

A Modified Ice Water Path Retrieval Algorithm Applicable to the ATMS

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ABSTRACT

The algorithm to retrieve the ice water path (IWP) from Microwave Humidity Sounder (MHS) measurements of two window channels at 89 and 157 GHz was already developed, and the IWP retrieval products have been made operationally available since NOAA-15. An adaptation of the same algorithm to the Advanced Technology Microwave Sounder (ATMS) is not straightforward due to differences of central frequencies and fields-of-view (FOVs) of the window channels between ATMS and MHS. In this study, ATMS and MHS orbit data from May 2016 to April 2017 are first collocated using the Simultaneous Nadir Overpass (SNO) method. Then two linear relationships between ATMS and MHS window channels are established using the SNO data: one between MHS channel 1 (89.0 GHz, 15-km nadir resolution) and ATMS channel 16 (88.2 GHz, 32-km nadir resolution), and the other between MHS channel 2 (157.0 GHz, 15-km nadir resolution) and ATMS channel 17 (165.5 GHz, 16-km nadir resolution). Since MHS IWPs are calculated differently when the scattering parameters are small ($\Omega_{89} < 0.15$ or $\Omega_{157} < 0.18$) or large ($\Omega_{89} \geq 0.15$ and $\Omega_{157} \geq 0.18$), the histogram of IWP is found to have an unrealistic local minimum around 0.4 kg m^{-2} . A modification is made to use the same algorithm as MHS when the scattering parameter at 89 GHz $\Omega_{89} < 0.08$ or $\Omega_{89} > 0.19$, and a linear interpolation within the interval of $0.08 \leq \Omega_{89} \leq 0.19$. The ATMS IWP is then derived using the modified algorithm by obtaining equivalent MHS brightness temperatures according to the regression relationships, while the MHS IWP is derived directly using the modified algorithm. Also, the ATMS results are collocated with MHS orbits for comparison purposes. The spatial distributions of ATMS- and MHS-derived IWPs are consistent. A quantitative analysis shows that the two results are approximately same with deviations smaller than about $\pm 0.02 \text{ kg m}^{-2}$.

Keywords: ATMS, MHS, IWP retrieval

1. Introduction

Ice clouds cover nearly 20% of the earth's surface and play an important role in regulating the energy budget of the earth and in influencing weather forecasts and climate prediction. Ice clouds usually occur at high altitudes and have ice optical depths of varying thicknesses. Different from liquid clouds, ice clouds reflect solar radiation and reduce the radiance reaching the surface, resulting in an 'albedo effect' that cools the surface; and have relatively low temperatures so that less infrared radiation is emitted into space than under clear-sky conditions to generate the 'greenhouse effect' which has a heating effect on the atmosphere. Numerical studies have shown that the net radiative flux of the above two processes are mainly decided by the cloud optical depth associated with the

processes of radiative transfer calculations in climate models (Stephens and Webster, 1981; Liou, 1986; Stephens, 2005). Also, the ice water content has been added into most numerical weather prediction (NWP) models as a prognostic variable to predict its value in high-level clouds (Lohmann and Roeckner, 1996; Buehler et al., 2007; Liou et al., 2008). Therefore, a quantitative derivation of IWP from satellite observations is important for weather forecasting and climate prediction.

In 2000, an algorithm was developed to retrieve IWP and ice particle effective diameter (De) from Microwave Imaging Radiometer dual-channel microwave measurements (Weng and Grody, 2000). In their study, Weng and Grody found that for a given particle bulk volume density, a relationship between IWP and De could be derived using the two-stream model and that both variables could be retrieved simultaneously from microwave measurements at two different

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frequencies (89 and 150 GHz) from the Millimeter-wave Imaging Radiometer (MIR). In 2002, the algorithm was further improved to be more generally applicable to Microwave Humidity Sounders (MHS) (Zhao and Weng, 2002), as well as Special Sensor Microwave Imager/Sounder (SSMIS) data (Sun and Weng, 2012). Results showed that the uncertainty of the retrieval over coastal areas was greatly reduced due to high instrument precision and observation accuracy. The errors incurred by this algorithm and the continuity of the retrieved IWP over coastal areas are both smaller than those from generic algorithms. Not only global IWP fields can be derived from the two MHS window channels centered at frequencies 89 and 157 GHz, Holl et al. (2014) showed that the MHS sounding channels around 183 GHz could be employed for a synergistic IWP retrieval along with infrared channels from AVHRR.

The Suomi National Polar-orbiting Partnership (S-NPP) satellite was successfully launched on 28 October 2011. It was the first satellite in the preparatory project of the National Polar-orbiting Operational Environment Satellite System. The Advanced Technology Microwave Sounder (ATMS) onboard the S-NPP satellite represents a new generation of microwave temperature and humidity radiometers (e.g. Advanced Microwave Sounding Unit-A (AMSU-A) and MHS). Exploring and testing the retrieval of global IWP products from ATMS data is therefore important. Currently, there are MHS but not ATMS-derived IWP products available to the user community. Although the ATMS inherited similar MHS channels, the two high frequencies ATMS window channels 16 (88.2 GHz) and channel 17 (165.5 GHz) are not exactly the same as MHS window channels, and the FOVs of the ATMS channel at 88.2 GHz is 35 km at nadir, which is much coarser than the 15 km MHS FOVs at nadir. So, the MHS IWP algorithm cannot be directly applied to ATMS data. In this study, two linear relationship models are first established between ATMS channel 16 and MHS channel 1 from the National Oceanic and Atmospheric Administration satellite 19 (NOAA-19), as well as between ATMS channel 17 and MHS channel 2 using Simultaneous Nadir Overpass (SNO) data. Then the MHS IWP retrieval algorithm is modified and applied to MHS-like ATMS data calculated from these relationships.

The article is organized as follows. Section 2 briefly discusses the characteristics of MHS and ATMS window channels. Section 3 describes the traditional IWP retrieval scheme of MHS, a SNO collocation method, linear relationships between ATMS and MHS window channels, and modifications made to the traditional IWP retrieval algorithm. In Section 4, the performance of the modified algorithm for retrieving IWPs from ATMS measurements is analyzed. Section 5 provides a summary and conclusions.

2. MHS and ATMS data characteristics

The MHS is carried by two NOAA polar-orbiting environment satellites, NOAA-18 and -19, and European meteorological operational satellites MetOp-A and -B. Its predecessor is the AMSU-B onboard NOAA-15, -16, and -17. The MHS inherits all the channels of the AMSU-B, of which channels 1, 2, and 5 have slight differences in frequency. All five channels of the MHS, ranging from 89 to 190 GHz, are humidity-sounding channels primarily designed for profiling low-level moisture.

The S-NPP satellite circulates the earth in a near-polar orbit at an altitude of 824 km with an inclination angle of $98.7 \pm 0.05^\circ$. The ATMS onboard the S-NPP satellite is a cross-track scanning microwave instrument with 22 channels from 23 to 183 GHz in frequency designed for profiling atmospheric temperature and humidity under clear-sky and non-heavy precipitation weather conditions. The ATMS integrates its two predecessors, the AMSU-A and the MHS, into a single instrument and inherits most of their channels, plus an additional temperature-sounding channel and two humidity-sounding channels. The scan swath of the ATMS is wider than that of the MHS, greatly reducing the gap between two neighboring orbits in low latitudes. In general, the ATMS provides atmospheric temperature and humidity observations with a more comprehensive horizontal coverage and more detailed information in the vertical.

Similar to MHS channels 1 and 2, ATMS channels 16 and 17 are two window channels with their frequencies centered at 88.2 GHz and 165.5 GHz, respectively. Table 1 lists the channel characteristics of ATMS channels 16 and 17, and MHS channels 1 and 2, including channel number, frequency, and resolution at nadir. The frequency of ATMS channel 16 is similar to that of MHS channel 1, while the frequency of ATMS channel 17 is similar to that of MHS channel 2. ATMS channels 16 and 17, and MHS channels 1 and 2 are all window channels with high frequencies which mainly receive longwave radiances from the earth's surface and radiances scattered by ice clouds if they exist. These channels are thus sensitive to ice clouds. The resolutions of the MHS channels 1–2, ATMS channel 17, and ATMS channel 16 are 15, 16, and 32 km, respectively.

Table 1. Characteristics of ATMS window channels 16–17 and MHS window channels 1–2 onboard the NOAA-19 satellite.

