Relationships between lightning flash rates and passive microwave brightness temperatures at 85 and 37 GHz over the tropics and subtropics

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[1] Using 13 years of Tropical Rainfall Measuring Mission (TRMM) Microwave Imager observations, the precipitation features are defined by grouping contiguous raining regions over the tropics and subtropics. The lightning flash rate in each precipitation feature is determined using the TRMM Lightning Imaging Sensor. Relationships are investigated between lightning flash rate and minimum brightness temperature of each feature, as well as the area with low brightness temperatures at 85 and 37 GHz wavelengths in the precipitation features. These relationships are treated separately on a 4° × 4° grid between 36°S and 36°N. Consistent with earlier studies, the systems over land have more flashes and higher probabilities of lightning than those over ocean given the same brightness temperatures at 85 and 37 GHz. The minimum 37 GHz brightness temperature in the precipitation feature is found to be a good indicator of the probability of lightning. However, the area of low brightness temperatures of the precipitation features is better correlated with the lightning flash rates than the minimum brightness temperature. This implies that the flash rate is not as highly correlated to the maximum convective intensity of the thunderstorm. It is the total amount of ice passing through the mixed phase region in the convective core(s) that better correlates to the area-total flash rates. Over some land regions, high correlations between flash rate and the area of low brightness temperature at 85 and 37 GHz are established. However, there are large regional variations of these relationships.

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1. Introduction

[2] The noninductive electric charge separation process in the ice and water mixed phase region is one of the major sources for the lightning in thunderstorms [*Takahashi*, 1978; *Saunders and Peck*, 1998]. The key to the charging process is the differential vertical flux of small and large ice particles lifted by the strong updraft in deep convection. These particles become charged during collisions in the mixed-phase region, and gravitational sorting helps produce charge centers. The strong correlation between the production of lightning and the mass of precipitation size ice particles supports this theory [*MacGorman and Rust*, 1999; *Blyth et al.*, 2001; *Petersen et al.* 2005]. However, owing to the difficulties of measuring the microphysical properties in the mixed phase region within the thunderstorms [*Brandes et al.*, 1995; *Carey and Rutledge*, 1996], the details of the storm variations in the perspective of charge separation are mostly based on laboratory and theoretical studies [*Williams and Zhang*, 1991; *Williams et al.*, 2005]. This is one of the major obstacles in simulating lightning occurrence using numerical models [*Barthe et al.*, 2010].

[3] Graupel and hail within thunderstorms efficiently scatter the upwelling microwave radiation at 85 and 37 GHz wavelengths and lead to large brightness temperature depressions. Therefore, using remote sensing of the microwave radiances from space, it is possible to retrieve some useful information regarding the total amount of ice in the vertical column from 85 GHz brightness temperatures [*Vivekanandan et al.*, 1991], or the presence of large precipitation ice particles, such as hail, from 37 GHz brightness temperatures [*Cecil*, 2009]. There are some studies relating the characteristics of 85 and 37 GHz brightness temperatures with the lightning flashes in thunderstorms suggesting that systems with high flash rate tend to have colder 85 and 37 brightness temperatures [e.g., *Toracinta and Zipser*, 2001; *Blyth et al.*, 2001; *Toracinta et al.*, 2002]. Also, with the same brightness temperatures, thunderstorms over land tend to have more flashes than those over ocean [*Toracinta et al.*, 2002; *Cecil et al.*, 2005]. Further, important information regarding the various microphysical properties in different thunderstorm regimes, such as supercooled liquid water

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Table 1. Population of All Precipitation Features Defined by TRMM 2A12 Rain Area and Those With Lightning Flashes During 1998–2010

	Ocean	Land	All
All precipitation features	9.5 million	3.4 million	12.9 million
Thunderstorms with flashes	119,261	354,618	473,879
Percent with flashes	1.2	10.5	3.7
Flash rate >10 flash/minute	11,926	63,019	74,945
Percent with flash rate >10 flash/minute	0.1	1.9	0.6

[*Toracinta et al.*, 2002], could hide in the correlations between the lightning flashes and the different brightness temperatures. While several studies have reported aspects of the relationships between lightning and brightness temperatures, none have quantified the regionally varying correlations with the detail intended in this paper. This leads to the motivation of this study:

[4] 1. What specific properties of 85 and 37 GHz brightness temperatures can quantitatively determine if a storm is likely to have lightning or not? What are the regional variations of those properties?

[5] 2. What are the mean characteristics of thunderstorms as seen by microwave radiometers at 85 and 37 GHz wavelengths? What are the minimum requirements of brightness temperatures at 85 and 37 GHz for a thunderstorm?

[6] 3. Can we estimate storm flash rate by using 85 and 37 GHz brightness temperatures? Are there large regional and seasonal variations of the correlations between flash rate and the properties from 85 and 37 GHz observations?

[7] To address these questions, 13 years of Tropical Rainfall Measuring Mission (TRMM) [*Kummerow et al.*, 1998] Microwave Imager (TMI) and Lightning Imaging Sensor (LIS) observations during 1998–2010 are collocated to investigate the relationship between the lightning flash rate from LIS and the characteristics of brightness temperatures at 85 and 37 GHz from TMI.

2. Data and Methodology

[8] The primary tool used in this study is the University of Utah TRMM precipitation feature database [*Liu et al.*, 2008]. In this database, first the TRMM TMI and LIS [*Christian et al.*, 1999; *Boccippio et al.*, 2000] observations are collocated. Then the contiguous pixels in a TRMM orbit with nonzero rainfall from TRMM 2A12 algorithm (TMI based rainfall retrieval algorithm) [*Kummerow et al.*, 2001] are grouped together and defined as TMI Precipitation Features (TPFs). Then the microwave radiometric characteristics and the number of lightning flashes from LIS inside these TPFs are summarized (see details in the work of *Liu et al.* [2008]). The flash rate in each TPF is estimated by dividing the number of flashes by the LIS view time (usually around 90 s). To remove the differences between land surface emissions and water surface emissions, polarization-corrected temperatures (PCTs) [*Spencer et al.*, 1989; *Kummerow*, 1993] at 85 and 37 GHz are calculated. We focus on investigating the correlation between the characteristics of 85 and 37 GHz PCTs and the lightning flash rates in each of these TPFs. Several parameters are calculated from 85 and 37 GHz PCTs, including the minimum 85 and 37 GHz PCTs, as the proxies of the maximum convective intensity of the TPFs, and the areas with the 85 and 37 GHz PCTs lower than 275, 250, 225, 200, 175, 150 K showing the size of the TPFs and the size of convective core(s) of the TPFs. To limit noise, only TPFs with at least 2 contiguous TMI 85 GHz pixels with size greater than 120 km^2 are used in this study.

[9] A three-step approach is used to describe the correlations between the microwave radiometric properties and the flash rates in these TPFs. The first step is to investigate the probability of the TPFs having at least one flash on the basis of their 85 and 37 GHz PCTs. Note that the LIS views a particular TPF for 80–100 s, so the minimum detectible flash rate of a TPF is about 0.6–0.8 flash per minute [*Cecil et al.*, 2005]. Therefore, the results of the first step could help infer the probability of lightning rate greater than about one flash per minute on the basis of the 85 and 37 GHz PCTs of a storm. After identifying the TPFs with lightning, the second step is to summarize the microwave radiometric properties of these TPFs. Those with the least ice scattering signal (the highest minimum PCT values) are investigated globally. The third step is to correlate the lightning flash rate to the properties of 85 and 37 GHz PCTs, and to investigate if there is any skill to estimate the lightning flash rate on the basis of only the 85 and 37 GHz brightness temperature fields. Besides showing the bulk correlations between the PCTs and the flash rates in TPFs over land and ocean, the regional variations of these correlations are analyzed by using TPFs samples in each 4° × 4° box between 36°S and 36°N.

3. Results and Discussion

[10] With 13 years of the TRMM observations during 1998–2010, about 13 million TPFs are identified between 36°S and 36°N, in which about 3.7% of them have at least one lightning flash (Table 1). Consistent with the dominant lightning contribution from thunderstorms over land as pointed out by many earlier studies [e.g., *Vorpahl et al.*, 1970; *Orville and Henderson*, 1986; *Zipser and Lutz*, 1994; *Christian et al.*, 2003; *Cecil et al.*, 2005], there is a much higher percentage of TPFs with lightning flashes over land (10.5%) than over ocean (1.2%). This land versus ocean contrast is clearly shown in Figures 1b and 1c. The detailed regional differences of thunderstorm population are also shown by percent of TPFs with lightning flashes over both land and ocean. For example, there is a relatively higher percentage of TPFs with flashes over the Sahel, central and South Africa, Argentina, northern India and Pakistan, and northwest Australia than over other land regions (Figure 1c). A larger proportion of TPFs off the coast of major continents and over subtropical oceans, such as within the SPCZ, have more flashes than those in the ITCZ over equatorial oceans (Figure 1c).

