Intense Tropical Thunderstorms Detected by the Special Sensor Microwave Imager/Sounder

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Abstract—The 150-GHz microwave window channel and the three water vapor channels, 183.3 ± 7 , 183.3 ± 3 , and 183.3 ± 1 GHz of the Defense Meteorological Satellite Program's (DMSP) Special Sensor Microwave Imager/Sounder (SSMIS) are used to detect intense thunderstorms over the tropics (30° S– 30° N). This application utilizes the advantages of conical scanning and high surface horizontal resolution of the SSMIS compared to the same measurements made with cross-track scanning radiometers. The criteria to detect intense tropical thunderstorms are derived by the combination of the brightness temperature differences between the three water vapor channels and brightness temperatures at the four frequencies. One year of SSMIS data (December 2005–November 2006) is surveyed for intense tropical thunderstorms. The most intense tropical thunderstorms are predominant over land and are mainly concentrated over Central and South America, tropical west Africa, and northern Australia. Over most regions these very intense tropical thunderstorms have a strong regional dependence and a pronounced seasonal migration.

Index Terms—Clouds, microwave measurements, microwave radiometry, remote sensing, Special Sensor Microwave Imager/Sounder (SSMIS), thunderstorm.

I. INTRODUCTION

TROPICAL thunderstorms consist of the most complex meteorological events. They play a major role in the global climate by transporting heat, moisture, and momentum from the lower to the upper troposphere [1]–[4]. They also influence the Earth's radiation budget by interacting with incoming shortwave and outgoing longwave radiations [5]–[7]. Additionally, intense thunderstorms can cause huge financial losses (e.g., [8]).

For over two decades, satellite observations providing high spatial and temporal resolution have been extensively used to detect tropical thunderstorms. These techniques include both active and passive measurements from sensors ranging from the visible over the infrared to the submillimeter and millimeter region of the electromagnetic spectrum (e.g., [9]–[18]).

Satellite-observed infrared and visible radiances are sensitive only to the top parts of clouds. The infrared brightness temperatures become saturated when the cloud's optical thickness is near 10 [19]. Because of this limitation, it is difficult to distinguish thunderstorms from their anvil cirrus shields that are tightly connected with thunderstorm systems (e.g., [18], [20], and [21]).

Because of the microwave frequencies' unique capability to penetrate clouds, they have been used to detect convective storms since the 1980s. Wilheit *et al.* [22] presented the aircraft measurements of microwave brightness temperatures at 19, 92, and 183 GHz, respectively, over tropical storms. Spencer *et al.* [9] examined the 37-GHz brightness temperatures over heavy thunderstorms observed over land by the Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR). Since the SMMR, several satellite microwave sensors have been carried on satellites to detect clouds and precipitation, including the Defense Meteorological Satellites Program (DMSP) Special Sensor Microwave/Imager (SSM/I), the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), and the Advanced Microwave Scanning Radiometer–Earth Observing System (AMSR-E). However, microwave radiances at frequencies less than 90 GHz are influenced by the surface emissivity [13].

Radiances at high microwave frequencies covering 90–190 GHz have been observed by the DMSP Special Sensor Microwave Moisture (SSM/T2), the Advanced Microwave Sounding Unit-B (AMSU-B) aboard the National Oceanic and Atmospheric Administration (NOAA) satellite series, and the AMSU Humidity Sounder for Brazil (HSB) aboard the Aqua spacecraft. These high microwave frequencies are sensitive to scattering by the frozen hydrometeors in convective systems; therefore they have been employed extensively to study precipitation via detecting frozen hydrometeors (e.g., [4], [6], [16], [20], and [23]–[28]). Hong *et al.* [20] investigated the sensitivity of microwave brightness temperatures at the frequencies of 89–190 GHz to surface emissivities and hydrometeors in a tropical deep convective cloud system.

The 89-GHz window channel has an apparent dependence on surface emissivity. Under tropical conditions, the 150-GHz window channel is nearly independent of surface emissivity, and the water vapor channels around 183.3 GHz are completely independent. Based on the advantage of independence of surface emissivity for the water vapor channels around 183.3 GHz and their different sensitivities to frozen hydrometeors in convective clouds, the 183.3 ± 7 -, 183.3 ± 3 -, and 183.3 ± 1 -GHz channels of the AMSU-B have been used to detect tropical deep convective clouds and convective overshooting [17] and convective strength [16].