Pair	Channel number		Frequency (GHz)		Resolution at Nadir (km)	
	ATMS	MHS	ATMS	MHS	ATMS	MHS
1	16	1	88.2	89.0	32	15
2	17	2	165.5	157.0	16	15

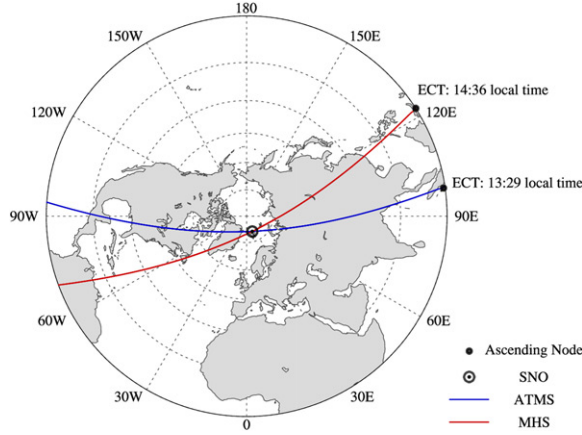


Fig. 1. An ATMS and MHS simultaneous nadir overpass (SNO) point located at 20.1°E and 80.8°N and the associated ATMS (blue curve) and MHS (red curve) swaths on 8 January 2017 shown under a polar stereographic projection. The collocation criteria are 3 min in time and 8 km in spatial separation. The local equator crossing times (ECTs) of these two ATMS and MHS swaths are 1329 local time (LT) and 1436 LT, respectively.

3. Retrieval scheme

3.1. Collocation between the ATMS and the MHS

SNO data are defined as nadir measurements at locations simultaneously observed by two different polar-orbiting satellites (e.g. S-NPP and NOAA-19 in this study). They are used for establishing the relationships between MHS and ATMS of relevant channels. The uncertainty of the observations between the two satellites caused by differences in radiance path, observation position, and time is minimized at SNO data points.

The orbital plane of each satellite intersects the surface of the earth to form a great circle. Two such great circles (satellites' orbits) create two intersections. If the two satellites are both polar-orbiting satellites, then their orbit intersections must occur near the polar regions, i.e. from ~70°N-80°N or ~70°S-80°S (Cao et al., 2004). Figure 1 shows a SNO point between the ATMS and the MHS located at 20.1°E and 80.8°N along with the associated ATMS and MHS swaths on 8 January 2017. The local equator crossing time of these two ATMS and MHS swaths is 1329 local time (LT) and 1436 LT, respectively. Since the S-NPP satellite is lower than the NOAA-19 satellite, it orbits the Earth slightly faster and catches up with the NOAA-19 satellite to create a SNO.

The radii of the FOVs at nadir of ATMS channel 17 and MHS channels 1 and 2 are around 8 km, so when collocating ATMS with MHS data, the spatial distance of 8 km is set as one of the criteria. The two criteria are:

$$\begin{cases} \Delta t < 3\text{min} \\ \Delta d < 8\text{km} \end{cases} \quad (1)$$

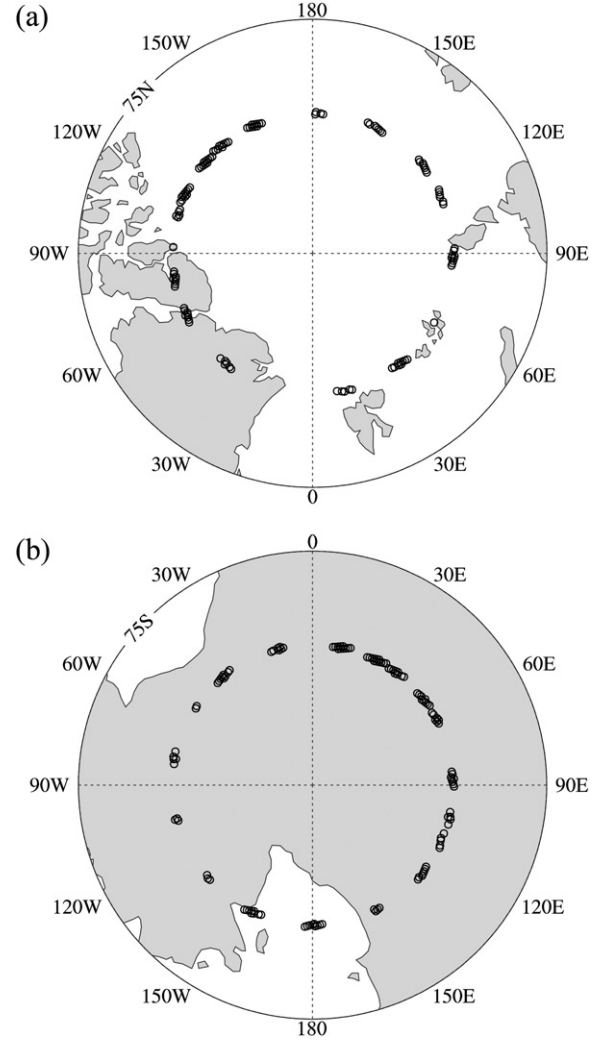


Fig. 2. Geographical distributions of all SNOs found near the (a) North and (b) South Poles in January 2017 under a polar stereographic projection.

where Δt and Δd are the distances between ATMS and MHS data in time and in space, respectively. The spatial distance between two points on Earth observed by the ATMS and the MHS is calculated by the following formula:

$$\Delta d = R \cdot \cos^{-1}(\sin \varphi_1 \sin \varphi_2 + \cos \varphi_1 \cos \varphi_2 \cos(\delta_2 - \delta_1)) \quad (2)$$

where φ_1 and φ_2 are the latitudes of ATMS and MHS data, respectively, and δ_1 and δ_2 are the longitudes of ATMS and MHS data, respectively.

A total of 3161 SNO points with ATMS and MHS observations are found during the one-year period from 1 May 2016 to 30 April 2017. Figure 2 shows the geographical distributions of all SNO points found near the two poles in January 2017. As expected, the SNO points of the two satellites were located and are evenly distributed

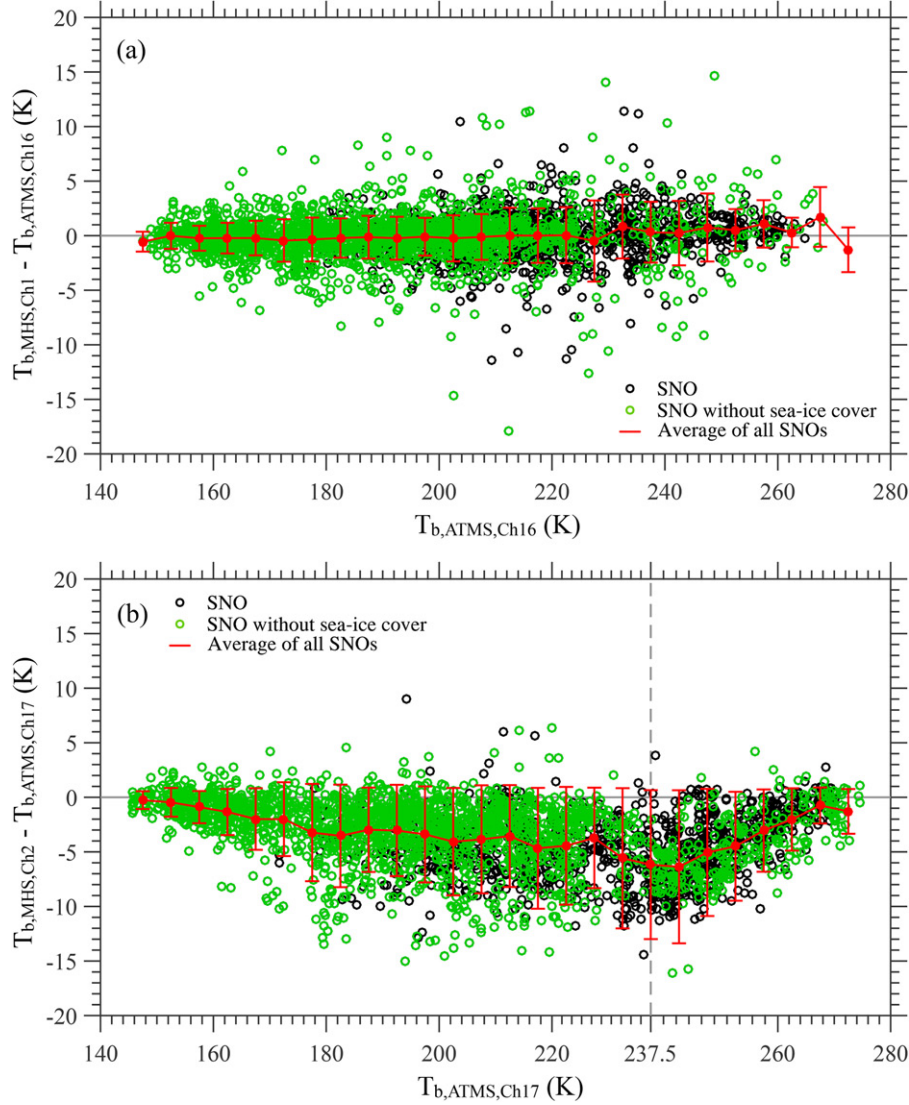


Fig. 3. Scatterplots of the differences in observed brightness temperatures between (a) MHS channel 1 and ATMS channel 16, and (b) MHS channel 2 and ATMS channel 17 with respect to ATMS channel 16 and 17 observations without (green circles) and with (black circles) sea ice cover for a total of 3161 SNO points from May 2016 to April 2017. Means (solid red circles) and standard deviations (vertical red lines) are calculated at 5-K intervals. The dashed vertical line in (b) represents the pivot point demarking the decreasing and increasing trends (237.5 K).

