The Vertical Profile of Radar Reflectivity of Convective Cells: A Strong Indicator of Storm Intensity and Lightning Probability?

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ABSTRACT

Reflectivity data from Doppler radars are used to construct vertical profiles of radar reflectivity (VPRR) of convective cells in mesoscale convective systems (MCSs) in three different environmental regimes. The National Center for Atmospheric Research CP-3 and CP-4 radars are used to calculate median VPRR for MCSs in the Oklahoma–Kansas Preliminary Regional Experiment for STORM-Central in 1985. The National Oceanic and Atmospheric Administration–Tropical Ocean Global Atmosphere radar in Darwin, Australia, is used to calculate VPRR for MCSs observed both in oceanic, monsoon regimes and in continental, break period regimes during the wet seasons of 1987/88 and 1988/89.

The midlatitude and tropical continental VPRRs both exhibit maximum reflectivity somewhat above the surface and have a gradual decrease in reflectivity with height above the freezing level. In sharp contrast, the tropical oceanic profile has a maximum reflectivity at the lowest level and a very rapid decrease in reflectivity with height beginning just above the freezing level. The tropical oceanic profile in the Darwin area is almost the same shape as that for two other tropical oceanic regimes, leading to the conclusion that it is characteristic.

The absolute values of reflectivity in the 0° to −20°C range are compared with values in the literature thought to represent a threshold for rapid storm electrification leading to lightning, about 40 dBZ at −10°C. Most oceanic cells have reflectivities below the threshold; most midlatitude continental cells exceed the threshold, and the tropical continental cells are about equally divided above and below the threshold. The large negative vertical gradient of reflectivity in this temperature range for oceanic storms is hypothesized to be a direct result of the characteristically weaker vertical velocities observed in MCSs over tropical oceans. It is proposed, as a necessary condition for rapid electrification, that a convective cell must have its updraft speed exceed some threshold value. Based upon field program data, a tentative estimate for the magnitude of this threshold is 6–7 m s^{-1} for mean speed and 10–12 m s^{-1} for peak speed.

1. Introduction

Radar has been used as an essential ingredient for studies of convective storms for over a generation. Pictures of individual vertical slices through convective storms have been a classic method of gaining insight into storm structure. An individual vertical slice, however, does not necessarily show the maximum reflectivity at each altitude unless the storm is aligned perfectly along the plane of the vertical scan. We define this desired vertical profile of radar reflectivity (VPRR) as the maximum reflectivity of a cell as a function of height. Because individual cells tend to tilt, the VPRR requires some attention to detail to derive quantitatively. Donaldson (1961) performed such a study, a classic paper that derived the VPRR for convective cells in New England. Comparing the VPRR for thunderstorms with rain only, with rain and hail, and with tornadoes, the storms with hail and tornadoes had greater radar reflectivity at all altitudes, with the greatest differences in the midtroposphere.

Few studies since Donaldson's explicitly compute the VPRR for a large sample of storms. Not only is considerable effort required but the interpretation of the reflectivity where ice particles exist is difficult and inherently ambiguous. Nevertheless, the VPRR is remotely sensed, a great advantage over parameters that must be derived from in situ sampling of storms if a large sample is desired.

The GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment (GATE) was the first opportunity to analyze a large sample of quantitative, calibrated, digital radar data in the Tropics. Szoke et al. (1986) found profound differences between VPRR statistics for tropical oceanic cells and midlatitude cells. Their working hypothesis was that high reflectivities in

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the mixed-phase or ice regions of cells are good indicators of large particles and, by inference, also of updraft speed. Weak updrafts are, in fact, characteristic of oceanic cumulonimbus cells within mesoscale convective systems (MCSs), whether sampled in GATE (LeMone and Zipser 1980), hurricanes (Jorgensen et al. 1985), the Taiwan Area Mesoscale Experiment (TAMEX, Jorgensen and LeMone 1989), or off northern Australia (Lucas and Zipser 1994).

This paper is motivated by the belief that there is enough information in a large sample of VPRR to be worthwhile comparing VPRR statistics for different regions, as has already been done for vertical velocities within convective cells. We wish to learn more about the global distribution of convective rainfall and thunderstorms. Why, for example, are tropical thunderstorms so common over land but so rare over oceans (Zipser 1994)?