All aforementioned microwave sensors with 183.3-GHz channels use a cross-track scanning scheme so that any method to detect convective systems must consider the influence of variations of the satellite incident angle [17]. The first DMSP Special Sensor Microwave Imager/Sounder (SSMIS) was launched on October 18, 2003. The SSMIS is a passive microwave

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TABLE I
SPECIFICATIONS OF THE SSMIS CHANNELS USED IN THIS STUDY

Center Frequencies (GHz)	Half Bandwidth (MHz)	Polarization	Instantaneous Field of View	Sample Spacing (km $\times$ km)	NEDT* at 305 K (K)
150.0 $\pm$ 1.25	1640	H	14 $\times$ 13	13 $\times$ 16	0.53
183.31 $\pm$ 7.0	1530	H	14 $\times$ 13	13 $\times$ 16	0.56
183.31 $\pm$ 3.0	1020	H	14 $\times$ 13	13 $\times$ 16	0.39
183.31 $\pm$ 1.0	510	H	14 $\times$ 13	13 $\times$ 16	0.38

* NEDT is the noise equivalent temperature difference.

radiometer scanning conically at a 53.1° Earth incidence angle. It includes 24 channels covering the wide frequency range of 19–183 GHz, thus combining the capabilities of the SSM/I, SSM/T-1, SSM/T-2, AMSU-A, and AMSU-B on a single platform and under a unified scanning system with a constant incidence angle. This avoids the errors caused by aligning scenes from separately cross-track and conically scanning instruments and by incidence angle variations. The channels above 90 GHz of the SSMIS have a horizontal resolution of 14 $\times$ 13 km, which is higher than that of the SSM/T2 (resolution 48 km at nadir) and the AMSU-B (20 $\times$ 16 km at nadir and 64 $\times$ 52 km at edge scanning [29]). Thus, the SSMIS is the first instrument to provide global observations at microwave frequencies between 150 and 190 GHz at a high resolution and a constant incidence angle.

Zipser *et al.* [18] have used the observation technique to look for small percentages of extreme values to identify extreme thunderstorms from microwave observations at 37 and 85 GHz, respectively. Profiting from the advantages of conical scanning and high resolution of the SSMIS, this paper extends the technique of looking at extreme values to the high frequencies up to 190 GHz to detect intense thunderstorms over the tropics (30° S–30° N). The data and method are introduced in Section II. Section III presents the results, including the distributions and seasonal variations of intense tropical thunderstorms. Finally, the conclusions are presented in Section IV.

II. DATA AND METHOD

One year of the Level 1C data of the SSMIS from December 2005 to November 2006 obtained from the Precipitation Research Group at Colorado State University (<http://mrain.atmos.colostate.edu/LEVEL1C/>) [30] were used in this study. The dataset is based on the Sensor Data Record data produced by the Navy's Fleet Numerical Meteorology and Oceanography Center (FNMOC). The Level 1C calibration for the SSMIS was unchanged from the 1B data produced by the FNMOC. Only 11 channels of the total 24 channels most relevant to remotely sensing precipitation are contained in the Level 1C dataset. To avoid the influence of the surface, the channels at 150, 183.1 $\pm$ 7, 183.1 $\pm$ 3, and 183.1 $\pm$ 1 GHz, respectively, which are not sensitive to surface emissivity under tropical weather conditions with strong storms [20], are used to detect tropical thunderstorms. The channel specifications are shown in Table I [31].

The channels at 150 and 183.3 GHz, respectively, have been used to detect convective clouds [12], [16], [17], [21] or to screen out convective clouds before water vapor retrieval [32]–[35]. The methods for detecting convective clouds from

Hong *et al.* [17] and Ferraro *et al.* [16] are based on the brightness temperature differences between the channels at 183.3 $\pm$ 1 and 183.3 $\pm$ 7 GHz (ΔT_{17}), 183.3 $\pm$ 1 and 183.3 $\pm$ 3 GHz (ΔT_{13}), and 183.3 $\pm$ 3 and 183.3 $\pm$ 7 (ΔT_{37}), respectively. Additionally, in the method of Hong *et al.* [17], a threshold value of 235 K for a 183.3 $\pm$ 1-GHz channel has been used to identify cold clouds associated with precipitation.