at high latitudes ($\sim 80^\circ\text{N}$ and $\sim 80^\circ\text{S}$). Also, the number of SNO points over oceans almost equals that over land. The geographical distributions of SNO points in other months are similar (figures omitted). So, the relationships between ATMS and MHS window channels are applicable to both oceans and land. S-NPP and NOAA-19 satellites are also sun-synchronous satellites which means that they experience similar scene lighting conditions when they pass through their SNO points at the same LT. Based on the information presented here, SNO data relies on frequency only so that the relationships built by SNO data can represent the relationships between channels with different frequencies.

3.2. Linear model

After obtaining the SNO data from the ATMS and the MHS, variations in the differences between ATMS and MHS brightness temperatures with respect to the ATMS brightness temperature are analyzed to determine the relationships between paired channels. Figure 3 shows scatterplots of the differences in observed brightness temperatures between MHS channel 1 and ATMS channel 16, and those between MHS channel 2 and ATMS channel 17 for the 3161 SNO points found from May 2016 to April 2017. The pixels with sea-ice cover over ocean are determined based on the European Centre for Medium-Range Weather Forecasts

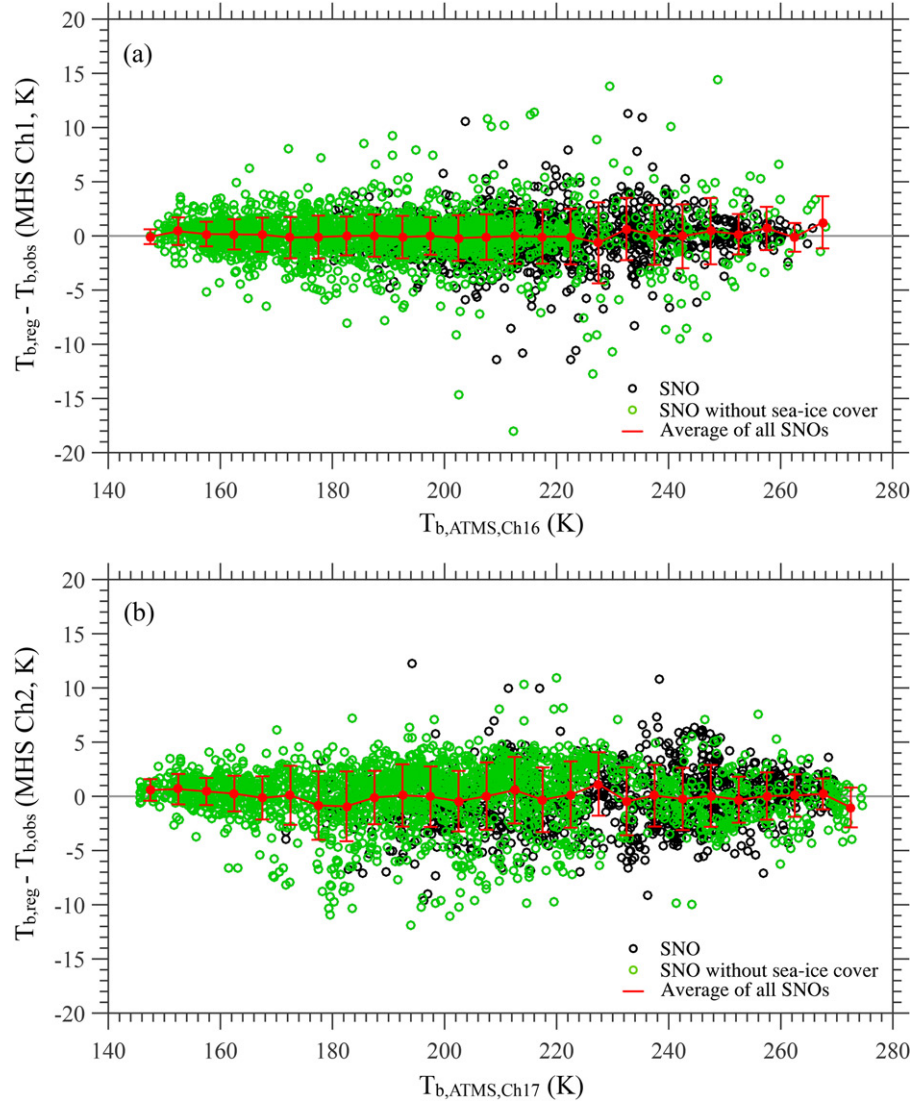


Fig. 4. Same as Fig. 3 except for differences between regressed and observed MHS channel 1 (upper panel) and channel 2 (lower panel) brightness temperatures as a function of ATMS channel 16 and 17 brightness temperatures, respectively.

(ECMWF) ERA-interim analysis. The near-zero trend in the differences between MHS channel 1 and ATMS channel 16 measurements for the entire range of ATMS channel 16 values (Fig. 3a) suggests a linear relationship between ATMS channel 16 and MHS channel 1 measurements. Figure 3b shows a decreasing then increasing trend in the differences between MHS channel 2 and ATMS channel 17 measurements for the entire range of ATMS channel 17 values with

the pivot point at 237.5 K. Therefore, two different linear relationships will be established: one for the case where ATMS channel 17 brightness temperatures are less than 237.5 K and the other for when the ATMS channel 17 brightness temperatures are greater than or equal to 237.5 K. A single relationship is established between the ATMS channel 16 and MHS channel 1. Appendix A provides a detailed mathematical derivation of the following regression equations

$$\begin{cases} T_{b,MHS,89GHz}^{reg} = 1.008 \cdot T_{b,ATMS,88.2GHz}^{obs} - 1.67 \\ T_{b,MHS,157GHz}^{reg} = \begin{cases} 0.947 \cdot T_{b,ATMS,165.5GHz}^{obs} + 6.982, & T_{b,ATMS,165.5GHz}^{obs} < 237 \\ 1.207 \cdot T_{b,ATMS,165.5GHz}^{obs} - 56.5, & T_{b,ATMS,165.5GHz}^{obs} \geq 237.5K \end{cases} \end{cases} \quad (3)$$

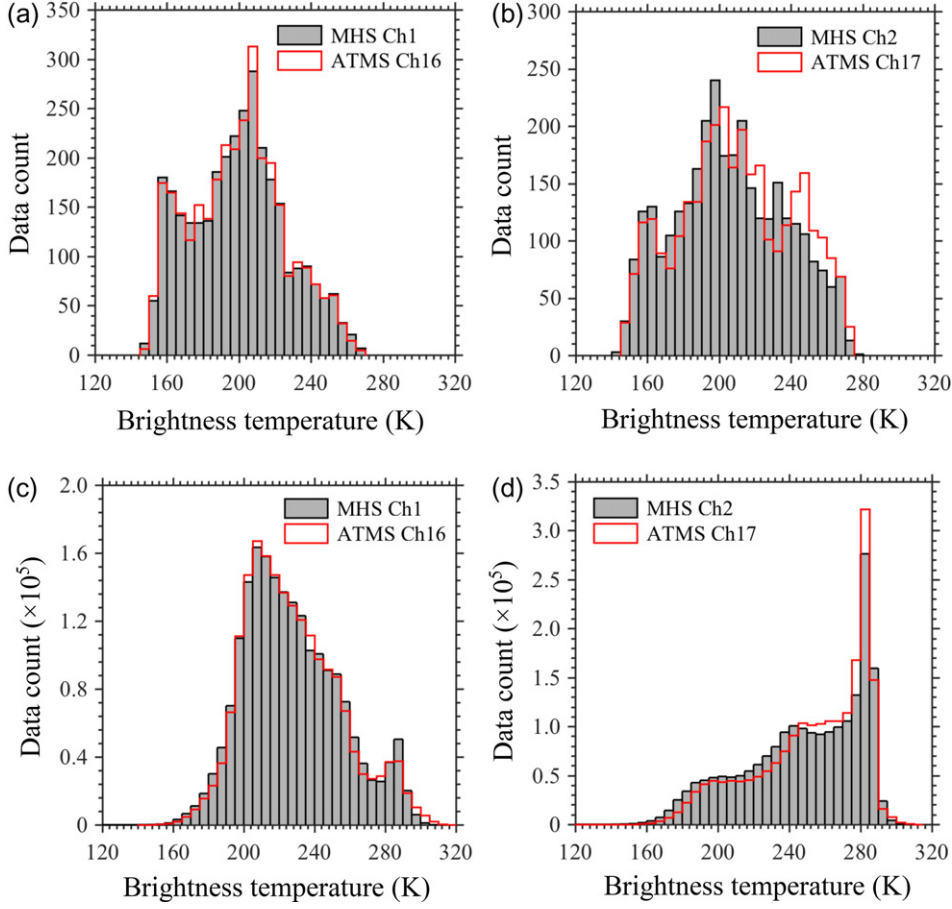


Fig. 5. Histograms of brightness temperatures sampled by (a)–(b) the SNOs of the year from 1 May 2016 to 30 April 2017 and (c)–(d) one-month nadir measurements in January 2017.