For the Darwin, Australia, region, several field programs have focused on this specific question. Rutledge et al. (1992) and Williams et al. (1992) have reported results from a number of Darwin wet seasons. They studied many convective storms and have presented examples of cross sections through individual storms showing dramatic differences between the monsoon regime and the break regime. During the break periods, winds are generally light, and strong thunderstorms form inland during the afternoon and evening. On occasion, storms propagate toward the coast during the night, often as large squall line systems. Figure 2 of Williams et al. (1992) illustrates such storms, with high reflectivities extending well into the upper troposphere. During periods of strong monsoon westerlies, thick cloud cover is the rule, the normal diurnal cycle is disrupted, and precipitation tends to be organized into large MCSs in monsoon disturbances. Cross sections through these systems (e.g., Fig. 3 of Williams et al. 1992) show reflectivity profiles similar to those of the GATE oceanic systems, with rapid decrease in reflectivity above the freezing level and low reflectivity extending throughout the remainder of the troposphere.

Rutledge et al. (1992) and Williams et al. (1992), in their joint studies of the kinematic, radar reflectivity, and electrical properties of the Darwin area's storms, found that the monsoon regime storms had very low flash rates compared with the break regime storms. They showed that the monsoon regime was characterized by low convective available potential energy (CAPE) and the break regime by high CAPE. They concluded that this was the most essential difference between the two regimes, accounting for the obviously greater vigor and greater vertical velocities within the break period storms. They attributed the great difference in electrical activity to this great difference in updraft intensity, citing numerous laboratory, theoretical, and field studies, which indicate that electrification through the noninductive ice–ice collision process requires the presence of both large graupel and supercooled liquid water in the mixed-phase region. Such conditions are likely with strong updrafts and unlikely with weak updrafts.

One objective of this paper is to take advantage of the strategically placed radar data in the Darwin area to construct a large sample of VPRR for storms in the monsoon (oceanic) regime and the break (continental) regime. By using the same radar, scan strategy, and data processing techniques for both land and ocean storms, the possibility of bias is minimized. Another is to compare the VPRR for Darwin area ocean systems with the VPRR already derived for other parts of the oceanic Tropics. The VPRR is also computed for some ''typical'' midwestern United States squall lines and compared with the Darwin results. Finally, the issue of whether the VPRR is a good indicator of electrification in convective cells is addressed; we do not consider processes in stratiform regions.

2. Data and procedures

This study uses reflectivity data from the National Center for Atmospheric Research (NCAR) CP-3 and CP-4 radars during the Oklahoma–Kansas Preliminary Regional Experiment for STORM-Central (OK PRE-STORM) experiment during May and June 1985. Biggerstaff and Houze (1991), among many others, show a location map of the radars as used in that program. For the Darwin region, the reflectivity data from the National Oceanic and Atmospheric Administration (NOAA)–Tropical Ocean Global Atmosphere (TOGA) radar were used from the monsoon seasons of 1987/88 and 1988/89. The NOAA–TOGA radar was operated by the Bureau of Meteorology Research Centre (BMRC) in conjunction with the National Aeronautics and Space Administration (NASA) Tropical Rainfall Measuring Mission (TRMM). Rutledge et al. (1992), among many others, show a location map of the radars as used in that program. The NOAA–TOGA radar is the one closest to Darwin and was the one used for this work because it covered more of the oceanic area than the Massachusetts Institute of Technology radar at Koolpinyah. The characteristics of the radars used for this paper are given in Table 1.

Uniform criteria were adopted to assure comparability of the results for different storm systems. For the midlatitude continental (PRE-STORM), tropical continental (Darwin break monsoon regime), and tropical oceanic (onshore monsoon flow regime), two different MCSs were selected from each regime. For each MCS case, volume scans from two different times were selected for analysis. Each volume scan was required to contain a number of individual convective cells, predominantly in the mature stage of cell development, with a time difference of at least 30 min between volume scans to ensure that the same cells were not being counted twice.

TABLE 1. Radar characteristics of the CP-3 and CP-4 radars as used in PRE-STORM and the NOAA–TOGA radar as used at Darwin, adapted from Rutledge and MacGorman (1988) and Rutledge et al. (1992).

Characteristic	CP-3/CP-4	NOAA/TOGA
Wavelength (cm)	5.45/5.49	5.30
Peak power (kW)	400	250
Number of gates	512	171
Gate spacing (m)	260	1000
Maximum elevation angle	58°	25°
Beamwidth	1.0°	1.65°
Vertical beam dimension (beamwidth X range) at range of		
10 km	0.2 km	0.3 km
30 km	0.5 km	0.9 km
60 km	1.0 km	1.7 km
80 km	1.4 km	2.3 km
100 km	1.7 km	2.9 km

Table 1 also illustrates the most restrictive criterion, that the vertical dimension of the radar beam must be less than 2 km and preferably less than 1.5 km. This was not difficult to meet for the PRE-STORM cases, because the beamwidth of the NCAR radars is 1.0° and the preferred 1.5-km figure could be met within a range of 80 km. The larger beamwidth (1.65°) of the TOGA radar restricted the maximum range to about 60 km. An additional restriction, not as serious, was imposed by the maximum elevation angle of 25° for the TOGA volume scans, so the minimum slant range to the cells was about 25 km to ensure data coverage to an altitude of at least 12 km. The combined effect of these restrictions was that the case selection from the TOGA radar was severely limited.

