Characteristics of Strong Updrafts in Precipitation Systems over the Central Tropical Pacific Ocean and in the Amazon

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ABSTRACT

Airborne in situ measurements of updrafts in tropical convective storms were analyzed to determine the similarities and differences between updrafts in a tropical continental and a tropical oceanic region. Two hundred fifteen updraft cores from the Tropical Rainfall Measuring Mission (TRMM) component of the Large Scale Biosphere–Atmosphere (LBA) experiment (tropical continental wet season) and 377 updraft cores from the Kwajalein Experiment (KWAJEX) (tropical oceanic) were analyzed in a similar manner to that of previous studies of tropical updrafts. Average speed, maximum speed, width, and mass flux of the updraft cores from the TRMM-LBA and KWAJEX were generally similar to each other and also were similar to results from previous studies of tropical updrafts.

1. Introduction

The study of updrafts in tropical clouds is an essential part of research on tropical convective systems. Previous studies have successfully used in situ airborne measurements of updraft kinematics to examine several features of tropical updrafts. These studies, which are described below, provide much of the basis for our current understanding of tropical updraft structure together with remote sensing and modeling studies. However, the in situ studies to date have been in oceanic tropical regions, and only a few regions have been studied. This paper provides the first measurements of this type made in an important continental tropical region, the southern Amazon region of Brazil (during the wet season), and includes measurements at higher altitudes than previously have been reported. The results are compared to the results from previous tropical oceanic updraft measurements and a second region that was studied in the central tropical Pacific.

This paper examines the structure of updrafts, following the definition of an updraft core in LeMone and Zipser (1980), which has been used in previous tropical updraft studies. Updraft cores are required to have a vertical velocity of 1 m s^{-1} or more for a length of at least 500 m. They applied these criteria to vertical velocity events during the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE). Table 1 reviews previous studies that have dealt with tropical updraft cores since the GATE papers. With the exception of the Monsoon Experiment (MONEX), all of the studies in Table 1 use the updraft core definition of LeMone and Zipser (1980).

2. Sources of data and methodology

In situ data from two field campaigns that are associated with the Tropical Rainfall Measuring Mission (TRMM) were utilized for this study. Two field projects in 1999 were designed as ground validation experiments for the TRMM satellite. The first project was held in January and February, in conjunction with the Brazilian Large Scale Biosphere–Atmosphere experiment (LBA). TRMM-LBA was located in Amazonia, a tropical continental site that is centered on Ji Parana, Brazil. The second project was the Kwajalein Experiment (KWAJEX), which was held in August and September. The location of KWAJEX was in the Republic of the Marshall Islands, a tropical oceanic site centered on the Kwajalein Atoll. Both projects had in situ measurements of cloud microphysics from research aircraft.

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TABLE 1. Studies of tropical oceanic updraft cores.

	Related work	Years of project	Location of project	No. of cores
GATE	LeMone and Zipser (1980), Zipser and LeMone (1980)	1974	Atlantic Ocean, off the west coast of Africa	253
MONEX	Warner and McNamara (1984)	1978–79	South China Sea, Arabian Sea, Bay of Bengal	99
Atlantic hurricanes and rainbands	Jorgensen et al. (1985)	1977, 1980	Atlantic Ocean	1901
TAMEX	Jorgensen and LeMone (1989)	1987	Waters surrounding Taiwan	92
EMEX	Lucas et al. (1994)	1987	North of Australia	511
TOGA COARE	Igau et al. (1999)	1992–93	Western Pacific	268
KWAJEX	This study	1999	Marshall Islands, Pacific Ocean	377

This study focuses on the data collected in both projects from the University of North Dakota's Cessna Citation II aircraft (Stith et al. 2002). A recent paper (Stith et al. 2004) examines the microphysical characteristics of these updrafts.