Using Equation (3), the regressed MHS-like ATMS brightness temperatures can now be calculated. Figure 4 shows scatterplots of the deviation between the regressed and observed MHS brightness temperatures with respect to ATMS observations. Differences of the ATMS-regressed and MHS-observed data for MHS channel 1 and channel 2 show stable, near-zero trends. This suggests that the regressed and observed values are very close in magnitude. The root-mean-square errors for the two regressed channels are 2.1 and 2.6 K, respectively. Outliers with large differences between the ATMS regressed and MHS observed brightness temperatures, although of small amount, make the RMSE relatively large. These outliers could be associated with mixed fields of view. Further improvement of the regression models requires a quality control algorithm be developed to eliminate the outliers and is planned for future study.

It is noted that collocations between MHS and ATMS data occur only in the high arctic, which may produce a sample with a small dynamic range for either satellite. John et al. (2012) showed how comparisons could be

biased by only using polar collocations. Figure 5 presents the histogram of brightness temperatures sampled by the SNOs of the year from 1 May 2016 to 30 April 2017 and the histogram of one-month nadir measurements in

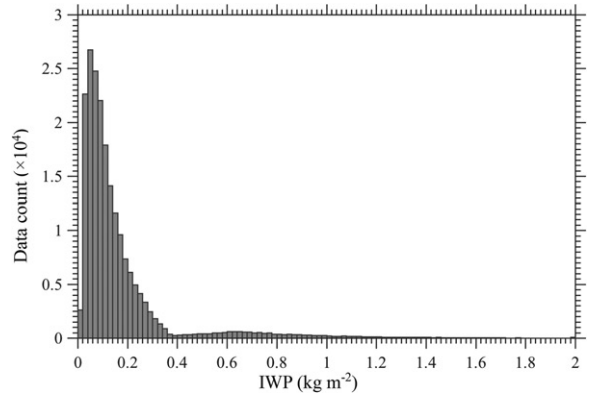


Fig. 6. Data counts of MHS-retrieved IWP at 0.02 kg m^{-2} intervals calculated using the original MHS IWP retrieval algorithm for all data on 12 December 2016 and 4 February 2017.

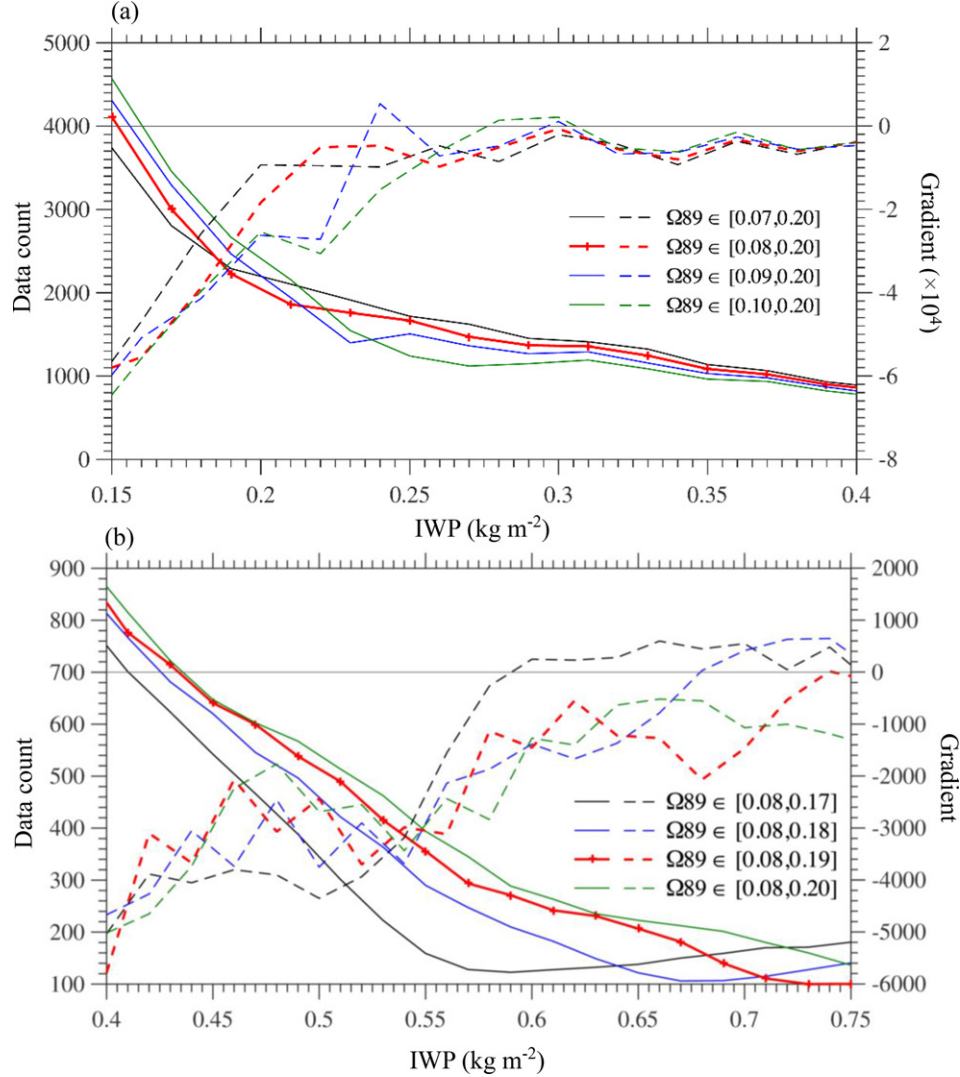


Fig. 7. Variations in the data count with respect to the MHS-retrieved IWP at 0.02 kg m⁻² intervals (solid curves) on 4 February 2017. The IWP retrieval scheme was applied for different ranges of Ω_{89} : (a) 0.07–0.20 (black), 0.08–0.20 (red), 0.09–0.20 (blue), 0.10–0.20 (green), and (b) 0.08–0.17 (black), 0.08–0.18 (blue), 0.08–0.19 (red), and 0.08–0.20 (green). The gradients of the data counts are also shown (right-hand ordinate, dashed curves).

January 2017. The result shows that the dynamic ranges for SNOs only and global nadir data are nearly the same for both instruments. This ensures that little extrapolation is needed for deriving global IWP.

3.3. Retrieval scheme

The same method for retrieving the IWP from MHS window channels is applied to the ATMS data that is mapped to the two window channels MHS by the regression Equation (3). This method was first proposed by Weng and Grody in 2000 and improved and subsequently applied to AMSU-B and SSMIS data in 2002 and 2012,

respectively (Weng and Grody, 2000; Zhao and Weng, 2002; Sun and Weng, 2012). The theoretical basis of the IWP retrieval is that for a constant bulk volume density, the only relationship between brightness temperature and IWP and De at microwave frequencies can be calculated using the two-stream radiative transfer model. Two main steps are carried out first: (1) estimating the cloud-base brightness temperature, the ice particle effective De, and finally the IWP, and (2) discriminating the surface type and removing the IWP over snow-, ice-, and desert-covered areas to avoid the error arising from surface scattering characteristics that are similar to those of ice clouds (Zhao and Weng, 2002).

