Retrieving Integrated Water Vapor Using AMSU-B Channels over Arctic Region

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***Abstract*—**There are two parts in this paper: in the first part the influence of ice surface emissivity variation on water vapor retrieval accuracy in Arctic region using AMSU-B channels is analyzed; in the second part we analyzed the accuracy of Miao's method and its feasibility (time and locations) in retrieving integrated water vapor (IWV) with AMSU-B data over Arctic region. To the first part, the Arctic ice surface emissivity data are agree with the results of SEPOR-POLEX campaign, and six types of surfaces including open water, nilas, pancake ice, flat first-year ice, ridged first-year ice, multi-year ice are analyzed respectively. Both Miao's method and improved version by Selbach are used to retrieve IWV over each type of surface. Analyzing the IWV retrieved with the two methods mentioned above, several results can be obtained. First, the uncertainty of retrieved IWV results from emissivity variance is calculated over each kind of surface. Second, retrieval algorithms over nilas and pancake need new coefficients independently for their emissivities are relatively larger than that of other surfaces. Third, the IWV retrieved with improved version of Selbach has less average bias but larger variance than that with Miao's method over five kinds of surfaces except pancake ice. To the second part, first the errors of retrievals in every month between August 2005 and July 2006 are estimated by comparing with that from radiosonde data, second, IWVs retrieved from satellite brightness temperature are projected to Arctic region, which is uniformly divided into equal-area grids, day by day and monthly average is given over all-year retrievable region. The results show that 3.48% of the Arctic area, mainly located in Greenland, is whole-year retrievable, while 44.76% is six-month retrievable. In this process, we judge whether the IWV is retrievable in a month over the area corresponding to a uniform grid by counting the number of retrievable days more than 15. The monthly average retrieved IWV and its bias over all-year retrievable area is analyzed too.

***Keywords*—**Integrated Water Vapor, surface emissivity, AMSU-B, feasibility in retrieving IWV with Miao's method.

I. Introduction

Atmospheric water vapor is essential in meteorological and environmental study due to its greenhouse effect and its influence on weather prediction [1]. Till now, integrated water vapor (IWV) content retrieval can be successfully done over oceans from microwave sensor measurements. However, water vapor retrieval method over land is still being explored for the error of IWV retrieved with existing methods are relative large. The root-mean-square (rms) error of IWV retrieved with AMSRE data and neural network algorithm is about 3.0kg/m^2 over European land [2], and that with infrared measurement reaches 6.8kg/m^2 over European and African regions [3]. The error of IWV retrieved with GPS measurement varies in different region. While in Antarctic the standard deviation is about 1.0kg/m^2 [4], and in European the rms reaches 6.0kg/m^2 [3]. Ground-Based millimeter wave radiometry measurement can be used to retrieve IWV in Arctic with uncertainty less than 5% [5] and some hyperspectral far infrared radiosonde instrument can even retrieve humid profile [6], but the application of these methods are limited by location.

The polar regions are an important but ill-understood component of the global climate system and understanding water vapor over these regions are significant. Miao's method was proposed in 1997 to retrieve the low amount IWV using SSM/T2 channels over the ice covered polar regions [7][8]. This method has been proved to be very effective in both Arctic and Antarctic region by subsequent studies [9][10][11][12]. Comparing to the relative large error of IWV retrieved with GPS measurements, Miao's method only induce mean bias -0.08kg/m^2 and standard deviation 0.79kg/m^2 with AMSU-B data in Antarctic [4].

Although Miao's method can only retrieve IWV less than 6.0kg/m^2 with AMSU-B channels combinations [8][13], the value is generally satisfied within the cold and dry Antarctic plateau area [8]. In Miao's method, emissivities at 150GHz and 183GHz are assumed equal to each other. Wang improved the water vapor retrieval accuracy by introducing 220GHz channel on MIR (Millimeter-Wave Imaging Radiometer) into combination with AMSU-B channels, and he assumed that ice surface emissivity changes linearly with frequency in the range of 150-220GHz [9][10]. Although this method can not apply to current satellite sensors for there is no similar channel combination, the result shows that the difference of surface emissivities at different channels has influence on the accuracy of IWV retrieval. In order to determine the highly variable emissivity of ice surface, Europe launched the airborne SEPOR-POLEX campaign in March 2001 over Arctic region. Measurement results show a clear linear relationship between the surface emissivities at 157 and 183GHz with a rms of 0.012 [14]. This result has been applied to improve Miao's method for retrieving IWV with correction scheme by Selbach [14].

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The improved version of Selbach assumed the emissivities at 157 and 183GHz satisfy linear relationship according to SEPOR-POLEX results [14][15] and reduced the systematic offset of retrieved IWV. However, the rms error of retrieved IWV remains the same or even becomes larger.