A description of the instrumentation and calibration techniques for the Citation during TRMM-LBA and KWAJEX is given by Stith et al. (2002). Microphysical data from the Particle Measuring Systems, Inc. (PMS), Forward Scattering Spectrometer Probe (FSSP) and 2D cloud (2D-C) probe instruments were used in this study to determine cloud boundaries, as described below. Temperature measurements were made by the Rosemount probe, which has well-known sensor-wetting problems (e.g., Lawson and Cooper 1990). Vertical velocity was determined from data collected by a radome gust probe/inertial navigation system using the methods described in Lenschow (1986).

As described above, the vertical velocity must be at least 1 m s^{-1} for a flight length of 500 m or longer to qualify as an updraft core. An additional requirement is that the updraft core must also be in a straight and level flight leg. Thus, only updraft cores in a flight leg with a constant altitude and a roll angle of less than 10° were considered. Also, the updraft core had to be less than 7 km across, matching the definition of LeMone and Zipser (1980). The vertical wind data from the flight legs were corrected for any offset from zero. This involved averaging the vertical wind over all of the flight legs at a certain level each day and setting the mean to 0 m s^{-1}, as in Lucas et al. (1994). Any leg with an original offset in excess of 1 m s^{-1} was not included. This rarely happened, and it was usually due to water freezing in the system. The last condition was that the cores had to occur in a cloud. The cloud definition that was used was a FSSP concentration of at least 10 cm^{-3}, or a 2D-C shadow or concentration of at least 0.5 L^{-1}. The shadow or concentrations are from the total counts of any particles that trigger the 2D-C probe, divided by the sample volume.

The results are computed using an average value of the 1-Hz data (originally sampled at 25 Hz) over the width of the updraft core, except when noted. There are four main characteristics of updraft core structure discussed: average updraft core speed, maximum updraft core speed, updraft core width, and mass flux per unit distance. These are the same characteristics described in LeMone and Zipser (1980) and many of the other updraft cores studies since then. The average updraft core speed is defined as the mean of the 1-Hz vertical velocities over the width of the updraft core. The maximum updraft core speed is the peak 1-Hz value within the core. Updraft core width is determined by multiplying the mean flight speed (m s^{-1}) by the number of seconds that the aircraft was in the updraft core. Mass flux per unit horizontal distance across the aircraft track is defined as the product of the air density, updraft core width, and mean updraft core speed[1] (LeMone and Zipser 1980). For brevity's sake, it will be referred to simply as mass flux in this paper. Twenty missions in TRMM-LBA recorded updraft cores and 19 missions in KWAJEX recorded updraft cores.

3. Representativeness of the in situ data

As with most airborne cloud sampling efforts, it is difficult to obtain a sample that can be truly representative of a particular category of clouds (e.g., tropical clouds, tropical oceanic, tropical continental, etc.). There are at least several contributors to bias in the dataset. First, the data are from clouds in a rather limited area and for specific periods of time (February 1999 for TRMM-LBA, and August and September 1999 for KWAJEX). The TRMM-LBA data, in particular, are from the wet season, which has weaker convection than during the transition period of September–November and clean conditions (e.g., Petersen et al. 2002; Williams et al. 2002). Most of the clouds from both projects were associated with deep (including the ice phase) convection that is associated with developing systems organized around various mesoscale features; tropical cyclones were not sampled. Flights were made

[1] As in LeMone and Zipser (1980) we use the term mass flux to represent the rate of transport of mass per unit distance perpendicular to the flight track; the total mass flux (kg s^{-1}) of the cores was not calculated because it requires knowledge of the shape of the draft.