The cases chosen to represent the three regimes are outlined in Table 2. The two cases from PRE-STORM are thought to be representative of strong squall lines, neither producing particularly severe weather when studied. The 11 June storm has been studied very extensively (Rutledge et al. 1988; Rutledge and MacGorman 1988; Johnson and Hamilton 1988; Biggerstaff and Houze 1991). The 28 May and 11 June systems had similar lightning flash rates (Rutledge et al. 1990). Neither of the two examples of continental Darwin storms were as strong as some of the individual storms cited in the literature (e.g., Williams et al. 1992) but they are probably representative of squall line systems propagating to the coast during the night and slowly weakening. The two examples of extensive monsoon regime MCSs appear to be representative, although the convective cells appear to have somewhat lower reflectivities than some of the MCSs that were observed during the Equatorial Mesoscale Experiment (EMEX).

The reflectivity data were obtained in polar coordinates; they were interpolated to Cartesian grids of either 1.0- or 1.5-km resolution in the horizontal and 0.5 km in the vertical. The interpolated data were used to generate contour plots at 0.5-km intervals in the vertical from 0.9 to 14.9 km. The SPRINT and CEDRIC routines developed at NCAR (Mohr and Vaughn 1979; Mohr and Miller 1983) were used to perform the above operations.

Using the contour plots, cells were defined as relative maxima in the fields of (equivalent radar) reflectivity on the convective scale. Based on the differences in characteristic reflectivities for the different regimes, it was necessary to choose somewhat different dBZ thresholds: 40 dBZ for midlatitude and 35 dBZ for tropical cells. Once selected, a uniform procedure was developed to construct the VPRR of all convective cells selected for this paper.

Cells were selected based on the contour plots at 4.4-km altitude for the midlatitude cells and 3.9 km for the tropical cells. The idea was to select the lowest altitude for which one could easily distinguish the convective-scale maximum from the adjoining reflectivities in a squall line or other MCSs.

Vertical profiles of maximum reflectivity within boxes centered on the horizontal grid point of maximum reflectivity at the 4.4-km level (3.9-km level for the tropical cases) were constructed. Boxes of 4 km × 4 km, 6 km × 6 km, and 8 km × 8 km dimension were tested and compared with a vertical profile determined by inspection using each level in the vertical and selecting the local maximum manually. The 8 km × 8 km box was selected as the standard after examining samples of six cells from each of the three regimes. The smaller boxes were not always large enough to ensure that the cell remained in the box at all altitudes, and the 8 km × 8 km box hardly ever was so large that an adjacent cell intruded into the box. An example of

TABLE 2. Number of cells selected by date and time.

Midlatitude continental cases: PRE-STORM experiment: total 57 cells		
11 June 1985	0139 UTC	21
	0209 UTC	12
28 May 1985	1120 UTC	13
	1148 UTC	11
Tropical oceanic cases: Darwin: total 41 cells		
18 December 1987	1837 UTC	9
	1908 UTC	9
1 December 1988	2012 UTC	10
	2039 UTC	13
Tropical continental cases: Darwin: total 44 cells		
13 January 1988	1733 UTC	11
	1802 UTC	13
16 January 1988	1602 UTC	8
	1820 UTC	12

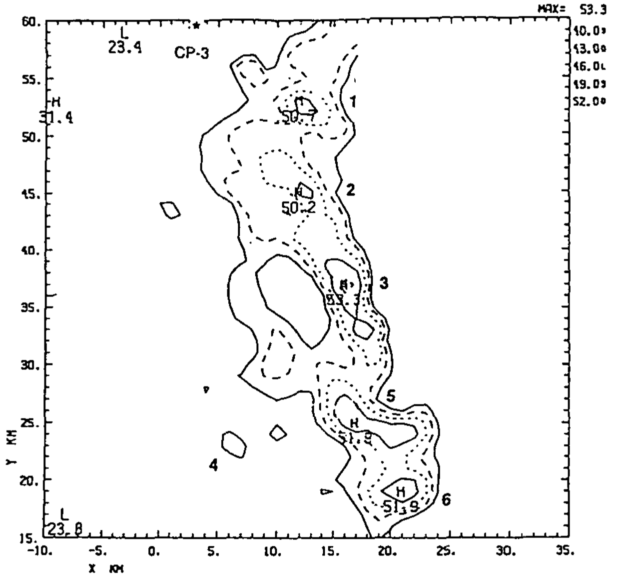

FIG. 1. Reflectivity contour plot at 4.4-km height from a portion of the 10–11 June 1985 PRE-STORM squall line at 0139 UTC. Contours are in 3-dBZ increments, with a minimum value of 40 dBZ. The six local maxima of reflectivity are six of the cells selected.

a reflectivity field used to select cells and a comparison of the manual and automatic VPRR methods of computation are given in Figs. 1 and 2. We believe that there is no significant difference between the results using the two methods; the specific examples in Fig. 2 are near-worst cases. Later, in comparing the results with the Szoke et al. (1986) results, some differences in the low-level profiles may be introduced by their cell selection having been made at the lowest altitude, while here it is made near the 0°C level.

