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The Contribution to Tropical Rainfall with respect to Convective System Type, Size, and Intensity Estimated from the 85-GHz Ice-Scattering Signature

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ABSTRACT

This study compiled a database of precipitating cloud clusters from 85-GHz data in 10 regions of the wet Tropics for a calendar year (November 1992–October 1993). The cloud clusters were grouped into four classes of basic system types, based on size (closed 250 K contour greater or less than 2000 km²) and minimum enclosed 85-GHz brightness temperature (greater or less than 225 K) to indicate the presence or absence of large areas of active, deep convection. For each cloud cluster, instantaneous volumetric rain rates (mm km² h⁻¹) were calculated using an 85-GHz ice-scattering-based rain-rate retrieval algorithm. Because the ice-scattering signature is linearly related to but does not directly measure rain rate, the methodology was appropriate for estimating relative contributions rather than quantifying tropical rainfall.

For the 3-month wet season of each study region, the rainfall contributions with respect to system type, size, and intensity were calculated. Regional differences were small among the contributions with respect to system type and to precipitating area. Although mesoscale convective systems constituted 10%–20% of the regional populations, they contributed 70%–80% of the rainfall. With respect to cloud cluster area, the top 10% of cloud cluster areas contributed more than 70% of the rainfall, and the top 1% (greater than 20 000 km²) contributed about 35% of the total rainfall. Regional differences were apparent in the distributions of rainfall contribution with respect to minimum brightness temperature. The Amazon's distribution more closely resembled the oceanic distributions than the continental distributions. The distributions of the oceanic regions peaked at 200 K, and over half of the rain in the oceanic regions was contributed by the fewer than 20% of the cloud clusters colder than 210 K. Distributions in the continental regions peaked at 175 K. A total of 70%–80% of the rain was contributed by the 20%–30% of continental cloud clusters colder than 200 K, with nonnegligible contributions from a small number of cloud clusters colder than 120 K. Sub-Saharan Africa had the largest contribution from cloud clusters colder than 120 K.

1. Introduction

Multicellular mesoscale convective systems (MCSs) account for 30%–70% of the April–September rainfall in the central United States (Fritsch et al. 1986). Since tropical convection tends to cluster, it has long been believed MCSs are responsible for the majority of tropical precipitation also. However, the contribution of MCSs to rainfall in the Tropics remains to be quantified. The purpose of this study is to estimate the contribution to tropical rainfall with respect to convective system type, size, and intensity. The contributions from MCSs are compared to the contributions from systems either

smaller and/or weaker than MCSs. The study examines 10 regions in the wet Tropics to investigate regional differences in rainfall contributions and draw global inferences. Knowledge of these relationships may improve long-term rainfall prediction, water resource management, and the parameterization of hydrologic processes in weather and climate models at regional and larger spatial scales.

In the microwave spectrum, emission from the earth's atmosphere is directly proportional to blackbody temperature. The brightness temperature is the intensity of this emission expressed in units of temperature (degrees kelvin). Hence, microwave brightness temperatures upwelling from a cloud are related to the types, size distribution, and number density of hydrometeors within the cloud (e.g., Wilheit et al. 1977; Wu and Weinman 1984; Spencer et al. 1989). Ice has a particularly high albedo at frequencies greater than 30 GHz. In deep convective cores with a high number density of graupel,

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much of the upwelling radiation at 85 GHz is scattered away. The result of this process is the ice-scattering signature at 85 GHz. Recent rainfall climatologies include rainfall retrievals incorporating the 85-GHz ice-scattering signature (e.g., Xie and Arkin 1997; Ferraro 1997). Mohr and Zipser (1996a,b) created a census of tropical MCSs from the size and magnitude of their ice-scattering signatures. In this study, the 85-GHz ice-scattering signature is used to quantify the contributions of MCSs and related cloud systems to tropical rainfall. The advantages and disadvantages of using the 85-GHz and the assumptions required in constructing the study database are detailed in, section 2.

