Retrieval of Cloud Ice Water Path from Special Sensor Microwave Imager/Sounder (SSMIS)

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ABSTRACT

The Special Sensor Microwave Imager/Sounder (SSMIS) aboard the Defense Meteorological Satellite Program F-16 spacecraft measures the Earth-emitted radiation at frequencies from 19 to 183 GHz. From its high-frequency channels at 91 and 150 GHz, cloud microphysical parameters can be observed at a spatial resolution of 15 km. In this study, a simplified two-stream radiative transfer model is applied for microwave applications as a three-parameter equation and then used to retrieve the ice cloud water path (IWP) and ice particle effective diameter $D_e$. Since SSMIS is a conically scanning instrument, the retrieved IWP is less dependent on scan position and is a useful product for imaging atmospheric ice-phase clouds related to precipitation. Thus, IWP is also used to estimate surface rainfall rate through the same relationship derived previously and used in Advanced Microwave Sounding Unit (AMSU-B) and Microwave Humidity Sounder applications. The SSMIS-derived ice cloud products are compared with those from other microwave instruments on the MetOp-A satellite, and both agree well in their spatial distributions.

1. Introduction

Ice clouds play a vital role in modulating the earth’s radiation energy budget and influencing weather and climate prediction. The high-altitude clouds, such as cirrus, have relatively smaller optical depths, which make its radiative properties distinct from other types of clouds. The reflection of shortwave solar radiation by cirrus clouds reduces the solar energy reaching the earth’s surface and leads to the potential cooling effect on the surface. On the other hand, the cold temperatures of cirrus clouds indicate much less infrared radiation emitted into space than in condition of clear skies so that a larger greenhouse effect would occur. Numerical studies have shown that the net radiative flux of both processes largely depends on the optical thickness of clouds associated with the processes for radiative transfer calculations in climate models (Liou 1986; Stephens and Webster 1981; Stephens 2005). Recently, most numerical weather prediction models have included ice water content as a prognostic variable, and predicted its values for high-level clouds (Buehler et al. 2007; Liou et al. 2008). Other important parameters, such as cloud ice particle size as it determines the radiative effect per mass and the ice cloud lifespan (through the particle fall speed), also have been used in the model for cloud microphysical parameterizations (Bennartz and Petty 2001). Therefore, the global quantitative measurements of ice cloud microphysical parameters, including vertically integrated cloud ice mass [ice water path (IWP)] and ice particle size in ice clouds, are critical for both validation of global climate models and understanding of climate changes.

Global measurements of ice cloud parameters because of their high altitude and wide spatial distribution can be detected from satellite. A number of studies have been conducted on the remote sensing of ice cloud parameters with passive millimeter and submillimeter radiometers (Evans and Stephens 1995b; Evans et al. 2005; Liu and Curry 2000; Vivekanandan et al. 1991; Weng and Grody 2000). In comparison with visible/IR techniques, microwave radiometers can penetrate deeper into dense clouds and provide more information of ice cloud bulk
properties, especially for precipitating-size ice particles commonly associated with convective cloud systems.

The microwave radiation emanating from a precipitating cloud top and received by a satellite radiometer can be related to scattering and emission from clouds in liquid, melting phase, and ice phases. The scattering effects of ice clouds are strongly frequency dependent. Observational studies (Adler et al. 1990; Bennartz and Bauer 2003; Hakkarinen and Adler 1988; Liu and Curry 1998; Petty 2001; Spencer et al. 1989; Wilheit et al. 1982; Wu and Weinman 1984) have shown that brightness temperature near 85 GHz can be strongly depressed because of the presence of precipitating-size ice particles. A time-dependent cloud model has been used to examine the temporal evolution of the cloud drop-size distribution and its impact on the microwave brightness temperature (Mugnai and Smith 1988).