Cecil *et al.* [36] and Zipser *et al.* [18] identified intense thunderstorms using low brightness temperatures at 37 and 85 GHz, respectively. They documented that extremely intense storms are associated with lower brightness temperatures, caused by the scattering by the larger cloud ice particles (> 0.1 mm). In this study, the method of Hong *et al.* [17] based on the brightness temperature at 183.3 $\pm$ 1 GHz and the brightness temperature differences ΔT_{17} , ΔT_{13} , and ΔT_{37} is adapted to detect intense tropical thunderstorms from the SSMIS data at 150 GHz and higher frequencies. The higher horizontal resolution of the channels between 150 and 190 GHz of the SSMIS provides an opportunity to detect small cloud systems that may be missed using previous sensors. Moreover, the higher frequencies used here make the method more sensitive to smaller particles than can be detected by the brightness temperature depression at 37 and 85 GHz, respectively. The criteria to detect intense tropical thunderstorms are

$$\Delta T_{17} > \Delta T_{13} > 0 \text{ K} \quad \Delta T_{17} > \Delta T_{37} > 0 \text{ K} \quad (1)$$

and

$$T_f \leq T_{c,f} \quad (2)$$

where T_f is the brightness temperature at the frequency f , which can be one of the four channels at 150, 183.3 $\pm$ 7, 183.3 $\pm$ 3, and 183.3 $\pm$ 1 GHz, respectively. $T_{c,f}$ is the brightness temperature threshold for frequency f that is determined by the method of Zipser *et al.* [18].

Criterion (1) recognizes deep convective clouds according to the method of Hong *et al.* [17]. The basic idea can be explained intuitively as follows. If we denote the brightness temperature of the channel at 183 $\pm$ X GHz as T_X ($X = 1, 3, \text{ or } 7$), then under cloud-free conditions we expect

$$T_7 > T_3 > T_1 \quad (3)$$

because the nearer the frequency is to the center of the water vapor absorption line at 183 GHz, the higher the atmospheric opacity, and from the higher (thus colder) layers of the atmosphere stems the received radiation. In the presence of deep convective clouds, however, the radiation from the deeper

Fig. 1. Cumulative distribution functions (CDF_{BT}) of brightness temperatures for tropical deep convective clouds detected from (1) over 30° S– 30° N during the period from December 2005 to November 2006. The upper thresholds for (2) are shown for the channels at (a) 150, (b) 183.3 ± 7 , (c) 183.3 ± 3 , and (d) 183.3 ± 1 GHz.

TABLE II
THRESHOLD BRIGHTNESS TEMPERATURES $T_{c,f}$ AT SPECIFIED
FREQUENCIES AND CUMULATIVE DISTRIBUTION FUNCTIONS (CDF_{BT})

Frequencies (GHz)	$T_{c,f}$ (K)			
	$CDF_{BT} < 1\%$	$CDF_{BT} < 0.1\%$	$CDF_{BT} < 0.01\%$	$CDF_{BT} < 0.001\%$
150.0	135.4	113.2	96.7	86.3
183.3 ± 7	136.0	115.3	100.4	89.1
183.3 ± 3	146.1	121.1	104.3	92.9
183.3 ± 1	166.1	137.0	116.8	102.9

layers experiences more scattering than the radiation from the higher layers, and (3) reverses to

$$T_7 < T_3 < T_1$$

which directly leads to (1).

The cumulative brightness temperature distribution functions (CDF_{BT}) for tropical deep convective clouds detected using (1) with different $T_{c,f}$ values for each frequency are shown in Fig. 1. Following the method of Zipser *et al.* [18], the CDF_{BT} values less than 1%, 0.1%, 0.01%, and 0.001%, respectively, are used to categorize intense thunderstorms from detected storms by the SSMIS. The values of $T_{c,f}$ at each frequency for four types of thunderstorms with $CDF_{BT} < 1\%$, 0.1%, 0.01%, respectively, and 0.001% are listed in Table II. They generally increase with the CDF_{BT} threshold value (columns) and atmospheric opacity of the channels (rows). Thus, (2) provides a statistical classification of the deep convective clouds recognized by (1). It selects percentages of clouds of lowest brightness temperatures. Low brightness temperatures can be caused by cold targets (atmosphere and surface) or by particles

in the radiation path to the sensor. Criterion (1) enforces the latter. That means the thresholds of (2) select pixels at those places where the convective clouds at the levels near the peak of the weighting function and above reduce the brightness temperature to the lower values of this channel according to the four CDF_{BT} threshold values 1%, 0.1%, 0.01%, and 0.001%, respectively.