Then a question arises, the influence on accuracy of retrieved IWV by ice surface emissivity variance, how large will it be? As there is no measured data of emissivity at 150GHz, we use the emissivity at 157GHz instead, which is retrieved from SEPOR-POLEX campaign. We analyze the water vapor retrieval algorithm based on AMSU-B channels although the 157GHz channel has replaced 150GHz channel in MHS sensor unit onboard some current satellite of NOAA series (such as NOAA-18) [16].

Based on the work of Miao [8] and of Selbach [14], we analyze the accuracy of retrieved IWV under two assumptions about the relationship between emissivity at 150 and 183GHz over six types of surfaces in Arctic region, including: open water, nilas, pancake ice, flat first-year ice, ridged first-year ice, multi-year ice. For the first assumption, we consider the emissivity at 150 and 183 GHz are equal to each other, which is adopted by Miao [8]. Then Miao's method is applied to retrieve IWV over each kind of ice surface. For the second assumption, it is assumed that the emissivity at 150 and 183GHz satisfy linear relationship, which is adopted by Selbach [14]. Improved version of Selbach is applied to retrieve IWV over each kind of ice surface too. At last, average bias and standard deviation of retrieved IWV against radiosonde IWV with the two assumptions are calculated and analyzed respectively.

Another question is that as Miao's method has been used by many science research organizations all over the world, what about its accuracy and feasibility (time and locations) in retrieving IWV with AMSU-B data over Arctic region?

To resolve this question, we have to make use of both satellite data and radiosonde profile over Arctic. First, satellite data and radiosonde data are matched by the limitation condition of measuring at the same location simultaneously. Then, IWV are retrieved with satellite data of AMSU-B channels brightness temperature and the errors of IWV are estimated by comparing with that derived from radiosonde profiles. Third, the retrieved IWV data of each satellite scan trajectory orbits are projected into divided uniform grids of Arctic according to their actual footprint locations, and the projection in grids are statistically analyzed for every month to get conclusion.

II. STUDY AREA AND MATERIAL

In the process mentioned above, our researches focus on Arctic region, and 3000 radiosonde profiles recorded in this area are selected from IGRA [17] database within the time range 1991-2007. The water vapor burden in each profile is less than 6.0kg/m^2 with 50 profiles in every 0.1kg/m^2 interval. Fig.1 shows the locations of stations for these profiles. Then, we simulate the brightness temperature of AMSU-B channels with VDISORT [18] and truncate the upper levels of the data leaving 30 levels of each profile in calculation. The numerical

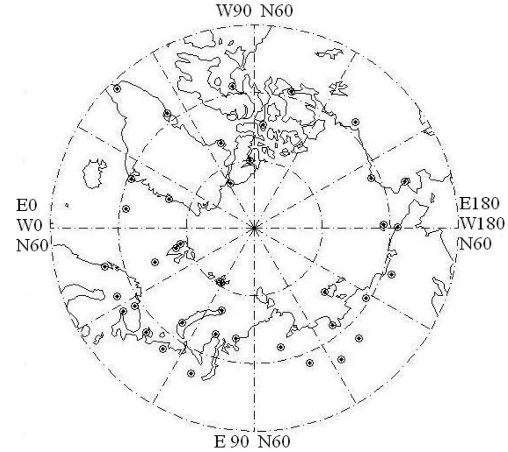

Fig.1: Radiosonde stations of selected profiles in Arctic.

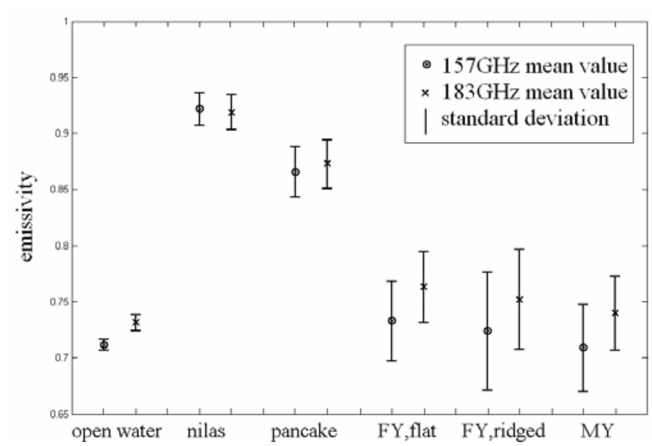

Fig.2: Emissivity of 157 and 183 GHz over six kinds of surfaces: open water, nilas, pancake, flat first-year ice, ridged first-year ice, multi-year ice. [14]

characteristic of Arctic surfaces emissivities origin from SEPOR-POLEX [14][15], which include mean and standard deviation at 157 and 183GHz over six kinds of ice surfaces as shown in Fig.2. In the process of simulating brightness temperature of AMSU-B channels, equivalent surfaces emissivities data are generated according to their numerical characteristics. The satellite data used to estimate the accuracy of Miao's method and its feasibility (time and locations) are origin from NOAA-15 AMSU-B channels (channel 16 to 20) [19] with time range from August 2005 to July 2006. There are 4382 satellite orbits in this period.

