A Radar and Electrical Study of Tropical "Hot Towers"

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13 March 1991 and 25 November 1991

ABSTRACT

Radar and electrical measurements for deep tropical convection are examined for both "break period" and "monsoonal" regimes in the vicinity of Darwin, Australia. Break period convection consists primarily of deep continental convection, whereas oceanic-based convection dominates during monsoonal periods, associated with the monsoon trough over Darwin. Order-of-magnitude enhancements in lightning flash rates for the "break period" regime are associated with 10–20-dB enhancements in radar reflectivity in the mixed-phase region of the convection compared with the monsoonal regime. The latter differences are attributed to the effect of convective available potential energy (CAPE) and its nonlinear influence on the growth and accumulation of ice particles aloft, which are believed to promote charge separation by differential particle motions. CAPE, in turn, is largely determined by the boundary-layer wet-bulb temperature. Modest differences (1°–3°C) in wet-bulb potential temperature between land and sea may account for the order-of-magnitude contrast in recently observed land–ocean lightning activity.

1. Introduction

This paper is concerned with a radar and electrical study of cumulonimbus clouds in the vicinity of Darwin, Australia, located in the southern portion of the Maritime Continent. These observations were carried out as part of the Down Under Doppler and Electricity Experiment (DUNDEE), conducted during the periods of November 1988–February 1989 and November 1989–February 1990. (A description of the DUNDEE program can be found in Rutledge et al. 1992.) Darwin's location at 12°S latitude was well suited for this study, since it allowed observations of two distinctly different cumulonimbus regimes over the course of the wet season: the classical "hot towers" (Riehl and Malkus 1958) embedded in the monsoonal convection on the axis of the equatorial trough (henceforth to be termed "monsoon" convection), and the more vigorous and more sparsely distributed thunderstorms displaced from the axis of the equatorial trough (henceforth to be termed "break period" convection) (Holland 1986). Attention is given to thermodynamic and microphysical explanations for the pronounced differences in electrical activity between the "break period" and "monsoonal" regimes, which will prove useful in accounting for the order-of-magnitude contrast between continental and oceanic lightning (Kotaki and Katoh 1983; Orville and Henderson 1986) on a global scale.

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2. Radar and electrical observations

Doppler radar and electrical observations of break period and monsoonal convection were carried out during the two consecutive seasons of DUNDEE. Two Doppler radars were used in DUNDEE, the MIT and NOAA TOGA (Tropical Ocean and Global Atmosphere) C-band radars, which permitted dual-Doppler observations of convective storms. The operational characteristics of these radars are given in Table 1. These coordinated observations were interspersed with shorter periods of independent RHI (Range–Height Indicator) scanning with both radars for purposes of "snapshot" documentation of the vertical development of the regions of convection. Low-level PPI (Plan-Position Indicator) scans were also obtained with the MIT radar at intervals of 10–20 minutes for purposes of estimating the total mass flux associated with radar-observed precipitation.

Rainfall data from a network of 30 gages in the vicinity of Darwin (Keenan et al. 1988; Short et al. 1989) were used in placing a lower bound on the latent heat released in storms observed by radar. These gage locations are shown in Fig. 1.

The electrical activity in the Darwin region was documented through measurements of both total lightning flash rate and cloud-to-ground (CG) flash rate. Total

TABLE 1. Characteristics of the MIT and TOGA radars used in DUNDEE.

Characteristic	MIT	TOGA
Wavelength (cm)	5.4	5.3
Peak power (kW)	250	250
Pulse length (μs)	1.0	0.50, 1.9
Beamwidth (deg) (at 3 dB points)	1.4	1.65
Minimum detectable signal (dBm)	−106	−113
Pulse repetition frequency (s^{-1})	921	921
Number of gates	512	224
Polarization	Horizontal	Horizontal

lightning rates were determined by field change measurements with a flat-plate antenna at the MIT radar site, and by a mesonetwork of corona points during the 1988/89 season. The useful detection range for electric field change from the flat-plate antenna was about 40 km and about 10–15 km from individual corona points. Detection of cloud-to-ground lightning was afforded by a single station LLP (Lightning Location and Protection, Inc.) sensor at the MIT radar in 1988–89, and by a network of four LLP direction finders in 1989–90. These sensors are shown on the map in Fig. 1. The area of detection with the latter network ($\gtrsim 10^5$ km^2) exceeded the area of radar surveillance (4×10^4 km^2).

Regular radiosoundings taken at the Darwin airport (1000 UTC and 2200 UTC) and separate soundings at more opportune times from the MIT radar site (using an NCAR OMEGAsonde system) were used in the evaluation of convective available potential energy (CAPE) (Moncrieff and Miller 1976) for selected cases in both monsoonal and continental convection. The lightning activity and convective structure were found to be sensitively related to CAPE, which in turn will be shown to be sensitively influenced by modest changes in wet bulb temperature in the subcloud layer.