3. Results and discussion

a. Comparison of VPRR in different regimes

The median VPRR for each of the three different regimes is given in Fig. 3 for comparison purposes. The midlatitude and tropical continental profiles both have a maximum reflectivity somewhat above the surface and a gradual decrease in reflectivity with height above the freezing level. In sharp contrast, the tropical oceanic profile has a maximum reflectivity at the lowest level and a very rapid decrease in reflectivity with height beginning just above the freezing level.

How does the VPRR for the Darwin monsoon regime compare with that for convective cells in other tropical oceanic areas? Figure 4 compares the Darwin results with the profiles from GATE (Szoke et al. 1986) and TAMEX (Jorgensen and LeMone 1989). There are remarkable similarities, most notably the rapid decrease in reflectivity with height beginning just above the freezing level. The differences in absolute value of the reflectivity are not judged to be significant, because they could be explained as an effect of small sample size or calibration differences or both.

This study, by carefully preserving lower reflectivity values that are characteristic of the upper troposphere, is able to demonstrate and quantify something that we know from case studies. It is that the rapid decrease in reflectivity above the 0°C level does not signify a low storm top but rather a very deep layer of low reflectivity.

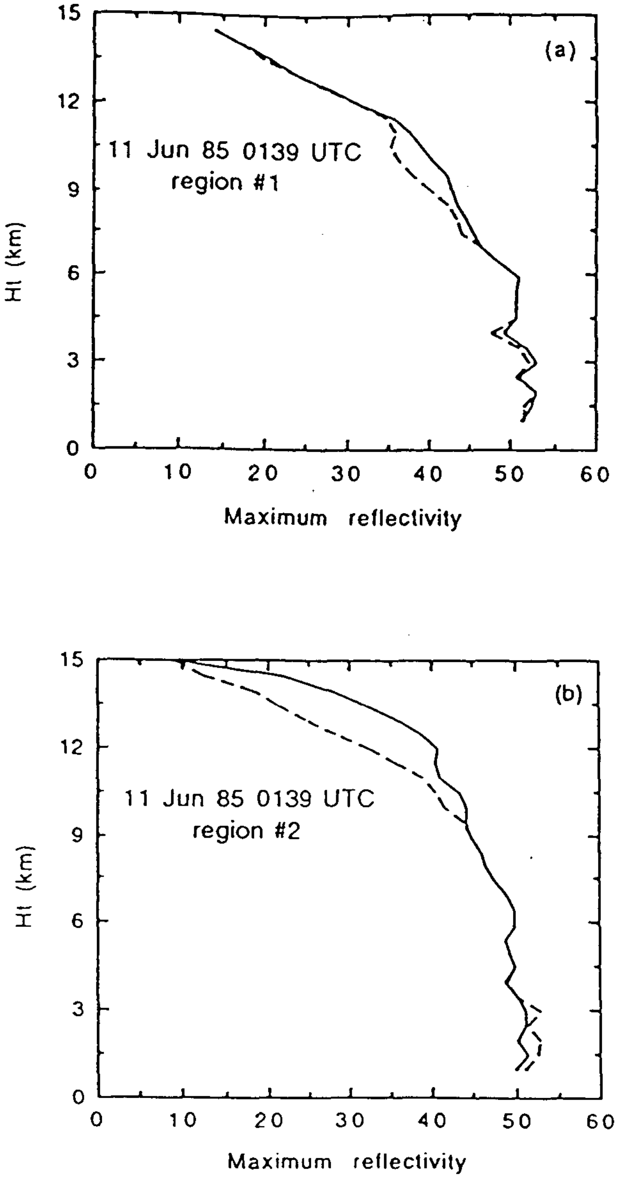

FIG. 2. VPRR as a function of height determined by following local reflectivity maxima manually (solid) and by the automatic selection of the maximum at each level in an 8 km × 8 km box centered on the cell at 4.4 km. Regions 1 and 2 are cells 1 and 2 of Fig. 1.

