NOTES AND CORRESPONDENCE

Passive Microwave Brightness Temperatures as Proxies for Hailstorms

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ABSTRACT

The Tropical Rainfall Measuring Mission (TRMM) satellite has been used to infer distributions of intense thunderstorms. Besides the lightning measurements from TRMM, the radar reflectivities and passive microwave brightness temperatures have been used as proxies for convective vigor. This is based on large graupel or hail lofted by strong updrafts being the cause of high–radar reflectivity values aloft and extremely low brightness temperatures. This paper seeks to empirically confirm that extremely low brightness temperatures are often accompanied by large hail at the surface. The three frequencies examined (85, 37, and 19 GHz) all show an increasing likelihood of hail reports with decreasing brightness temperature. Quantification is limited by the sparsity of hail reports. Hail reports are common when brightness temperatures are below 70 K at 85 GHz, 180 K at 37 GHz, or 230 K at 19 GHz.

1. Introduction

Satellite-borne passive microwave radiometers record brightness temperature depressions due to the scattering of upwelling radiation by large ice hydrometeors (graupel, hail). Spencer et al. (1983, 1987) and Spencer and Santek (1985) examined satellite measurements of 37-GHz brightness temperature as an indicator of intense convection and severe thunderstorms. In particular, Spencer et al. (1987) matched storm brightness temperatures to U.S. severe weather reports and Spencer and Santek (1985) mapped low–brightness temperature storm events globally. More recently, Cecil et al. (2005) and Zipser et al. (2006) have used Tropical Rainfall Measuring Mission (TRMM) measurements of several parameters as proxies to examine intense thunderstorms. These parameters include minimum 85- and 37-GHz brightness temperatures, maximum radar reflectivity at certain altitudes and maximum heights attained by certain reflectivities, lightning flash rates, and other measures. This paper queries the U.S. severe storm database to quantitatively link TRMM Microwave Imager (TMI) measurements to the occurrence of large hail.

TMI measurements from 1998 to 2006 are used in this study. For satellite overpasses of the central and eastern United States (30.5°–38°N, 105°–81.5°W), local minima in the brightness temperature fields are identified. The TMI domain extends to about 38°N. The other spatial bounds were chosen to avoid ocean or the Rocky Mountains, where spotter reports of severe weather are unlikely and contamination of the microwave signal by surface snow cover is more often an issue. A space and time range is searched around each local minimum, recording whether there is a large (at least 0.75 in. or ~20 mm) hail report and recording the largest diameter if a hail report is found.

The purpose of this paper is to provide an observational basis for diagnosing hailstorms globally based on satellite imagery. It is recognized that a hailstone *might* be more likely to melt before reaching the surface in tropical Africa than in the United States, for example, although terminal velocities for large hail and ground truth hail reports during hot weather both argue against this having much effect. Furthermore, regional or regime-dependent variabilities can lead to similar brightness temperatures coming from different hydrometeor profiles. Nonetheless, this provides an approach for objective climatologies that do not rely on surface reports or spotter networks, which vary greatly from region to region.

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2. Data and methods

Brightness temperature data are taken from the TRMM satellite, described by Kummerow et al. (1998). For the 85- and 37-GHz channels, a polarization corrected temperature (PCT) is used to avoid mistaking water surfaces for storms. In the storms themselves, the PCT and the horizontally and vertically polarized channels are all nearly equal. The 19-GHz horizontally polarized (H) channel is used, because a polarization corrected temperature that effectively removes the land–water contrast is not available. A parallax adjustment is applied to the TMI data to account for the radiometric signal coming from an ice region aloft.

The hail reports are taken from the archive at the Storm Prediction Center, based on storm spotter reports as documented in the National Climatic Data Center publication *Storm Data*. While there is some uncertainty associated with the precise times and locations from these spotter reports, the much greater uncertainty concerns hailstorm events that were not reported. Several metropolitan areas are easily identifiable in a basic map of all hail reports, demonstrating that hail is more likely to be reported in more populated areas. Even after filtering out multiple reports within an hour of each other (potentially coming from the same storm), cities such as Dodge City, Kansas, Little Rock, Arkansas, and Lubbock, Texas, have a factor of 2–3 more hail reports than the adjacent rural areas. Dobur (2005) examined severe weather reports and severe thunderstorm warning verification in northern and central Georgia. The more urban counties had more severe weather reports (per unit area), and the more rural counties had greater false-alarm rates for the warnings. The lack of a report does not mean hail did not fall to the surface. Instead it means that no one reported it if it did fall, or reports were not continuous throughout the hail swath. The overall percentage of ‘‘missed’’ hailstorms cannot be known, and trying to estimate it from the storm reports is beyond the scope of this paper. This uncertainty, however, is one reason that an objective satellite-based climatology is desirable.