3. Comparisons of precipitation structure in monsoonal and continental convection

A good sample of both monsoonal and continental ("break period") convection was obtained during the two wet seasons of observation. The radar observations of the vertical development of convection in the two regimes show important differences that will be linked to notable differences in lightning activity. Figures 2 and 3 show radar RHI scans for selected cases of continental and monsoonal convection, respectively. These scans were taken close to times and azimuths of maximum vertical development and lightning rate. The flash rates in the continental towers were generally an order of magnitude larger than the flash rates in the monsoon. For the specific continental cases in Fig. 2, the maximum total flash rates were 60 min^{-1} (10 January 1989), 11 min^{-1} (8 January 1990), and 40 min^{-1} (with a 5 min^{-1} peak ground flash rate) for 6 February 1989. For the monsoon examples in Fig. 3, the peak flash rates were 3 min^{-1} for the 30 November 1988 case and zero for 10 January 1990. For the 28 January case of offshore deep convection, the most active monsoon example documented in Darwin, the total lightning sensor was not functioning in the heavy stratiform precipitation over the radar, but the LLP equipment indicated a peak ground flash rate of 3 min^{-1}. The monsoon "hot towers" are embedded in stratiform precipitation whose areal extent can exceed that of embedded towers by 1–2 orders of magnitude. The continental hot towers selected for study were isolated, with radar diameters at midlevels that are only about half the cell depths. Both monsoon and continental towers can grow to considerable depth (15–20 km), but whereas the monsoonal convection exhibits radar reflectivity of 10–30 dBZ in the mixed-phase region (where 0°C $\geq T \geq$ −40°C), the continental towers often show 30–50 dBZ. In the monsoon cases, the radar observations suggest that a large fraction of the precipitation forms beneath the melting layer over a large fraction of the precipitation area. Direct measurements of Doppler radial velocity at near vertical incidence show peak values of 10–15 m s^{-1} for the vigorous monsoon tower observed on 30 November 1988, with values of 1–10 m s^{-1} more frequent, whereas maximum velocities of 20–40 m s^{-1} were recorded in continental cases (10 November 1988, 10 January 1989).

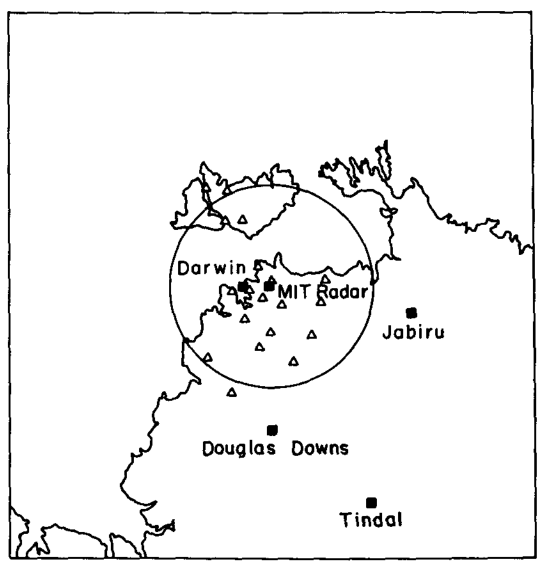

FIG. 1. Map showing the vicinity of Darwin, N.T., on the northern coast of Australia, including locations of the MIT Doppler radar, direction finders for cloud-to-ground lightning (labeled squares) and raingages (triangles). Precipitation and ground flash totals are estimated within the circular region surrounding the MIT radar (radius: 113 km).