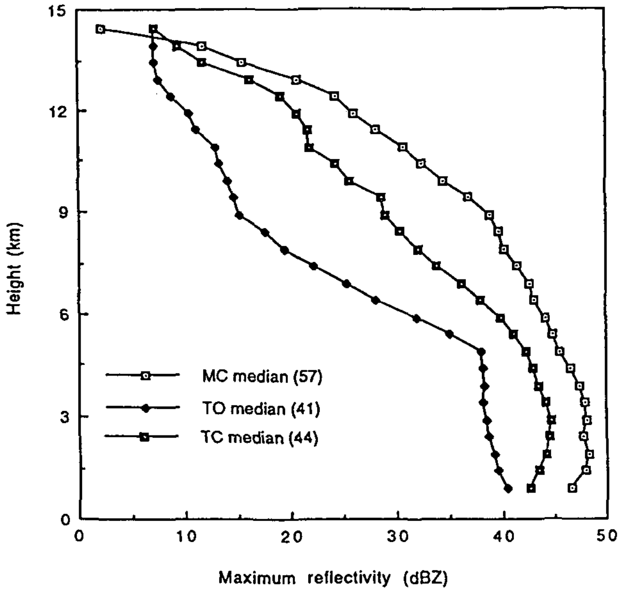

FIG. 3. Median VPRR from convective cells in the 41 tropical oceanic (TO) MCS events studied, 44 tropical continental (TC) MCS events studied, and 57 midlatitude continental (MC) MCS events studied.

For example, the well-documented GATE case of day 257 [Zipser et al. (1981)—note especially their Figs. 9 and 10—and Szoke et al. (1986)—note especially their Fig. 8] had numerous radar cells containing reflectivities greater than 40 dBZ, convective cloud tops to at least 13 km, but not a single instance of a 20-dBZ echo extending above 8 km. Similar reflectivity profiles for monsoon regime storms in the Darwin area are shown in the examples in Williams et al. (1992). While absolute values of reflectivity are somewhat greater than for the GATE example, the shape of the VPRR matches the typical oceanic examples; rapid decrease in reflectivity just above the freezing level, with a deep layer of low reflectivity through the upper troposphere.

In agreement with Szoke et al. (1986), Rutledge et al. (1992), and Williams et al. (1992), we interpret these results as evidence for near-complete glaciation and near absence of large particles in the upper troposphere. In extensive sampling in hurricane clouds, Black and Hallett (1986) report that even at temperatures as warm as −2° to −5°C the dominant microphysical conditions are low supercooled liquid water content, high concentrations of small ice particles (<0.5 mm), and near absence of large ice particles (>1.05 mm). Zipser and LeMone (1980) showed that the GATE convective cells had low vertical velocities, too weak to lift raindrops through the freezing level, and speculated that the VPRR would have the characteristic shape cited above for oceanic cells. Jorgensen and LeMone's (1989) and Lucas and Zipser's (1994) results show that these weak vertical velocities are characteristic of many oceanic regimes around the world; Fig. 4 makes it plausible to conclude that the characteristic oceanic cell, not coincidentally, has a correspondingly "weak" VPRR. Szoke and Zipser (1986) studied the life history of 43 cells in GATE and their VPRR, concluding that a random sample of cells with high reflectivity at low levels would yield VPRR statistics very similar to those of mature cells; that is, the occasional inclusion of cells very early or very late in their lifetimes did not yield a seriously biased result.

b. *VPRR as an indicator of strong convection and/or electrification*

In comparing the VPRR statistics taken from different regions, we wish to place the emphasis upon the vertical derivative of reflectivity in the middle and upper troposphere, not simply the absolute values of reflectivity. Particular focus is on the behavior of the profiles in the temperature range from 0° to −20°C. For the PRE-STORM cases, the freezing level is near 3.9 km, and for both tropical regimes it is near 4.9 km. Examination of soundings from each regime shows that to good approximation the environmental lapse rate is such that the −20°C level is 3.0 km higher than the 0°C level.

We contrast the radar datasets in the different regimes by comparing the reflectivity decrease between the 0° and −20°C levels. The result is given in Table

