan plateau. They changed strongly so much during a short period (1~2 day). So we used MYD10C1 daily snow cover products in Tibetan Plateau. (2) Insitu data. Snow depth and SWE measurements and land surface temperature acquired by meteorology station in Xinjiang and Tibetan Plateau. (3) Ancillary data sets which include IGBP classification map, MOD12Q1 V004 vegetation coverage and MODIS NDVI products MYD13A2 were required. Ancillary data was used to observe the forest cover and eliminate the disturbing factor like surface water body in the study area.

3 Methods

Microwave radiation from snow covered land includes two parts one is emission from snowpack and the other is underlying soil emission. Microwave signal volume scattering is distinctive at >23 GHz with brightness temperatures depression relative to low frequencies. Lower frequencies (<23 GHz) less affected by volume scattering from snow. With the snow depth increasing, more microwave radiation will be extinct. Extinction coefficient was dominated by scattering [9]. The brightness temperatures detected by sensor is less as the snow depth increasing. Most important physical snow characteristics effecting on microwave emission include: SWE, snow grain size, snow liquid water content and stratification of snowpack.

Base on methods and studies of the former researcher [10~12] we try to develop a new empirical snow depth and SWE algorithm for western China. First, choose northern Xinjiang province as a test area due to the area less complex topography, less vegetation cover and less the impact of frozen ground than in Tibetan plateau and records of snow depth and SWE are intactness. From the ancillary data set we found the fraction of forest cover and NDVI are very small most places are 0 even minus value in western china during the winter. So we neglected the impact of vegetation. Use IGBP classification map to eliminate the meteorology stations where the large water bodies around them. For the impact of wet snow, we chose only the records that max land surface temperature (T_{sur}) which measured four times a day great than 0°C.

Brightness temperature difference indices, typically applied in inversion algorithms which mentioned in the first part, may reduce the effects of disturbing factors. To produce semi-all semi-empirical SWE inversion algorithm over western China, all combinations of frequency and polarization differences for AMSR-E channels were computed except for 10 GHz due to the snow depth is less than 60 cm in western china. We developed algorithm the based on the regression technique. Through analysis, it is shown that snow cover factor would help to improve SWE estimation in 25 km ×25 km mixed pixel. In this study, we used MODIS 0.5deg 8-day snow fraction. Table 1 shows all the frequency and polarization difference used as independent variables.

Table 1 AMSR-E channel differences used in development of new algorithm

	18.7V	18.7H	36.5V	36.5H	89V	89H
18.7V	*	P	F	X	F	X
18.7H	*	*	*	F	*	F
36.5V	*	*	*	P	F	X
36.5H	*	*	*	*	*	P
89V	*	*	*	*	*	P
89H	*	*	*	*	*	*

P-polarization difference, F-frequency difference, X-frequency and polarization difference. * Not used

All combinations of frequency and polarization differences for AMSR-E channels were computed except for 10 GHz due to the snow cover is too shallow in western china and 23 GHz which responds to atmospheric water. The regression technique was used to produce the new algorithm. MODIS snow cover as an adjusting parameter also used. Table 1 shows all the frequency and polarization difference used as independent variables.

We get two new formulas to estimate SWE and snow depth respectively.

$$SWE = -11.5.73 + 0.922 \times sf \times (T_{b19V} - T_{b37H}) + 1.079 \times (T_{b37V} - T_{b37H}) - 0.381 \times (T_{b89V} - T_{b89H}) \quad (4)$$

$R = 0.761$, $R^2 = 0.579$.

$$SD = -6.489 + 0.493 \times sf \times (T_{b19V} - T_{b37H}) + 0.869 \times (T_{b37V} - T_{b37H}) - 0.18 \times (T_{b89V} - T_{b89H}) \quad (5)$$

$R = 0.814$, $R^2 = 0.663$

Where SWE is snow water equivalent (mm), SD is snow depth (cm). sf (%) daily snow fraction processed from MODIS daily snow cover product. $T_{bx(VH)}$ is AMSR-E brightness temperature in different frequency and polarization.

Most empirical algorithms use a spectral difference between the 19GHz and 37GHz to estimate SWE and snow depth since it has been correlated to SWE [3,13,14]. The 37GHz and 89GHz cross pole terms in the algorithms are correlated to the depth hoar. In equation (4), (5) we add a new parameter snow fraction (sf) into the algorithm. If the parameter snow fraction do not put into regression, the correlation coefficient (R) for SWE and snow depth reduce to 0.691 and 0.772, respectively. Through incorporating snow fraction factor, the new empirical algorithm estimate SWE and snow depth have the better performance than AMSR-E retrieval algorithm.