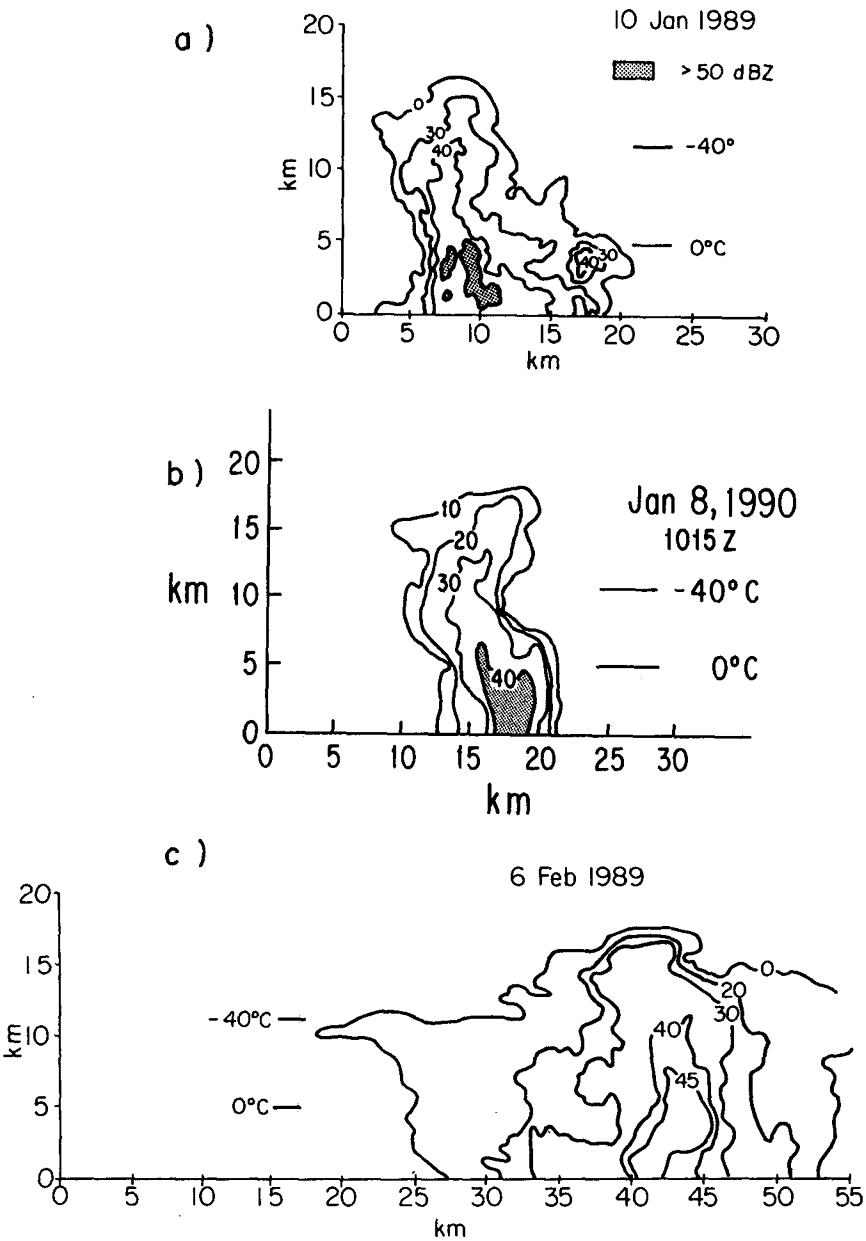

FIG. 2. Radar vertical cross sections (RHIs) through selected examples of continental convection. (a) 10 Jan 1989, (b) 6 Feb 1989, and (c) 8 Jan 1990.

4. Comparisons of precipitation and lightning yields from monsoon and continental convection

The total rainfall over a circular area of 4×10^4 km^2 around the MIT C-band radar was estimated with both the radar and the raingage network shown in Fig. 1 for selected days of continental and monsoon convection. Reflectivity values from the 0.7° elevation PPI scan to a maximum radius of 113 km were converted to rainfall rate using the fixed Z–R relation

$$Z = 400R^{1.3}$$

where Z has units of mm^6 m^{-3} and R is expressed in mm h^{-1}. This Z–R relation has been used previously in New England thunderstorms (Austin 1987), and has been found to agree closely with disdrometer–raingage measurements in Darwin. The rainfall rates were integrated over the scan area to produce mass flux estimates in kilograms per second. These scan-to-scan estimates were then integrated over the course of a day