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on an opportunity basis when suitable storms were forecast to be available for study; no attempt was made to get a diurnally representative sampling of storms that occurred. Second, the aircraft was not able to sample all of the strongest regions of the storms, especially in TRMM-LBA, due to safety concerns. Flight paths could not always sample directly through the center of a storm, and even for flight paths that did go through the center of the storms (following guidance from ground-based radar) there is no assurance that the centers of the updraft regions were sampled. Although stratiform regions associated with these storms were also sampled, the criteria defining the updraft core should have eliminated most (but perhaps not all) of the updrafts in the stratiform regions of the storm from the dataset. In KWAJEX the Citation was used at cloud midlevels, in TRMM-LBA it was used through a greater depth of the clouds. In TRMM-LBA, flight legs ranged in altitude from 1.0 to 10.7 km, with a majority of the legs between 4.6 and 7.6 km. In KWAJEX the flight legs ranged in altitude from 3.7 to 9.1 km. Third, an aircraft is able to sample only a tiny volume of a cloud in situ. Even when multiple passes through a particular region are attempted, the conditions in the cloud changes rapidly enough that the cloud is significantly different on subsequent passes.

In summary, our data are biased toward smaller subsets of deep tropical storms in clean conditions. In spite of these biases, which are difficult to overcome in any aircraft study, a wide variety of updrafts of different sizes and strengths at various altitudes were sampled.

Observations from remote sensing, such as radar, avoid some of the bias found in aircraft sampling. For example, Peterson and Rutledge (2001) found that the composite reflectivity distributions, ice water contents, and lightning flash densities observed during the wet season in the Amazon exhibit characteristics that are similar to those observed over isolated regions of the tropical ocean. Based on their results, one might expect similarities between TRMM-LBA and KWAJEX in their microphysical structure, when clouds of similar sizes are compared, and indeed this appears to be the case (Stith et al. 2002, 2004).

Several recent radar studies of storms in the area where our sampling was conducted in TRMM-LBA (see Stith et al. 2004, and references therein) demonstrate that synoptic regimes favoring low-level easterly winds produce stronger storms than westerly regimes. However, the radar studies have also shown that the properties (e.g., radar reflectivities) of the *smaller* storms that exist in the easterly regimes are rather similar to storms of similar sizes in the westerly regimes (see the discussion in Stith et al. 2004). Because most of the Citation flights in LBA were in easterly periods, the in situ samples should be during periods when stronger storms were present, but the smaller, weaker regions of the storms were sampled. Therefore, based on the results from the radar studies, we might expect that the storm regions we sampled were similar to storms during westerly periods (i.e., of weaker deep tropical convection).

4. Results

Figure 1 shows the distribution of the updraft variables, with the altitude of the updraft cores sampled during TRMM-LBA and KWAJEX. The distributions for maximum updraft core speed, diameter, and mass flux were similar for the two projects. For example, Fig. 2 shows the frequency distribution of core average updraft speed from TRMM-LBA and KWAJEX, over all of the altitudes sampled. The shapes of the distributions are remarkably similar, given that there were likely biases in flight sampling patterns.

To facilitate comparisons between this and other studies, the data are divided into altitude ranges. Care was taken to have a similar number of cores in each altitude range, but not at the expense of separating updraft cores that were only a few meters apart. Table 2 shows the altitude ranges and the number of updraft cores. There were 215 updraft cores that are analyzed in TRMM-LBA and 377 from KWAJEX. Twelve of the LBA cores were not represented in the altitude separation statistics in Table 1 because they were not closely associated with any of the altitude groups (e.g., Fig. 1a, cores from 1 to 3 km). After the updraft cores were placed in their altitude categories, the 10% and 50% values for the four main characteristics were calculated. Ten-percent values indicate that 90% of values fall below that number, while the median is represented by the 50% value. The 10% and 50% values will be used in comparing the TRMM-LBA and KWAJEX results to other studies.

The intensity of the average updraft core speeds in TRMM-LBA and KWAJEX are quite similar (Fig. 1a, Table 2). The median values of the average updraft core speed for both projects reach a maximum near 3 m s^{-1} in the 6–7-km altitude range. The difference between the two study areas increases slightly in the upper levels. For the 7.5–8.8-km range, the median average updraft core speed during TRMM-LBA was 2.2 m s^{-1}, compared to 3.1 m s^{-1} for the 7.0–9.1-km range in KWAJEX.