Further studies show that the scattering process is also sensitive to distribution of the ice particle size (Bennartz and Petty 2001; Evans and Stephens 1995a; Evans et al. 2005; Mugnai and Smith 1988; Smith and Mugnai 1988). Brightness temperature simulated at millimeter to submillimeter wavelengths are found to be very sensitive to ice clouds having a relatively low IWP (Evans and Stephens 1995b; Gasiewski 1992). In addition to particle size distribution, the ice particle habit is also critical in the estimate of particle scattering property. Evans and Stephens (1995b) used discrete dipole approximation (DDA) to compute scattering quantities of particles by different shapes and found that shape is the dominant effect on the polarization of the scattering, with the thinner shapes having the more polarizing effect. A number of studies (Baum et al. 2005a,b; Yang et al. 2007; Liu 2008; Hong et al. 2009) reported the sensitivity of ice crystal optical properties and relevant retrievals to the assumed ice crystal habit distribution in the optical spectrum. Hong et al. (2009) also developed a database of the single-scattering properties of nonspherical ice particles in terms of particle maximum dimension. Liu (2004) performed DDA modeling for selected frequencies and particle shapes in an effort to form an empirical formula to compute the single-scattering properties and also developed a database in terms of frequencies (Liu 2008). Kim et al. (2007) also employed DDA method to study optical properties of selected types of idealized nonspherical ice particles and found that overall differences among the various ice habit results at 89 GHz are generally not that expansive, whereas 150 GHz shows increased sensitivity to ice particle shapes.

The response of the Advanced Microwave Sounding Unit (AMSU)-B water vapor channels at 183.3 GHz on mixed-phase clouds (Deeter and Vivekanandan 2005) showed that those water vapor channels only see the surface in very dry conditions and are particularly sensitive to ice particles but are also impacted by the water vapor contents. Measurements made at 150, 220, and 340 GHz display different spatial characteristics for nonraining anvil cirrus and precipitating clouds, while both visible and thermal infrared measurements show very little variations within the clouds (Heymsfield et al. 1996; Weng et al. 1997). Therefore, the millimeter-wavelength measurements may potentially make up the sensitivity gap between visible and microwave data so that cloud ice parameters can be measured over a wider dynamic range. It is also shown that the sensitivity of brightness temperatures to IWP at submillimeter frequencies is nearly independent of cloud temperatures and the details of the underlying atmosphere because of the higher scattering effects.

Soon after the launch of Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager/Sounder (SSMIS), many environmental data records and geophysical parameters were requested by the user community. In this study, a simplified two-stream radiative model (Weng and Grody 2000) will be extended to SSMIS higher-frequency channels at 91.655 and 150 GHz to retrieve ice cloud parameters by taking an advantage of its constant scan angle along the scan line. In the algorithm, both IWP and ice particle effective diameter $D_e$ can be retrieved simultaneously from dual millimeter-wavelength measurements for a given particle bulk volume density $\rho_{\text{ice}}$. The physical base of this algorithm has been operationally used for the AMSU at 89- and 150-GHz channels and proved to be successful in estimating precipitating-size ice particle clouds property (Zhao and Weng 2002). This paper is organized as follows: Section 2 describes the characteristics of the SSMIS instrument and its calibration. Section 3 briefly introduces the retrieval algorithm. Section 4 shows the case studies of the IWP retrievals associated with various cloud systems. In addition, the relationships between IWP and rainfall rate (RR) are examined. In section 5, an in-depth error analysis is conducted to assess the retrieval uncertainties from instrument noise, cloud-base temperature, and particle size distribution. A summary and remarks are given in section 6.

2. SSMIS characteristics

The DMSP F-16 satellite was successfully launched on 18 October 2003, carrying the first SSMIS on board. This instrument marks a beginning of a new series of passive microwave conically scanning imagers and sounders to be launched. Seven out of its 24 channels are similar to Special Sensor Microwave Imager (SSMI) and have both vertical polarizations (V-POL) and horizontal polarizations.
(H-POL), except 22.235 GHz, which is only vertically polarized. SSMIS also has seven lower-atmosphere temperature sounder (LAS) and six upper-atmosphere temperature sounder (UAS) channels near the 50–60-GHz oxygen absorption band. In addition, SSMIS contains a channel at 150 GHz and three channels at 183.31 GHz that are double-side banded for troposphere water vapor sounding. SSMIS also has a larger scan swath than SSM/I and thus the number of scan positions of five SSM/I-like channels at 19.35, 22.235, and 37.0 GHz [imager (IMG)] is extended to 90 from 64 in the SSM/I A scan. Meanwhile, the 128 scan positions in SSM/I B scan for 85.5-GHz channels is also extended to 180 for 91.655, 150, and 183.31 GHz [environment (ENV)] channels. As a result, SSMIS orbit gap is significantly decreased from SSM/I. This study will use both imaging and water vapor channels for the retrieval.