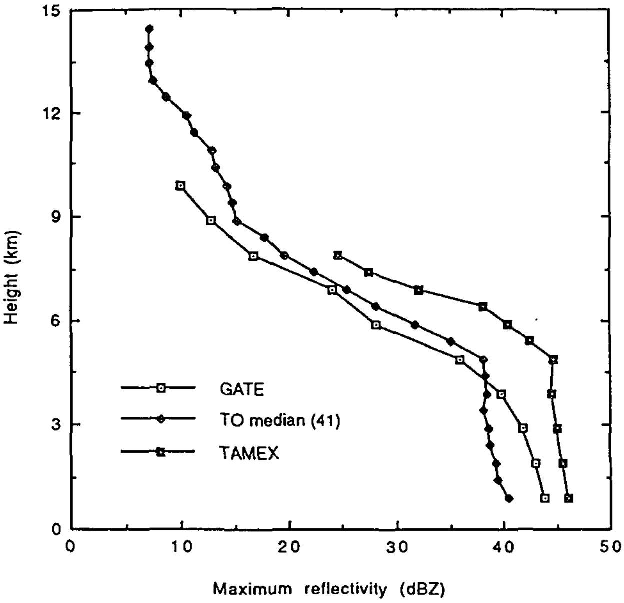

FIG. 4. Comparison of the tropical oceanic (TO) median VPRR from this study with the median VPRR of convective cells in GATE and with the top 10% of convective cells from TAMEX.

TABLE 3. Median reflectivity lapse rate (defined as the negative of the vertical gradient of reflectivity) for the 3-km interval above the freezing level—that is, between 0° and -20°C, for radar data samples from different regimes.

Data from	Reflectivity lapse rate between 0° and -20°C
Darwin. Monsoon oceanic regime. (TO, this study)	6.5 dBZ km^{-1}
GATE. Oceanic regime. (Szoke et al. 1986)	6.0 dBZ km^{-1}
TAMEX. Oceanic regime. (Top 10%; Jorgensen and LeMone 1989)	6.0 dBZ km^{-1}
Darwin. Continental, monsoon break regime. (TC, this study)	3.5 dBZ km^{-1}
New England rainstorms. (Donaldson 1961)	2.0 dBZ km^{-1}
OK PRE-STORM squall lines. (MC, this study)	1.5 dBZ km^{-1}
New England hailstorms. (Donaldson 1961)	1.3 dBZ km^{-1}

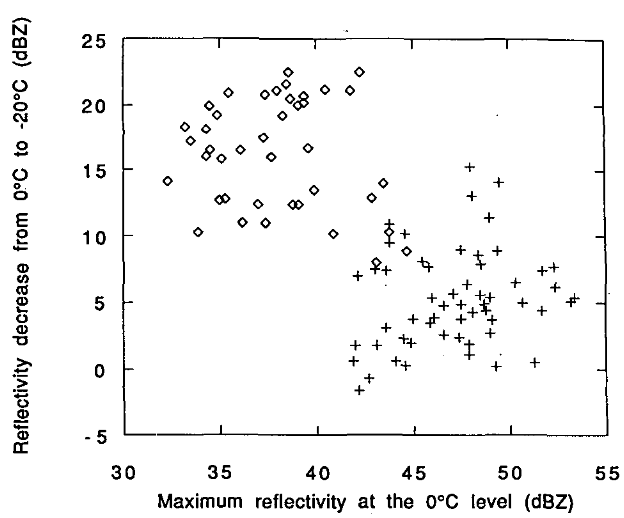

FIG. 5. Scatter diagram of the decrease in reflectivity with height over the lowest 3 km above the freezing level versus the maximum reflectivity at the freezing level for the tropical oceanic cells (diamonds) and the midlatitude continental cells (crosses).

3, showing that the *reflectivity decrease with height, in this critical temperature range for tropical oceanic convective cells, is much greater than that for "typical" midlatitude continental thunderstorm cells, by a factor of 3 or 4.* The inaccuracy introduced by assuming a mean temperature decrease of 20°C (3 km)$^{-1}$ is very slight compared with the gross differences in behavior of the VPRRs from the different regimes. In any case, the effect of a slightly different temperature sounding would be that reflectivity decreases would apply to a temperature range whose upper and lower limits would be no more than a few degrees different from 0° to -20°C.

We shall now ask whether these major differences in reflectivity profiles are consistent with the known differences in lightning frequency in the different regimes. We have no direct microphysical measurements in any of these storms, so we simply evaluate the reflectivity values for each storm in the mixed-phase region and compare them with suggested threshold values for lightning in the published literature.

Following many others, we adopt as a working hypothesis that an ice–ice collision process in the presence of supercooled water is primarily responsible for thunderstorm electrification (e.g., Jayaratne et al. 1983; Illingworth 1985; Krehbiel 1986; Williams 1989). No attempt is made here to differentiate between specific microphysical theories (see e.g., Williams et al. 1991; Dong and Hallett 1992). Laboratory and field studies (e.g., Takahashi 1978, 1990; Dye et al. 1986; Dye et al. 1989) lead to the conclusion that large, riming graupel particles are present in the -10° to -20°C range when rapid charge separation occurs. Dye et al. (1989) show that large electric fields (>1 kV m^{-1}) were always preceded by radar reflectivities exceeding 40 dBZ at the -10°C level in a large sample of New Mexico storms. They carefully noted, however, that the threshold might be different in regions with more extensive warm rain in the lower part of the clouds.