2. Data and methods

a. Development of the study database

Mohr and Zipser (1996a) construct their database from 85-GHz data from the Special Sensor Microwave/Imager (SSM/I) of the Defense Meteorological Satellite Program *F-11* satellite for the months of January, April, July, and October 1993. The study period covers one calendar year from November 1992 to October 1993, encompassing a warm ENSO event as well as the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response (TOGA COARE) field experiment (November 1992–February 1993). According to National Oceanic and Atmospheric Administration’s (NOAA) *Climate Diagnostics Bulletin* for 1993, elevated SST in the eastern Pacific resulted in enhanced convection in the eastern and central Pacific, but near-normal conditions prevailed elsewhere in the Tropics (Kousky 1993). The study database includes all clusters of SSM/I pixels with brightness temperatures less than or equal to 250 K. The footprint of the 85-GHz channel is 13 km × 15 km, which is too large to resolve individual convective towers but useful for examining tropical cumulonimbus cloud clusters.

All the data from the *F-11* orbits between 35°N and 35°S for the study time period were processed. To isolate the ice-scattering signature from the cold oceanic background, polarization-corrected temperatures (PCT) were derived from the polarized brightness temperatures in the raw data. The PCT takes advantage of the strong polarization dependence of obliquely sampled surface water emissions and is calculated by the following formula involving the horizontally (T_{B_h}) and vertically (T_{B_v}) polarized brightness temperatures (Spencer et al. 1989):

$$\text{PCT} = 1.818T_{B_v} - 0.818T_{B_h}. \quad (1)$$

A pattern-recognition algorithm applied to the data identified all pixels equal to or colder than the threshold PCT (250 K), grouping together the cold pixels into the largest possible clusters. The size, minimum enclosed PCT, and location were recorded for each cluster of cold PCTs. Elevations of each cluster centroid relative to

mean sea level were estimated from a 5-min resolution digital elevation database (ETOPO5). Because snow has a cold radiative signature at 85 GHz, the elevation data were required to screen out areas of snow, typically the Himalayas and the Andes mountain ranges. The snow screens used were similar to screens described in Mohr and Zipser (1996b).

For each pixel in each cluster, an instantaneous rain rate was calculated using the Goddard Scattering Algorithm (GSCAT), version 2 (Adler et al. 1994). The GSCAT relates rain rate, R , in millimeters per hour, to the horizontally polarized 85-GHz brightness temperature (T_{B_h}) for land-based clusters,

$$R = \frac{251.0 - T_{B_h}}{4.19}, \quad (2)$$

and for oceanic clusters,

$$R = \frac{251.0 - T_{B_h}}{2.19}. \quad (3)$$

Validation against precipitation data from small tropical Pacific atolls revealed that Eq. (2) underestimated oceanic precipitation by a factor of 2. Thus, different coefficients were adopted for land- and ocean-based clusters (Adler et al. 1994). Each cluster’s centroid was estimated from the cluster boundaries and matched to an elevation in ETOPO5. Because the datum of ETOPO5 is mean sea level, points over the ocean have negative elevations, making it possible to use elevation to classify clusters. Clusters whose centroid elevations were greater than or equal to 0 m were classified as continental, and those with centroid elevations less than 0 m as oceanic. For each pixel in a cluster, the rain rates were summed and then divided by the total number of pixels in the cluster to derive the average rain rate for the cluster. Since average instantaneous rain rates are hardly unique across the spectrum of cloud cluster areas, volumetric rain rates [$\text{L}^3 \text{T}^{-1}$ in MKS units] rather than depths (L T^{-1}) were calculated by multiplying each cluster’s average rain rate by its area in square kilometers. Regional rainfall totals were the sum of individual cluster rain volumes over 3 months.

Figure 1 is a map of the 10 regions of the wet Tropics chosen for this study. Table 1 lists the regions and their wet seasons. Using the Xie and Arkin (1997) Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) data, 19-yr (1979–97) monthly means were calculated for the study regions. The three consecutive months with the highest mean monthly rainfall from CMAP were designated the wet season and constituted each region’s sample. For regions designated “land,” such as India/Southeast Asia, clusters falling within the regional boundaries but whose centroid elevations were less than 0 m were dropped from the regional sample. Only in regions designated as “both” were clusters included in the regional sample without regard for elevation. Altogether, the majority of annual

FIG. 1. A map of the 10 study regions. Table 1 lists the boundaries and wet seasons.

tropical rainfall occurs in the study regions. Each of these regions has a high wet season rainfall total and several hundred MCSs per month during the wet season.