National Environmental Satellite, Data, and Information Service (NESDIS) received SSMIS antenna brightness temperature data records (TDRs) through a data-sharing agreement with DMSP. The F-16, F-17, and F-18 SSMIS TDRs have been archived at National Oceanic and Atmospheric Administration (NOAA)/NESDIS since January 2005 and used in NOAA operations. A preliminary analysis of the SSMIS TDRs distributed by Fleet Numerical Meteorology and Oceanography Center indicates that the SSMIS TDRs display notable anomalies, which could be associated with the main reflector and warm calibration loads (Kunkee et al. 2008). The SSMIS main reflector emits an additional radiation and its calibration targets are also occasionally illuminated by direct and stray lights. On average, brightness temperature anomalies range within a several degrees (Kunkee et al. 2008; Yan and Weng 2008). In fact, the reflector emission occurs for all scenes where the reflector and scene temperature differ, but its impact is most notable when the satellite is out of the earth shadow and the solar elevation angles are impinging from below the canister top, resulting in a dramatic jump in the reflector face temperature of 70 K or more, which complicates the assessment. Nevertheless, the SSM/I-like channels, especially those below 40 GHz, which are primarily used to produce heritage surface and hydrometeor parameters, do not exhibit very significant anomalies as LAS and UAS channels do. Because of the high uncertainty of surface parameters, temperature, and moisture profiles, it is difficult to use a radiative transfer forward model to accurately simulate the radiance at IMG and ENV channels, particularly over land. However, because of the sensor hardware limitation or deficiency (e.g., feed horn spill-over loss and leakage of vertical polarization signal into horizontal polarization receiver), the antenna pattern correction (APC) is needed to correct such errors in order to obtain sensor brightness temperature [sensor data records (SDRs)]. In fact, some NESDIS in-house-developed retrieval algorithms, such as snow coverage and rain rate, use both antenna temperatures and sensor brightness temperatures. Thus, the APC algorithm is developed and consists of a linear correction for the feed horn spillover loss and cross-polarization coupling as shown in Eq. (1):

$$TB_{\nu(h)} = \frac{[TA_{\nu(h)} - a_{\nu(h)}TA_{\nu(v)}]}{\eta_{\nu(h)}(1 - a_{\nu(h)})},$$  

where $TB_{\nu(h)} = SDR$ at V-POL/H-POL, $TA_{\nu(h)} = TDR$ at V-POL/H-POL, $\eta_{\nu(h)} = \text{feed horn spillover factor}$, and $a_{\nu(h)} = \text{cross-polarized coupling coefficient}$. In our retrieval, the TDRs to SDRs conversion coefficients are kindly provided by Mr. S. Swadley of the Naval Research Laboratory (2006, personal communication).

3. Methodology

The IWP and $D_x$ algorithm was first developed and applied to Microwave Imaging Radiometer (MIR) (Weng and Grody 2000) and extended to AMSU (Zhao and Weng 2002) for operations using the measurements at 89.0 and 150 GHz. The two studies demonstrated that the combination of these two frequencies can be used to retrieve the bulk properties of ice clouds containing large particles. Since SSMIS is a conically scanning instrument with a constant scan angle of 53.2°, it is ideal to use its similar but higher-resolution channels to image the ice-phase clouds and estimate its capability for cloud property retrieval.
a. Retrieval algorithm

The detailed theoretic description of the radiative transfer process in ice cloud has been given in the earlier studies (Weng and Grody 2000). The major principle is to simplify the radiative transfer equations by a two-stream approximation so that the upwelling radiance at the top of ice clouds will be determined by both the incident radiance at the bottom of the ice clouds and the particle scattering parameter \( \Omega \) that is related to the ice cloud microphysics, such as ice particle size and ice water path. In the model simulation, ice particles are assumed to be spherical and distributed with a gamma function with the exponent of 2 (Ulbrich 1983). The reason that the exponent of 2 is used here is that negative exponent in the gamma function generally indicates a broad particle size distribution shape with large number of small particles assumed in the ice cloud. In the retrieval of precipitating-size ice particles, 91- and 150-GHz channel observations used in this study are not sensitive to small-size particles. For a large positive exponent number, a narrower particle size distribution shape with reduced number of small particles is indicated. However, if it is a positive number larger than 3, the particle size distribution is so narrow that further increase in the exponent has less impact. Smith (2003) also found that there is little practical difference for the exponent between 0 and 3. Thus, IWP can be related to the particle effective diameter \( D_e \) through \( \Omega \) given the ice particle bulk density \( \rho_{ice} \), as shown in Eq. (2):

\[
\text{IWP} = \frac{\Omega}{\Omega_N(x, m)} \mu \rho_{ice} D_e,
\]