Figure 1b shows the maximum updraft core speed. The median values of the maximum updraft core speed peak around 6.0 km (Table 2) at about 5 m s^{-1}. The 10% values reach a peak at the lowest level for LBA, around 4.5 km, while the peak for KWAJEX is around 6.0 km. However, the strength differences between the two projects are relatively small. The average updraft core speed for the cores during the two projects was 66% of the maximum value, which is similar to other studies that have reported average updraft core speeds of half to just over half of the maximum value (Zipser and LeMone 1980; Jorgensen and LeMone 1989).

KWAJEX had the majority of the widest updraft cores (Fig. 1c), but the differences in the overall width

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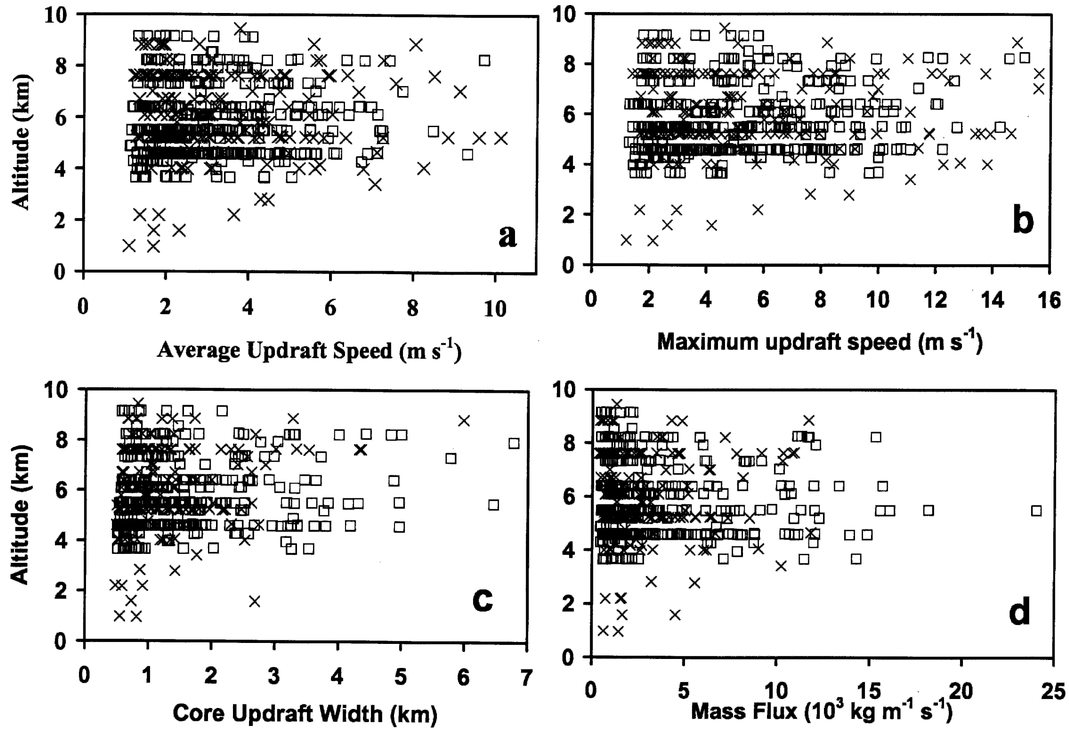

FIG. 1. Distribution of (a) average speed, (b) maximum speed, (c) width, and (d) mass flux of updraft cores sampled during TRMM-LBA (X) and KWAJEX (outlined squares).

statistics are small (Table 2). The median values of the updraft core width for both TRMM-LBA and KWAJEX are constant above 5 km, while the 10% values increase only slightly above 5 km (Table 2). It has been theorized that updraft width and strength are correlated, because entrainment and mixing should reduce the buoyancy of a parcel of air (Lucas et al. 1994), decreasing the intensity of a rising updraft. Wider updrafts are less susceptible to entrainment and mixing, so they should remain stronger. However, the data from LBA and KWAJEX do not strongly support that theory. The correlation between the updraft core width and speed is poor (R^2 values of less than 0.2). Zipser and LeMone (1980) performed the same analysis with the data from GATE and also found only a slight positive correlation.