b. Study considerations

Although the SSM/I has three other channels (19, 22, and 37 GHz), this study uses the 85-GHz channel exclusively because the resolutions of these channels are at least two times more coarse than the 85-GHz channel, and their use would reduce the study sample size and scope. Thus, only statistical/empirical methods involving the 85-GHz channel such as GSCAT were suitable for this study. A particularly important advantage of GSCAT is that Eqs. (2) and (3) are easy to implement on a pixel-by-pixel basis in a large database. Because of the sensitivity of the 85-GHz to large ice particles, the 85-GHz brightness temperature does not directly reflect the water content or size distribution of liquid rainfall. The ice-scattering signature should be considered as a measure of the *potential* for rainfall from graupel rather than a direct measure of actual rainfall. Graupel is related to, but not necessarily proportional to, actual rainfall, introducing uncertainty in the rainfall estimates. This uncertainty, in addition to the discrete temporal and spatial sampling of the *F-11* SSM/I, makes assessing relative contributions rather than absolute amounts a more suitable goal for this study.

Retrievals using the ice-scattering signature miss the

contributions to rainfall from warm-topped precipitating clouds. Lin and Rossow (1997) use optical remote sensing data to detect the presence of warm-topped clouds ($T > 0^{\circ}\text{C}$) over the oceans and use a physically based microwave retrieval method to derive the rain rates from the clouds. They estimate that warm-topped precipitating clouds contribute 10%–20% of the rain over the open oceans. Also neglected in this study is the contribution from systems with rain rates less than 3 mm h^{-1} . The 250 K contour PCT encloses systems with rain rates greater than or equal to 3 mm h^{-1} and was deliberately chosen to reduce the chance of contamination from background emission (Spencer et al. 1989).

The ascending pass of the *F-11* vehicle occurs around local sunset and the descending pass occurs just before local sunrise. At local sunset continental convection is at or near peak intensity, and just before local sunrise oceanic convection is at or just past peak intensity. These nodal crossing times make it likely that the cloud clusters in the database were sampled at or near their peak size and intensity. The calculated rain volumes are thus a reflection of the lifecycle stages of the cloud clusters at the satellite overpass times.

c. Classifying cloud cluster types

This study defines the MCS using the criteria of Mohr and Zipser (1996a,b). They define an MCS as a closed 250 K contour with a contiguous minimum area greater

TABLE 1. Study region boundaries and wet seasons.

Land/Ocean	Region	Latitudes	Longitudes	Wet season
Land	Amazon Basin	3°N–15°S	45°–75°W	Jan, Feb, Mar
Both	Central America	12°–2°N	75°–85°W	Jul, Aug, Sep
Ocean	East Pacific	15°–3°N	90°–150°W	Jun, Jul, Aug
Ocean	South Pacific Convergence Zone (SPCZ)	12°–35°S	120°W–180°	Jan, Feb, Mar
Ocean	Atlantic	15°N–0°	7°–50°W	Aug, Sep, Oct
Land	Congo Basin*	5°N–8°S	10°–28°E	Mar, Apr, May
Land	India/Southeast Asia	35°–12°N	70°–122°E	Jun, Jul, Aug
Ocean	Central Pacific	12°–2°N	155°E–150°W	Aug, Sep, Oct
Both	Maritime Continent	2°N–15°S	95°–155°E	Dec, Jan, Feb
Land	Sub-Saharan Africa	18°–5°N	18°W–45°E	Jul, Aug, Sep

* The Congo Basin has a second wet season in September–November, but March–May will be used here.

TABLE 2. Cloud cluster classification criteria.

System type	Abbreviation	Size range (km ²)	Minimum PCT range (K)
MCS	MCS	≥ 2000	≤ 225
Large, warm cluster	LW	≥ 2000	250–226
Small, cold cluster	SC	< 2000	≤ 225
Small, warm cluster	SW	< 2000	250–226
Intense MCS*		≥ 2000	≤ 175

* Subclass of MCSs. The intense MCS is contoured by the 200 K PCT rather than 250 K PCT.

than or equal to 2000 km² and a minimum enclosed brightness temperature less than or equal to 225 K. Since a single 85-GHz pixel is nearly convective-scale, “mesoscale” is defined arbitrarily as one order of magnitude larger, that is, 10 pixels, or 2000 km². The contour PCT, 250 K, is low enough to ensure that precipitation and not background emission is being sampled (Spencer et al. 1989). A minimum enclosed PCT ≤ 225 K ensures that the bounded areas contain convective structures (McGaughey et al. 1996). Hence, the Mohr and Zipser criteria identify organized mesoscale regions of convectively produced ice particles, that is, an ice-scattering MCS. Earlier studies (e.g., Spencer et al. 1989; McGaughey et al. 1996; Toracinta et al. 1996; Mohr et al.