[11] The intense thunderstorms are identified here as the TPFs with flash rate greater than 10 flashes per minute. About 1.9% of the TPFs over land have more than 10 flashes per minute (Table 1), with higher percentages over Sahel, central Africa, southeastern United States, Argentina, Western Australia and India and Pakistan (Figures 1d and 1e). TPFs with more than 10 flashes per minute are very rare over equatorial open oceans (Figures 1d and 1e). However, they

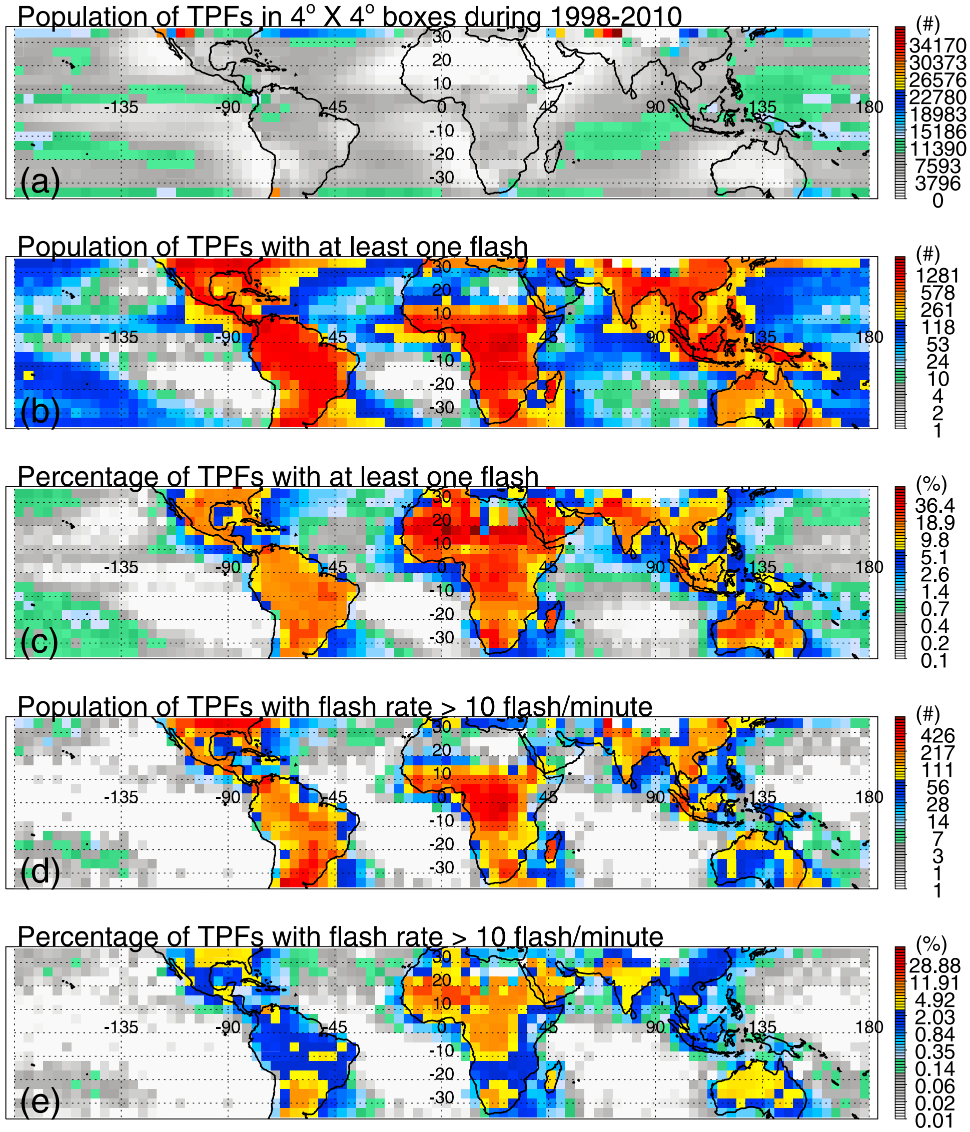

Figure 1. (a) Population of precipitation features defined by rain area from TRMM TMI 2A12 product (TPFs) in 4° × 4° boxes during 1998–2010. (b) Population of TPFs with at least one flash. (c) Percentage fraction of TPFs with at least one flash in 4° × 4° boxes. (d) Population of TPFs with flash rate greater than 10 flashes per minute. (e) Percentage fraction of TPFs with flash rate greater than 10 flashes per minute. Note that there are more samples near 30°S and 30°N by TRMM; therefore Figures 1a, 1b, and 1d are biased to high values at the subtropical regions. The sample bias is removed with the fraction calculation in Figures 1c and 1e.

do occur sometimes over subtropical oceans, such as the SPCZ and the North Atlantic and Pacific.

3.1. Probability of Lightning Versus 85 and 37 GHz Brightness Temperature

[12] What kinds of the storms are more likely to have lightning flashes on the basis their microwave radiometric properties? To answer this question, the TPFs are binned by their minimum 85 and 37 GHz PCTs and the areas of the PCTs lower than certain temperatures. Then the probability of the lightning in each bin is estimated as the percentage of the TPFs with at least one lightning flash. The selected results are shown in Figure 2.

[13] It is obvious that TPFs with lower PCTs on 85 and 37 GHz (with stronger ice scattering) are more likely to have flashes (Figure 2a). When TPFs with minimum 85 GHz PCTs are between 120 and 200 K, there are a large variety of lightning probabilities depending on the different minimum 37 GHz PCTs (Figure 2a). However, when minimum 37 GHz PCTs are between 220 and 260 K, there is much less variation of lightning probabilities for TPFs with different minimum 85 GHz PCTs (Figure 2a). This indicates that the probability of lightning is a stronger function of minimum 37 GHz PCT than of the minimum 85 GHz PCT. It is reasonable to speculate that larger TPFs, or TPFs with larger regions of convection, are more likely to have lightning than