III. RESULTS

Fig. 2 shows the geographical distributions of intense tropical thunderstorms over 30° S– 30° N during the period from December 2005 to November 2006. Criterion (2), with different brightness temperature thresholds shown in Table II for the four frequencies, is combined with (1) to identify the four types of intense thunderstorms corresponding to the four CDF_{BT} intervals $1\% > CDF_{BT} > 0.1\%$, $0.1\% > CDF_{BT} > 0.01\%$, $0.01\% > CDF_{BT} > 0.001\%$, and $CDF_{BT} < 0.001\%$, respectively.

The intense tropical thunderstorms detected with $T_{c,f}$ at 150, 183.3 ± 7 , 183.3 ± 3 , and 183.3 ± 1 GHz, respectively, show similar patterns [Fig. 2(a)–(d)] with the exception of some intense thunderstorms around the coasts of South America [Fig. 2(b)] which are detected at 183.3 ± 7 GHz. The major concentrations of the intense tropical thunderstorms are found over the Intertropical Convergence Zone (ITCZ), the South Pacific Convergence Zone (SPCZ), tropical Africa, the Indian Ocean, the Indonesia Maritime Continent, southern Asia, northern Australia, and tropical and South America. A weak double ITCZ shown by intense thunderstorms is found

Fig. 2. Geographical distributions of the intense tropical thunderstorms over 30° S–30° N during the period from December 2005 to November 2006. Four frequencies at (a) 150, (b) 183.3 ± 7 , (c) 183.3 ± 3 , and (d) 183.3 ± 1 GHz are used. The four intensity types of thunderstorms with CDF_{BT} intervals $1.0\% > CDF_{BT} > 0.1\%$, $0.1\% > CDF_{BT} > 0.01\%$, $0.01\% > CDF_{BT} > 0.001\%$, and $CDF_{BT} < 0.001\%$, respectively, are marked with the same upper thresholds in Fig. 1. Corresponding brightness temperatures are listed in Table II.

Fig. 3. (a) Geographical distributions of mean flash rates (fl/h) from TRMM LIS measurements in $0.5^\circ \times 0.5^\circ$ (longitude, latitude) over 30°S – 30°N from December 2005 to November 2006. (b) Locations of the intense thunderstorms with flash rate CDF_{LIS} intervals $1.0\% > CDF_{LIS} > 0.1\%$, $0.1\% > CDF_{LIS} > 0.01\%$, $0.01\% > CDF_{LIS} > 0.001\%$, and $CDF_{LIS} < 0.001\%$, respectively.

around 5°S over the eastern Pacific. The features of the intense thunderstorms are consistent with those of tropical deep convective clouds and convective overshooting [3], [4], [17]–[19], [37], [38].

The intense thunderstorms with $0.001\% < CDF_{BT} < 0.01\%$ (yellow in Fig. 2, probability density function = 0.009%) are concentrated over the region of 10°S – 15°N in west Africa, the region over and around Madagascar, South America, the coastal regions of Central America and Mexico, southern Asia, the Bay of Bengal, the Maritime Continent, and northern Australia. Over the Indian Ocean, the SPCZ, and some regions around the ITCZ, there are a few scattered distributions of intense thunderstorms. The most intense thunderstorms with $CDF_{BT} < 0.001\%$ (red) are predominant over land, with few exceptions over the South Atlantic for those detected by (2) at $183.3 \pm 7\text{ GHz}$. Their preference over land has been found to be consistent with precipitation, convective clouds, and thunderstorms from independent measurements (e.g., [3], [4], [13], [17], [18], [36], [39], and [40]). Moreover, the intense thunderstorms detected by the SSMIS are mainly concentrated over Central and South America, tropical west Africa, and northern Australia.