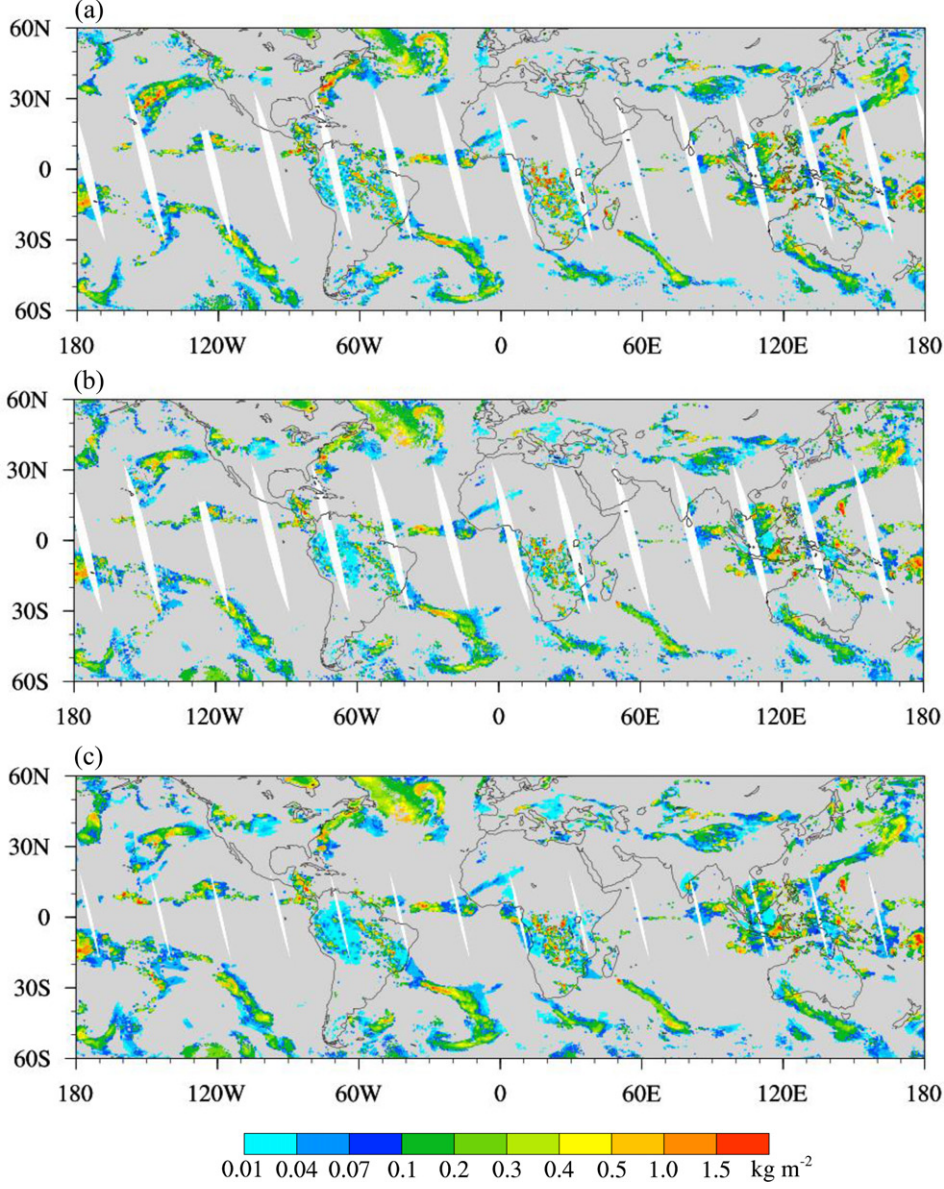


Fig. 8. Spatial distributions of (a) MHS-retrieved IWP calculated by the modified algorithm, (b) ATMS-derived IWP overlaid on MHS swaths, and (c) ATMS-derived IWP calculated by the modified algorithm. Data are from 12 December 2016.

Microwave channels have different sensitivities to ice particles of different sizes and are generally less sensitive to small ice particles. According to Weng and Grody (2000) and Zhao and Weng (2002), ice particles with the ice particle effective De less than 0.4 mm is considered as small, for which the scattering parameters at 89 GHz (Ω_{89}) and 157 GHz (Ω_{157}) are less than 0.15 and 0.18, respectively. Here the scattering parameter is a cloud microphysical parameter determined by both the upwelling radiance at the top of the ice clouds and the incident radiance at the bottom of the ice clouds. Therefore, two formulas for retrieving IWP are used:

$$\text{IWP} = \begin{cases} \Omega_{89} \times 0.4 \times 10^{-3} \times \cos \theta \times \frac{920}{0.15}, & \Omega_{89} < 0.15 \text{ or } \Omega_{157} < 0.18 \\ \Omega_{89} \times De \times 10^{-3} \times \cos \theta \times \frac{920}{\Omega_N}, & \text{otherwise} \end{cases} \quad (4)$$

where θ is the scan angle and Ω_N is the standard scattering parameter. In the first part of Equation (4), De and Ω_N are set to constant values.

The data count histogram of IWP calculated by Equation (4) is shown in Fig. 6. There exists a minimum around 0.4 kg m^{-2} located between the two maxima of IWP data counts. In other words, the IWP data counts do not decrease monotonically after they reach the

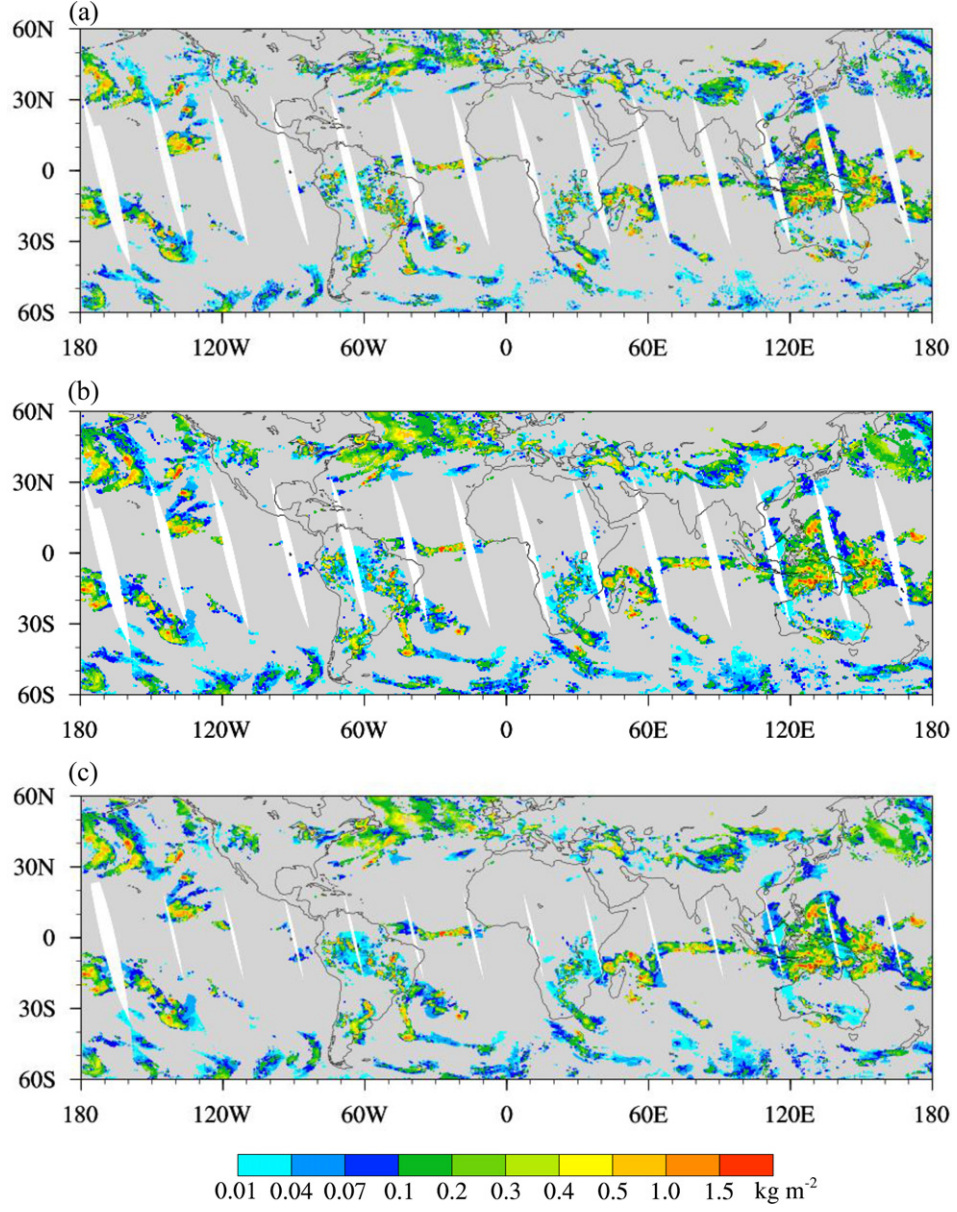


Fig. 9. Same as Fig. 8 except that results for 4 February 2017 are shown.

maximum. Scatterplots of IWP with scattering parameters at 89 and 157 GHz (figures omitted) show that when Ω_{89} is ~ 0.15 or when Ω_{157} is ~ 0.18 , a local minimum in the data count of IWP at $\sim 0.4 \text{ kg m}^{-2}$ is seen. Here, the two parts of Equation 12 are linearly combined to obtain a new IWP in the vicinity of Ω_{89} equal to 0.15 and Ω_{157} equal to 0.18, so that the IWP varies continuously with Ω_{89} and Ω_{157} . The following two criteria are used to determine the improved interval of the scattering parameter: (1) The minimum data count around 0.4 kg m^{-2} that arises from the use of two different formula for the IWP retrieval in Equation (4) is eliminated; and (2) Once

condition (1) is satisfied, the interpolation interval should be as small as possible.