III. METHODOLOGY

The influence of ice surface emissivity variation on the IWV retrieval accuracy is analyzed in following procedure. First, twelve groups of equivalent emissivities at 150 and 183GHz of all six kinds of surfaces are generated according to the mean values and standard deviations of 157 and 183GHz, which origin from SEPOR-POLEX campaign. Second, the emissivities in each group and all profiles are inputted into VDISORT to calculate brightness temperatures of all AMSU-B channels. Third, so-called "focal point" position and new

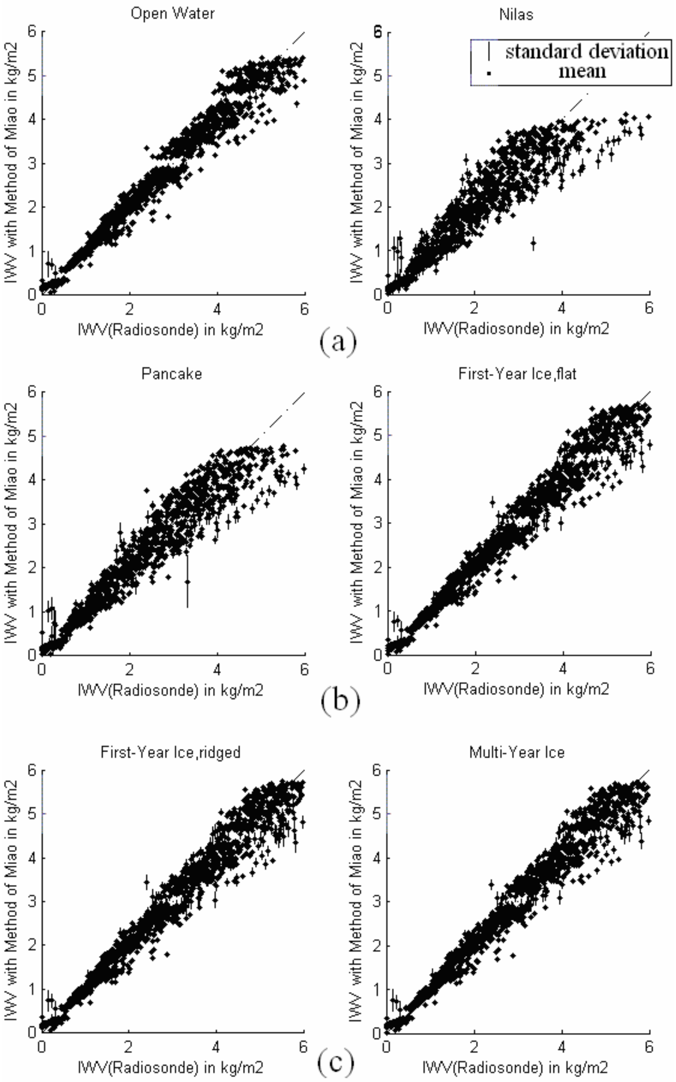

Fig.3: Retrieved IWV obtained from Miao's method [8] vs radiosonde IWV over six kinds of surfaces: open water, nilas, pancake, flat first-year ice, ridged first-year ice, multi-year ice. Every point and short line is corresponding to one profile used for retrieval.

coefficients are drawn with Miao's method [8] and improved version of Selbach [14] respectively. At last, the results of IWV retrieved with these two new algorithms are analyzed and compared over every kind of surface. All the process is done under two schemes: assuming the emissivities at 150 and 183GHz are equal to each other or satisfy linear relationship.

A. Scheme 1: Assume ε_s Equal

Assuming the emissivities at 150 and 183GHz are equal to each other, we take the emissivity data at 183GHz as the base and retrieve IWV with the new "focal point" and coefficients created according to Miao's method [8].The selected 3000 profiles are divided into two groups: 1500 profiles are used to draw new coefficients and "focal point" position in the algorithm; the other 1500 profiles are used to verify error of retrieved IWV against radiosonde IWV. The biases and standard deviation of retrieved IWV corresponding to every