The intense thunderstorms detected by the SSMIS are compared to those detected from the TRMM Lightning Imaging Sensor (LIS), which have been used to study tropical thunderstorms (e.g., [13], [18], and [36]). One year of TRMM LIS version 4 data from December 2005 to November 2006 were used to calculate the lightning flash rate and to identify the intense thunderstorm. Mean flash rates [flashes per hour, (fl/h)] were calculated by the ratio of the flash counts to the effective view times [41] in $0.5^\circ \times 0.5^\circ$ (longitude, latitude) boxes [Fig. 3(a)]. The lightning flash rate has been used to categorize precipitation features (e.g., [13], [18], and [36]). Cecil *et al.* [36] found that 2.4% of the detected precipitation features using their method had lightning from December 1997 to November 2000. The precipitation features with lightning that were associated with $1.0\% > CDF_{LIS} > 0.1\%$, $0.1\% > CDF_{LIS} > 0.01\%$, $0.01\% > CDF_{LIS} > 0.001\%$, and $CDF_{LIS} < 0.001\%$, respectively, of the total precipitation features have been identified as four categories of intense thunderstorms [18], [36]. These categories are used in this study. The lightning flash rates were calculated in $0.1^\circ \times 0.1^\circ$ boxes by dividing the flash counts by the effective view time, however, which were derived

from the $0.5^\circ \times 0.5^\circ$ view times. The locations of the four categories of intense thunderstorms are shown in Fig. 3(b).

The geographical distributions and patterns of intense thunderstorms from the SSMIS (Fig. 2) are in agreement with those from the LIS (Fig. 3), which are also consistent with the results from Zipser *et al.* [18]. However, the intense thunderstorms with $CDF_{LIS} < 0.001\%$ from the LIS tend to cover more regions such as around southern Florida and Cuba, and south of China [Fig. 3(b)]. Also, the different temporal sampling schemes of the SSMIS and TRMM could result in some differences in distributions of thunderstorms detected by them. The sun-synchronous SSMIS crosses the equator at about 08:13 and 20:13 local time (<http://www.wmo.ch/web/sat/POLpresent.html>), whereas the LIS can catch the diurnal variations of intense thunderstorms because TRMM samples the diurnal cycle for about 46 days when it returns to a given position at a given local time [42]. The strong influence of the diurnal cycle sampling strategy is also shown by the land–ocean contrast of the intense thunderstorms from the SSMIS and LIS. Strong convective clouds frequently occur in the afternoon over land, whereas in the morning the clouds occur over the ocean (e.g., [3], [21], and [42]). Thus, the intense thunderstorms from the LIS show much stronger land–ocean contrast than those from the SSMIS.

Seasonal variations of the two most intense thunderstorm types (with CDF_{BT} values $< 0.01\%$ and $< 0.001\%$ shown in Fig. 2 in yellow and red) are illustrated in Fig. 4. The months December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON) are denoted as winter, spring, summer, and fall, respectively, in the Northern Hemisphere. Again, the extremely intense thunderstorms detected with $T_{c,f}$ at 150, 183.3 ± 7 , 183.3 ± 3 , and 183.3 ± 1 GHz, respectively [Fig. 4(a)–(d)] show very similar seasonal variations, which have also been found by independent measurements [4], [18], [36], [39], [40]. The intense thunderstorms already observed in Fig. 2(b) only at 183.3 ± 7 GHz off the coast of South America can now be attributed to the months JJA.

It is evident that the occurrence of extremely intense thunderstorms has a strong seasonal variation over most regions. Those over Central America are dominant in JJA and SON. Those over South America are dominant in DJF and MAM and also with some exceptions over the Amazon, Paraguay, and northern Argentina in JJA and SON [Fig. 4(a), (c) and (d)]. Additional exceptions include some intense thunderstorms around the coasts of South America [Fig. 4(b)] in JJA, which are detected with $T_{c,f}$ at 183.3 ± 7 GHz. Similar to America, Africa also shows a pronounced seasonal migration. Extremely intense thunderstorms over southern Africa with latitudes greater than 5°S occur only in DJF and MAM. Those over northern Africa with latitudes greater than 10°N usually occur only in JJA and SON. In western Africa between 5°S and 10°N , extremely intense thunderstorms occur all in four seasons, although they tend to occur more frequently in JJA and SON toward the northern regions and in DJF and MAM toward the southern regions. Over Australia, the Indian Ocean, and the Pacific with latitudes greater than 10°S , extremely intense thunderstorms occur only in DJF and MAM. Extremely

intense thunderstorms over southern India, the Arabian Sea, and the Bay of Bengal are dominant in DJF and MAM. Those over the regions with latitudes greater than 10°N over Southeast Asia and the West Pacific occur primarily in JJA and SON. Extremely intense thunderstorms over northern India and Bangladesh predominantly occur in JJA and, with some exceptions, in MAM. Over the Maritime Continent, extremely intense thunderstorms occur in all four seasons but less in JJA.