1996) have shown that areas of cold brightness temperatures are collocated with regions of high radar reflectivity (6 km) within the same MCS. Defining an MCS by the ice-scattering signature is physically consistent with defining it using radar reflectivity.

Since this study does not limit itself to MCSs, Table 2 lists the definitions of four classes of basic system types and one subclass used in this study. The definitions of the large, warm clusters (LW); small, cold clusters (SC); and small, warm clusters (SW) are variations of the definition of the MCS. Cloud clusters are grouped into the LW, SC, or SW classes depending on size (greater or smaller than 2000 km²) and the presence or absence of large, active convective structures (minimum PCT colder or warmer than 225 K, respectively). Figure 2a depicts clusters from the four classes. The intense MCS subclass follows the definition of Mohr and Zipser (1996b). The intense MCS criteria emphasize the size of the 200 K contour because it suggests a high degree of system organization. This subclass is intended to identify those MCSs with a good probability of high lightning flash densities, multiple severe weather events, and long lifetimes (Toracinta et al. 1996; Mohr et al. 1996). Figure 2b is an example of an intense MCS.

Without coincident radar reflectivity time series, it is not possible to identify absolutely individual LW, SC,

FIG. 2. (a) A series of cloud clusters representing the four basic system types. The 225 K contour is in bold to help distinguish between SW and SC clusters. Clockwise from the top left, SC, MCS, SC, SC, SW, LW, SW. The SC at the 4 o'clock position is just under 2000 km², and the MCS at the 2 o'clock position is just over 2000 km². (b) An example of an intense MCS. Inside the southern lobe of the MCS lying along the 168th meridian is a large, closed 200 K contour. This closed contour's area is large enough and contains a minimum PCT cold enough to be classified as an intense MCS. The 200 K contour inside the northern lobe is smaller than 2000 km².

or SW clusters as the stratiform remnants of old MCSs, or the mature or vigorously growing clusters of cells too small to be MCSs. Examining contour plots like Fig. 2a of hundreds of clusters that formed in the TOGA COARE area and global maps of LW, SW, and SC clusters make some distinctions possible. The LW clusters are few, averaging less than 5% of total systems and 20% of systems greater than or equal to 2000 km², are more prevalent over the oceans, and often occur in close proximity to MCSs. The LW clusters fall into the range of brightness temperatures McGaughey et al. (1996) are able to associate with stratiform structure. It is likely that LW clusters are either the (largely) stratiform remnants of old MCSs or large pieces of a large stratiform anvil with a closed contour separate from the more active part of the parent MCS. In the subtropical oceans LW clusters may be associated with baroclinic waves rather than cumulus convection.

PCT contour maps such as Fig. 2a of individual SC clusters show that some SC clusters have numerous, closely spaced, concentric contours with a very cold central core. Other SC clusters have only a few contours, consisting of a larger area of warm (<230 K) brightness temperatures and only a much smaller area, perhaps only a few pixels, less than 225 K. The former case is likely to be a mature convective cloud system too small to be an MCS, and the latter may be either a very young or very old small convective cloud system. Because the *F-11* SSM/I tends to sample clusters at or just past their peaks, it is possible but not likely that the typical SC cluster may expand and become an MCS later. The SW clusters probably span the range of possibilities mentioned for LW and SC clusters but on a smaller and weaker scale. This is hardly an exhaustive description of possible structures associated with the four basic classes in this study, but additional distinctions cannot be made solely with *F-11* SSM/I data.