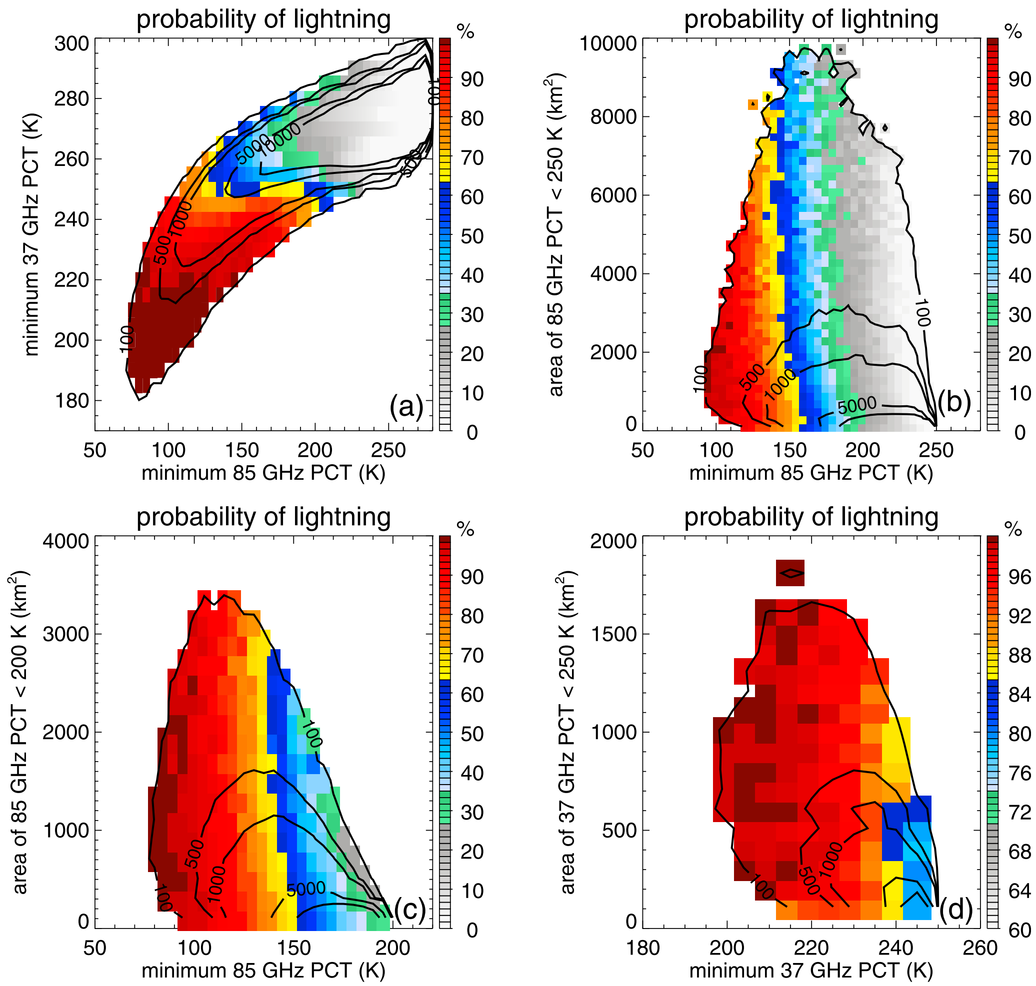

Figure 2. (a) Two-dimensional histogram of TPFs with different minimum 85 and 37 GHz PCTs. The number of samples is shown with contours. The probability of the lightning in bins with more than 100 samples is shown with color fill. (b) Same as Figure 2a but for TPFs with different minimum 85 GHz PCT and an area of 85 GHz PCT colder than 250 K. (c) Same as Figure 2a but for TPFs with different minimum 85 GHz PCT and an area of 85 GHz PCT colder than 200 K. (d) Same as Figure 2a but for TPFs with different minimum 37 GHz PCT and an area of 37 GHz PCT colder than 250 K. Here the TPFs over mountains higher than 1500 m are excluded from the samples to remove the cases with cold brightness temperatures caused by the cold surface over high terrains.

smaller TPFs (all else being equal). Figures 2b–2d suggest this is not the case. For a storm with a given maximum convective intensity defined by the minimum 85 and 37 GHz PCTs, probabilities of lightning vary little against the size of the system and the size of the convective core inside the system (Figures 2b–2d). This suggests that the minimum 37 GHz PCT could be used as a better indicator of lightning than the minimum 85 GHz PCT and the areas of the low PCTs (size of the system and the convective core).

[14] To investigate the regional variations of the lightning probability depending on different 85 and 37 GHz PCTs, the probability of lightning for TPFs with certain 85 and 37 GHz PCT values are calculated in 4° × 4° boxes in 36°S–36°N (Figure 3). With the same minimum 85 and 37 GHz PCTs, TPFs over land have much higher probability to have lightning flashes than those over ocean (Figures 3a–3d). Over land, TPFs with minimum 85 GHz PCT around 230 K and 200 K over Argentina, the United States and Mexico, central and southern Africa, Australia and southeastern China have higher probabilities of lightning than other land regions (Figures 3a and 3b). For all of the thresholds, Africa has the highest probabilities of lightning. In the highest latitudes of this domain (+/−32–36°), the lightning probabilities for TPFs with minimum 37 GHz PCT near 265 K (Figure 3c) are less than the probabilities at lower latitudes. This is at least partly an artifact of surface temperature, since 265 K requires only a modest brightness temperature depression from the typical background scene. TPFs with minimum 37 GHz PCT around 250 K always have very high probability (>85%) of lightning over land, around 50% probability over subtropical ocean, and about 20% probability over equatorial oceans (Figure 3d).

[15] A different way to demonstrate the regional variations of the lightning probability against the 85 and 37 GHz PCT

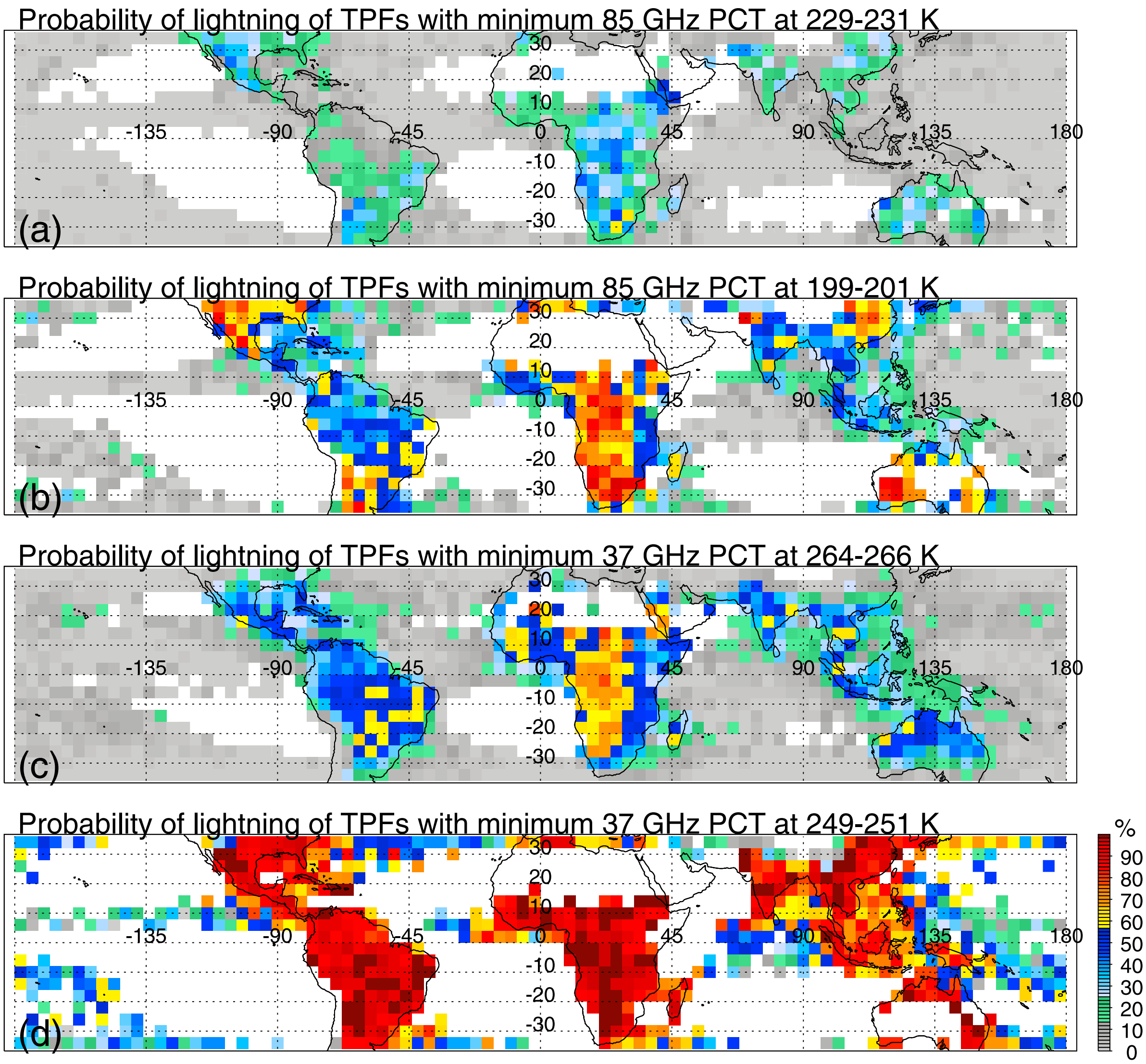

Figure 3. (a) Percentage of TPFs with minimum 85 GHz PCT around 230 K with at least one lightning flash in 4° × 4° boxes. (b) Same as Figure 3a except around 200 K. (c) Percentage of TPFs with minimum 37 GHz PCT around 265 K with at least one lightning flash. (d) Same as Figure 3c except around 250 K. Results only show for 4° × 4° boxes with at least 10 samples.

is to show the PCT values with which TPFs would have 50% and 90% probability of lightning. Consistent with Figure 3, Figure 4 shows that much lower brightness temperatures are required to give a 50% and 90% probability of lightning over ocean than over land (Figures 4a–4d). Relatively higher 85 GHz PCTs are sufficient for 50% and 90% probability of lightning over Argentina, the United States, Mexico, central and southern Africa, Australia, and southeast China (Figures 4a and 4b). Again, higher minimum 85 GHz PCTs over Argentina are sufficient for 50% and 90% lightning probability than for those over Brazil (Figures 4a and 4b). However, higher minimum 37 GHz PCTs over Brazil are sufficient to produce lightning compared to those over Argentina. In general, minimum 37 GHz PCT less than about 255 K would predict more than 50% lightning probability over land, and about 250 K over ocean. Minimum 85 GHz PCT less than about 200 K would predict more than 50% lightning probability over land, compared with about 140 K over ocean (Table 2).