To investigate the occurrence frequencies of intense tropical thunderstorms, the fractions of thunderstorms with $CDF_{BT} < 1\%$, 0.1% , and 0.01% , respectively, are calculated as the ratio of the counts flagged as intense thunderstorms to the total SSMIS observations within $2^\circ \times 2^\circ$ (latitude, longitude) boxes over the tropics from December 2005 to November 2006. Both the geographical distributions (Fig. 2) and the seasonal variations (Fig. 3) of intense tropical thunderstorms show similar patterns if any of the four frequencies 150 , 183.3 ± 7 , 183.3 ± 3 , and 183.3 ± 1 GHz, respectively, are used. Because the 183.3 ± 1 -GHz observations were used to derive information for precipitation and clouds [25], [33]–[35], we also use the 183.3 ± 1 -GHz data here to study the fractions of intense thunderstorms. The total number of samples and fractions of intense thunderstorms with $CDF_{BT} < 1\%$, $< 0.1\%$, and $< 0.01\%$ are shown in Fig. 5(b)–(d), respectively.

As Fig. 5(a) shows, the number of samples in the Southern Hemisphere is generally slightly larger than those in the Northern Hemisphere. Over South America, the Caribbean Sea, and partial regions of Southeast Asia and the Maritime Continent, the number of samples is much lower than other regions. Among them, those over the Amazon have the lowest values. The average number of samples in each grid box was 173–275 with a standard deviation of 5539 during the study period.

Intense thunderstorms with $CDF_{BT} < 1\%$ [Fig. 5(b)] frequently occur over the regions between 0° and 10°N of Central America, the regions between 5°S and 15°N of west Africa, partial regions of the ITCZ and SPCZ, the western Bay of Bengal and its nearby coasts, and northern Australia. The distributions of fractions of intense thunderstorms with $CDF_{BT} < 0.1\%$ [Fig. 5(c)] are, in general, consistent with those of intense thunderstorms with $CDF_{BT} < 1\%$. The intense thunderstorms with $CDF_{BT} < 0.1\%$ are more frequent over land, however. The high fractions clearly shown over the ITCZ and SPCZ in Fig. 5(b) are much weaker for intense thunderstorms with $CDF_{BT} < 0.1\%$ shown in Fig. 5(c). This feature is more pronounced for the extremely intense thunderstorms with $CDF_{BT} < 0.01\%$ [Fig. 5(d)]. The fractions of extremely intense thunderstorms with $CDF_{BT} < 0.01\%$ are associated with the distribution densities shown in Fig. 2(b); the more concentrated the distributions, the higher the fractions of the intense thunderstorms. The higher fractions of the most intense thunderstorms with $CDF_{BT} < 0.01\%$ are mainly over Colombia, South America, tropical west Africa, and northern Australia. In conclusion, we find that the patterns of Fig. 4(b)–(d) are similar to those of the different colors of Fig. 2. However, Fig. 4(b)–(d) allows an estimate of the absolute frequency of the extremely intense thunderstorms in each of the $2^\circ \times 2^\circ$ grid cells.

Fig. 4. Seasonal distributions of the intense thunderstorms with $CDF_{BT} < 0.01\%$ detected by the four channels at frequencies (a) 150, (b) 183.3 ± 7 , (c) 183.3 ± 3 , and (d) 183.3 ± 1 GHz.