We compared the new algorithm estimated snow depth and SWE with the records of snow depth and SWE measured by meteorology station in January 2004 a-month measured data. The results indicate the RMSE of new algorithm is 15.7 mm better than those of AMSR-E 31.8 mm JAN 2004 in Xinjiang. For snow depth RMSE of new algorithm is 9.2 cm.

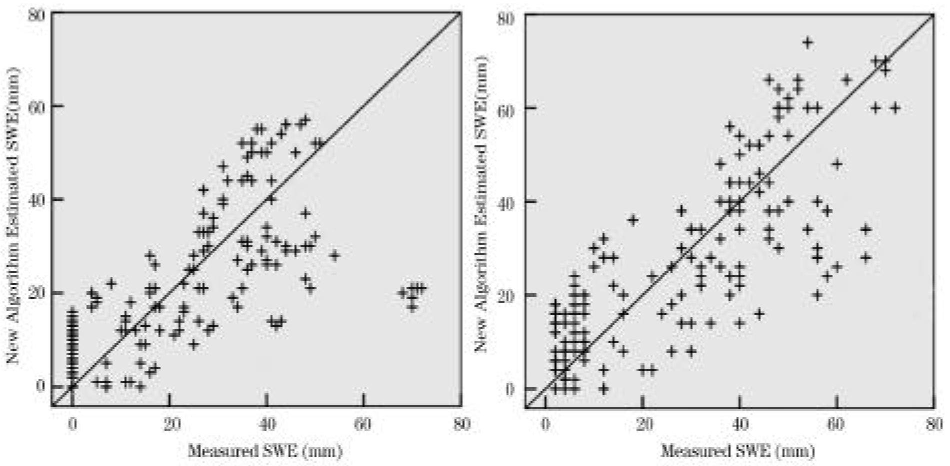

Fig.2 (a) Scatter plot of measured SWE versus new algorithm estimated value in Northern Xinjiang in January 2004. RMSE = 15.7 mm better than the AMSR-E 31.8 mm. Max absolute error is 53 mm; (b) Scatter plot of measured snow depth versus new algorithm estimated value in northern Xinjiang in January 2004. RMSE = 9.2 cm, max absolute error is 31cm

We required the measured snow depth and land surface temperature from 35 meteorological in Tibet and Qinghai province in 2003, the same time AMSR-E ascendant brightness temperature data, daily snow cover product MYD10C1 [15] and some other ancillary data sets same as in test area of northern Xinjiang descript in upper part. After examined the measured snow depth in the records, we found that shallow snowpack existing in Tibetan plateau widely. There are more than 90% records are shallow snopack (snow depth below 3cm). Using the same techniques as descript upper parts for Xinjiang we tried to establish an empirical algorithm to estimate snow depth in Tibetan plateau area. But the effort is useless.

The combinations of frequency and polarization differences for AMSR-E channels were used as independent variables. The Pearson Correlation's of these variables with snow depth shows as follow Table 2. From Table 2 we can found that the most correlative between Brightness temperature difference indices and snow depth are difference of 18 GHz and 89 GHz in horizon polarization. And value only 0.143 that mean they are irrelevance.

The methods which suit for Xinjiang did not fit for Tibetan plateau that because the shallow patchy snow cover in most area. Snow depth less than 3 cm will be negligible low than 37 GHz in microwave.[14] Estimating snow storage in the mountainous region is a challenging task. This is because the complex topography together with protruding exposed rock with a microwave footprint make it difficult to extract the snow signature[16] Another disturbing factor for the establishing of retrieval algorithm in Tibetan Plateau is the wildly existing frozen ground. In order to establishing a better empirical SWE and snow depth algorithm in Tibetan Plateau, we will focus on solve these problems in the future work.