3.2. Radiometric Properties of Precipitation Features With Flashes

[16] The convective intensities of thunderstorms are very different over various regions, especially between those over land and over ocean. Figure 5 compares the land versus ocean differences in the cumulative distribution of the characteristics of 85 and 37 GHz PCTs in TPFs with at least one flash. TPFs with lightning over ocean have a stronger ice scattering signature with lower minimum 85 and 37 GHz PCT (Figure 5a) and larger areas with low 85 GHz (Figure 5b) and 37 GHz (Figure 5c) PCTs than those over land (Figure 5a). This may seem contradictory to prior studies, but relates to the small fraction of oceanic TPFs with lightning (Table 1) and stronger thresholds for lightning occurrence (Figure 4). Although the strongest TPFs in other studies generally come from land regions, the land sample of TPFs with lightning also has a disproportionately large

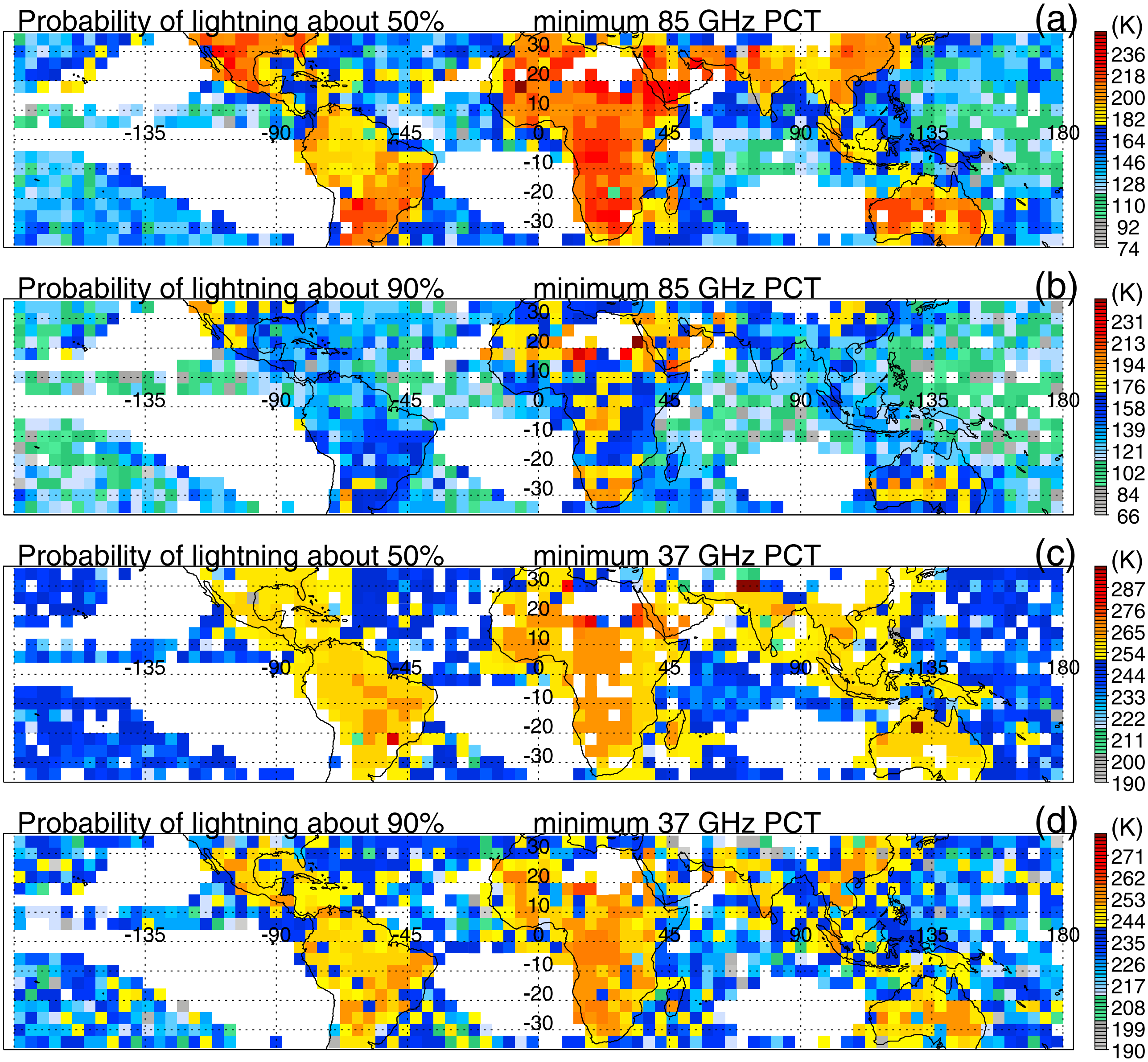

Figure 4. (a) Minimum 85 GHz PCTs which have about 50% probability of lightning in 4° × 4° boxes. (b) Minimum 85 GHz PCTs which have about 90% probability of lightning in 4° × 4° boxes. (c) Minimum 37 GHz PCTs which have about 50% probability of lightning in 4° × 4° boxes. (d) Minimum 37 GHz PCTs which have about 90% probability of lightning in 4° × 4° boxes. Results only show for 4° × 4° boxes with at least 10 samples.

number of storms with high brightness temperatures. Such storms are mostly missing from the ocean sample. This is consistent with earlier studies [*Zipser and Lutz*, 1994; *Toracinta et al.*, 2002; *Cecil et al.*, 2005] that it is more difficult for oceanic convective systems to have lightning, but once they have lightning, they have relatively "stronger" ice scattering signatures than storms with similar flash rates over land. (In the extreme, the highest flash rates and strongest ice scattering signatures are mostly confined to land, as in the work of *Zipser et al.* [2006].)

[17] This land versus ocean contrast is more clearly shown in Figures 6a and 6b. The median values of minimum 85 GHz PCT of TPFs with flash rate below 10 flashes per minute over land is relatively higher than those over ocean

Table 2. Minimum 85 and 37 GHz PCTs of TPFs With the Probability of Lightning at About 50% and 90%

	Ocean (K)	Land (K)	All (K)
Minimum 85 GHz PCT of TPFs with 50% lightning	140	200	166
Minimum 85 GHz PCT of TPFs with 90% lightning	100	150	116
Minimum 37 GHz PCT of TPFs with 50% lightning	250	255	253
Minimum 37 GHz PCT of TPFs with 90% lightning	231	236	232

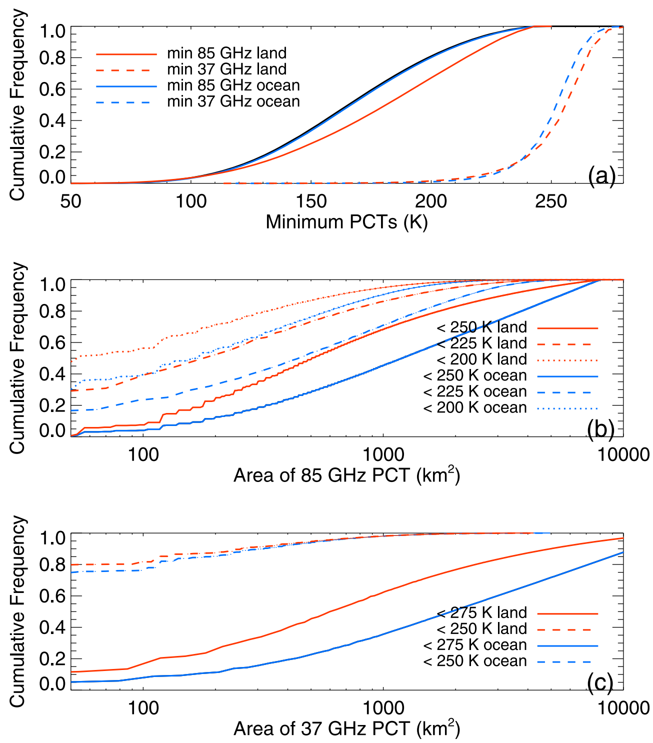

Figure 5. (a) Cumulative distribution of TPFs with flashes by minimum 85 and 37 GHz PCTs over land and ocean. (b) Cumulative distribution of oceanic and continental TPFs by an area of 85 GHz PCT colder than 250, 225, and 200 K. (c) Cumulative distribution of oceanic and continental TPFs by an area of 37 GHz PCT colder than 275 and 250 K.