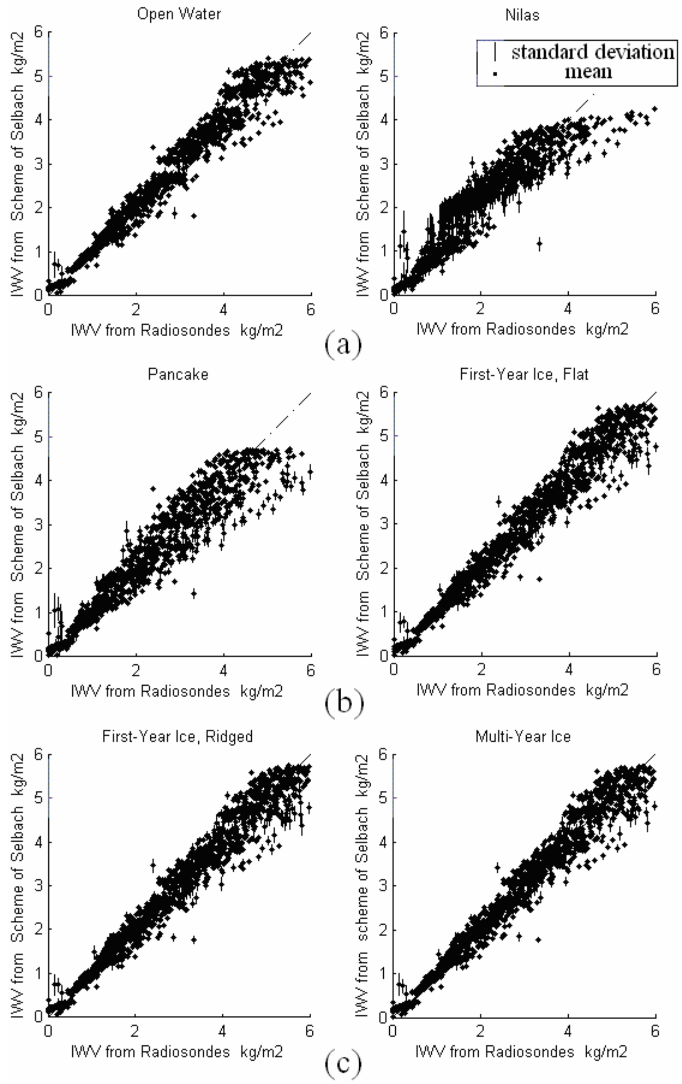

Fig.4: Retrieved IWV obtained from improvement version of Selbach [14] vs radiosonde IWV over six kinds of ice surfaces: open water, nilas, pancake, flat first-year ice, ridged first-year ice, multi-year ice. Every point and short line is corresponding to one profile used for retrieval.

profile are shown in Fig.3.

B. Scheme 2: Assume ε_s Linear

Assuming the emissivity at 150 and 183GHz satisfy linear relationship of

$$\varepsilon_{s150} = 1.12 \times \varepsilon_{s183} - 0.1111 \quad (1)$$

Equivalent emissivities at 150 and 183GHz are needed to generate firstly in this process. When the IWV is less than 1.5kg/m^2 and only three channels centered at the strong water vapor absorption line at 183GHz will be used, we generate the equivalent emissivities at 183GHz as same as in the first scheme. But, when the retrieved IWV become larger than

1.5kg/m^2, the 150GHz channel has to be taken into combination. The emissivities at 183GHz are generated as a base, and then the corresponding data at 150GHz are generated with the limitation of satisfying the equation (1) and the rms between ε_{s150} and ε_{s183} is 0.012 [14]. The same 3000 profiles are used as the first scheme, and the new coefficients and "focal point" position drawn according to improved version of Selbach are used in the new retrieval algorithm [14]. The biases and standard deviations of retrieved IWV corresponding to every profile are shown in Fig.4.

C. Accuracy of Miao's Method Estimation

In the process of estimating the accuracy of Miao's method in retrieving IWV over Arctic region, we select satellite data with limitation the latitude is equal or larger than +60^o (+ represent north, - represent south), and then, match the satellite data with radiosonde profile data. The match conditions include the distance between the center of satellite data projection and radiosonde station location is less than 50 km, and the time interval between satellite data time and radiosonde measure time is less than 3 hours. The selected satellite data of AMSU-B channels are used to retrieve IWV with Miao's method, and then the retrieved IWV and radiosonde IWV are compared and analyzed. The average bias and standard deviation of retrieved IWV are calculated monthly. There are 6711 groups of match data in all, in which the retrieved IWV is no more than 6.0 kg/m^2. The results of monthly error estimation and numbers of matched groups are show in the Fig.5 and Fig.6 respectively.

It can be seen from the Fig.5 and Fig.6 that during November 2005 to March 2006, the average bias value change from -0.13kg/m^2 to -0.31kg/m^2 and the standard deviation value change from 0.66 to 1.49. However, the average bias value during April to October change from -0.58kg/m^2 to -23.78kg/m^2. In June, July and August, the average bias values are especially large, one of reasons is the numbers of sample in these months are so small that the results are statistic meaningless. Another reason is that the criterion of application in Miao's method is loose, which will cause retrieving small IWV value with a few large radiosonde IWV value samples. The detailed average bias and standard deviation of every month are listed in TABLE. 1.

D. Feasibility of Miao's Method Estimation

In this process, the selected satellite data of AMSU-B channels in the first process can be used here. First, for convenient to analyze location of projection, the Arctic region is divided into 98675 uniform grids with their side-length corresponding to 18.8 km in actual spatial, which is equal to the average diameter of AMSU-B footprint. Then, one grid is almost corresponding to one projection area on average. Second, brightness temperature values of channel 17 to channel 20 from satellite are input Miao's method to retrieve IWV. To every footprint of satellite scanning, if IWV is retrievable, it will be recorded with its location, and the projected onto the uniform grids with the same area in Arctic. To every day satellite data, as long as the location of one footprint center is projected in a unit grid, the retrieved IWV value of this area will be record in the grid.