where \( \mu \) is the cosine of incident angle, and \( \Omega_N \) is the normalized scattering parameter, which is the function of the particle size parameter \( x = \pi D/\lambda \) and the complex refractive index \( m \). For the microwave remote sensing of ice particle, \( m \) is chosen as a constant. Here, particle effective diameter is defined as

\[
D_e = \frac{\int_0^\infty N(D)D^2 \, dD}{\int_0^\infty N(D)D \, dD},
\]

and the particle scattering parameter \( \Omega \) is defined as

\[
\Omega(\mu) = \frac{1}{2\mu} (1 - \cos \tau),
\]

where \( \tau \) is the ice cloud optical thickness, \( g \) is the asymmetry factor, and \( \mu \) is the cosine of the zenith angle as defined in Weng and Grody (2000).

For a single layer of ice cloud, when the upwelling brightness temperature at the bottom of ice cloud \( T_b(z_{bottom}, \mu) \) is known, the scattering parameter \( \Omega \) can be obtained from Eq. (3) as

\[
\Omega(\mu) = \frac{T_b(z_{bottom}, \mu) - T_b(z_{top}, \mu)}{T_r(z_{top}, \mu)}. \quad (3)
\]

It is noteworthy that brightness temperature at millimeter wavelengths is sensitive to both IWP and \( D_e \) so that dual-frequency measurements are required to unambiguously determine both IWP and \( D_e \) for a given particle bulk density \( \rho_{ice} \) (Evans and Stephens 1995b). However, because of the variation of ice particle bulk density with particle size, the uncertainty remains with this dual-frequency approach.

The relationship between the normalized scattering parameter \( \Omega_N \) and the particle effective diameter \( D_e \) is given in Fig. 1a using the simulated data from the radiative transfer model with above assumptions (Weng 1992). The simulation uses the Mie theory for scattering and absorbing property determination. Studies (Warren 1984; Warren and Brandt 2008) showed that ice refractive index is strongly dependent on the temperature and a revised set of optical constants was compiled at 266 K according to the latest study (Warren and Brandt 2008). However, the temperature dependence of the refractive index of ice was not taken into consideration in this study. Cloud ice water content is randomly generated within a range of 0 to 0.5 g m\(^{-3}\). The ice cloud base is set to 9 km with the thickness of 1 km. The ice particle effective diameter randomly varies within a range of 0.1–3.5 mm. The incident radiation at the cloud base is set to a constant corresponding to a temperature of 280 K. The 91.655- and 150-GHz channels are selected in this study because 150 GHz presents a stronger scatter signature for precipitating-size ice particles, and the surface scattering impacts are effectively reduced in the retrieval by using a scattering parameter ratio (Bennartz and Bauer 2003). As shown in Fig. 1a, for extremely small ice particles, the normalized scattering parameters of 91.655 and 150 GHz are both close to zero and increase with the particle effective diameter. Also, the increasing rate of the normalized scattering parameter \( \Omega_N \) at 150 GHz is higher than that at 91.655 GHz and reaches its optical limit around 2.0 mm, while \( \Omega_N \) at 91.655 GHz continues increasing for \( D_e \) larger than 2.0 mm. Thus, the scattering parameter ratio between two frequencies also is a unique function of particle effective diameter.

To determine ice particle effective diameter \( D_e \) from dual-frequency channels, a scattering parameter ratio \( r \) defined from 91.655 and 150 GHz is used here as
\( r(D_e) = \frac{\Omega_{91.655}}{\Omega_{150}} = \frac{\Omega_{N_{91.655}}(x_e, m)}{\Omega_{N_{150}}(x_e, m)} \) \quad (4)

Figure 1b gives the relationship between the scattering parameter ratio \( r \) and the particle effective diameter \( D_e \). For the dual-frequency measurements at 91.655 and 150 GHz, the reliable results are expected when the ratio ranges from 0.2 to 0.8. Table 1 gives the coefficients for the regression equations:

\[ D_e = a_0 + a_1 r + a_2 r^2 + a_3 r^3 \] \quad (5)

\[ \Omega_N = \exp[b_0 + b_1 \ln(D_e) + b_2 \ln^2(D_e) + b_3 \ln^3(D_e)] \] \quad (6)

The regression fitting plots of \( \Omega_{N_{91.655}} \) and \( D_e \) using the derived coefficients are presented by the blue line in Figs. 1a,b. If the upwelling brightness temperature at the bottom of ice cloud is known, the channel scattering parameter can be calculated by Eq. (3). Thus, \( D_e \) and IWP can be retrieved for a given ice particle bulk volume density.