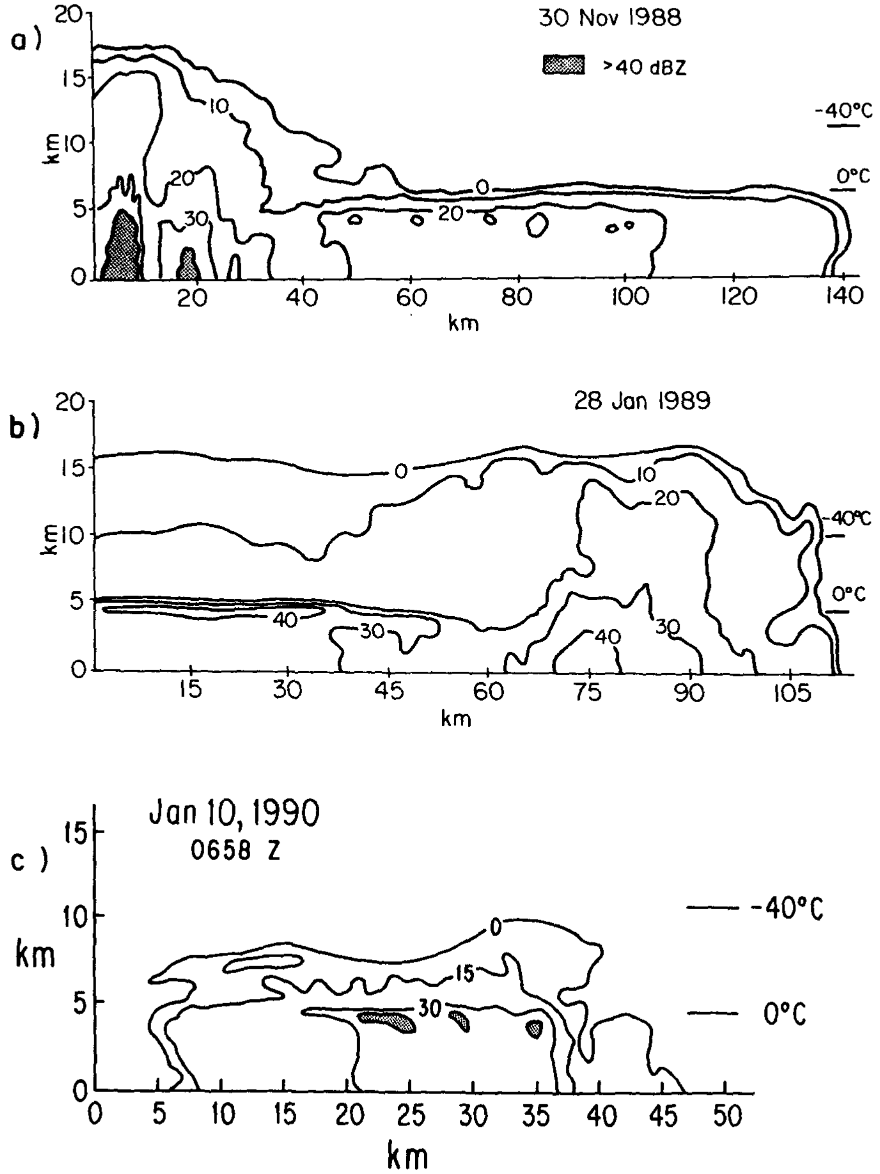

FIG. 3. Radar vertical cross sections (RHIs) through selected examples of monsoonal precipitation with embedded "hot tower" convection. (a) 30 Nov 1988, (b) 28 Jan 1989, and (c) 12 Jan 1990.

(0000 UTC to 2400 UTC) to obtain total precipitation yields in kilograms.

The problems with attenuation at C band are well recognized (Geotis 1975; Austin 1987) and comparisons of the radar-derived precipitation yields with values obtained from the raingage network for three cases of widespread convection at Darwin (28 January, 2 February, and 11 February 1989) showed that the radar-derived precipitation compared to gage-measured amounts was low by a factor that ranged from 4.5 to 5. A recent investigation of the adequacy of commonly used attenuation rates (e.g., Geotis 1975) at 5 cm based on radar data collected by the TOGA radar at Darwin has been reported by Wolfe et al. (1991). Their radar rain estimates were based on relations between radar-observed reflectivity Z_e and gage-measured rain rates R using the probability matching method (PMM) (Calheiros and Zawadski 1987). Radar estimates of rainfall were found to be, on average, a factor of 3.94 lower than gage-derived rates, which led Wolfe et al. (1991) to conclude that previously published attenuation rates are not valid for the tropical site at Darwin.

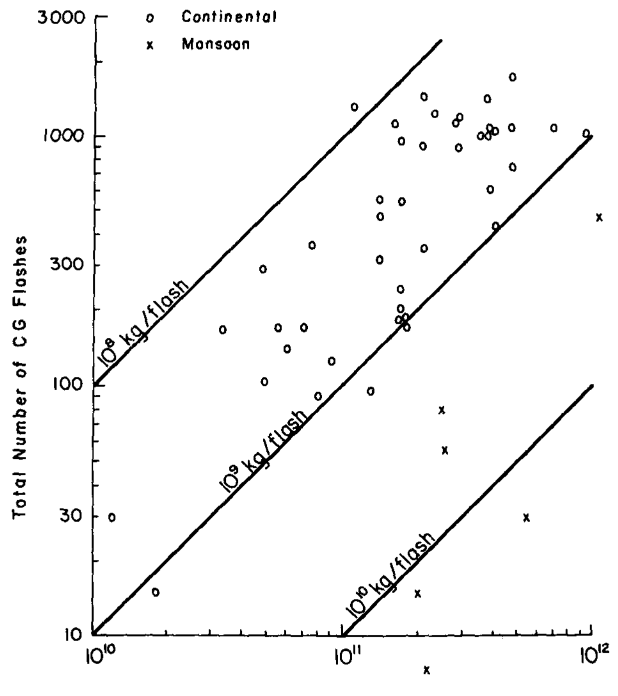

FIG. 4. Comparisons of total precipitation yields and cloud-to-ground lightning yields for selected days from the wet seasons 1988/89 and 1989/90. Diagonal lines represent constant precipitation yields per CG flash. The error bar on precipitation yield is a factor of 2–3. The error bar on cloud-to-ground lightning is 30%.

The study by Wolfe et al. (1991) provides independent support for our correction factor of 4–5 based on individual radar–gage intercomparisons. On the basis of our radar–raingage comparisons and the work of Wolfe et al. (1991), all radar-derived precipitation estimates were inflated by a factor of 5 for those storms that proved too isolated or heterogeneous to be resolved accurately by the gage network. It should be recognized that all such precipitation estimates are probably uncertain by a factor of 2–3. The estimates of total water yield for several days, with examples from the monsoon and from both squall lines and isolated thunderstorms in the continental regime, are shown in Fig. 4. The total yields range from values of 4–8 $\times$ 10^{10} kg for isolated continental thunderstorms to values of 5 $\times$ 10^{11} kg for squall lines to a value approaching 10^{12} kg for vigorous monsoon events (28 January 1989).

Total lightning flash rates were recorded in the Darwin storms, as discussed in section 2, but the range of detection (30–40 km) was substantially less than both the range of radar surveillance and the range covered by the CG lightning network in Fig. 1. The determination of CG locations on a large scale ($\gtrsim 10^5$ km^2) led to their use as a measure of the electrical activity for the two convective regimes.