Mass flux values (Fig. 1d) show a vertical distribution similar to the updraft core width. The median values (Table 2) for both projects are similar below 5.5 km, but then the KWAJEX cores have slightly increasing values above that, while the TRMM-LBA values are constant, then decrease above 7.5 km. The 10% values show more of a difference, with the KWAJEX cores above 5.8 km nearly double the value of the LBA cores.

5. Comparisons with other studies

The results from TRMM-LBA and KWAJEX are compared with other previous in situ studies of tropical updrafts in this section. The data from TRMM-LBA, KWAJEX, GATE, the Taiwan Area Mesoscale Experiment (TAMEX), the Equatorial Experiment (EMEX), and Atlantic Ocean hurricane eyewalls and rainbands are used in the updraft core comparisons (Table 1). Each study did not report the same data, and so the comparisons do not include every project. The data from MONEX and the Tropical Ocean Global Atmosphere (TOGA) Coupled Ocean–Atmosphere Response Experiment (COARE) were not used in the direct comparisons. The MONEX data are omitted be-

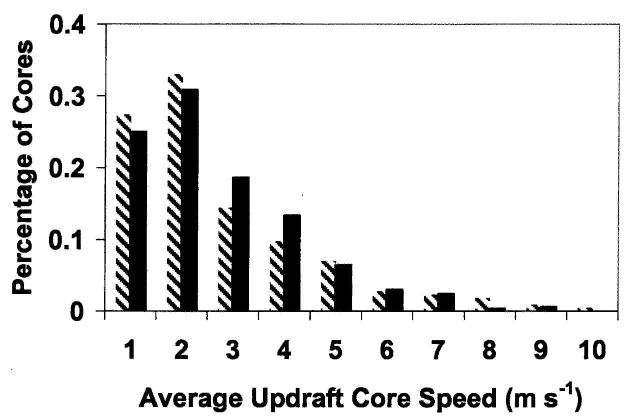

FIG. 2. The frequency distribution of the average updraft core speed for KWAJEX (black) and TRMM-LBA (diagonal stripes).

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TABLE 2. Characteristics of updraft cores sampled during TRMM-LBA and KWAJEX.

Alt range (km)	No. of cores	Diam (km) 50%	Diam (km) 10%	Avg (m s^{-1}) 50%	Avg (m s^{-1}) 10%	Max (m s^{-1}) 50%	Max (m s^{-1}) 10%	Mass flux (10^3 kg m^{-1} s^{-1}) 50%	Mass flux (10^3 kg m^{-1} s^{-1}) 10%
TRMM-LBA									
3.9–5.2	79	0.9	2.0	2.5	5.8	4.1	11.8	1.8	6.2
5.3–7.3	55	1.0	2.0	2.9	5.4	4.8	9.6	1.7	5.2
7.5–8.8	69	1.0	2.7	2.2	5.6	3.2	10.2	1.1	4.8
KWAJEX									
3.6–4.6	144	0.9	2.7	2.6	4.9	4.1	8.3	1.8	8.0
4.8–5.5	97	1.2	2.5	2.5	4.8	3.7	8.0	1.9	6.7
5.8–6.7	65	1.2	2.6	3.2	5.9	5.5	9.9	2.5	10.2
7.0–9.1	71	1.2	3.3	3.1	5.4	4.9	9.6	2.0	9.1

cause their definition of an updraft core was slightly different than the other projects. The TOGA COARE data are omitted because most of their data occurred in a narrow altitude range.