### Table 1. The coefficients used in the \( D_e \) and \( \Omega_N \) retrieval algorithm.

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<th>( a_1 )</th>
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<td>( b_1 )</td>
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#### b. Estimation of upwelling brightness temperature at bottom of ice cloud

In our study, the ice cloud-base brightness temperature is estimated using an empirical relationship between the SSMIS lower and higher frequencies. To ensure accuracy, the brightness temperatures are collected under cloud-free conditions at each field of view of environmental channels. The cloud-free location is identified with small cloud liquid water path over ocean (Weng and Grody 1994) and the rainfall-free location is identified with small cloud liquid water path over land (Ferraro and Marks 1995). As shown in Fig. 2, the cloud-base brightness temperatures at 91.655 and 150 GHz can be estimated with a root-mean-square (RMS) of 1.5 K at 91.655 GHz and 2.5 K at 150 GHz over land.

### 4. Results and discussions

#### a. Hurricane Gustav

Hurricane Gustav was one of the most destructive hurricanes of the 2008 Atlantic hurricane season. It caused serious damage and casualties in several Caribbean countries and triggered the largest evacuation in U.S. history. Gustav was formed on 25 August 2008 southeast of Haiti and rapidly strengthened into a tropical storm that afternoon and into a hurricane early next day. Its intensity remained at a category-2 level until landfall on the morning of 1 September 2008 in Louisiana. The \( D_e \) and IWP at the time of landfall are presented in Figs. 3a,b. Both retrievals consistently show the typical hurricane features, such as the eyewall and spiral rainfall bands associated with the large IWP of more than 2 kg m\(^{-2}\) and \( D_e \) close to 1.5 mm. The maximum \( D_e \) and IWP bands exist at the south section of the hurricane, where the most dangerous part of the hurricane is generally found because of the combined effect of the storm circulation and atmospheric flow (Powell 1990). The relatively calm eye and downdraft area between the spiral bands are also clearly shown. The distribution of \( D_e \) and IWP show a smooth transition along the coastal area. This illustrates that the cloud-base brightness temperatures at high-frequency channels are estimated fairly accurately using lower-frequency channels and the
Uncertainties from land and ocean emissivity discontinuities are reduced to minimal. Because the IWP is determined by not only $D_c$ but also the ratio of the scattering parameter and the normalized scattering parameter, a large $D_c$ does not necessarily mean a large IWP and vice versa. However, it should be pointed out that this pair of channels (91.655 and 150 GHz) is more sensitive to precipitating-size ice particles; smaller ice particles whose diameters are less than 100 $\mu$m might not be well detected. Therefore, the retrieved IWP may be lower than other in situ observations.

Shown in Fig. 3c is the superimposed plot of Geostationary Operational Environmental Satellite (GOES-12) visible channel image at 1415 UTC 1 September 2008 and the IWP retrieval demonstrated earlier. It is observed

Fig. 2. Regression relationship derived to estimate cloud-base brightness temperature at (a) 91.655-GHz V-POL, (b) 91.655-GHz H-POL, and (c) 150-GHz H-POL over land under clear sky.

Fig. 3. (a) SSMIS ice particle effective diameter, (b) SSMIS ice water path, and (c) GOES-12 imager and SSMIS ice water path superimposed plot for Hurricane Gustav at the time of landfall at 1430 UTC 1 Sep 2008.
that most of precipitation ice clouds exist near the hurricane eye although the clouds are distributed over a vast area in GOES visible channel image. Because of its high penetration depth, the microwave and millimeter-wave-length algorithm can identify the large particles and heavy rainfall locations from visible or infrared cloudy regions.

b. Midlatitude multicell storm

Presented in Figs. 4a,b are the retrieved $D_c$ and IWP of a midlatitude strong multicell storm associated with tornadoes and wind damage that happened on 4 April 2007. The multicell storm extended in the northeastern–southwestern direction with a distinct strong leading-edge thunderstorm line. There are at least three strong cells along the cold front line. Because the strong updrafts associated with the super cells favor the creation of hail, the moderate to larger ice particle effective diameter exists. However, there is a distinct distribution pattern in the IWP retrieval, compared to the $D_c$. This might be caused by the fixed bulk density used in the retrieval that may in reality deviate substantially in hail storm conditions. Meanwhile, the large ice particle effective diameter is not necessarily consistent with large IWP since it is also related to the concentrations of ice particles. Following the strong updraft zone in the leading edge, there is a large area of relatively stratified clouds with smaller ice particles. Figures 5a,b give the brightness temperature measurements at 19.35-, 91.655-, and 150-GHz frequencies and corresponding scattering parameters in the IWP retrieval along the cross line between A and B shown in Fig. 4b. The brightness temperature depressions are stronger at 150 GHz than that at 91.655 GHz. Multiple peaks of the scattering parameter indicate that several individual thunderstorms may exist and some may be associated with large hail. These updrafts are clearly associated with larger $D_c$ and higher IWP even though the magnitudes are smaller than the previous hurricane case.