The total number of CG flashes detected by the network within the 4 $\times$ 10^4 km^2 area of radar surveillance are compared with the precipitation yields in Fig. 4 for individual days from two wet seasons. Both the monsoon and continental cases exhibit a wide range of values for both precipitation and lightning yields. It is noteworthy, however, that most continental cases (squall lines and individual thunderstorms alike) are located in the upper part of the diagram, while the monsoon cases are systematically offset to the lower part of the diagram. Roughly, an order of magnitude more precipitation accompanies each lightning flash in the monsoon (5 $\times$ 10^9 kg/flash) than in the continental regime (5 $\times$ 10^8 kg/flash). This result was anticipated qualitatively on the basis of the comparisons in precipitation structure noted in the RHI cross sections in Figs. 2 and 3, which emphasize the contribution to total rainfall from the broad and persistent stratiform regions associated with monsoon convection.

5. The role of convective available potential energy

The dramatic differences in structure between continental (Fig. 2) and monsoon convection (Fig. 3) and the lightning activity in Fig. 4 are believed to be caused by differences in conditional instability. This section is concerned with evaluations of the convective available potential energy (CAPE) in the vicinity of Darwin, and with its rather sensitive dependence on the thermodynamic properties of boundary-layer air.

CAPE is represented by the positive area bounded by the temperature sounding and the wet-bulb adiabat,

$$\mathrm{CAPE} = \int_{\mathrm{LFC}}^{\mathrm{LNB}} (T_{\mathrm{vp}} - T_{\mathrm{va}}) R_d d \ln P,$$

where LFC is the level of free convection, LNB is the level of neutral buoyancy, and T_{vp} and T_{va} are the virtual temperatures of the parcel and the environment, respectively; R_d is the gas constant for dry air and P is pressure.

Figure 5 shows calculated values of CAPE and corresponding values of surface wet-bulb temperature for a large number of consecutive soundings (four per day) during the Australian Meteorological Experiment (AMEX) (January–February 1987) for Darwin. No distinction is made here between continental and monsoonal regimes. Pseudoadiabatic ascent from the surface was assumed in the calculations. Contrary to the assumptions implicit in the pseudoadiabatic calculations, the radar observations of "hot towers" show evidence for substantial condensate well above the 0°C isotherm. It has been shown, however, that CAPE values following reversible thermodynamics that includes the ice phase are not substantially different from the pseudoadiabatic results (Williams and Renno 1992). With rather modest variance, CAPE is seen to increase

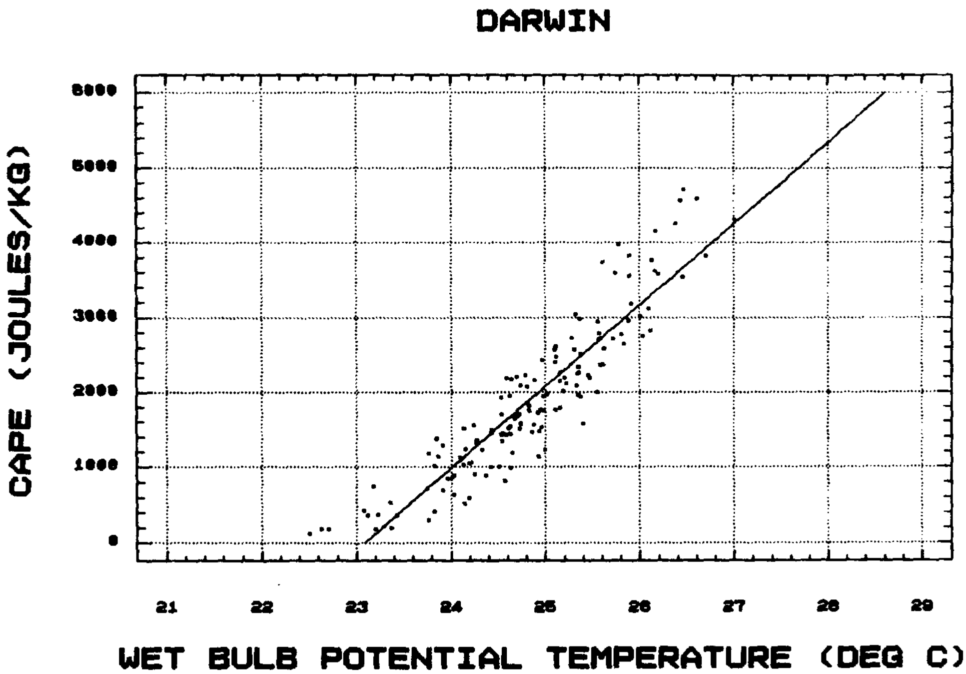

FIG. 5. CAPE versus surface wet-bulb temperature for Darwin from AMEX soundings.

roughly linearly with wet-bulb potential temperature Θ_w. The slope of the line of best fit shows that a 1°C change in wet-bulb potential temperature results in a change in CAPE of about 1 kJ kg^{-1}. A CAPE value of 1 kJ kg^{-1} is equivalent to 45 m s^{-1} of maximum updraft strength following parcel theory.