Because TRMM is in low Earth orbit, it records a snapshot of the storms while passing over instead of continuously monitoring them. The sample size would be too small if we limited analysis to only the precise times of the satellite measurements. Instead, we consider the instantaneous satellite measurements to be broadly representative of the vigor of convection in that region for some time before and after the measurement. Continuous measurements would certainly show great variability in time. This is a source of noise in the quantitative results below, but should not affect qualitative interpretation.

Two approaches are taken for matching the TMI data and the hail reports. In the first approach, TMI data over the region of interest (30.5°–38.0°N, 105.0°–81.5°W, 1998–2006) are searched for local minima in the brightness temperature fields. For each frequency, the brightness temperature is stored for any point that does not have a lower brightness temperature within 0.3° latitude and longitude, up to ~45 km. To limit this search to strong convection, only pixels that have 85-GHz PCT below 200 K are considered. Such a threshold is necessary to save computational time and eliminate many nonconvective artifacts (e.g., snow and water surfaces). Only a very small fraction (~1%) of storms near this threshold has associated hail reports. Higher brightness temperatures are allowed for the other frequencies, as long as they coincide with an 85-GHz measurement meeting this criterion. For each local minimum that is found, a search is done for any hail reports within 0.3° latitude and longitude and 30 min. The number of hail reports and maximum hail diameter are recorded. One limitation is that a hail report will not be recorded unless it is within that distance from a local minimum brightness temperature—it may instead be along a line of low brightness temperatures, but not close enough to the minimum brightness temperature. Another limitation is that surface snow cover has a low brightness temperature, similar to that associated with hail in the 19-GHz channel especially. For that reason, the winter months (December–February) are excluded from this analysis.

The second approach is based on the TRMM precipitation features (Nesbitt et al. 2000), defined as contiguous areas with at least 20-dBZ near-surface radar reflectivity or 85-GHz PCT $\leq$ 250 K. In the level-2 precipitation feature products used here, only the centroid location (not the entire extent of the precipitation feature) is stored. As in the previous approach, the study domain is restricted to 30.5°–38.0°N, 105.0°–81.5°W, 1998–2006. The hail database is searched for reports within 1 h and 1.0° latitude and longitude from the precipitation feature centroid. This larger search region is used because the strongest precipitation features often extend over 100 km from their centroids and are long-lasting systems. Several parameters are already stored for each precipitation feature, including minimum 85- and 37-GHz PCT, maximum radar reflectivity at 9-km altitude, and total lightning flash rate. Cecil et al. (2005) segmented the precipitation feature populations into the strongest 1%, strongest 0.1%, etc. based on these parameters. The same approach for segmenting precipitation feature populations is used here to quantify the fraction of these strongest precipitation features that has corresponding hail reports.

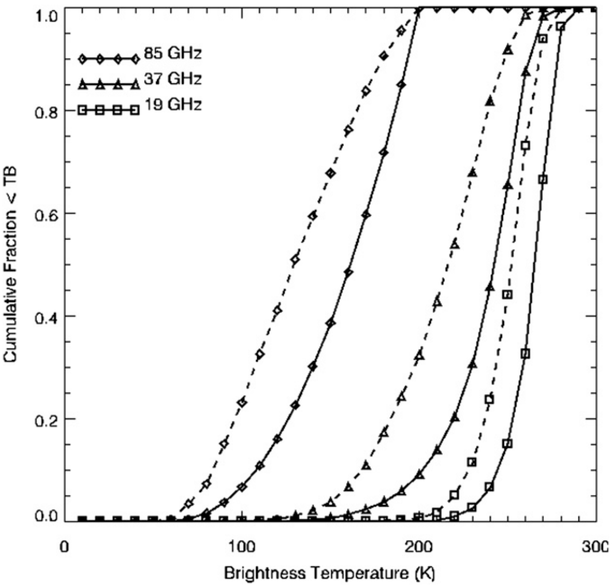

FIG. 1. Cumulative frequency distributions of brightness temperatures for local minima (solid lines) and for hail reports (dashed lines).