(Figure 6a). There is also a clear land versus ocean separation in the median values of the minimum 37 GHz PCT (Figure 6b). Note that median values of 85 GHz PCT of TPFs over Amazon, West Africa and maritime continents are lower than their subtropical counterparts (Figure 6a). This is probably due in part to the larger depth of the systems over the tropics, leading to larger brightness temperature depression. Consistent with these results, *Cecil* [2011] showed that radar reflectivity profiles associated with a given minimum 37 GHz PCT tend to be "stronger" (higher reflectivity in the mixed-phase region) for land than for ocean. Comparing subtropics to the tropics, the reflectivity profiles tended to be "stronger" for the subtropics and taller for the tropics. So a given brightness temperature over land tends to be associated with a stronger reflectivity profile and more lightning than a similar brightness temperature from an oceanic storm. Likewise, it takes a lower brightness temperature from the deep tropics to suggest a strong reflectivity profile and lightning than it does from the subtropics.

[18] The median values of the minimum 85 and 37 GHz PCTs of the TPFs with flash rate greater than 10 per minute are shown in Figures 6c and 6d. The storms are stronger over Argentina, southeastern United States, Congo and Bay of Bengal with lower median PCTs, consistent with the locations of the strongest storms [*Zipser et al.*, 2006].

[19] It would be interesting to find the "marginal" ice scattering signal for thunderstorms. The highest minimum 85 and 37 GHz PCTs in TPFs with flashes over different regions are shown in Figure 7. The minimum requirements of low PCTs for thunderstorms over ocean are mostly lower than those over land. High values of minimum requirement for 85 and 37 GHz PCTs are found over some desert regions, such as Mexico, Chile, Sahel, Iran, Pakistan, Australia and Kalahari. Because of high signal/noise ratio over these regions, the minimum 85 and 37 GHz PCT over these regions are higher. Note that the high values of minimum requirement for minimum 85 GHz PCT in the TPFs off the coast of Argentina may well be artifacts because LIS has the largest noise/signal ratio over the region owing to the South Atlantic Anomaly [*Boccippio et al.*, 2000].

3.3. Correlation Between Flash Rate and Characteristics of Brightness Temperatures at 85 and 37 GHz

[20] To quantify the correlation between flash rate and the microwave radiometric properties of thunderstorms, the Pearson product moment correlation between the parameters summarized from 85 and 37 GHz PCTs and the flash rate in TPFs over land and ocean are calculated and listed in Table 3. These correlations are conditional, with at least 1 lightning flash required for all TPFs in the sample for subsequent analyses. Clearly the sizes of precipitation systems have almost no correlation to the flash rate based on the low correlation to the area of 85 GHz PCT <250, 275 K and 37 GHz <275 K (usually encompassing most of the rain area). High values of correlation are found from flash rate to the size of the convective core with low 85 and 37 GHz PCTs. This is consistent with the good correlation of flash rate with the updraft *volume* as pointed out by *Deierling and Petersen* [2008]. The best correlations of 0.8 over land and 0.72 over ocean are with area of the 37 GHz PCT <250 K. Figures 2d and 3d showed that TPFs with at least one pixel reaching this threshold are likely to have lightning. A TPF with a large area below the threshold likely has many individual cells with lightning. It also likely has some cells well below the threshold, themselves producing many flashes.

[21] Note that there are relatively higher correlations (0.6) of flash rate with the minimum 37 GHz PCT than with the minimum 85 GHz PCT (Table 3). This is also shown in the scatterplot between the flash rates and the minimum 85 and 37 GHz PCTs of TPFs in Figures 8a and 8b. There are probably two reasons behind this:

[22] 1. First, 37 GHz PCT is more sensitive to the large ice particles, such as large graupel and hail, and the presence of large ice particles is important in the charge separation; small ice particles above the charging zone would contribute little to the charge separation but would still contribute to ice scattering at the shorter wavelength of 85 GHz.

[23] 2. Second, 37 GHz has a larger footprint than 85 GHz [*Kummerow et al.*, 1998]. Some information of the size of the convective core is translated into the minimum PCT at 37 GHz if the core of a storm fills the large footprint.

[24] The correlations from flash rate to the minimum 85 GHz (Figure 9a), 37 GHz PCT (Figure 9c), the area of 85 GHz PCT <150 K (Figure 9b), and area of 37 GHz PCT <250 K (Figure 9d) are higher over land than over ocean. Over most land regions, minimum 37 GHz PCT

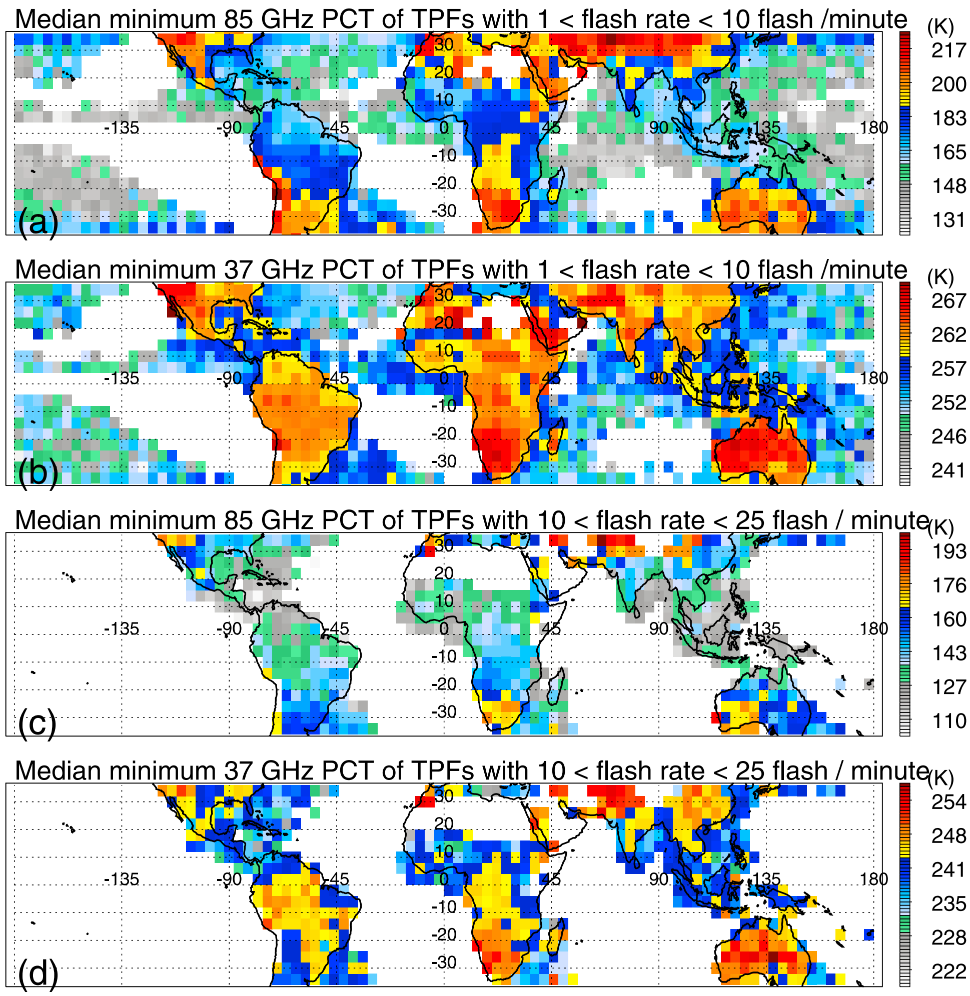

Figure 6. (a) Median minimum 85 GHz PCT of TPFs with flashes 4° × 4° boxes during 1998–2010. (b) Same as Figure 6a but for minimum 37 GHz PCT. (c) Same as Figure 6a but for an area of 85 GHz colder than 250 K. (d) Same as Figure 6a but for area of 37 GHz colder than 275 K. Results are shown only for 4° × 4° boxes with at least 10 samples.

has a decent correlation (>0.6) with the flash rate. The best correlations (>0.8) are found between flash rate and the areas of 85 GHz PCT <150 K and 37 GHz PCT <250 K over Australia, east China and the regions known for strong thunderstorms, including Argentina, Congo, and southeastern United States (Figures 9b and 9d). *Blyth et al.* [2001] demonstrated a way of estimating the flash rates and the mean 85 and 37 GHz PCT near the convective cores from 11 orbits of TRMM data. With more data available, the relationships can be refined for various regions. The correlations above 0.8 in Figure 9 indicate that there could be some skill in deriving the flash rate from the areas with low PCTs in the thunderstorms over these regions.