For comparison with the results in Fig. 5, Fig. 6 shows the behavior of maximum daily wet-bulb temperature, T_w (surface measurements), at Darwin over the course of the 1988–89 wet season. These values approximate the wet-bulb potential temperature of surface air. These maximum values were almost invariably recorded at either 1200 or 1500 local time (3-hour sampling intervals for T_w), prior to the diurnal maximum in convective activity. The three major 1988/89 monsoon episodes are clearly evident as pronounced minima (1°–2°C deficits) of short duration (1–3 days) near the ends of the months of November, December, and January. The days of monsoon onset at Darwin exhibited the most vigorous and most electrically active monsoonal convection. Two examples from this study are 30 November 1988 (Fig. 3a), 2 days ahead of a T_w minimum (Fig. 6), and 28 January 1989, one day ahead of a T_w minimum. The elevated T_w values and associated CAPE values at the time of monsoon onset and the subsequent diminishment of these quantities as the center of the trough moves in over the continent supports the observations of Hendon (1988) that conditional instability is fundamental to monsoon energetics.

The three monsoon visitations evident in Fig. 6 are interspersed with much longer break periods characterized by elevated wet-bulb temperatures and isolated continental convection. The "hot towers" occurring on 10 January and 6 February and illustrated in RHI sections in Fig. 2 are characterized by local T_w maxima (28°C and 29°C, respectively) in Fig. 6.

Nearly continuous documentation of cloud-to-ground lightning on a large scale was possible in this second season of DUNDEE (1989/90) because of the availability of the four-station LLP network. Figure 7 shows the evolution of CAPE and daily counts of ground flashes over the 40 000 km^2 area surrounding the radar for the "break period" prior to monsoon onset (8 January 1990), for the period into the monsoon (11–14 January), and finally back to a "break period" (16–18 January). CAPE values are again based on pseudoadiabatic assumptions, with the 1000 UTC and 2200 UTC local soundings both used to obtain a daily average. Once again, a fairly pronounced threshold is evident. Going into the monsoon, the lightning yield decreases by more than an order of magnitude for a halving of CAPE (a decrease in CAPE of the order of one kJ kg^{-1}), which, following the result in Fig. 5, is equivalent to a decrease in surface wet-bulb temperature of about 1°C. Buechler et al. (1990) have noted a similar sensitivity of lightning activity to conditional instability for midlatitude thunderstorms. Coming out of the monsoon in Fig. 7, some hysteresis is evident, with less lightning for the same CAPE on six of seven

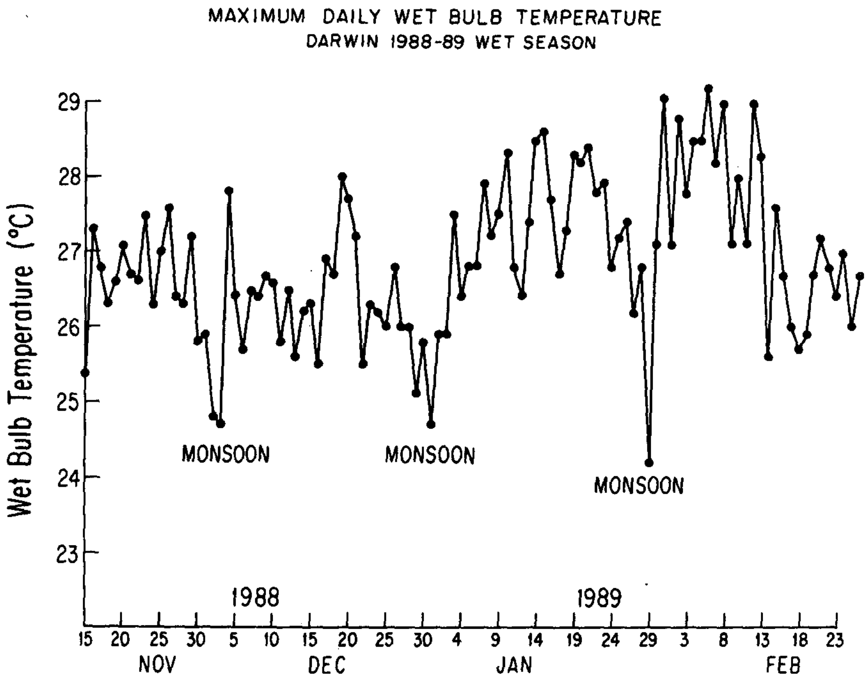

FIG. 6. Daily maximum in surface wet-bulb temperature for Darwin during the 1988–89 wet season. The three monsoon periods are also identified.

days. The strong upward trend of lightning with increasing CAPE is still evident, however.

A few comments are in order on the determination of CAPE in the monsoon, as it affects our interpretation of the results shown in Fig. 7. First of all, the environment of the monsoon is not well specified and the acquisition of a representative sounding of that environment is less probable than in the break period. Second, by any measure, the CAPE values associated with the monsoon drop below 1 kJ kg^{-1}. The ambiguity concerning parcel specification and the inaccuracy of the thermodynamic measurements both suggest that the inaccuracy in CAPE is as large as CAPE itself for the monsoon regime. The available observations are not at variance with the idea (Emanuel 1988) that the upwelling zone in the fully developed monsoon trough is moist neutral and the vertical motions observed in the hot towers (in this case a misnomer) are not the result of released CAPE but rather are the result of synoptic-scale convergent air motions themselves, driven by horizontal pressure gradients that in turn are set up by latitudinal gradients in surface temperature.