For a qualitative comparison, Fig. 6 shows the IWP retrieved from MetOp-A in Microwave Surface and Precipitation Products System (MSPPS) (Ferraro et al. 2005). Please note that the local scan time of F-16 is about 2 h earlier than that of MetOp-A. From the figure, the multiple cell structure can be easily found. Because the northernmost area of the storm belt kept almost the same location for couple of hours a flooding warning probably was issued in Kentucky for this case. However, the IWP at storm centers derived from MetOp-A are smaller than that retrieved from F-16, which may be caused by both the dissipation of the system and the instrument field of view difference. It is also worthwhile to note that there are large areas in the north of Midwest flagged with nonretrievable areas, which are resolved in SSMIS retrievals by applying the different coefficients for different surface type estimated from SSMIS low-frequency channels.

c. Application of IWP in rainfall rate retrieval

The physical retrieval of rainfall rate over ocean and land by passive and active microwave instruments has been widely explored (Ferraro and Marks 1995; Kummerow et al. 2001; Liu and Fu 2001; Petty 1994, 1995; Wentz and Spencer 1998). To demonstrate the potential application of precipitation cold cloud IWP on the rainfall rate retrieval, a relationship between RR and IWP was derived using the cloud model results (Weng et al. 2003) as follows:

$$RR = r_0 + r_1IWP + r_2IWP^2.$$  (7)

In most precipitation systems, the rain layer extends above the freezing level and contains a mixture of water
and ice particles. The scattering at SSMIS high frequencies may also result from liquid-phase particles within the precipitation layer. Depending on the cloud microphysics and vertical structures, RR is retrieved using different sets of coefficients under different cloud types. By adopting the similar criteria used by the NOAA operational MSPPS (Ferraro et al. 2005), the convection index is calculated using three double-side-band channels at 183.31 ± 6.6 GHz, 183.31 ± 3 GHz, and 183.31 ± 1 GHz. This provides an alternative algorithm to retrieve the surface rainfall rate through IWP for the DMSP SSMIS applications.

Shown in Figs. 7a,b are rainfall rates of the multicell storm derived from IWP and from the heritage retrieval algorithm, which uses the low-frequency vertically polarized channels at 19.35 and 22.235 GHz (Ferraro and Marks 1995). It is found that both products well illustrate the heavy rainfall areas corresponding to the multiple cells in the storm. Both of the maximum rainfall rates exceed 20 mm h⁻¹. However, it should be noticed that the rainfall rates derived from IWP are generally smaller than those derived from the heritage algorithm especially over the stratified precipitation area and after the convection zone. It is shown that the new rainfall rate retrieval algorithm can successfully handle the coastal areas because of its use of high frequencies.

Figure 7c displays the National Weather Services (NWS) operational 1-h cumulative rainfall product derived from both radar reflectivity and gauge observations (Fulton et al. 1998) around the F-16 SSMIS scanning time. Because there are no instantaneous in
situ rain-rate observations available, NWS operational 1-h cumulative rainfall products were the only datasets for rainfall product retrieval validation when we conducted this study. For a clear illustration, the scale is set to the same as rainfall rate retrieval even though the units are different. Qualitatively, the best consistence can be found along the storm leading edge where both 1-h cumulative rainfall and rainfall rate derived from the ice water path have maximum values. However, in the area behind the leading convective zone, SSMIS-derived rainfall rate is larger than the ground-based product. This inconsistency is partially due to the higher sensitivity of SSMIS measurements to smaller ice particles. In this area, the ice-phase clouds could be anvil cirrus clouds that are nonprecipitating (Weng and Grody 2000). It is noteworthy that, unlike GOES series satellites, the polar orbital satellite provides an instant snapshot of the earth’s surface and atmospheric information so that it is not quite suitable for the analysis of cumulative parameters. It is a future mission to include the high-frequency microwave observations for a geostationary platform to improve the storm monitoring.