Specifically, the right threshold is first set to 0.2 with the left threshold changing to see the effect of this change. In Fig. 7a, different left thresholds are chosen and variations in the data count are calculated for different intervals of Ω_{89} : 0.07–0.20, 0.08–0.20, 0.09–0.20, and 0.10–0.20. The gradients of the data counts are also shown. As the value of the left threshold decreases, the variation in the data count gradually meets criterion (1). When the left threshold is less than 0.08, the gradient of the data count is always less than zero which means that the IWP data count decreases as the IWP increases in the

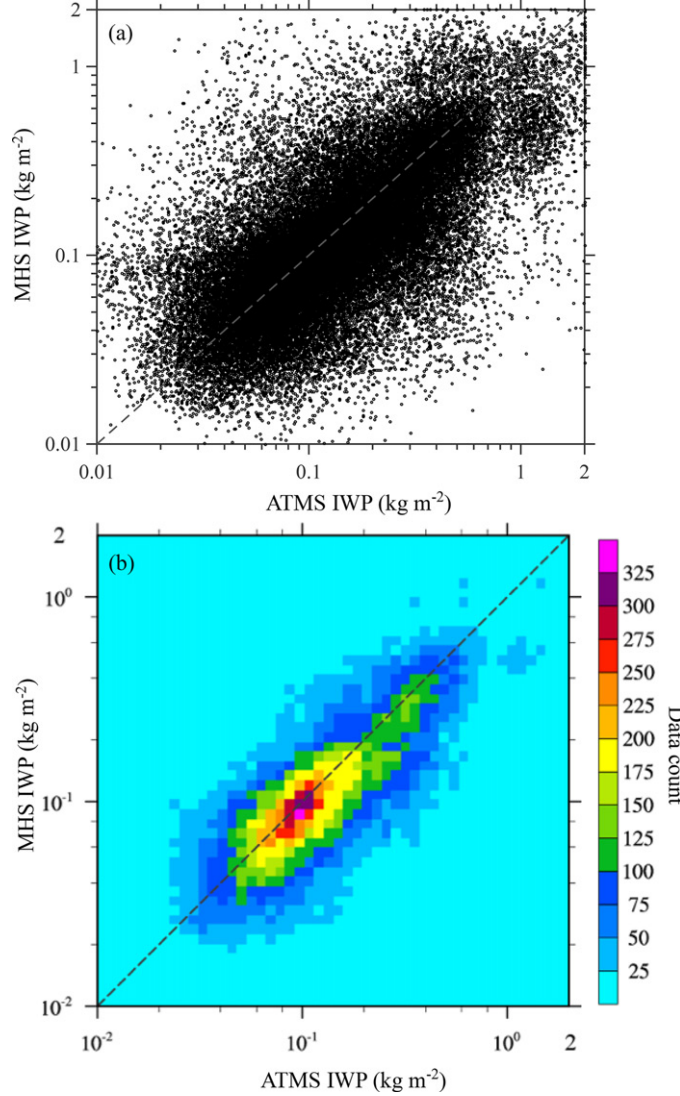


Fig. 10. (a) MHS-derived IWP as a function of ATMS-derived IWP where the modified algorithm was applied to both retrievals and (b) associated data counts. Data are from between 60°S and 60°N on 12 December 2016 and 4 February 2017.

range that is mainly affected by the left threshold. To meet criterion (2) at the same time that the improved interval should be as small as possible, 0.08 is chosen to be the left threshold of the improved interval of Ω_{89} (red solid curve in Fig. 7a). Then the left threshold is set at 0.08 with the right threshold changing to see its effect on the IWP data count. The same method as above is used. In light of Fig. 7b, when the right threshold is greater than 0.19, the gradient of the IWP data count is always less than zero, i.e. the IWP data count decreases as the IWP increases. Also, to make the improved interval as small as possible, 0.19 is finally chosen to be the right threshold of the improved interval of Ω_{89} (red solid curve in Fig. 7b). Based on the above analysis, $\Omega_{89} \in [0.08, 0.19]$ and $\Omega_{157} \in [0.11, 0.22]$ are determined to be the improved intervals and the modified formula for calculating IWP becomes

$$\text{IWP} = \begin{cases} \text{IWP}_1, \Omega_{89} < 0.08 \\ -0.1518 + 1.4591 \cdot \text{IWP}_1 + 0.2191 \cdot \text{IWP}_2, 0.08 \leq \Omega_{89} \leq 0.19 \\ \text{IWP}_2, \Omega_{89} > 0.19 \end{cases} \quad (5)$$

where

$$\begin{aligned} \text{IWP}_1 &= \Omega_{89} \times 0.4 \times 10^{-3} \times \cos \theta \times \frac{920}{0.15} \\ \text{IWP}_2 &= \Omega_{89} \times De \times 10^{-3} \times \cos \theta \times \frac{920}{\Omega_N}. \end{aligned} \quad (6)$$

4. Retrieval results

The modified algorithm is applied to both MHS and ATMS global IWP retrievals made on 12 December 2016