An explanation for the pronounced continental–monsoonal differences in vertical reflectivity development shown in Figs. 2 and 3 and for the dramatic increases in lightning activity with increasing CAPE illustrated in Fig. 7 rests on the nonlinear relationship between vertical air velocity and the development of ice phase condensate aloft. The terminal velocity of graupel particles (growing by accretion of supercooled water) varies as the square root of particle diameter, and in the presence of updrafts a balance condition (Atlas 1966; Lhermitte and Williams 1985) is frequently achieved at which the Doppler velocity at vertical incidence is zero, with upward velocity above and downward velocity below this level. According to parcel theory, the maximum air velocity at level i depends on $\sqrt{\mathrm{CAPE}_i}$, where CAPE_i is the integrated CAPE to that level. The particle mass varies as D^3 and the radar reflectivity as D^6, so rather small changes in CAPE and vertical air velocity can result in substantial increases in the mass and reflectivity associated with ice particles aloft. For example, a modest 40% ($\sqrt{2}$) velocity increase (associated with a doubling of CAPE) results in a doubling of the diameter of the velocity-balanced graupel, an eightfold increase in graupel mass, an 11-fold increase in the gravitational power of falling precipitation (Williams and Lhermitte 1983) and a 64-fold increase (18 dB) in radar reflectivity. The latter predictions can be judged against the differences between continental and monsoon convection evident in the RHI measurements in Figs. 2 and 3, respectively, and against the lightning–CAPE relationship shown in Fig. 7.

These results on vertical development in monsoon conditions (Fig. 3) tie in directly with earlier studies of tropical oceanic convection (Jorgensen and LeMone 1989; Gamache 1990) showing that modest updrafts were associated with a rapid decline of reflectivity above

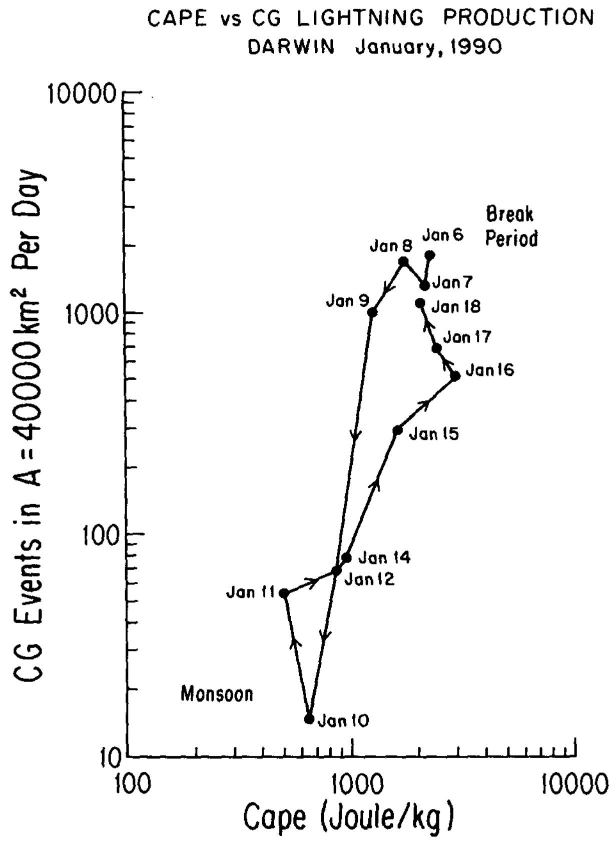

FIG. 7. Daily ground flash totals (within radar surveillance area 4 $\times$ 10^4 km^2) versus CAPE (Darwin soundings) during transition from "break period" to monsoon and back again.

the melting level and predominantly glaciated conditions in the mixed-phase region attributable to a paucity of supercooled water.

While the Darwin observations have shown that storms with strong vertical development aloft (as in Fig. 2) are invariably active lightning producers, the observations have also shown frequent intracloud lightning (several per minute) from convective cells with weaker (25–35 dBZ) echoes in the mixed-phase region. We do not interpret this observation as evidence against a process based on ice particle collisions (Williams et al. 1991) because the radar observations provide information on only one major ingredient of this mechanism: the large ice particles (i.e., graupel). Information on supercooled water content and smaller ice particle concentrations, which are recognized to exhibit great variability, is not available from radar observations alone.

6. Discussion

Comparisons of hot towers in the break period and in the monsoon have revealed distinct differences that can be traced to variations in conditional instability and updraft speed, which in turn are sensitively influenced by modest changes in wet-bulb temperature. The most dramatic difference is lightning production. We now return to the original goal of comparing the lightning and rainfall for tropical continental and oceanic regions on a global scale.