[25] Though there are correlations greater than 0.8 between flash rate and the area of the convective core(s), there is still a large spread of the sizes of convective cores against any specific flash rate as shown in Figures 8c and 8d. This is largely due to regional variations in the quantitative relationship between the flash rate and the size of the convective core determined by the 85 and 37 GHz PCTs. Linear fits have been made between the lightning flash rates and the areas of the 85 GHz PCT <150 K and 37 GHz PCT <250 K of TPFs in each 4° × 4° box from 36°S to 36°N as well as the tropical land, open ocean and coastal regions using equation (1).

$$flashrate = A \cdot area + B \quad (1)$$

[26] Then the geographical distribution of slopes A and constants B are shown in Figure 10 and those for tropical land, open ocean and coastal regions are tabulated in Table 4. There are large variations of the slopes A and constants B over different regions even with the same correlation (Figure 10). Slopes are steeper over land than over ocean (see Figure 10 and Table 4), meaning that with same area of convective core(s) determined by the 85 GHz PCT <150 K or 37 GHz PCT <250 K, the storm over land would have higher flash rate than over ocean, which is consistent with the earlier findings. The correlation between the flash rate and area of cold 85 and 37 GHz PCT in TPFs over tropical open oceans is low (0.43). However, there is a notable 0.68 relationship over tropical coastal regions with

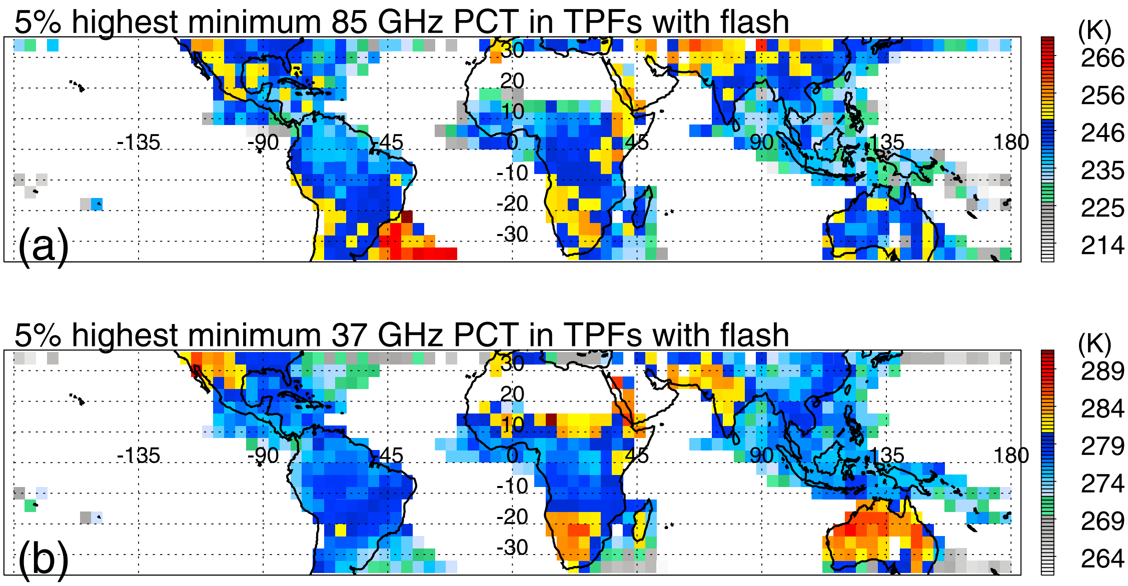

Figure 7. (a) Top 5% highest minimum 85 GHz PCT in TPFs with flashes in 4° × 4° boxes during 1998–2010. (b) Same as Figure 7a but for 37 GHz PCT. Results are shown only for 4° × 4° boxes with at least 100 samples.

slope more like that over land (Table 4). This is consistent with a presumption that updraft strength in convection over coastal regions would be closer to that over land. This presumption is in agreement with observations of vertical velocity by airborne Doppler radar [*Heymsfield et al.*, 2010]. As noted in the work of *Heymsfield et al.* [2010], most of their oceanic data come from coastal regions, and most of their land data come from locations such as Florida or Amazonia, rather than the known locations of the most severe storms. As noted above, there are large regional variations over land. For example, a thunderstorm over Amazon would have lower flash rate than another thunderstorm over Congo with the same area of 85 GHz <150 K (Figures 10b and 10d). This is probably due to the different microphysical properties and convective intensities in the thunderstorms over different regions, but direct measurements to make this comparison are lacking.

[27] To simplify the empirical relationships between flash rate and 85 and 37 GHz PCTs over the regions with good correlations, the mean and standard deviation of the slopes A and constants B over selected regions with correlation >0.8 are listed in Table 5. Note that there are some variations of slopes and constants even among the regions with 0.8 correlations. These relationships could be useful in identifying areas that might have excessive lightning, especially over South America, Africa and Central Asia where have limited or no ground observations.

[28] To investigate the applicability of these correlations between flash rate and the areas of low PCTs for different seasons, a sensitivity test is made on the linear fits with TPFs over subtropical land with different surface temperatures derived from version 1 NCEP reanalysis with 2.5° × 2.5° resolution [*Kistler et al.*, 2001] (Figure 11). The correlations start decreasing once the surface temperature is below 20°C (Figure 11b). The Slope A is not sensitive to the surface temperature, but the constant B shows a large sensitivity when surface temperature is above 27°C or below 20°C.

4. Conclusions

[29] Using a large database of the precipitation features generated from 13 years of TRMM observations, correlations between lightning flash rates and microwave radiometric properties at 85 and 37 GHz have been investigated over various regions globally. The major findings include:

[30] 1. Besides confirming the differences of lightning properties between precipitation systems over land versus ocean in the earlier studies, detailed regional variations of the relationships between flash rate and the 85 and 37 GHz properties have been revealed. For example, there is a higher

Table 3. Pearson Product–moment Correlation Coefficients Between Storm Flash Rate and Some Parameters Derived From TMI 85 and 37 GHz Observations Within TPFs With Flashes

	Ocean	Land	All 36°S–36°N
Minimum 85 GHz PCT	−0.34	−0.46	−0.41
Area of 85 GHz PCT <100 K	0.50	0.62	0.60
Area of 85 GHz PCT <125 K	0.60	0.73	0.70
Area of 85 GHz PCT <150 K	0.60	0.78	0.72
Area of 85 GHz PCT <175 K	0.56	0.78	0.69
Area of 85 GHz PCT <200 K	0.49	0.75	0.62
Area of 85 GHz PCT <225 K	0.35	0.54	0.42
Area of 85 GHz PCT <250 K	0.12	0.30	0.20
Area of 85 GHz PCT <275 K	0.02	0.14	0.09
Minimum 37 GHz PCT	−0.54	−0.64	−0.60
Area of 37 GHz PCT <175 K	0.36	0.44	0.43
Area of 37 GHz PCT <200 K	0.58	0.61	0.61
Area of 37 GHz PCT <225 K	0.72	0.76	0.75
Area of 37 GHz PCT <250 K	0.72	0.80	0.77
Area of 37 GHz PCT <275 K	0.05	0.20	0.13