IV. CONCLUSION

The SSMIS aboard DMSP F16 is the first conically scanning sensor covering high microwave frequencies at 150–190 GHz, in contrast to the previous sensors with similar frequencies,

such as the SSM/T2, AMSU-B, and HSB, which employ a cross-track scanning scheme. The conical scanning allows having constant retrieval procedures, avoiding adjustments to the viewing angles, and thereby avoiding potential adjustment

Fig. 5. (a) Number of samples of SSMIS measurements and fractions of intense tropical thunderstorms with (b) $CDF_{BT} < 1.0\%$, (c) $CDF_{BT} < 0.1\%$, and (d) $CDF_{BT} < 0.01\%$.

errors. Another advantage of SSMIS is the improvement of the horizontal resolution with respect to the SSM/T2, AMSU-B, and HSB.

The method for detecting tropical deep convective clouds [17] on the basis of the brightness temperature differences

between the channels at 183.3 ± 1 and 183.3 ± 7 , 183.3 ± 1 and 183.3 ± 3 , and 183.3 ± 3 and 183.3 ± 7 GHz, respectively, is combined with the brightness temperatures at 150, 183.3 ± 7 , 183.3 ± 3 , and 183.3 ± 1 GHz, respectively, to develop criteria to detect intense tropical thunderstorms. The

tropical deep convective clouds with cumulative distribution function (CDF_{BT}) values $< 1\%$, $< 0.1\%$, $< 0.01\%$, and $< 0.001\%$, respectively, were identified as four types of tropical thunderstorms of increasing intensity. Brightness temperature thresholds $T_{c,f}$ corresponding to these CDF_{BT} thresholds were determined from the dataset.

The intense tropical thunderstorms over 30°S – 30°N were surveyed using one year of SSMIS data from December 2005 to November 2006. The intense tropical thunderstorms detected with thresholds $T_{c,f}$ at 150 , 183.3 ± 7 , 183.3 ± 3 , and 183.3 ± 1 GHz, respectively, show similar patterns [Fig. 2(a)–(d)]. The major concentrations of the intense tropical thunderstorms with CDF_{BT} of 1% and 0.1% were found over the Intertropical Convergence Zone (ITCZ), the South Pacific Convergence Zone (SPCZ), tropical Africa, the Indian Ocean, the Indonesia Maritime Continent, southern Asia, northern Australia, and tropical and South America. The extremely intense tropical thunderstorms with $CDF_{BT} < 0.01\%$ and $< 0.001\%$ are predominant over land. These most intense tropical thunderstorms are mainly concentrated over Central and South America, tropical west Africa, and northern Australia (Fig. 2). The geographical distributions and patterns of intense thunderstorms from the SSMIS are in agreement with those from the LIS. Regional differences between the intense thunderstorms from the SSMIS and LIS are attributed to the sampling schemes of DMSP F16 (sun synchronous) and TRMM (not sun synchronous). However, sampling of the diurnal cycle with SSMIS will be extended by DMSP F17 launched on November 4, 2006 and the planned DMSP satellites also equipped with SSMIS instruments (<http://www.wmo.ch/web/sat/POLfuture.html>).

The seasonal variations of the intense tropical thunderstorms with a CDF_{BT} of 0.01% were investigated (Fig. 4). The occurrence of intense tropical thunderstorms has a strong regional dependence over most regions. Furthermore, these extremely intense tropical thunderstorms have a pronounced seasonal migration. The fractions of intense tropical thunderstorms with a CDF_{BT} of 1% and 0.1% , respectively, have similar patterns [Fig. 5(b) and (c)]. They are frequent over the regions between 0° and 10°N of Central America, the regions between 5°S and 15°N of west Africa, partial regions of the ITCZ and SPCZ, the western Bay of Bengal and its nearby coasts, and northern Australia. The tendency for extremely intense tropical thunderstorms to be over land is found for those with a CDF_{BT} of 0.1% , particularly for those with a CDF_{BT} of 0.01% [Fig. 5(d)]. Those with a CDF_{BT} of 0.01% are mainly over Colombia, South America, tropical west Africa, and northern Australia.

The convective clouds observed from satellites have been used to evaluate general circulation models (e.g., [3], [43], and [44]). Only a few of them have used clouds detected from microwave measurements, however [45]. Because the cloud properties detected from space were sensitive to the retrieval algorithms and sensors used [46], [47], it is important to evaluate the representation of clouds in general models using measurements from different sensors and retrieval methods [21]. The detected intense thunderstorms with different intensities from the SSMIS are complementary to those detected from other sensors, such as infrared sensor or cloud radar, and may

evaluate the representations of their geographical and seasonal distributions in general circulation models.

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