We first reconsider the daily totals for Darwin shown in Fig. 4. Both precipitation yields and lightning yields show considerable variability, but the precipitation yield per ground flash is systematically and substantially greater for all monsoonal convection than for continental convection. These numbers can be compared with results from midlatitude studies (summarized in Piepgrass et al. 1982) showing ratios (2–9 $\times$ 10^7 kg flash^{-1}) that are an order of magnitude smaller than the Darwin continental cases. The reason for this discrepancy may be partly attributable to the rules for calculation. For example, Piepgrass et al. (1982) considered only periods of lightning activity over a small area (350 km^2) rather than for an entire day over a large area (40 000 km^2), as in this study. Furthermore, where we are probably underestimating the number of ground flashes (due to imperfect detection efficiency), Piepgrass et al. (1982) may have overestimated the number of ground flashes, particularly for active storms. On the other hand, the radar evidence for high radar reflectivity and intense precipitation beneath the melting level in Darwin (in both the continental and monsoon regimes) suggests that an active coalescence process "short circuits" the ice phase and gives rise to real differences between the tropics and midlatitudes in the precipitation yield per lightning flash.

While the analyses in Fig. 4 apply to an area of 40 000 km^2, such an area is still a small piece of the Maritime Continent (Ramage 1968), which itself is a small piece of the entire equatorial trough. The longitudinal variability of the equatorial trough is well recognized (Riehl 1954), but other zones in which land and warm water are juxtaposed for monsoon development not unlike that near Darwin are India (Ramage 1971), Southeast Asia, equatorial Africa, and Mexico. In making an assessment of the global situation, we need to know what fraction of the equatorial trough experiences high CAPE convection of the break period variety and what fraction experiences monsoon-type convection.

For this purpose, an appeal is made to other data on the global distribution of precipitation (Riehl 1954; Newell et al. 1972; Taylor 1973; Hansen et al. 1983) and the global distribution of lightning (Kotaki and Katoh 1983; Orville and Henderson 1986). The various precipitation maps are not entirely self-consistent. Two of four analyses show precipitation totals over the three major tropical continental regions to be 50% to 200% larger over land than over water. This result is qualitatively consistent with the evidence for the upwelling over continents that is called the Walker Circulation (Newell et al. 1972). The midnight lightning activity over the central Atlantic and Pacific oceans is an order of magnitude less than the activity over land. Radar observations (Szoke et al. 1986) over the Atlantic in GATE show reflectivity profiles similar to those of the Darwin monsoon (Fig. 3), again suggesting abundant liquid-phase precipitation but a deficit of ice-phase precipitation relative to continental convection. Satellite-derived maps of persistent deep convection (Susskind 1984) show a low incidence over the central oceans, and computed values for CAPE over the central oceans (Williams and Renno 1992) are systematically less than for Darwin. For all these reasons, it seems appropriate to assign all oceanic precipitation (with the exception of the western portions of the oceans where surface wet-bulb temperatures are 1°–2° higher) to the synoptically forced monsoon category. This conclusion and the precipitation statistic noted earlier suggest that perhaps half of precipitation over land in the tropics is in the "continental" category, with the other half monsoonal. If the continental precipitation yields 10 times more lightning per unit mass, consistent with the results of Fig. 4, then we expect on average about ten times more lightning per unit area over continental areas than over the deep ocean in the ITCZ, roughly consistent with the observations of Kotaki and Katoh (1983) and Orville and Henderson (1986).

7. Conclusions

This study of lightning and precipitation in tropical convection has shown that the ground flash production per kilogram of precipitation in tropical convection is approximately 10 times greater in continental hot towers than in monsoon convection. This result is attributed to differences in the relative amounts of liquid and ice phase condensate and to the sensitive link between thermodynamics (wet-bulb potential temperature and CAPE) and the microphysical growth of ice. The monsoon convection is closer to a condition of moist neutrality, and is significantly less efficient in producing lightning. With the premise that the observed differences between continental and oceanic convection in the vicinity of Darwin are representative of differences elsewhere in the tropics, it is concluded that the large contrast in lightning between land and ocean (Kotaki and Katoh 1983; Orville and Henderson 1986) is caused by differences in ice-phase condensate in the mixed-phase region over land and over ocean.

Acknowledgments. We thank the Meteorology Section of the U.S. National Science Foundation (R. Taylor, M.-Y. Wei) for supporting the field program during two seasons, under Grants ATM-8818654 to CSU and ATM-8818695 to MIT; the Bureau of Meteorology (J. Arthur, J. Core, B. Passmore, R. Keith, T. Keenan, and a host of others) for their assistance in the conduct of the experiment and provision of meteorological data; Brown and DeReau Aviation (F. Coustley and B. Garrett) for installation and operation of the lightning network in difficult conditions; Lightning Location and Protection (P. Zumbusch, W. Neumann, C. Nordiello, W. Hiscox, and K. Cummins) for providing a network, its maintenance, and for considerable assistance in the data reduction; and J. Hallett and W. Cotton for collaboration on the field observations. P. Austin provided helpful advice on the radar measurement of rainfall. D. Wolff and T. Keenan supplied Darwin raingage data in timely fashion. R. Atkinson and K. Rothkin provided invaluable assistance with the mass flux calculations and S. Heckman processed LLP data. M. Brook, H. Christian, W. Jafferis, R. Markson, C. B. Moore, D. Rust, and B. Vonnegut generously loaned equipment for measurements in the field.

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