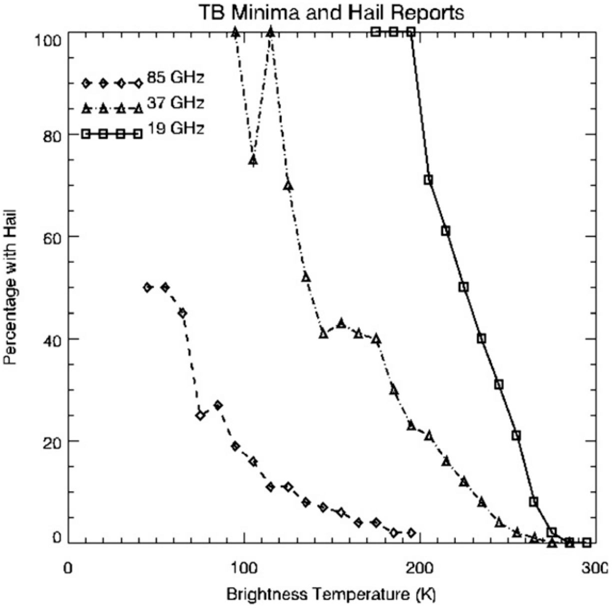

FIG. 2. Percentage of brightness temperature local minima associated with hail reports.

3. Results

a. Hail and local minima of brightness temperatures

As brightness temperature decreases, the population of storm events also decreases. The fraction of those events with an associated hail report increases. Figure 1 shows the cumulative frequency of storm cases as a function of brightness temperature, and the cumulative frequency of hail reports also as a function of brightness temperature. For the 37-GHz channel, about 10% of the storms (using the first approach described in section 2; local brightness temperature minima with 85-GHz PCT below 200 K) have 37-GHz PCT below 200 K. About 25% of the hail reports have a nearby measurement of 37-GHz PCT below 200 K. Thus, hailstorms are 2.5 times as likely to have brightness temperatures below 200 K relative to the entire population of these storms.

In Fig. 2 and Table 1 we compute the fraction of cases that have associated hail reports as a function of brightness temperature. Figure 2 indicates the likelihood that a storm has hail if its minimum brightness temperature is the value on the x axis (±5 K). Table 1 lists the cumulative likelihood of hail for brightness temperatures *at or below* the values listed. So 24% of the 649 storms with minimum 37-GHz PCT in the 190–200-K range have associated hail reports in Fig. 2. Out of 1762 storms with minimum 37-GHz PCT at or below 200 K, 34% have hail reports (Table 1). For reasons described in section 2, these percentages represent lower limits on what would be expected given more complete records of hail occurrences.

To identify with confidence that a case is likely to have large hail, the 19-GHz channel is most effective and 85-GHz least effective in Table 1. The likelihood of having a hail report increases with decreasing brightness temperature for all channels, but this likelihood levels off at about 50% for 85-GHz brightness temperature below about 70 K. The nine cases with the lowest 19-GHz brightness temperatures (below 200 K) all have hail reports nearby. Eleven of the twelve cases with the lowest 37-GHz PCT (below 125 K) have hail reports. But only three of the seven cases with the lowest 85-GHz PCT (below 56 K) are associated with hail reports.

For brightness temperatures that have several associated hail reports, there is a broad range of hail sizes.

TABLE 1. Number of cases and percentage coinciding with hail reports for local brightness temperature minima below the indicated thresholds.

85-GHz PCT	<60 K	<70 K	<80 K	<90 K	<100 K
Sample size	24	162	487	1098	1980
% with hail	50	46	32	30	25
37-GHz PCT	<130 K	<140 K	<150 K	<180 K	<200 K
Sample size	28	62	135	734	1762
% with hail	75	63	51	43	34
19-GHz H	<200 K	<210 K	<220 K	<240 K	<250 K
Sample size	9	30	103	693	1573
% with hail	100	80	67	47	39

TABLE 2. Median brightness temperature as a function of hail diameter.