5. Error analysis

As pointed out earlier, several major uncertainties in ice particle bulk volume density, scattering parameters, and ice particle effective size may affect the quality of retrievals. Discussions of error sources and their impacts on the IWP/D_e retrieval using similar algorithms have been given in a number of studies (Weng and Grody 2000; Zhao and Weng 2002). For example, as indicated in Fig. 1b, small errors in the ratio of scattering parameters can lead to large errors in the particle effective diameter estimation. Therefore, it is important to find out the minimum detectable scattering parameter using brightness temperature difference at bottom and top of cloud.

FIG. 6. As in Fig. 4b, except retrieved from MetOp-A in MSPPS.

FIG. 7. (a) Rainfall rate derived from ice water path, (b) rainfall rate from NOAA heritage algorithm, and (c) hourly total rainfall derived from the radar reflectivity and gauge observations for the midlatitude multicell storms at 0130 UTC 4 Apr 2007.
Grody (1991) estimated that 7 K is the minimum brightness temperature difference at 89 GHz to reliably detect atmospheric scattering signature for global applications. Weng and Grody (2000) also illustrated the relationship between minimum detectable IWP/D_e and remote sensing frequencies and found that for convective ice clouds the minimum detectable ice particle size at 89 GHz is about 500 μm, while it is 300 μm at 150 GHz.

In this section, the particle effective diameter retrieval errors (caused by scattering parameters and bulk volume density) as well as ice water path retrieval errors (caused by scattering parameters, particle effective diameters, and bulk volume density) are briefly discussed following the similar methods described in earlier studies (Zhao and Weng 2002).

a. Error in effective size retrieval

The ice particle effective size is obtained through the regression relations between D_e and scattering parameter ratio r from Eq. (5) (Weng and Grody 2000; Zhao and Weng 2002). Therefore, the error of D_e retrieval errors can be derived as

\[ \frac{\Delta D_e}{D_e} = f_1 \frac{\Delta r}{r} + f_2 \frac{\Delta \rho_i}{\rho_i} \]  

where

\[ f_1 = \frac{a_1 r + 2a_1 r^2 + 3a_1 r^3}{a_0 + a_1 r + 2a_1 r^2 + 3a_1 r^3}, \]

and

\[ f_2 = \frac{a_0 \rho_i + a_1 \rho_i r + a_2 \rho_i r^2 + a_3 \rho_i r^3}{a_0 + a_1 r + 2a_1 r^2 + 3a_1 r^3}, \]

\[ a_x \rho_i \] represents the derivative of coefficient with respect to bulk volume density.

The error due to scattering parameter ratio can be determined from cloud-base temperature as

\[ \frac{\Delta r}{r} = g_1 \frac{\Delta T_{b91.655}(z_b, \mu)}{T_{b91.655}(z_b, \mu)} - g_2 \frac{\Delta T_{b150}(z_b, \mu)}{T_{b150}(z_b, \mu)}, \]

where

\[ g_1 = \frac{T_{b91.655}(z, \mu)}{T_{b91.655}(z_b, \mu)} \Omega_{91.655} \]

and

\[ g_2 = \frac{T_{b150}(z, \mu)}{T_{b150}(z_b, \mu)} \Omega_{150}, \]

The \( \Delta T_b \) represents the error of brightness temperature estimated at bottom of ice cloud and observed at top of clouds, respectively.

From Eq. (8), the uncertainties of the cloud-base brightness temperature estimations and bulk volume density affect the \( D_e \) retrieval quality. Figure 8a gives the estimation of the impact on the \( D_e \) retrieval by cloud-base temperature with a particle size as a parameter. It is found that the error in the cloud-base temperature introduces more errors for the smaller ice particle retrievals. However, the impact of cloud-base temperature error on \( D_e \) retrieval decreases with the particle size. A 5-K error in the cloud-base temperature can result in 4%–8% error for \( D_e \) retrievals. The sensitivity of the particle size error to the particle bulk volume density is shown in Fig. 8b. It is shown that \( D_e \) error is less sensitive to the density error for smaller ice particles but greatly increases with particle size.