3. Results

a. Regional differences in MCS intensity

Radar studies by Williams et al. (1992), Rutledge et al. (1992), and Zipser and Lutz (1994) have noted structural differences between oceanic and continental cumulonimbus. Oceanic cumulonimbus tends to have higher reflectivity lapse rates above the freezing level and less large ice in the mixed-phase region. The term “convective intensity” is defined here as the magnitude of the convective updrafts producing ice particles within the clouds. Because of the sensitivity of the 85-GHz ice-scattering signature to presence of large ice particles, the minimum enclosed PCT is a useful proxy for convective intensity (Mohr and Zipser 1996b). Consistent with the predictions of the radar studies, Mohr and Zipser observe that continental MCSs tend to have colder minimum brightness temperatures, implying greater convective intensity, than oceanic MCSs.

FIG. 3. Cumulative frequency distribution for minimum PCT for wet season MCSs in the study regions.

The difference in MCS minimum PCT between the oceanic and continental regions of this study for wet season MCSs is illustrated in Fig. 3. There is a statistically significant (>99%) gap between some of the continental and all of the oceanic regions. The slope of the distributions on the right of the gap is smaller than the slope of the distributions on the left of the gap. This difference in slopes implies that MCSs with colder minimum PCTs are more prevalent in the four regions on the right. Two anomalies are apparent in the division between oceanic and continental distributions. Although the Amazon is a continental region, its distribution is more oceanic in character. Of the mixed regions, the Maritime Continent, a mosaic of ocean and mostly small islands, is understandably oceanic in character, but Central America has a continental distribution. Since the Central American region does not extend far from coastal waters, it is likely that the “oceanic” MCSs in the Central American sample have an essentially continental vertical profile (Williams et al. 1992; Rutledge et al. 1992). For the remainder of the paper, Central America will be considered a “continental” region and the Amazon an “oceanic” region to reflect the nature of their MCS-distribution in Fig. 3. It is beyond the scope of this paper, but would be an interesting topic of research, to explain why the Amazon wet season MCS intensity distribution appears oceanic.

b. Contribution to rainfall with respect to cluster type

Figures 4a and 4b depict the percent share of total precipitating clusters and the percent contribution to regional rainfall by the four classes in each study region, respectively. In Fig. 4a, clusters greater than or equal to 2000 km², most of which are MCSs, make up no more than 20% of the regional populations. Of the clusters less than 2000 km², 60% or more are SC clusters, except in Africa. African MCSs tend to be much smaller than the other regions, so the arbitrary MCS/no-MCS boundary at 2000 km² appears to cause a greater share of African cloud clusters to fall into the SC category than in the other regions. Figure 4b is nearly a reversal

FIG. 4. (a) Percent share of total precipitating clusters by the four classes. (b) Percent contribution to regional rainfall by the four classes.

of Fig. 4a. Although MCSs make up 10%–20% of the cluster population, their mean contribution to rainfall in the study regions is 77%, ranging from 71% in the Maritime Continent to 82% in the Congo. Conversely, the SC and SW clusters are nearly 80% of the total clusters but contribute about 20% of the rainfall. Although the intensity of MCSs clearly varies from region to region, the importance of MCSs to regional rainfall is remarkably similar. The standard deviation of the MCS contribution is just 4%, and the standard deviations for the other cluster types are 2%–3%.

The contributions of intense MCSs to regional rainfall are plotted in Fig. 5. Intense MCSs make a contribution to regional rainfall well in excess of their representation in the cloud cluster population. In the four continental regions, Central America, India/Southeast Asia, the Congo, and Sub-Saharan Africa, only 1%–3% of clusters meet the intense criteria, but their percent contribution to regional rainfall is to four to six times their representation in the population. Even though fewer than 1% of clusters meet the intense criteria in the oceanic regions, the contribution from intense MCSs to regional rainfall is still more than four times their representation in the population. The four continental regions have, in absolute terms, at least three times as many intense MCSs as the oceanic regions. However,

FIG. 5. Contribution to regional rainfall by intense MCSs.

the larger number of intense MCSs in the four continental regions relative to the oceanic regions is partly because the number of intense MCSs in the four continental regions peaks during the wet season months. In the oceanic regions, the 3 months with the greatest number of intense MCSs are 1–3 months before or after the 3 months designated as their wet seasons.