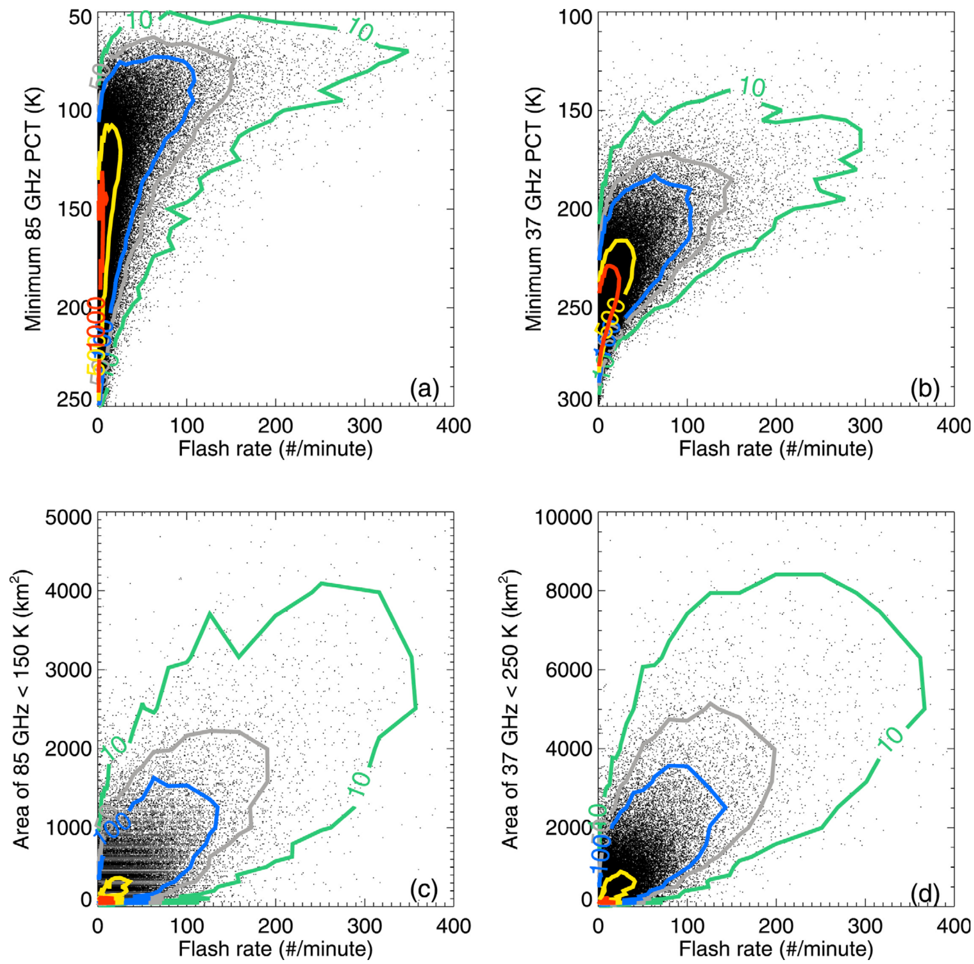

Figure 8. Scatterplots between flash rates and minimum (a) 85 and (b) 37 GHz PCT and (c) an area of 85 GHz PCT colder than 150 K and (d) an area of 37 GHz PCT colder than 250 K in all TPFs during 1998–2010.

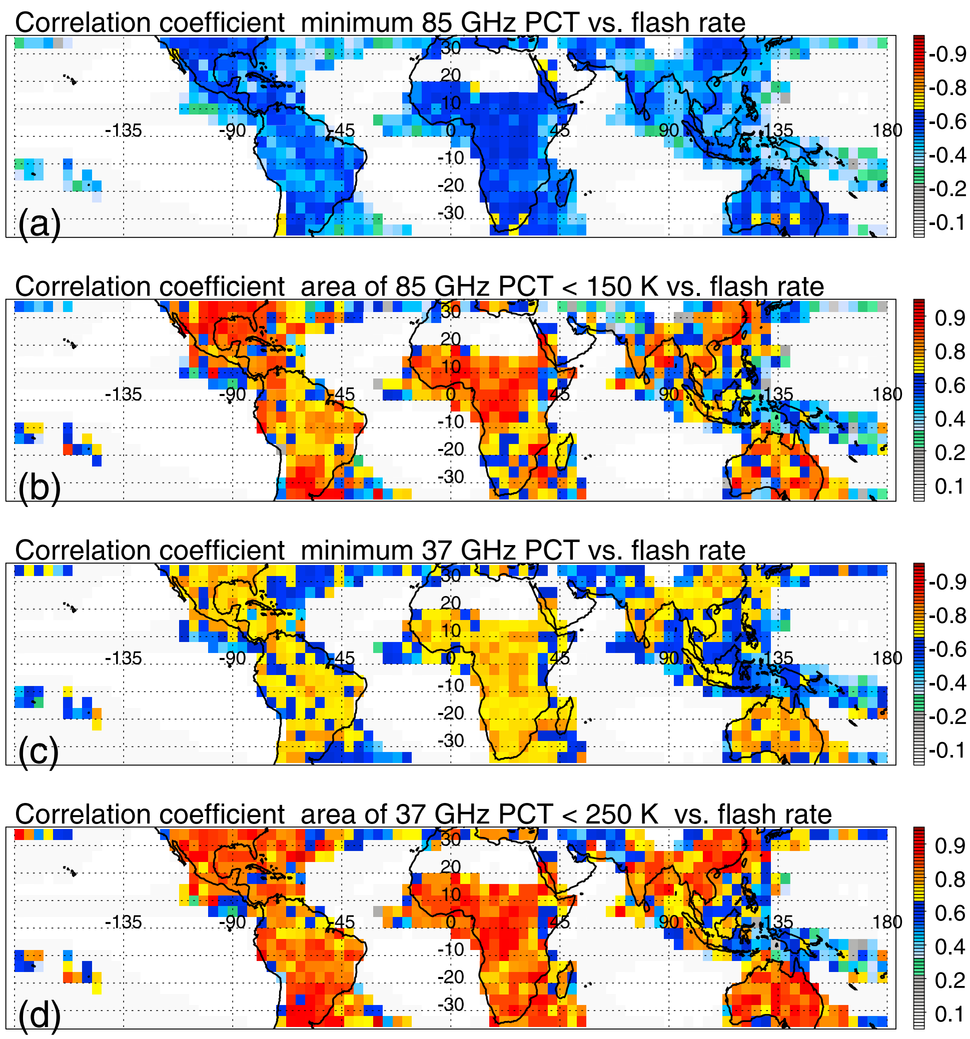

Figure 9. (a) Pearson product–moment correlation coefficients between storm flash rate and minimum 85 GHz PCT of TPFs with flashes in 4° × 4° boxes during 1998–2010. (b) Same as Figure 9a but for an area of 85 GHz PCT colder than 150 K. (c) Same as Figure 9a but for minimum 37 GHz PCT. (d) Same as Figure 9a but for an area of 37 GHz PCT colder than 250 K. Results are shown only for 4° × 4° boxes with at least 50 samples.