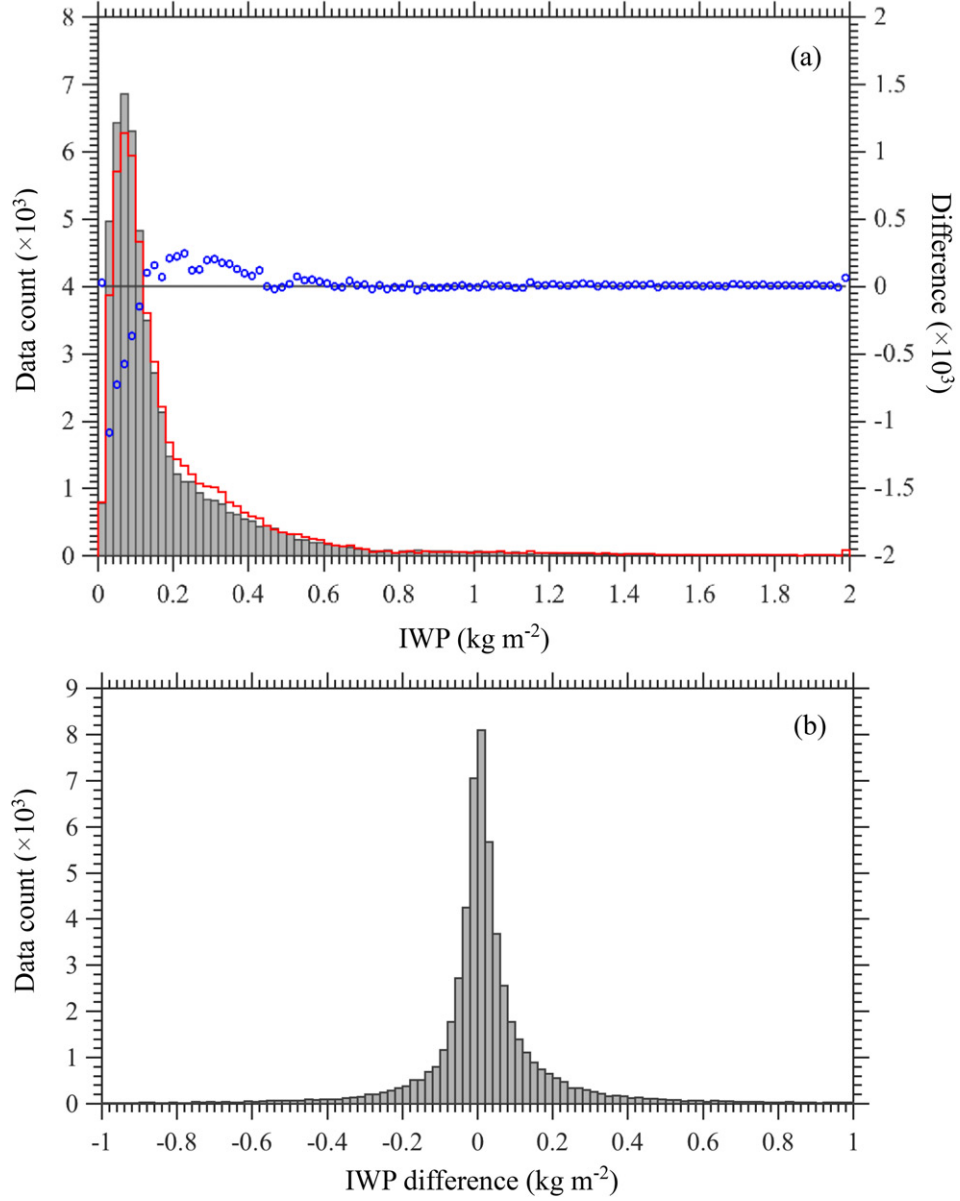


Fig. 11. Data counts at 0.02 kg m^{-2} intervals of (a) collocated ATMS- (red) and MHS-derived (grey) IWPs calculated by the modified algorithm and the difference between the two data counts (right ordinate, blue circles), and of (b) differences between ATMS- and MHS-derived IWP. Data are on 12 December 2016 and 4 February 2017 between 60°S and 60°N .

(Fig. 8) and 4 February 2017 (Fig. 9). The IWP derived by the ATMS within the swaths of the MHS (Fig. 8b) are compared with MHS IWP (Fig. 9b). Results from these two days show that the IWP derived from ATMS data compares favorably with that derived from MHS data in terms of spatial distribution. Differences are seen in some areas with strong mesoscale cloud systems. For example, IWPs derived by the MHS in the western Atlantic on 12 December 2016 are greater than those derived by the ATMS. On the same day, IWPs derived

by the MHS in North Africa are less than those derived by the ATMS. From the spatial distribution of IWP derived by the MHS and the ATMS on 4 February 2017 (Fig. 9), the values of MHS-derived IWP in the northern Pacific Ocean are greater than ATMS-derived IWPs while the coverage of ATMS-derived IWP in this area is larger. These differences may arise because of the differences in observed brightness temperatures of the ATMS and the MHS, since in most cases, the ATMS and the MHS do not observe the same place simultaneously.

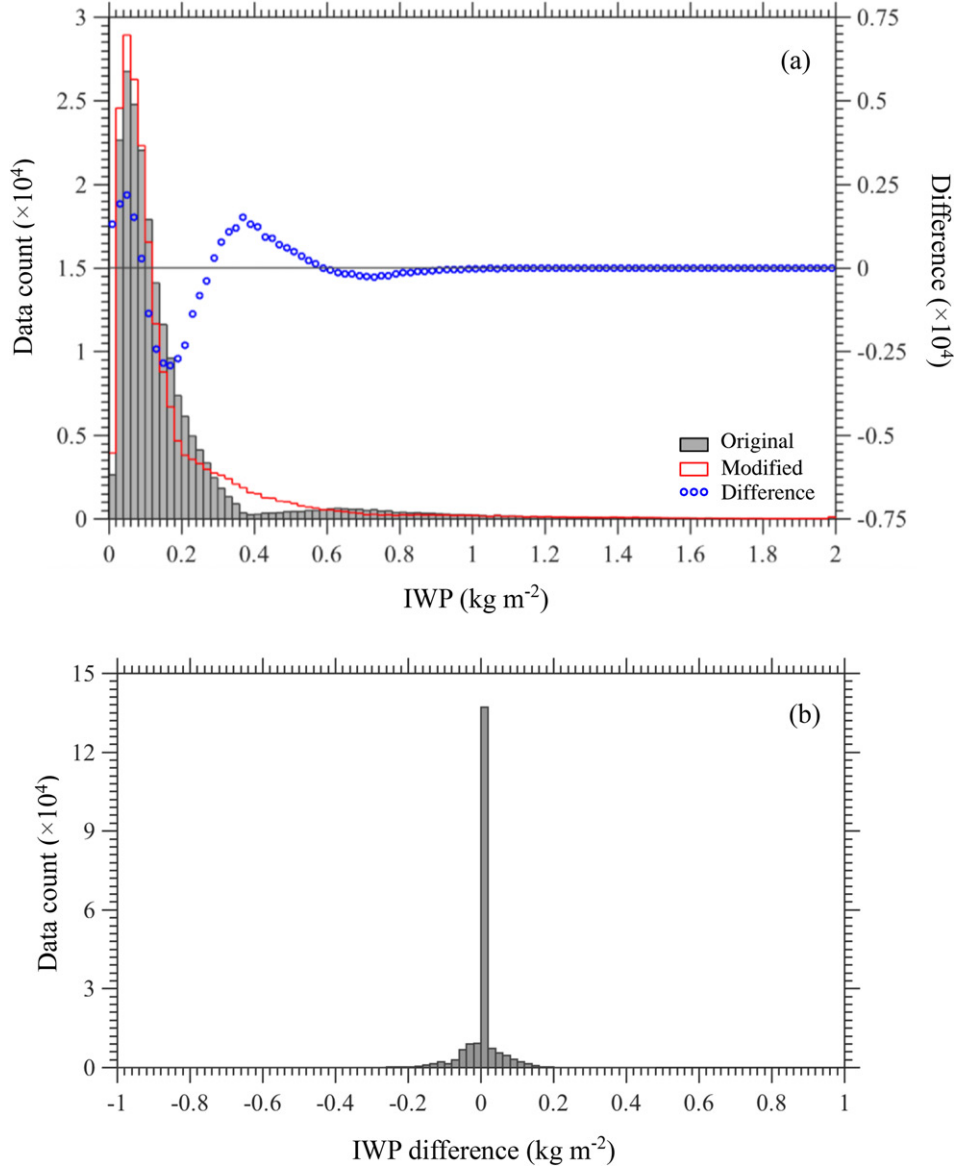


Fig. 12. Data counts of (a) MHS-retrieved IWP at 0.02 kg m^{-2} intervals calculated using the modified (red) and the original (grey) algorithms and (b) differences between MHS-derived IWP with the modified and original algorithms for all data on 12 December 2016 and 4 February 2017.

ATMS and MHS IWP retrievals from 12 December 2016 and 4 February 2017 were matched according to the distance between their fields of view at nadir, i.e. distances less than 8 km. Based on paired data between 60°S and 60°N , the scatterplot and data count of ATMS- and MHS-retrieved IWP calculated by the modified algorithm are shown in Fig. 10. The IWP derived from ATMS and MHS data are generally equally distributed around the 1:1 line (Fig. 10a). The number of IWP values decreases as the distance from the 1:1 line increases (Fig. 10b). The number of points below the 1:1 line is slightly more than that above the 1:1 line. Figure 10 suggests that the IWP derived from

ATMS and MHS data is linearly correlated with a slope of ~ 1 with slightly larger values for the ATMS retrievals.

Figure 11a shows the data counts of ATMS- and MHS-derived IWP calculated by the modified algorithm and the difference between the two data counts for all paired data on 12 December 2016 and 4 February 2017 between 60°S and 60°N . When IWP values range from 0.02 – 0.14 kg m^{-2} , the number of IWP values retrieved from MHS data is greater than that retrieved from ATMS data. In the range of 0.14 – 0.48 kg m^{-2} , the number of IWP values retrieved from ATMS data is greater than that retrieved from MHS data. When IWP values are greater than 0.48 kg m^{-2} , the number

of IWP values retrieved from ATMS and MHS data is almost the same. Overall, the numbers of ATMS and MHS retrievals show some differences when the IWP is small but are almost equal when the IWP is large. Figure 11b is a histogram of the data count of the differences between the ATMS- and MHS-derived IWP seen in Fig. 10a. A near normal distribution is seen with an expected value of zero concentrated on values between -0.2 kg m^{-2} and 0.2 kg m^{-2} . This suggests that the IWP retrievals based on ATMS and MHS observations are similar and that the improved retrieval algorithm can be applied to ATMS data with reasonable success.

The data counts of MHS-retrieved IWP at 0.02 kg m^{-2} intervals calculated using the modified algorithms for all data on 12 December 2016 and 4 February 2017 between 60°S and 60°N are also shown in Fig. 12. The data count of the IWP calculated by the modified algorithm changes monotonically with IWP, which means that the modified algorithm effectively solves the problem seen from the IWP data count distribution calculated by the two segments of the original algorithm. Since the differences shown in Fig. 10b are due to a combination of at least two effects: different algorithms and matchup uncertainty. Figure 12b presents differences due to the retrieval equation, which can be determined by applying both equations to the same MHS data. By comparing Figs. 11b and 12b, we conclude that differences due to different algorithms are much smaller than matchup uncertainty.