Figures 5 and 6 are scatter diagrams showing both the absolute value of reflectivity at the freezing level and the lapse rate of reflectivity (defined, as for temperature and the negative of the vertical gradient) over the lowest 3 km above the freezing level (a good approximation to the 0° to -20°C range) for each cell in each of the three regimes.

The tropical ocean cells and the midlatitude continental cells (Fig. 5) occupy different regions of the

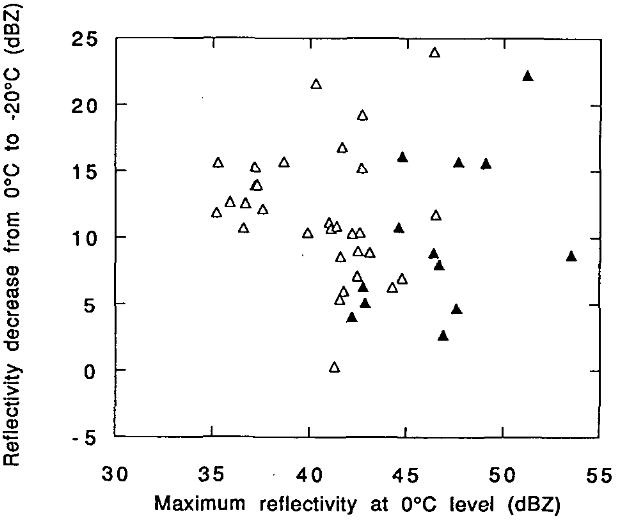

FIG. 6. As in Fig. 5 except for the tropical continental cells studied. The filled symbols represent cells that exceeded 40 dBZ at 6.4 km (-10°C level).

parameter space with nearly no overlap. It is particularly interesting to note the specific characteristics of the near-overlap region. The *strongest* few cells from the tropical ocean set and the *weakest* few cells from the midlatitude continental set have reflectivities near 45 dBZ at the freezing level and a reflectivity lapse rate near 10 dBZ (3 km)$^{-1}$. The −10°C level is about 1.5 km above the freezing level; therefore, the reflectivity at the −10°C level is about 40 dBZ, the threshold found by Dye et al. (1989) for rapid electrification.

We have examined the reflectivity of each cell at the nominal −10°C level. Of the tropical ocean cells, 1 of 41 exceeded 40 dBZ; of the midlatitude continental cells, 55 of 57 exceeded 40 dBZ (the other 2 exceeded 39 dBZ). They are indeed very nearly nonoverlapping datasets. The dataset for the tropical continental cells (Fig. 7) straddled the boundary between the other two datasets, with 14 of 44 exceeding 40 dBZ at −10°C. We believe that the specific tropical continental cells that we sampled were weaker than the average for this region; the restrictive conditions for an acceptable sample dictated using two squall line systems that were decreasing in intensity as they approached the radar site.

With due respect for the complexity of convective clouds, and their microphysics and electrification processes, we are encouraged to suggest that cells in the lower right part of the parameter space have a good chance of producing lightning, while those in the upper left part do not. In a statistical sense, if the rather small sample we have studied is representative, these results are consistent with the observations already cited that the monsoon regime and other tropical oceanic regimes have little lightning (Orville and Henderson 1986; Goodman and Christian 1992; Zipser 1994), while the continental regimes have a great deal of lightning. In the Darwin area, the continental (break regime) storms are often observed to have very high lightning flash rates. In spite of our specific sample likely being weaker than average, a substantial fraction of the cells exceed the 40 dBZ at −10°C "threshold," as seen in Fig. 6.

c. Hypotheses for testing

There is strong evidence that the updraft velocities in convective cells in MCSs over tropical oceans tend to be much weaker than those over land. In each dataset studied, the updraft speeds tend to follow a lognormal distribution, and comparisons show that the oceanic cells from different parts of the world are about equally weak, about a factor of 2–3 weaker than the Thunderstorm Project cells (Fig. 7). As the cited papers for Fig. 7 already note, it is plausible that the oceanic cells can neither lift large raindrops through the freezing level nor support large graupel above the freezing level. Further, it is rare to find large concentrations of supercooled liquid water in these "typical" oceanic cells (Black and Hallett 1986; Jorgensen and LeMone 1989). Therefore, there should be an absence of large raindrops *and* an absence of large ice particles, and the radar reflectivity in such cells *must* decrease rapidly above the 0°C level.