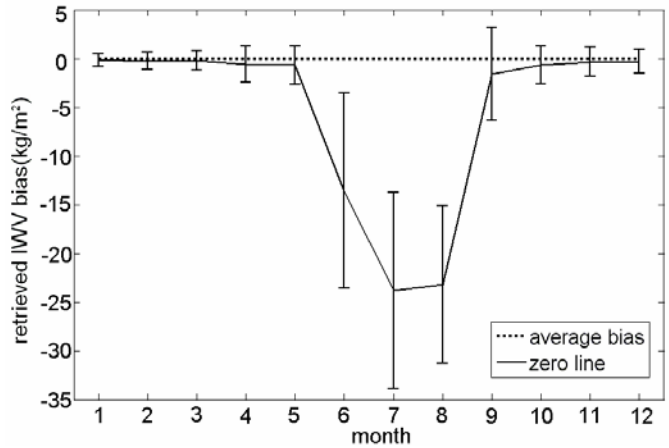

Fig. 5 Average bias and standard deviations of retrieved IWV.

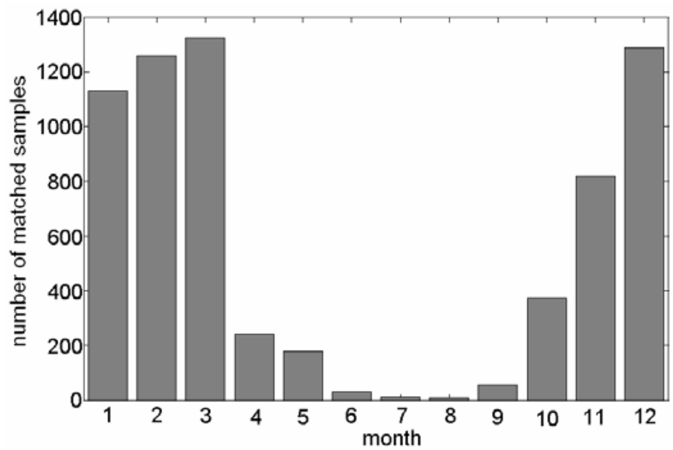

Fig. 6 Number of matched data samples in every month.

TABLE 1. Average bias and standard deviation for every month in a year.

Month	Bias(kg/m^2)	Standard deviation	Number of samples
Jan	-0.1335	0.6617	1130
Feb	-0.2441	0.8925	1259
Mar	-0.2155	0.9860	1322
Apr	-0.5771	1.8574	242
May	-0.6918	1.9675	179
Jun	-13.5570	10.0333	30
Jul	-23.7842	10.0725	11
Aug	-23.1728	8.0644	9
Sep	-1.5783	4.7515	54
Oct	-0.6678	1.9268	373
Nov	-0.3128	1.4920	813

Dec	-0.2668	1.2383	1289

If there are several footprint centers located in one grid, the mean of these retrieved IWV values will be record in it. These daily records will be statistic for every month, then, the monthly records will be statistic for all the year. During this process, we judge whether a unit grid is retrievable by counting retrievable days more than 15 in a month. After analyzed all the 12 months data, we can calculated the time ratio of retrievable in all year for Arctic region, and the result is show in Fig.7. Seeing Fig.7, we can conclude that only about 3.48% of Arctic area, mainly located in Greenland, can retrieve IWV with AMSU-B channels all the year and about 44.76% of Arctic area can retrieve IWV in half of a year. The detail area ratios for different retrievable time ratios are listed in TABLE.2.

The area ratio of retrievable IWV with AMSU-B channels for every month in Arctic are also analyzed. The monthly area ratios from November 2005 to April 2006 are larger than 60%, with the maximum ratio 82.83% in January 2006 and the minimum ratio 63.42% in April 2006. From May to July 2006, the area ratio decrease from 14.37% to 3.63% and the area ratios of August and September 2005 rise from 4.12% to 10.21%. The area ratios in these five months are less than 15%, till October, the area ratio increase to 41.7%, which may indicate that Arctic begin to icing at that time. The area ratio and of IWV retrievable for every month is shown in Fig.8.

In the region of the IWV are retrievable with AMSU-B channels and Miao's method in all year, we calculated the average IWV distribution in every month. The average IWV in this area is equal to the sum of all retrieved IWV records in the grid divide the number of grids in which projection is available. The monthly average IWV vary from 2.37 kg/m^2 in January to 3.63 kg/m^2 in May, as show in Fig.9. We can see that the average retrieved IWV of every month change periodically during the year. The reason is that the all year retrievable region is mainly located in Greenland, and the IWV burden changes as seasons change alternately.