The median value of the average updraft core speeds for each project is similar (Fig. 3a). The tropical studies have similar 10% values of the average updraft core speed (Fig. 4a), with the hurricane rainband having the weakest updraft cores, while TAMEX, TRMM-LBA, and KWAJEX have the strongest cores (above 2.0 km).

The median values of the maximum updraft core speeds are shown in Fig. 3b. The largest difference between the studies is around 6.0 km where the TRMM-LBA and KWAJEX values are higher than GATE and TAMEX.

The 10% maximum updraft core speeds, given in Fig. 4b, show that most of the values increase with height. At 1.5 km, the values range from around 4.0 to 6.0 m s^{-1}, while at 6.0 km the values range from 8.0 to 10.0 m s^{-1}. The two main outliers are the hurricane eyewall at 0.5 km and TRMM-LBA at 5.0 km. The weakest updraft cores were again found with the hurricane rainband, while the strongest updraft cores were from TRMM-LBA and KWAJEX at the higher altitudes.

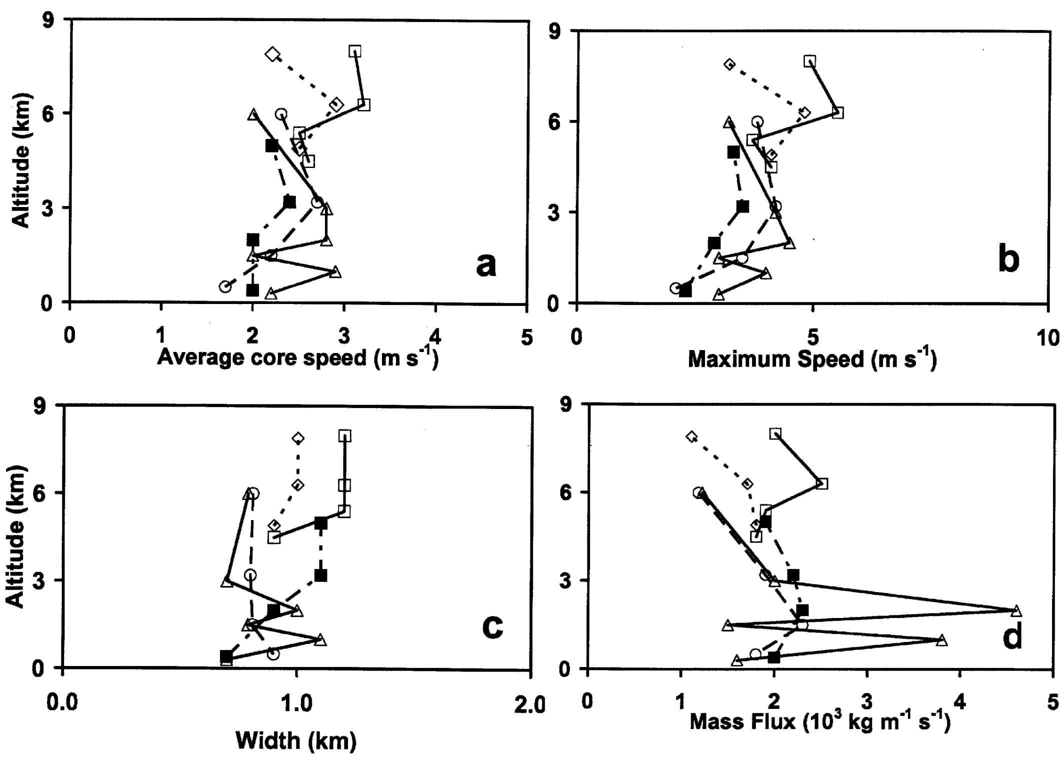

FIG. 3. Median values of (a) average speed, (b) maximum speed, (c) width, and (d) mass flux of updraft cores sampled during TRMM-LBA (diamonds), KWAJEX (outlined squares), GATE (outlined circles), TAMEX (outlined triangles), and EMEX (black squares).