c. Contribution to rainfall with respect to cluster size

Figure 6a is a cumulative frequency distribution for the areas of precipitating clusters for selected regions. The medians of the regions shown are around 500 km², and the MCS/no-MCS cutoff at 2000 km² is in the 80th percentile. Clusters larger than 10 000 km² are in the top 3% of the samples. In Fig. 6b are the contributions to total rainfall with respect to area (km²). The contributions rise sharply from less than 5% at 1000 km² to about 10% at 2000 km². The contribution nearly doubles at 5000 km², even though 5000 km² is above the 90th percentile. The top 10% (>2000 km²) of cluster areas contributes more than 70% of the rainfall, and the top 1% (>20 000 km²) contributes about half of that, or about 35% of the total rainfall. Despite the regional differences in MCS intensity depicted in Fig. 3, the contribution with respect to cluster area is remarkably uniform among the study regions. Table 3 lists the contributions for clusters between 2000 and 40 000 km², and their share of the cluster population. Fewer than 20% of the clusters contribute 70% or more of the rainfall. The one region below 70%, the Central Pacific, has a larger contribution from the largest clusters than the other regions.

d. Contribution to rainfall with respect to cluster minimum PCT (convective intensity)

Regional differences become more pronounced in considering the contribution to regional rainfall with respect to cluster minimum PCT. Figure 7a is the cu-

FIG. 6. (a) Cumulative frequency distribution for the areas of precipitating clusters for selected regions. Clusters were sorted without regard to system type. A log scale is used because the range of areas in the database spanned three orders of magnitude. (b) The contribution to total rainfall in each of the study regions with respect to cluster area.

cumulative frequency distribution for minimum PCT for selected regions. Medians of the regions in Fig. 7a range from 238 to 228 K. The minimum PCTs of clusters in Sub-Saharan Africa tend to be much colder than the other regions, and the minimum PCTs of clusters in the Amazon were only slightly colder than the oceanic regions. Minimum PCTs colder than 200 K fall in the 25th percentile in Sub-Saharan Africa compared to the 10th percentile in the other regions. The difference between Sub-Saharan Africa and the other regions is even more noticeable below 200 K. The top 3% in Sub-Saharan Africa is about 50 K colder than the other regions.

The contributions to total rainfall with respect to minimum PCT are plotted in Fig. 7b. In all of the regions, the contribution rises to 210 K and then doubles at 200 K. Unlike Fig. 6b, the distributions in Fig. 7b have significant land/ocean contrasts, as implied earlier by Fig. 3. The four continental regions on the right-hand side of Fig. 3, the Congo, India/Southeast Asia, Sub-Saharan Africa, and Central America, have broader distributions compared to the oceanic regions. The oceanic

TABLE 3. The contribution to regional rainfall for clusters 2000–40 000 km².

Region	Percent of total rainfall	Percent of total clusters
Amazon	72	16
Atlantic	77	16
Central America	76	20
Central Pacific	66	14
Congo	75	21
East Pacific	77	17
India/SE Asia	71	16
Maritime Continent	75	16
SPCZ	71	15
Sub-Saharan Africa	71	18

distributions peak sharply at 200 K. The contribution at 175 K is similar in all the regions but drops by more than half below 175 K in the oceanic regions. Compared to the oceanic regions, the four continental regions have a much smaller contribution from clusters warmer than 230 K and a much larger contribution from clusters

FIG. 7. (a) Cumulative frequency distribution for the minimum PCT of precipitating clusters for selected regions. Clusters were sorted without regard to system type. (b) The contribution to total rainfall in each of the study regions with respect to cluster minimum PCT, a proxy for convective intensity.

TABLE 4. The contribution to regional rainfall with respect to minimum PCT.

Region	Percent of total rainfall	Percent of total clusters 200–100 K
Central America	77	24
Congo	81	31
India/SE Asia	68	20
Sub-Saharan Africa	80	26
		Percent of total clusters 210–160 K
Amazon	56	20
Atlantic	56	15
Central Pacific	56	14
East Pacific	60	16
Maritime Continent	52	17
SPCZ	52	12

colder than 175 K. India/Southeast Asia has the largest contribution to its rainfall from intense MCSs. Sub-Saharan Africa has a larger contribution from the very coldest clusters (<120 K) than the other regions. Table 4 lists the contribution to rainfall from clusters 200–100 K in the four continental regions and 210–160 K in the other regions. In the four continental regions, 70%–80% of the rain is contributed by the 20%–30% of clusters colder than 200 K. In the oceanic regions, over half of the rain is contributed by the fewer than 20% of clusters colder than 210 K.