IV. Discussion

The average bias and average standard deviation of retrieved IWV with Miao's method [8] and with improved version of Selbach [14] are compared over all kinds of ice surfaces as shown in Fig.10. We can see in this figure that the improved version of Selbach get less bias but larger standard deviation than those with Miao's method over five kinds of surfaces except pancake. The results obtained from these two methods show that over all six kinds of surfaces, the average bias of retrieved IWV with two methods are both less than 0.5kg/m^2, and the average bias even less than 0.1kg/m^2 over open water, flat first-year ice, ridged first-year ice and multi-year ice.

Over open water, the influence of its surface emissivity variation on retrieved IWV accuracy is much less than its average bias. Over nilas and pancake, average bias and average standard deviation of retrieved IWV with both of methods are relatively larger than that over other surfaces and there is saturation when the IWV is less than 6.0kg/m^2 (shown in Fig.3 and Fig.4). The reason for these phenomena is that emissivity of

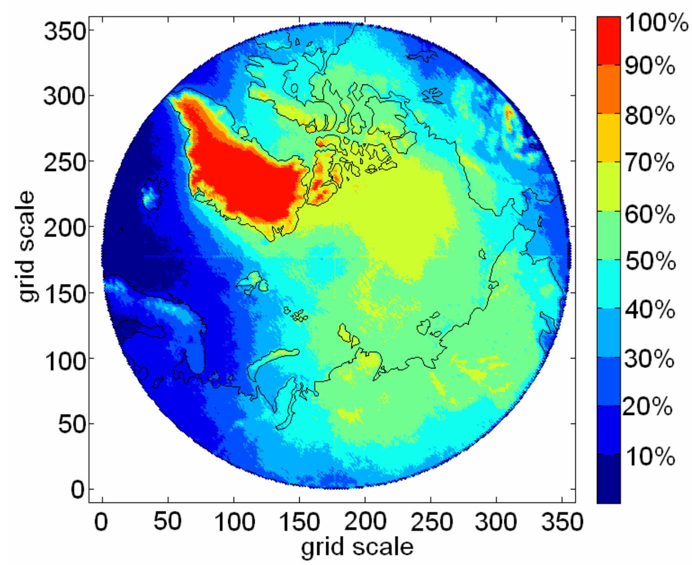

Fig. 7 Time ratio of suitable retrieving IWV with AMSU channels during Aug 2005 to Jul 2006.

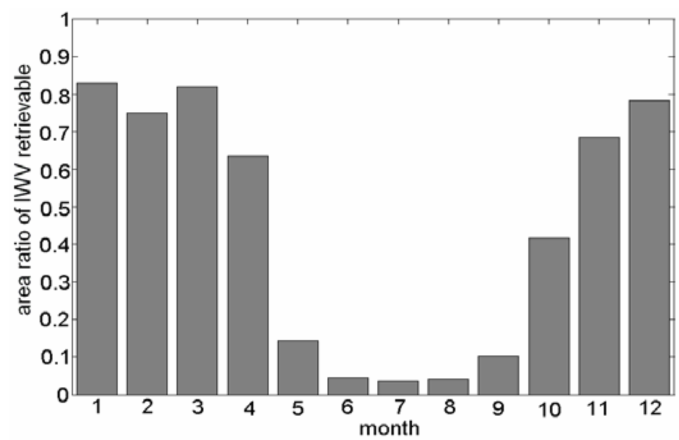

Fig. 8 Area ratio of suitable retrieving IWV with AMSU channels in every month over Arctic.

TABLE 2. Area ratios of different time scales, in which the IWV can be retrieved with Miao's method and AMSU-B channels.

Time ratio	Occupy grids (98675 in all)	Area ratio	Area ratio (sum)
0~10%	5142	5.21 %	
10~20%	9405	9.53 %	
20~30%	9148	9.27 %	
30~40%	11999	12.16 %	55.23 %
40~50%	18813	19.07 %	
50~60%	27286	27.65 %	
60~70%	11463	11.62 %	
70~80%	1007	1.02 %	
80~90%	978	0.99 %	44.76 %