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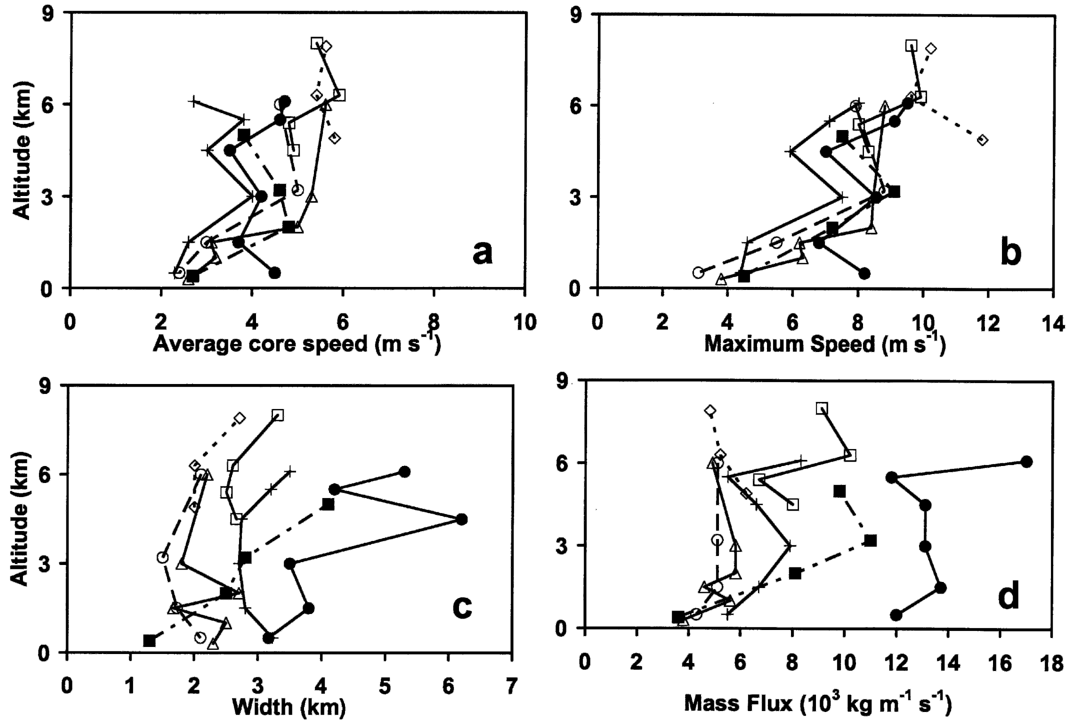

FIG. 4. As in Fig. 3, but for 10% values of the average core data. Data have also been included from Atlantic hurricane (Table 1) eyewalls (black circles), and hurricane rainbands (plus signs).

Figure 3c shows the median diameter of the updraft cores. Most of the studies show a steady size or a slightly larger core with increased altitude. The 10% values in Fig. 4c also show an increasing diameter with altitude for most of the projects. The hurricane eyewall updraft cores are considerably larger than those observed in the TRMM-LBA and KWAJEX data.

The differences that were found in the speed and size of the updraft cores show up in the comparisons of the mass flux values, because the amount of mass flux is dependent on both updraft core speed and width (as well as density). The median mass flux values are shown in Fig. 3d. The values decrease with increased altitude. This is because the air density decreases while the updraft core strength and width remain fairly constant. The high values for TAMEX at low levels may be an artifact of the small number of cores that were sampled (92 cores divided up into six altitude ranges).

The 10% values of mass flux are shown in Fig. 4d. Not surprisingly, because of their width, the highest values are from hurricane eyewalls. GATE, TAMEX, and TRMM-LBA all are rather weak, with mass flux values below 6×10^3 kg m^{-1} s^{-1}. The 10% values for KWAJEX and EMEX peak in excess of 1×10^4 kg m^{-1} s^{-1}.