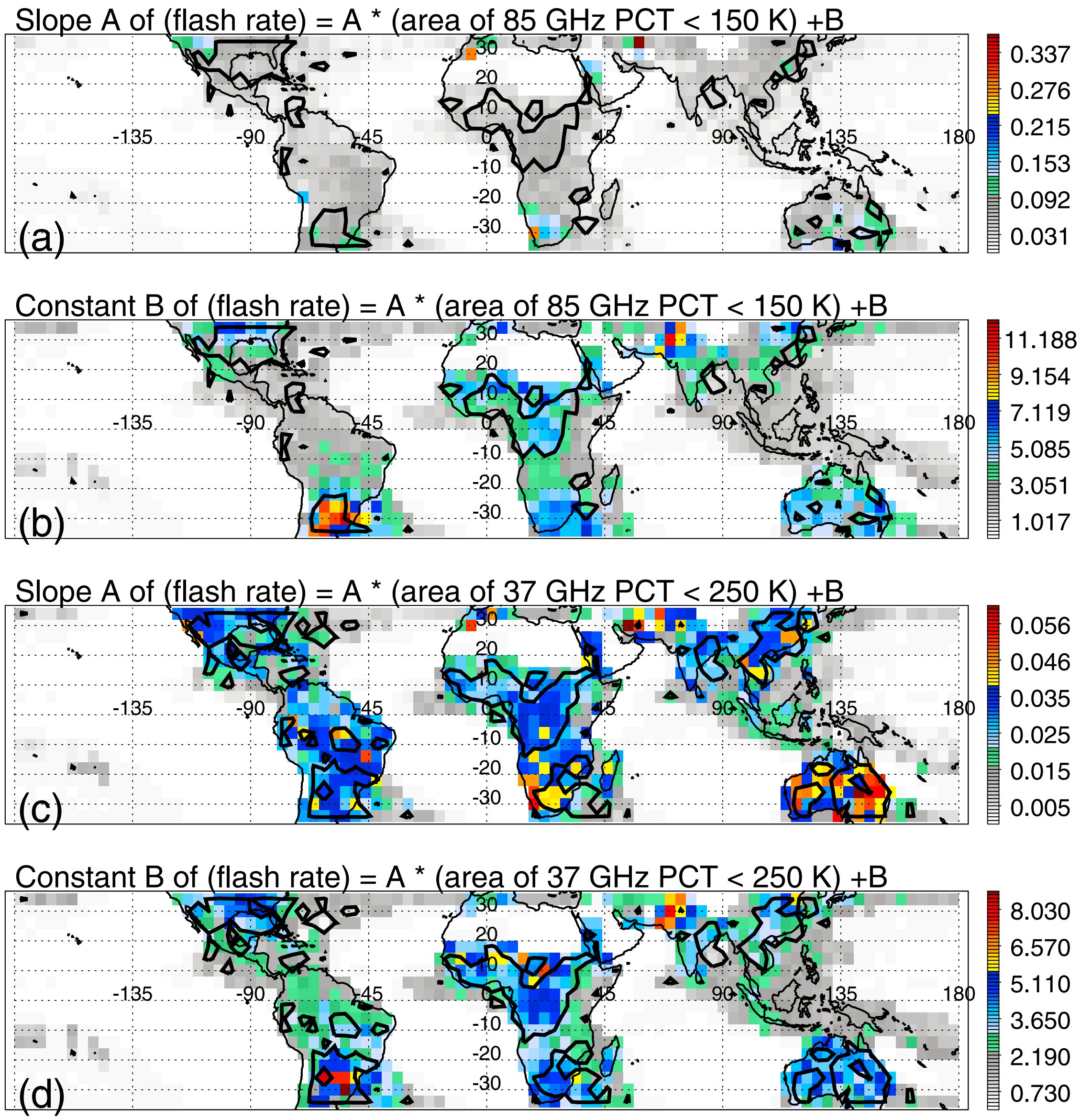

Figure 10. Linear fit between flash rate and the area of 85 GHZ PCT colder than 150 K and 37 GHz PCT colder than 250 K using a flash rate (flashes per minute) of A × cold PCT area (km^2) + B. (a) Slope A in relation between flash rate and the area of 85 GHz colder than 150 K. (b) Constant B in relation between flash rate and the area of 85 GHz colder than 150 K. (c) Slope A in relation between flash rate and the area of 37 GHz colder than 250 K. (d) Constant B in relation between flash rate and the area of 37 GHz colder than 250 K. Black contour shows the regions with the correlation coefficient greater than 0.8 between the flash rate and the cold PCT area. Results are shown only for 4° × 4° boxes with at least 50 samples.

Table 4. Correlation Coefficients and Linear Fit Parameters Between Flash Rate and the Area of 85 GHZ PCT <150 K and 37 GHz PCT <250 K Over Tropical Land, Open Ocean, and Coastal Regions in 20°S–20°N[a]

	Area of 85 GHz PCT <150 K			Area of 37 GHz PCT <250 K		
	Correlation Coefficient	A	B	Correlation Coefficient	A	B
Tropical land	0.78	0.058	3.4	0.81	0.030	3.4
Tropical open ocean	0.43	0.008	1.4	0.52	0.006	1.4
Tropical coastal regions	0.68	0.031	1.8	0.72	0.019	2.1

[a]Here coastal regions are the areas within 1000 km of coastlines of major continents. Open ocean is the area at least 1000 km away from coastline of major continents.

Table 5. Mean and Standard Deviation of Correlation Coefficients and Linear Fit Parameters Between Flash Rate and the Area of 85 GHZ PCT <150 K and 37 GHz PCT <250 K Over Some Regions With Correlation Coefficients Greater Than 0.8

	Area of 85 GHz PCT <150 K			Area of 37 GHz PCT <250 K		
	Correlation Coefficient	A	B	Correlation Coefficient	A	B
Southern United States	0.84 ± 0.028	0.064 ± 0.018	3.44 ± 1.90	0.85 ± 0.03	0.025 ± 0.009	2.92 ± 1.36
Central Africa	0.85 ± 0.027	0.061 ± 0.017	4.30 ± 1.03	0.84 ± 0.029	0.029 ± 0.006	3.93 ± 1.07
South Africa	0.85 ± 0.043	0.054 ± 0.017	3.85 ± 2.23	0.85 ± 0.035	0.030 ± 0.011	3.71 ± 1.02
Argentina	0.87 ± 0.040	0.086 ± 0.015	7.66 ± 2.01	0.86 ± 0.032	0.033 ± 0.005	4.27 ± 1.84
Australia	0.85 ± 0.038	0.12 ± 0.042	4.47 ± 0.85	0.86 ± 0.04	0.042 ± 0.010	3.89 ± 0.66

probability of lightning over subtropical oceans than equatorial oceans for a given brightness temperature at 85 or 37 GHz. A given areal extent of low brightness temperatures is associated with a much greater flash rate over most landmasses than over oceans or the Maritime Continent.

[31] 2. The maximum strength of the convective system is found to be a better indicator of the lightning strike probability than the size of the system or the areal extent of the convective core(s). Minimum 37 GHz PCT inside precipitation systems is found to be a good indicator of the lightning flash probability.

[32] 3. Better correlations are found between flash rate and the total area of the convective core(s) defined from low 85 and 37 GHz PCTs than to the minimum brightness temperatures. Therefore, the flash rate is more determined by the extent of the convective core(s) than by the maximum strength of the convection. This is consistent with the good correlation between updraft volume and the flash rate found by *Deierling and Petersen* [2008].

[33] 4. Because of the differences in the microphysical properties in the precipitation systems under different weather regimes, there is a large variation of the relationships

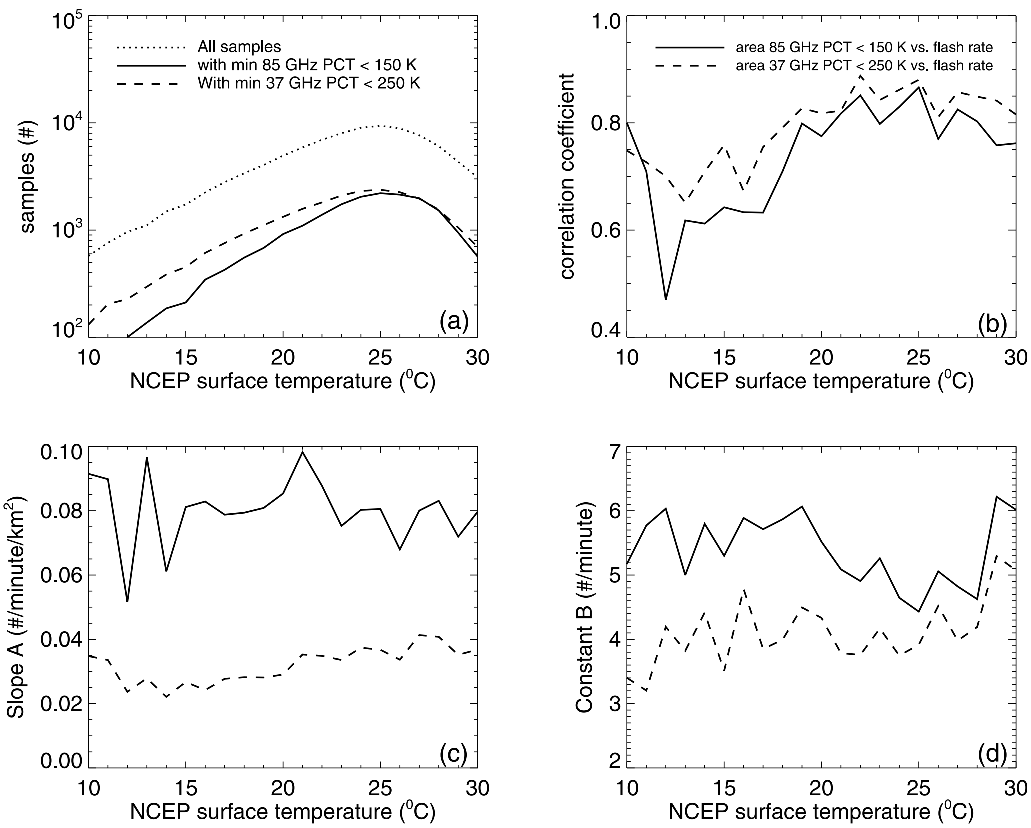

Figure 11. Variations of the correlations between lightning flash rates and the areas of 85 GHz PCT colder than 150 K and the areas of 37 GHz PCT colder than 250 K in the TPFs over subtropical land (20°N–36°N and 20°S–36°S) with different NCEP surface temperatures. (a) Number of TPFs with different NCEP surface temperatures and minimum 85 and 37 GHz PCTs. (b) Correlation coefficients between flash rates and the area of 85 GHz PCT colder than 150 K and 37 GHz PCT colder than 250 K. (c) Variation against surface temperature of slope A of the linear fit between flash rate and the area of 85 GHZ PCT colder than 150 K and 37 GHz PCT colder than 250 K using a flash rate (flashes per minute) of A × cold PCT area (km^2) + B. (d) Variation of constant B of the linear fit in Figure 11c against the surface temperature.

between flash rate and the size of the convective core(s) in the different types of precipitation systems. However, over some regions where certain weather regimes dominate, stable relationships between flash rate and the size of the convective core(s) may be established.

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