90~100%	3434	3.48 %	

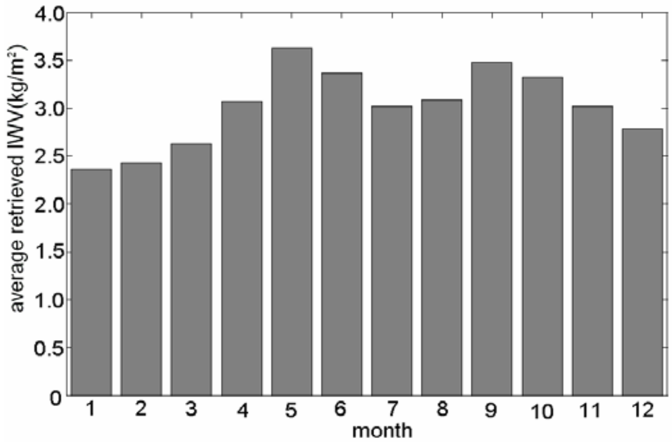

Fig. 9 Average retrieved IWV for all year retrievable region in every month

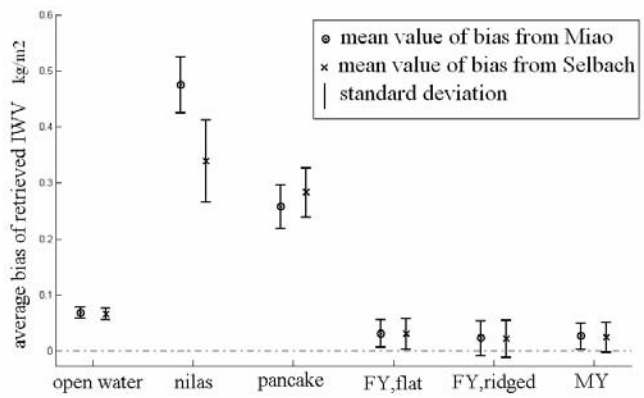

Fig.10: Average biases and standard deviations of retrieved IWV with Miao's method and improved version of Selbach over six kind of ice surface: open water, nilas, pancake, flat first-year ice, ridged first-year ice, multi-year ice.

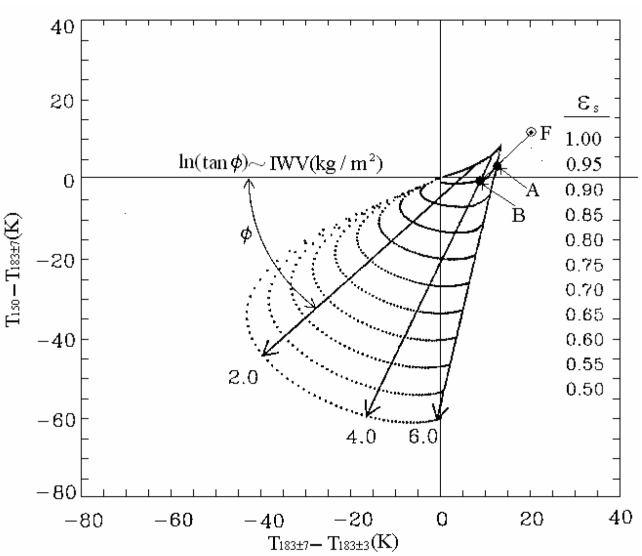

Fig.11: The chart used by Miao [8] to retrieve IWV under different surface conditions, in which F is so-called "focal point", and A and B represent respectively the retrieved IWV of 6.0kg/m^2 and 4.0 kg/m^2.