4. Discussion

Before considering the results presented in the previous section, it is worthwhile to understand how representative the regional samples may be. The discrete spatial and temporal sampling of the *F-11* SSM/I means that the database is only a sample of the population of cloud clusters in the study regions. It is possible to estimate statistically the population of randomly distributed subjects. Wildlife biologists estimate populations of slow-moving animal species by counting animals that occur within predefined strips of territory (e.g., Eberhardt et al. 1979; Kotz and Johnson 1982). In the strip-transect sampling method, minimum variability occurs when individual subjects are randomly distributed in space. For randomly distributed subjects (Poisson distribution), the total number N in the population is equal to the number counted n , as scaled by the ratio of the total area to the sample area (Eberhardt et al. 1979). The confidence limits are a function of $n^{-1/2}$. Since the 1400-km-wide transects of the *F-11* SSM/I cover 60%–80% of a study region each 12 h, the number of cloud clusters in a regional sample would be 60%–80% of the number in the regional population. With the majority of the possible clusters captured by the *F-11* SSM/I, it is reasonable to assert that the distributions

of size, intensity, and cluster types are the same in the regional populations as they are in the regional samples.

The implication of Figs. 4–7 is that MCSs dominate regional rainfall totals. MCSs represent less than or equal to 20% of the population of cloud clusters but contribute more than or equal to 70% of the wet season rain. The importance of MCSs to regional rainfall is nearly uniform among the study regions. Except for the months in regions with dry seasons (e.g., November–January in India/Southeast Asia), monthly time series of contribution by the MCS class by regions (not shown) exhibited very little change (0%–3%) in the contribution from month to month. These are consistent with a number of related studies on cloud size versus precipitation. The cumulative frequency distributions of radar echo areas and radar echo duration in a small regional study by López (1978) and highly reflective cloud cluster areas in a larger regional study by Mapes and Houze (1993) are lognormal. The 10% largest and therefore longest-lasting radar echoes in the GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment (GATE) region produced 90% of the precipitation in López's study. In the TOGA COARE region, MCS-scale squall lines contributed 80% of the rainfall compared to a 12% contribution from small isolated clusters of cells (Rickenbach and Rutledge 1998).

The larger and better-organized continental MCSs and mesoscale convective complexes (MCCs) in studies by Kane et al. (1987), McAnelly and Cotton (1989), and Negri et al. (1997) produced significantly more rain than smaller, less organized MCSs and MCCs. In Sahelian Africa, 41 MCCs accounted for 23% of the July–September 1987 precipitation (Laing et al. 1999). Late afternoon/early evening MCSs that develop into large, well-organized nocturnal MCCs have average rain rates significantly higher than shorter-lived systems (McAnelly and Cotton 1989). Over the oceans, Lin and Rossow (1997) observe heavy precipitation (>5 mm h⁻¹) almost exclusively in cold-topped systems about 0.5% of the time, but this small fraction produces 50% of oceanic rainfall. In continental regions particularly, the dependence on the rainfall from a few large, well-organized MCSs has important ramifications for the persistence of droughts and possible impacts of environmental change on cumulus convection and water resources management.

The results of this study must be viewed in light of the physics of the retrieval method and the composition and construction of the database. The objective is not to provide a quantitatively accurate rainfall climatology but to infer from the 85-GHz ice-scattering signature the relative contributions by system type, size, and intensity to tropical rainfall. The results depend upon on a number of assumptions, namely, that the sample size is sufficiently large, that the clusters in the database are at or near their peak size and intensity, and that the calculated rain volumes are reasonable approximations. Two questions arise regarding how representative the

TABLE 5. A comparison of the CMAP and regional sample rainfall volumes (mm km^{-2}).