Table 2 N = 293 (Correlation is significant at the 0.05 level (2-tailed))

Brightness temperature difference indices	Snow depth
P10	-0.090
P19	-0.065
P37	-0.058
P89	-0.038
F19H37H	0.134*
X19V37H	0.036
F19V37V	0.125*
F19V89V	0.124
X19V89H	0.091
F19H89H	0.143*
F37V89V	0.070
X37V89H	0.032
F37H89H	0.097

P-polarization difference, F-frequency difference, X-frequency and polarization difference

4 Summary

The obtained results indicate that AMSR-E SWE algorithm which overestimated SWE fail to work in western china. This is show in Fig1. (a) and Fig2. (b). In this research a new algorithm which clearly improves the SWE estimation accuracy has a good performance than AMSR-E SWE algorithm does in Xinjiang.

The same method did not fit for the Tibetan plateau. This is because several errors are mainly from the effects of complex topography with the protruding exposed rocks, shallow and patchy snow, wet snow, the existence of frozen ground and ice, surface water body, vegetation cover and lack of the records of regular observation of snowpack in no man's land area where exist most snow volume in Tibetan plateau.

Although the estimation accuracy has been improved, the new algorithm still has lager error in Tibetan plateau. The sources of errors mainly come from (1) The common existence problem in constructing empirical algorithm is that the meteorology stations measured snow depth and SWE lack of representation in large area especially, there are rare meteorological stations distribute in no man's land in northern Tibet. (2) Effects of topography. The AMSR-E 19 and 37 GHz footprint will not be able to resolve the complicated terrain effects and different view direction of the mountain by ascending and descending orbits further complicates the problem[16]. Tibet plateau is high altitude, complex topography cold area. (3) Existence of wet snow and patchy snow. The wet snow can strongly impact the microwave signal. While the snow water content increase 1%, the penetrate depth would decrease 10 cm at 19 GHz[17] Since thinner snowpack is transparence for the channel less then 37 GHz.[14] However, 35 meteorological station measured snow depth more than 90% records are less than 3 cm. (4) Large surface water body like lakes and reservoirs can strongly depress the microwave brightness temperature. Therefore, pixels contain fraction of water body exceed 40% will be water and can not be use to estimate snow parameters. (5) Forests present. To considering forests cover, we observed the NDVI over Tibet plateau in winter 2003. The results show in most area NDVI almost zero and even minus value. But the forest impact still existence in some area, especially in south-west

Nyainqentanghla. (6) the existence of frozen ground and ice. Frozen ground and snow have similar scatter character in microwave frequency[18]. Frozen ground is great interferential factor in Tibet plateau.

Estimate snow depth and SWE is a big challenge in Tibetan plateau by passive microwave remote sensing. The further research is needed to investigate mainly effect factors in estimate snow depth and SWE by passive microwave in Tibetan plateau.

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被动微波遥感反演中国西部地区雪深、雪水当量算法初步研究

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摘 要:雪深、雪水当量是积雪研究中重要参数,其在流域水量平衡和融雪径流预报以及雪灾监测与评价中起着重要作用。Chang等(1987)以辐射传输理论和米氏散射为理论基础,假定积雪密度和颗粒大小为常数,利用实测雪深数据和SMMR的亮温数据,通过统计回归方法,建立了雪深与18 GHz和37 GHz水平极化的亮温梯度之间的关系,发展了SMMR半经验的反演雪深的算法。后在此基础上又发展了针对SSM/I的半经验反演雪深算法。2002年发射的装载于Aqua卫星上的AMSR-E是新一代的被动微波辐射计,性能较以往星载被动微波辐射计有较大提高,采用了改进后的SSM/I的半经验算法作为其估算全球雪水当量的反演算法。

将AMSR-E的雪水当量产品与气象台站观测的雪水当量进行比较,发现在新疆地区和青藏高原地区雪水当量的RMSE分别达到31.8 mm和21 mm。本研究旨在建立基于AMSR-E亮温数据,适用于中国西部地区的雪深和雪水当量反演算法。首先收集整理了2003年新疆地区的雪深、雪水当量数据和AMSR-E亮温数据,去除错误样本,利用统计回归的方法,建立了新疆的反演雪深、雪水当量的半经验算法,算法中加入积雪覆盖度参数,较以往的算法有所改进,与气象台站观测数据比较,结果也表明新疆地区建立的经验算法较AMSR-E的雪水当量算法有较大改进,RMSE为15.7 mm。但青藏高原地区因海拔高,地形复杂,大部分地区积雪较浅,空间分布不均和冻土存在等诸多因素运用同样的方法建立反演算法,结果不甚理想,以后的研究将重点消除这些干扰因素。

关 键 词:雪水当量;雪深;被动微波遥感;AMSR-E;青藏高原地区;新疆

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