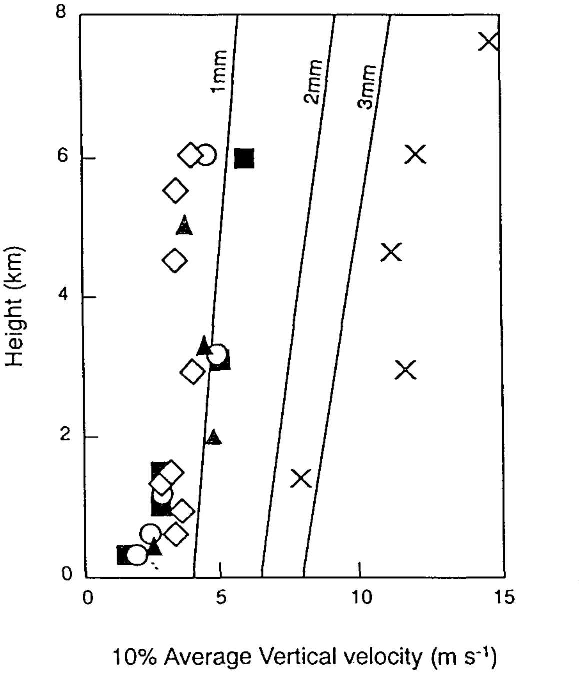

FIG. 7. Average vertical velocity in the strongest 10% of updraft cores over tropical oceans [triangles, EMEX, Lucas and Zipser (1994); circles, GATE, Zipser and LeMone (1980); diamonds, hurricanes, Jorgensen et al. (1985); squares, TAMEX, Jorgensen and LeMone (1989)] and over land [crosses, Thunderstorm Project, adapted from Zipser and LeMone (1980)]. The lines show terminal fall speeds of raindrops as a function of height, adapted from Gunn and Kinzer (1949) and Foote and DuToit (1969), after Lucas and Zipser (1994).

It is worth noting that there is some evidence for high vertical velocities in the upper troposphere in oceanic convective clouds. Typically these come from remote sensing, such as the vertically pointing wind profiler data cited in Balsley et al. (1988). Velocities greater than 10–12 m s^{-1} were observed rather frequently in the upper troposphere by the NOAA WP-3D Doppler radar during EMEX (R. Houze and B. Mapes 1992, personal communication). We agree with Ooyama (1990), Williams and Renno (1993), and others that release of latent heat of fusion could well be responsible for renewed buoyancy and upward acceleration above about the −10°C level in many oceanic clouds. This is an important issue but beyond the scope of this paper. Its relevance to this discussion is that oceanic storms may well exist with the customary weak updrafts in the mixed-phase region but with much stronger updrafts above, in the upper troposphere, which may not exhibit electrical activity.

It is well established that most tropical oceanic cumulonimbus clouds have weak updrafts. We hypothesize that if these updrafts remain below a threshold value, yet unspecified, in the 0° to −20°C range, that there will be two important consequences. One, there will be a characteristically weak VPRR, resembling those of Fig. 4. Two, the mixed-phase region will be dominated by small ice particles, which will compete for a rather small amount of supercooled liquid water, and there will not be enough large, riming ice particles for rapid electrification, and there will be no lightning.

If the preceding hypothesis is correct, such that a threshold vertical velocity for electrification exists, we can use the results of Figs. 5–7 to estimate its magnitude. Examining Fig. 7, in the light of the new evidence of Figs. 5 and 6, we propose that to a first approximation, convective cells with updrafts below the strongest 10th percentile over tropical oceans are too weak and that most of those of Thunderstorm Project strength are strong enough to lift or generate the necessary large ice particles and riming conditions needed for lightning. The fact is that there is lightning over tropical oceans; it is just not very frequent. The fact is that not all convective storms over land produce lightning but a high fraction of them do. We suggest, tentatively, that the threshold value for vertical velocity should be closer to the oceanic data than the continental data in Fig. 7 and that an updraft with a mean vertical velocity in the 0° to −20°C temperature range should exceed 6–7 m s^{-1} for significant electrification to occur. Following LeMone and Zipser (1980), Jorgensen and LeMone (1989), and Lucas and Zipser (1994), such an updraft would have peak speed of 10–12 m s^{-1}.

An updraft with diameter 2–3 km, average speed 6–7 m s^{-1}, and maximum speed 10–12 m s^{-1} would (Fig. 7) be capable of balancing raindrops with diameters in the 1.2–2.5-mm range. This is considerably stronger than the 10th percentile updraft over tropical oceans. We suggest that updrafts near this strength are near a bifurcation point, such that cloud microphysical properties in the cell are very different below and above this threshold. It remains to be seen whether further study will confirm or refute the notion of a simple threshold for either vertical velocity or for radar reflectivity profiles as an indicator of lightning. The TOGA COARE (Coupled Ocean–Atmosphere Response Experiment) database will be suitable for testing these ideas, using ship and aircraft in situ and Doppler radar data, and the first lightning detection network over the equatorial oceans.

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