5. Summary and conclusion

The ATMS onboard the S-NPP satellite has inherited most of the channels of the AMSU-A and the MHS through integration of the two instruments into a single sounder with great enhancements in coverage and precision. The ATMS has a wider swath than both the AMSU-A and the MHS, which means that there is almost no gap between two consecutive orbits. Measurements of ice clouds, covering 20% of the earth's surface, are important for weather and climate studies. Therefore, retrieving IWP based on ATMS observations is of great significance for weather forecasting and climate prediction.

In this study, linear relationships are established for ATMS and MHS window channels based on the similar characteristics of their respective channels. Regression results are very close to observations. Also, the traditional IWP retrieval algorithm based on the MHS is modified in this research to effectively remove an unrealistic drop of IWP data counts at $\sim 0.4 \text{ kg m}^{-2}$. The modified IWP algorithm is applied to both ATMS and MHS data. The spatial distributions of the IWP derived from MHS and ATMS data are similar. The data counts of IWP retrieved from ATMS and MHS data have similar

distributions when the IWP is large but are slightly different when the IWP is small. The differences in ATMS- and MHS-derived IWP are small. Based on the above discussions, the modified IWP retrieval algorithm could be applied to ATMS data and showed good results.

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References

- Buehler, S. A., Jiménez, C., Evans, K. F., Eriksson, P., Rydberg, B. and co-authors. 2007. A concept for a satellite mission to measure cloud ice water path, ice particle size, and cloud altitude. *Q. J. Meteorol. Soc.* **133**, 109–128. doi:10.1002/qj.143.
- Cao, C., Weinreb, M. and Xu, H. 2004. Predicting simultaneous nadir overpasses among polar-orbiting meteorological satellites for the intersatellite calibration of radiometers. *J. Atmos. Oceanic Technol.* **21**, 537–542. doi:10.1175/1520-0426(2004)021.
- Holl, G., Eliasson, S., Mendrok, J. and Buehler, S. A. 2014. SPARE-ICE: Synergistic ice water path from passive operational sensor. *J. Geophys. Res. Atmos.* **119**, 20. doi: 10.1002/2013JD020759.
- John, V. O., Holl, G., Buehler, S., Candy, B., Saunders, R. and Parker, D. E. 2012. Understanding intersatellite biases of microwave humidity sounder using global simultaneous nadir

- overpasses. *J. Geophys. Res.* **117**(D02305). doi:10.1029/2011JD016349.
- Liou, K. N. 1986. Influence of cirrus clouds on weather and climate processes: a global perspective. *Mon. Wea. Rev.* **114**, 1167–1199. doi:10.1175/1520-0493(1986)114.
- Liou, K. N., Gu, Y., Yue, Q. and McFarquhar, G. 2008. On the correlation between ice water content and ice crystal size and its application to radiative transfer and general circulation models. *Geophys. Res. Lett.* **35**, L13805.
- Lohmann, U. and Roeckner, E. 1996. Design and performance of a new cloud microphysics scheme developed for the ECHAM general circulation model. *Clim. Dynam.* **12**, 557–572. doi:10.1007/BF00207939.
- Stephens, G. L. and Webster, P. J. 1981. Clouds and climate: sensitivity of simple systems. *J. Atmos. Sci.* **38**, 235–247. doi:10.1175/1520-0469(1981)038.
- Stephens, G. L. 2005. Cloud feedbacks in the climate system: a critical review. *J. Climate.* **18**, 237–273. doi:10.1175/JCLI-3243.1.
- Sun, N. and Weng, F. 2012. Retrieval of cloud ice water path from Special Sensor Microwave Imager/Sounder (SSMIS). *J. Appl. Meteor. Climatol.* **51**, 366–379. doi:10.1175/JAMC-D-11-021.1.
- Weng, F. and Grody, N. C. 2000. Retrieval of ice cloud parameters using a microwave imaging radiometer. *J. Atmos. Sci.* **57**, 1069–1081. doi:10.1175/1520-0469(2000)057.
- Zhao, L. and Weng, F. 2002. Retrieval of ice cloud parameters using the Advanced Microwave Sounding Unit. *J. Appl. Meteor.* **41**, 384–395. doi:10.1175/1520-0450(2002)041

Appendix A: Regression models

A linear relationship of the following form is established between the ATMS channel 16 and MHS channel 1:

$$T_{b,MHS,i}^{\text{reg}} = \alpha_i + \beta_i \cdot T_{b,ATMS,i}^{\text{obs}} \quad (\text{A1})$$

where $i=1$ represents the relationship between ATMS channel 16 and MHS channel 1. Two different linear relationships between the ATMS channel 17 and MHS channel 2 are developed: one for the case where ATMS channel 17 brightness temperatures are less than 237.5 K ($i=2$) and the other for when the ATMS channel 17 brightness temperatures are greater than or equal to 237.5 K ($i=3$). The regression coefficients α_i and β_i are calculated by minimizing the cost function

$$J(\alpha_i, \beta_i) = \sum_{j=1}^N \left(T_{b,MHS,i}^{\text{obs}}(j) - T_{b,MHS,i}^{\text{reg}}(j) \right)^2 \quad (\text{A2})$$

where the subscript ' j ' ($j=1, 2, 3, \dots, N$) represents the N data points involved in the regression calculation.

Substituting Equation (A1) into Equation (A2) yields:

$$J(\alpha_i, \beta_i) = \sum_{j=1}^N \left(T_{b,MHS,i}^{\text{obs}}(j) - \alpha_i - \beta_i \cdot T_{b,ATMS,i}^{\text{obs}}(j) \right)^2 \quad (\text{A3})$$

The cost function (Equation (A2)) is a quantitative description of the deviation between observations and the regression equation, so the cost function should be minimized to make the error of the regression function as small as possible. Since the cost function is a function of α_i and β_i , the minimization problem can be solved by the extreme value theorem as:

$$\begin{cases} \frac{\partial J(\alpha_i, \beta_i)}{\partial \alpha_i} = 0 \\ \frac{\partial J(\alpha_i, \beta_i)}{\partial \beta_i} = 0 \end{cases} \quad (\text{A4})$$

After substituting Equation (A3), (A4) becomes:

$$\begin{cases} -2 \sum_{j=1}^N (T_{b,MHS,i}^{\text{obs}}(j) - \alpha_i - \beta_i \cdot T_{b,ATMS,i}^{\text{obs}}(j)) = 0 \\ -2 \sum_{j=1}^N (T_{b,MHS,i}^{\text{obs}}(j) - \alpha_i - \beta_i \cdot T_{b,ATMS,i}^{\text{obs}}(j)) \cdot T_{b,ATMS,i}^{\text{obs}}(j) = 0 \end{cases} \quad (\text{A5})$$

Since

$$\begin{cases} \frac{\partial^2 J(\alpha_i, \beta_i)}{\partial \alpha_i^2} > 0 \\ \frac{\partial^2 J(\alpha_i, \beta_i)}{\partial \beta_i^2} > 0 \end{cases} \quad (\text{A6})$$

the cost function is minimized when the coefficients satisfy Equation (A5). The coefficients can be written as

$$\begin{cases} \alpha_i = \frac{\sum_{j=1}^N T_{b,ATMS,i}^{\text{obs}}(j) \cdot T_{b,MHS,i}^{\text{obs}}(j) - N \cdot \bar{T}_{b,ATMS,i}^{\text{obs}} \bar{T}_{b,MHS,i}^{\text{obs}}}{\sum_{j=1}^N (T_{b,ATMS,i}^{\text{obs}}(j))^2 - N \cdot (\bar{T}_{b,ATMS,i}^{\text{obs}})^2} \\ \beta_i = \bar{T}_{b,MHS,i}^{\text{obs}} - \alpha_i \cdot \bar{T}_{b,ATMS,i}^{\text{obs}} \end{cases} \quad (\text{A7})$$

where

$$\begin{cases} \bar{T}_{b,MHS,i}^{\text{obs}} = \frac{1}{N} \left(\sum_{j=1}^N T_{b,MHS,i}^{\text{obs}}(j) \right) \\ \bar{T}_{b,ATMS,i}^{\text{obs}} = \frac{1}{N} \left(\sum_{j=1}^N T_{b,ATMS,i}^{\text{obs}}(j) \right) \end{cases} \quad (\text{A8})$$

Using the SNO data identified during the year from 1 May 2016 to 30 April 2017, the regression relationships are finally expressed as (11).