Hail size (in.)	No. of cases	85 GHz	37 GHz	19 GHz
Penny; 0.75	1473	147	231	258
Nickel; 0.88	678	143	230	257
Quarter; 1–1.5	1233	142	226	256
Golf ball; 1.75	800	140	224	255
Tennis ball; 2–2.5	107	122	214	248
Baseball and greater; 2.75+	141	122	213	249

Likewise, reports of hail with a particular diameter span a broad range of brightness temperatures. Table 2 lists the median brightness temperatures associated with the commonly reported hail sizes. As expected, large hail is more often associated with lower brightness temperatures than smaller hail. Hail that is baseball size or larger has median brightness temperatures of 122, 213, and 249 K at 85, 37, and 19 GHz, respectively. For penny-size hail, the medians are 147, 231, and 258 K. The upper and lower quartiles of 37-GHz PCT for penny-size hail range from 252 to 207 K. For baseball and larger hail sizes, the upper and lower quartiles range from 229 to 180 K. Although the brightness temperatures tend to be lower for larger hail sizes, there is too much overlap to distinguish hail size based on brightness temperature alone. The brightness temperatures that are most common for large hail also have many cases with no hail reports at all.

b. *Hail and precipitation feature minimum brightness temperature*

The TRMM precipitation feature database (Nesbitt et al. 2000; Liu et al. 2008) provides a convenient way to summarize many of the TRMM measurements for mesoscale storms. Cecil et al. (2005) established a procedure for setting criteria that group the strongest storms at the extremes of the population. Following that approach, we now check how many of those storms (grouped by the different TRMM measurements) have associated hail reports.

Table 3 segments the precipitation features into the strongest 1%, 0.1%, 0.01%, and 0.001% according to four different measures. The thresholds representing these levels are based on the entire TRMM population, not limited to the U.S. domain; that is why the sample sizes in Table 2 differ for each measurement.

Radar reflectivity aloft shows the best discrimination of hail likelihood. With the threshold of 52.5 dB*Z* for the top 0.001% of precipitation feature 9-km-altitude reflectivities, 18 of the 19 strongest features have associated hail reports. In the next range of 9-km reflectivities (49.1–52.5 dB*Z*), 74% of features have hail reports.

Sorting by minimum 37-GHz PCT instead, 15 of the 18 strongest features (those with PCT below 140 K) have hail reports. In the next grouping (140–180 K), 69% have hail reports. The 85-GHz channel is not quite as robust at distinguishing large hail because of its shorter wavelength. Only 3 of the 5 strongest cases by 85-GHz PCT have hail reports, and less than two-thirds of those falling in the top 0.01% level (below 75 K) have hail reports.

Precipitation features with very high lightning flash rates are also likely to have hail, but the flash rate is not as strong a hail indicator as the radar reflectivity or the brightness temperatures. Sixty percent of those having at least 125 flashes per minute (the top 0.01% of all precipitation features) have hail reports. Here the flash rate is totaled over the entire spatial extent of the precipitation feature, so a long line of strong convection can have a greater flash rate than a smaller but more intense localized cell.

4. Discussion

These results indicate that extremely low brightness temperatures can serve as useful proxies for hailstorms. There are more cases with extremely low 85-GHz

TABLE 3. Percentage of TRMM precipitation features in the United States associated with hail reports, grouped by four different measures of precipitation feature intensity: radar reflectivity (dB*Z*), brightness temperature (K) at 37 or 85 GHz, and lightning (flashes per minute). Columns are labeled by the percentage of precipitation features globally (35°S–35°N) reaching the listed values, before rounding.