6. Summary discussion

In addition to the above projects, there have been several other studies that have collected updraft data from tropical convection. The results listed in Table 1 of the MONEX and TOGA COARE projects were consistent with the other tropical studies. A study of Hurricane Emily showed stronger updraft cores and widths that were about 3 times as wide as GATE (Black et al. 1994). They also reported that the maximum updraft core encountered in Hurricane Emily was 23.9 m s^{-1}, which is high, considering that no core sampled during GATE, TRMM-LBA, or KWAJEX surpassed 17 m s^{-1}.

Profiler and radar observations can also be used to compare with the aircraft data. Numerous studies of tropical convection have been performed by these methods (Balsley et al. 1988; Cifelli and Rutledge 1994; May and Rajopadhyaya 1999; Cifelli et al. 2002; etc.). Profilers and radars have a temporal and spatial advantage over the aircraft data. However, we are not able to directly compare the values of updraft core strength and width because the remote sensing instruments do not replicate the aircraft data. The characteristic of vertical motion that we can best compare is the altitude of the maximum updraft speed. The studies mentioned above all show a peak in the vertical wind speeds at an altitude (7–11 km) above which most of the aircraft observations are located. Our measurement suggests that updraft speeds increase with altitude, and these studies suggest that this trend continues to higher altitudes. In contrast, Black et al. (1996) used airborne Doppler radar to show that updraft strengths in typical cyclones exhibit only slight increases in strength with altitude.

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Xu and Randall (2001) used GATE atmospheric conditions to model the convection. They simulated 6600 updraft cores, in contrast to the 253 that were available from aircraft sampling. The simulations and observations agreed fairly well. There was a difference in the average updraft core speed of only 0.5 m s^{-1} at most heights. However, they found that the peak level of the simulated updraft cores in the simulations occurred higher than the data from the aircraft had suggested. They note that this discrepancy could be due to the poor vertical resolution of the observations ($\sim$2 km) compared to the simulations (0.6 km).

The remote sensing and computer model data suggest that the strongest updrafts continue to increase in strength above the altitude of most of the aircraft observations. In addition, the aircraft are not able to sample the most intense part of the convective storms. For example, during TRMM-LBA, Atlas and Williams (2003) used a profiler to sample a 24 m s^{-1} updraft and Cifelli et al. (2002) sampled a $>$20 m s^{-1} updraft by dual-Doppler data analysis, utilizing airmass continuity. Both of these updrafts were stronger than any core sampled by the Citation during TRMM-LBA.

The characteristics of updraft cores from LBA and KWAJEX suggest the following:

1) Updraft cores from TRMM-LBA and KWAJEX were generally similar in strength, as suggested by the 10% and 50% values of average and maximum updraft core speeds. Cores from KWAJEX were slightly larger, which contributed to a higher amount of mass flux.
2) The updraft core characteristics for TRMM-LBA and KWAJEX are similar to other tropical studies performed by research aircraft.

Updraft cores that were sampled over the TRMM-LBA tropical continental areas and those sampled over the KWAJEX tropical oceanic areas were surprisingly similar. In addition to the Petersen and Rutledge (2001) study, suggesting that the wet season convective characteristics from the Amazon are similar to those of an isolated oceanic region, May and Rajopadhyaya (1999) examined tropical continental convection with a profiler and found that there was agreement between the continental tropical updraft speeds that they measured near Darwin, Australia, and previously published statistics on tropical oceanic updrafts. However, May and Rajopadhyaya found that updraft cores were larger for the storms that they studied than for the previously studied tropical oceanic storms. These studies are in accord with our results for updraft speed.

The studies in Stith et al. (2002, 2004) suggest that the microphysical characteristics of TRMM-LBA and KWAJEX clouds are similar, which is likely a reflection of the similar cloud dynamic features, such as updraft properties, that are shown to occur in this study and several other studies of tropical updrafts. This suggests that many of the smaller clouds in deep, clean tropical convective systems are likely to exhibit similar microphysical and dynamic characteristics.

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