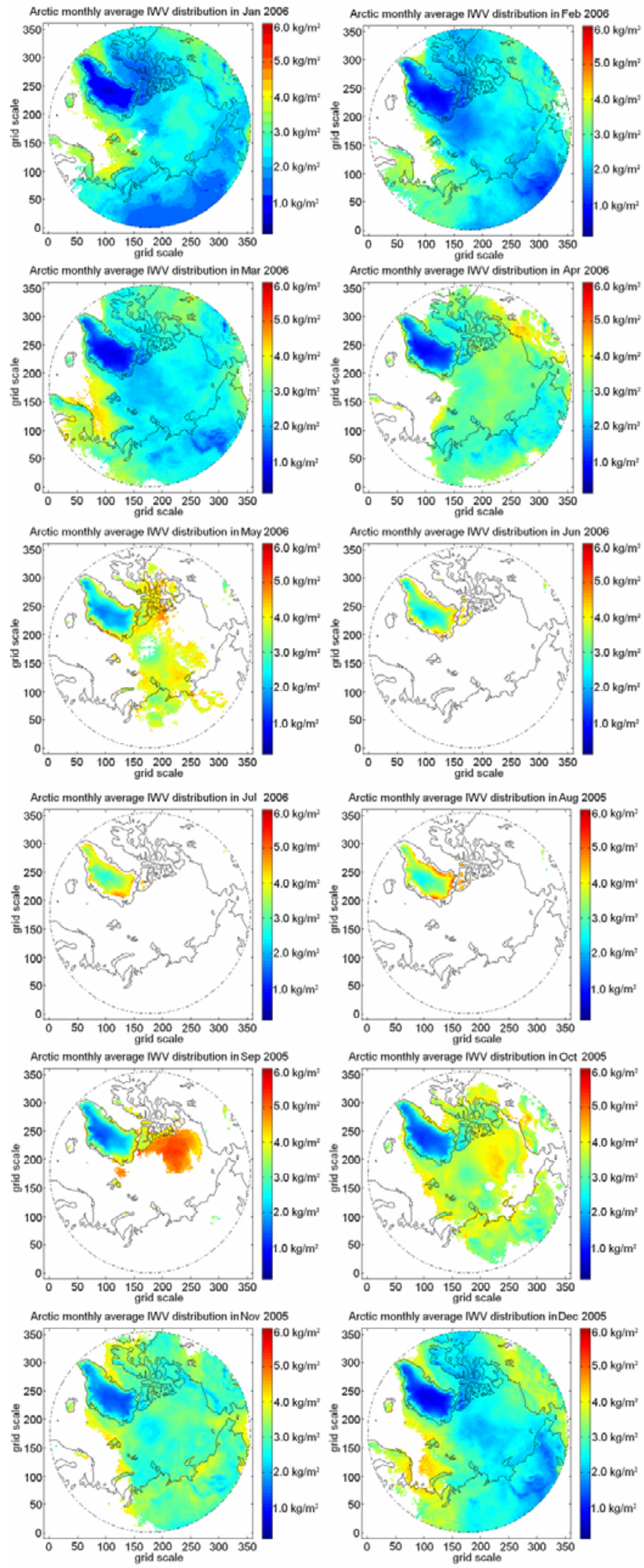

Fig. 12 Average retrieved IWV for every month in a year in

Arctic region. (Blank area in the dashed line circle means the IWV exceed 6kg/m2, and it cannot be retrieved with Miao's method and AMSU-B channels)

nilas and pancake is very high, but the coefficients and "focal point" position in retrieve algorithms are drawn with all six types of surfaces emissivity. If we use these unsuitable coefficients and "focal point" position to retrieve IWV over the two types of ice surfaces, large bias and saturation at a lower IWV burden will be caused, as shown Fig.11. In this figure, point A and B represent IWV are $6.0kg/m^2$ and $4.0kg/m^2$ respectively, however, if the unsuitable coefficients and "focal point" F are used in retrieve algorithms over high emissivity surfaces, the retrieved IWV of A and B are equal to each other. We can deduce if new coefficients and new "focal points" position of retrieval algorithm are drawn with emissivity features of nilas and pancake, the bias of retrieved IWV will become smaller. Over flat first-year ice, ridged first-year ice and multi-year ice, the average standard deviation is equal or even larger than average bias. That's mean the main influence of retrieved IWV accuracy is come from the emissivity variance of the three kinds of ice surfaces.

At first, the error of retrieving IWV using satellite ASMU-B channels data and Miao's method are estimated by comparing with radiosonde profile data monthly. The results show that the retrieval error are smaller during November to March of the next year, but from April to October, as lack of sample, the retrieval error become larger. To get accurate estimation of IWV retrieval error in summer, we not only need more samples, but also need to improve the criterion of applicable with Miao's method. Then we analyzed the temporal and spatial scope of IWV retrievable using AMSU-B channels and Miao's method over Arctic by retrieving IWV with satellite data from August 2005 to July 2006 and projecting to uniform grids in Arctic with the same area. Every time when the IWV is successfully retrieved, we record the retrieved IWV value and counting projection times in the grid. Although the time range of satellite data only last one year, the results can be used to estimate the time ratio of IWV retrievable for different region in Arctic and the area ratio of IWV retrievable for every month in all year. If a longer time range of satellite data is used, the result will be more accurate certainly. The average retrieved IWV value in every month over all-year-retrievable region of Arctic is shown in Fig.12, the blank area in the dashed line circle means the IWV exceed $6.0kg/m^2$, over where IWV cannot be retrieved with Miao's method and AMSU-B channels.

V. Conclusion

We analyzed the IWV retrieve performances over six kinds of surfaces with the two methods and drawn a series of conclusions. First, the uncertainty of retrieved IWV result from emissivity variance is much less than the bias from algorithm itself over open water. Second, retrieval algorithms over nilas and pancake need to draw new coefficients and new "focal point" position for their emissivity are relatively larger than other types of surfaces. The large standard deviation of retrieved IWV over these two kinds of ice surfaces is calculated with unsuitable coefficients in algorithms in this paper, which may overestimate the influence of emissivity variation on the accuracy of retrieved IWV. Third, the average bias and average standard deviation are almost the same over flat first-year ice, ridged first-year ice and multi-year ice surfaces. That's mean the variation of emissivity is the main influence factor to the accuracy of retrieved IWV over these ice surfaces, although the average bias and average standard deviation are both small.

As the results mentioned above, we can conclude that retrieving IWV using AMSU-B channels and Miao's method can retrieve IWV in the time scale of longer than half of the year over about 44% of area of Arctic region, and in six months, the IWV retrievable area ratio is larger than 63%. The two conclusions are not contradictory, for 63% area ratio include different region for every month, but only about 44% area ratio region is always included. To enlarge this applicability, new microwave channels near 183GHz and 23.3GHz have to be taken into consider. Because the current AMSU-B channels center 183GHz are so sensitive to the water vapor content that they are all become saturated when the IWV larger than $6kg/m^2$

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