	Top 1.0%	Top 0.1%	Top 0.01%	Top 0.001%
Max 9-km dB*Z*	32.9–43.1 dB*Z* 633/3120 hail (20%)	43.1–49.1 dB*Z* 362/828 hail (44%)	49.1–52.5 dB*Z* 111/149 hail (74%)	>52.5 dB*Z* 18/19 hail (95%)
Min 37-GHz PCT	220–255 K 563/3120 hail (18%)	180–220 K 280/732 hail (38%)	140–180 K 112/162 hail (69%)	<140 K 15/18 hail (83%)
Min 85-GHz PCT	105–160 K 480/2474 hail (19%)	75–105 K 203/494 hail (41%)	60–75 K 48/73 hail (66%)	<60 K 3/5 hail (60%)
Flashes per minute	3–33 740/4525 hail (16%)	33–125 294/869 hail (34%)	125–300 95/165 hail (58%)	>300 19/25 hail (76%)

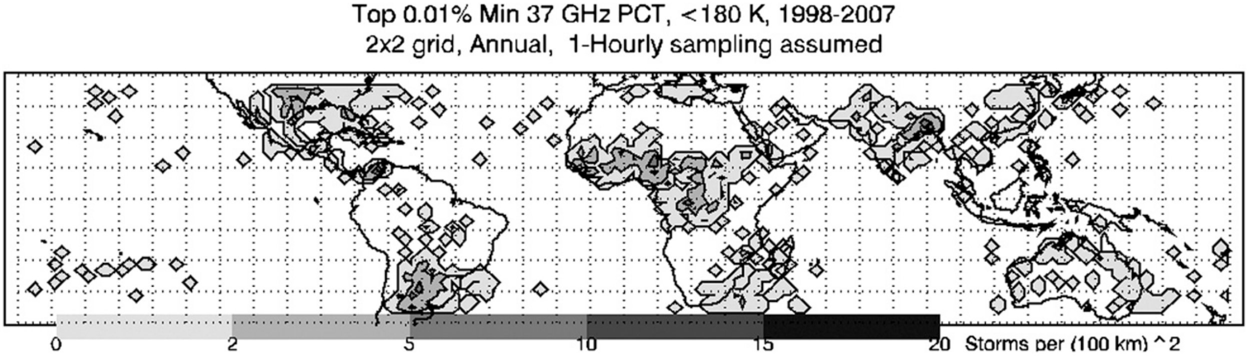

FIG. 3. TRMM precipitation features with 37-GHz PCT below 180 K, 1998–2007. Scaling is applied as if each 2° × 2° grid box was sampled by TRMM once per hour for 1 yr.

brightness temperature and no corresponding hail report than with extremely low 37- or 19-GHz brightness temperature and no corresponding hail report. This is probably because the smaller wavelength of the 85-GHz (~3.5 mm) channel allows it to experience substantial scattering of radiation by smaller particles than would scatter radiation at the longer wavelengths. The 19-GHz channel is more difficult to use because of its limited dynamic range in this ice-scattering regime, and its footprint size from current satellites being much larger (~20 km × 30 km from TRMM, but larger for other satellites) than the size of convective cores containing hail shafts. This leaves the 37-GHz channel best suited for mapping locations of hailstorms.

TRMM precipitation features with 37-GHz PCT below 180 K are very likely (~70%, with the limitations of this analysis) to have large hail. This makes it easy to map the locations that experience such storms most often (Fig. 3), and to compare how often they occur in one region (or season) to another. The TRMM measurements indicate that these storms occur most often in northern Colombia, northern Argentina, central and sub-Saharan Africa, and Bangladesh–eastern India.

The 37-GHz brightness temperature is not quite as sensitive to large hail as the radar reflectivity aloft, but the domain of suitable radar measurements is more limited. The TRMM radar swath is roughly a third of the size of the passive microwave radiometer swath. No other satellite-borne precipitation radar can be used for this, though 37-GHz measurements are taken from other satellites extending beyond the TRMM domain. Subsequent research will use the Advanced Microwave Scanning Radiometer for Earth Observing System (EOS) (AMSR-E) to extend these measurements to higher latitudes with sufficient horizontal resolution. In particular, this will allow objective comparison of inferred hailstorm counts for the North American plains with those for the regions cited above.