b. Error in ice water path retrieval

Similarly, because IWP retrieval algorithm is a function of \( D_e \), the ice particle bulk volume density \( \rho_{ice} \), and the scattering parameter \( \Omega \), the retrieval error can be analyzed as follows:

\[ \frac{\Delta IWP}{IWP} = h_1 \frac{\Delta T_b(z_b, \mu)}{T_b(z_b, \mu)} + h_2 \frac{\Delta D_e}{D_e} + \frac{\Delta \rho_i}{\rho_i}, \]

where

\[ h_1 = \frac{T_b(z_b, \mu)}{T_b(z_b, \mu) - T_b(z_b, \mu)}, \]

and

\[ h_2 = 1 - \frac{D_e \Omega'_N}{\Omega'^N} \]

where \( \Omega'_N \) is its derivative with respect to diameter. It should be pointed out that the error relationship between IWP and bulk volume density or cloud-base brightness temperature is not necessary linear because of the relationship in Eq. (8). Also, the sensitivity relationship is further complicated by the relationship between \( \Omega_N \) and \( D_e \). Figures 8c–e present the IWP retrieval errors in relation to cloud-base temperature error, ice particle effective size, and bulk volume density. A 2% error in cloud-base temperature estimation can introduce about 10% of IWP retrieval error. The particle effective size error demonstrates some different trends, which is shown in Fig. 8d. The overestimated \( D_e \) actually makes the IWP retrieval underestimated when the particle diameter is relatively small. For a larger particle, IWP error increases with particle diameter.
6. Summary and conclusions

A cloud retrieval algorithm developed previously is refined and improved to retrieve the ice particle effective diameter and ice water path from the DMSP SSMIS. The high-resolution environmental unit measurements at 91.655 and 150 GHz are used as primary channels in the applications. The SSMIS is a conically scanning instrument at 53.2° of local zenith angle and provides more consistent and accurate measurements from
For a single cloud layer, the upwelling and downwelling radiances are nearly independent of cloud-layer temperature and are directly linked to the scattering parameter $\Omega$, which can be determined by the brightness temperatures at the bottom and top of the ice cloud. The ratio of the scattering parameters measured at 91.655 GHz to that at 150 GHz is directly used to estimate the ice particle effective diameter $D_e$ when ice particle is near millimeter size. The relationship between particle effective diameter and scattering parameter is established, assuming gamma size distribution and spherical ice particles. The IWP is retrieved from the particle effective diameter and scattering parameter with a known ice particle bulk density. Previous studies showed that ice particle habit plays an important role in the estimate of scattering properties. The implementation of a nonspherical ice particle scattering database (Hong et al. 2009; Liu 2008) may help to improve the retrieval quality. However, the lack of dual-polarization information at higher-frequency channels on SSMIS makes the determination of particle shape impacts very difficult.

Several major sources of errors are identified and analyzed. The uncertainties of the cloud-base brightness temperature using the lower-frequency channels may contribute up to 10% of retrieval errors in the ice particle effective diameter. The particle effective diameter retrieval is sensitive to the exponential parameter in the gamma size distribution. The uncertainty in IWP retrieval is primarily associated with the errors of estimated cloud-base temperature and particle effective diameter. Specifically, an overestimated particle effective diameter can lead to an underestimated IWP for smaller particles.

In the calculation of scattering parameter, the cloud-base brightness temperatures at 91- and 150-GHz channels are obtained from empirical estimates from low-frequency channels assuming those channels have no impacts of ice particles in the clouds. However, the reality is that the accuracy of such estimating method is probably degraded by the scattering effects from melting and liquid-phase particles that were not included in the training dataset. In the heavy rainfall event the scattering from large liquid particles can be also significant. Additional corrections are required to improve the cloud-base brightness temperature estimate. This is also one limitation of the current approach.

It is also noteworthy that the application of a two-stream radiative transfer model could introduce error in the estimate of scattering properties. The obvious advantage of a two-stream model is that the upward and downward intensities can be solved analytically through the replacement of phase function by a summation over a finite number of quadrature points. However, a four-stream approximation can better describe the multiple-scattering feature but needs much more extra computation time. Because the SSMIS view angle at 53.2° is close to the first Gaussian quadrature points, $\mu = \pm 1/\sqrt{3}$, a two-stream model works well for our study. The algorithm is tested under several severe weather conditions of hurricane and multicell storms. The derived rainfall rates are also analyzed and show consistent results to those retrieved by the NOAA heritage rate algorithm using the measurements at lower microwave frequencies. The rainfall rate derived from this algorithm shows some consistency with NWS operational 1-h cumulative rainfall products in terms of precipitation areas and intensity, particularly over heavy rainfall regions. NWS products are derived synthetically from both radar reflectivity and gauge observations. In our future studies, more statistical analysis will be provided on retrieval accuracy. The new algorithm can also effectively reduce uncertainties in the coastal areas where the heritage algorithm has more errors and large discontinuity because of the large emissivity contrast.

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