5. Conclusions

Comparisons of large hail (at least 0.75-in. or ~20-mm diameter) reports in the United States and TRMM microwave brightness temperatures are used to establish satellite-based criteria for objectively mapping hailstorms. While the 85-, 37-, and 19-GHz channels all respond to large hail, the 37-GHz channel is considered most suitable. A threshold of 180 K for 37-GHz PCT indicates 43% likelihood of having associated hail reports from one approach, based on local minima in the brightness temperature fields. Another approach, based on TRMM precipitation features, has a 70% likelihood of associated hail reports with the 180-K threshold at 37 GHz. Precipitation features satisfying this threshold are often mesoscale entities with multiple strong convective cells. So there is a 70% likelihood that at least one of the cells in that mesoscale feature is producing hail. The other approach is more oriented toward the convective scale, with a 43% chance that the particular cell meeting the 180-K threshold has associated hail. Either way, these are probably underestimates of the likelihood of a hailstorm—the verification database of hail reports is likely missing some legitimate hailstorms.

The 180-K threshold for 37-GHz PCT is used to map the inferred locations of hailstorms using TRMM measurements. Regions having the most of these inferred hailstorms include northern Colombia, northern Argentina, central and sub-Saharan Africa, and Bangladesh–eastern India. Subsequent analysis using AMSR-E will expand these results beyond the 35° latitude bounds of TRMM, likely adding the North American plains (and possibly parts of Europe and Asia) to this list.

This approach provides a basis for building objective, satellite-based climatologies of hailstorms around the world. Such climatologies do not suffer from regional inconsistencies among ground-based observational and reporting networks. The satellite-based proxies for hailstorms are being used in ongoing work to examine the environmental conditions of hailstorms in the different regions identified above. With future technological improvements, a geostationary passive microwave sensor could provide continuous monitoring and nowcasting of hailstorms. This is not practical with the current low-Earth-orbit sensors, because they only provide an instantaneous snapshot while the satellite passes over a region. The challenge from geostationary orbit would be obtaining a sufficiently small footprint from a low-frequency channel. As seen from low Earth orbit in this study, a low frequency (long wavelength) substantially reduces the false-alarm rate.

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REFERENCES

Cecil, D. J., S. J. Goodman, D. J. Boccippio, E. J. Zipser, and S. W. Nesbitt, 2005: Three years of TRMM precipitation features. Part I: Radar, radiometric, and lightning characteristics. *Mon. Wea. Rev.,* **133,** 543–566.

Dobur, J. C., 2005: A comparison of severe thunderstorm warning verification statistics and population density within the NWS Atlanta county warning area. Preprints, *Fourth Annual Severe Storms Symp.,* Starkville, MS, East Mississippi Chapter National Weather Association/Amer. Meteor. Soc., D2–6.

Kummerow, C., W. Barnes, T. Kozu, J. Shiue, and J. Simpson, 1998: The Tropical Rainfall Measuring Mission (TRMM) sensor package. *J. Atmos. Oceanic Technol.,* **15,** 809–817.

Liu, C., E. J. Zipser, D. J. Cecil, S. W. Nesbitt, and S. Sherwood, 2008: A cloud and precipitation feature database from 9 years of TRMM observations. *J. Appl. Meteor. Climatol.*, **47,** 2712–2728.

Nesbitt, S. W., E. J. Zipser, and D. J. Cecil, 2000: A census of precipitation features in the Tropics using TRMM: Radar, ice scattering, and lightning observations. *J. Climate,* **13,** 4087–4106.

Spencer, R. W., and D. A. Santek, 1985: Measuring the global distribution of intense convection over land with passive microwave radiometry. *J. Climate Appl. Meteor.,* **24,** 860–864.

——, W. S. Olson, W. Rongzhang, D. W. Martin, J. A. Weinman, and D. A. Santek, 1983: Heavy thunderstorms observed over land by the *Nimbus 7* scanning multichannel microwave radiometer. *J. Climate Appl. Meteor.,* **22,** 1041–1046.

——, M. R. Howland, and D. A. Santek, 1987: Severe storm identification with satellite microwave radiometry: An initial investigation with *Nimbus-7* SMMR data. *J. Climate Appl. Meteor.,* **26,** 749–754.

Zipser, E. J., D. J. Cecil, C. Liu, S. W. Nesbitt, and D. P. Yorty, 2006: Where are the most intense thunderstorms on Earth? *Bull. Amer. Meteor. Soc.,* **87,** 1057–1071.