Region	CMAP	Regional sample	Percent difference
Amazon	1.21E+10*	8.71E+09	72%
Atlantic	9.84E+09	6.99E+09	71%
Central America	5.40E+08	4.05E+08	75%
Central Pacific	1.75E+10	8.05E+09	46%
Congo	1.19E+09	8.45E+08	71%
East Pacific	2.78E+10	1.64E+10	59%
India/SE Asia	2.72E+10	1.93E+10	71%
Maritime Continent	5.06E+10	2.07E+10	41%
SPCZ	5.12E+10	2.41E+10	47%
Sub-Saharan Africa	1.07E+10	7.70E+09	72%

* Read notation as 1.21×10^{10} , for example.

study results are: 1) How does looking at a warm phase of ENSO affect the results? 2) What is the effect of neglecting the contribution of warm-topped systems? The CMAP 19-yr (1979–97) monthly mean rainfall was compared to the CMAP 1993 monthly rainfall for the study regions. In accord with the NOAA Climate Analysis Center's view of 1993, departures from the mean were small, less than one standard deviation in 9 of 10 study regions. In the central Pacific, the rainfall was one standard deviation higher. Although, the rainfall was higher in absolute terms in the eastern and central Pacific, this would not necessarily cause the distributions in Figs. 4–7 to change. Examination of the characteristics of MCS populations during a cold phase of ENSO is warranted. With the possible exception of the central Pacific, 1993 appears to be representative of mean conditions in the Tropics.

Question 2 can be approached indirectly by comparing the CMAP and the regional rainfall totals. While neither dataset can be truly considered “ground truth,” they are adequate for first-order comparisons. In Table 5, the rainfall totals for the continental regions are around 70% of the CMAP totals. The oceanic regions exhibit more variability. The central Pacific and Maritime Continent totals are 40%–50% of CMAP, the East Pacific nearly 60%, and the Atlantic total over 70%. The central Pacific and Maritime Continent rainfall totals are below, the Atlantic was equal, and the East Pacific (nearly) equal to the estimated percent of the population of cloud clusters sampled by the *F-11* SSM/I. Even though the GSCAT oceanic coefficient was developed from Pacific atoll data, and it seems likely it reflects the relative contribution from warm rain processes, two of the three Pacific regions are still low. This suggests regional variability in the tropical oceans in the relative contribution of warm rain processes. Lin and Rossow's (1997) estimate of 10%–20% contribution from warm-topped systems appears applicable. This study's calculated contributions in the oceanic regions from small and warm cloud clusters are probably low. Even if the contributions from warm-topped systems were considered, oceanic MCSs would still contribute

the majority of the rainfall in oceanic regions (Simpson et al. 1993; Rickenbach and Rutledge 1998).

5. Conclusions

This study compiled a database of precipitating cloud clusters in 10 regions of the wet Tropics for a calendar year (November 1992–October 1993) from 85-GHz data from the *F-11* SSM/I. The cloud clusters were grouped into four classes of basic system types based on size (250 K contour greater or less than 2000 km^2) and minimum enclosed PCT (greater or less than 225 K). A subclass of intense MCSs grouped MCSs with a 200 K contour greater than or equal to 2000 km^2 and a minimum enclosed PCT less than or equal to 175 K. Physically, these classes distinguished systems with and without large areas of active, deep convection. For each region's 3-month wet season, instantaneous volumetric rain rates ($\text{mm km}^2 \text{h}^{-1}$) were calculated for each cloud cluster using a scattering-based rain-rate retrieval algorithm. Regional rainfall totals were the sum of individual cluster rain volumes over the wet season.

To evaluate regional differences in convective intensity among MCS populations, the cumulative frequency distributions of MCS minimum PCT were plotted for each of the study regions. Four regions, Central America, India/Southeast Asia, the Congo, and Sub-Saharan Africa, had distributions significantly (>99%) more intense than the oceanic regions. Although geographically continental, the Amazon's distribution closely resembled the oceanic distributions. How and why Amazonian MCSs differ from the other continental regions and whether this relationship may change seasonally would be an interesting topic of research but was not treated in this study.

For each study region, the rainfall contributions with respect to system type, size, and intensity were calculated. Regional differences were small among the distributions of contribution to rainfall with respect to system type and with respect to precipitating area. Although cloud clusters greater than or equal to 2000 km^2 , most of which were MCSs, constituted 10%–20% of the regional populations, they contributed 70%–80% of the rainfall. The contributions from each of the four basic classes varied less than 10% among the study regions. In all of the study regions the contribution from intense MCSs was four to six times their representation in the population. The four continental regions had, in absolute terms, the largest number of intense MCSs, and the contribution to wet season rainfall by this small number (<2%) of cloud clusters was nontrivial ($\approx 10\%$). With respect to precipitating area, rainfall contributions in the study regions rose sharply from less than 5% at 1000 km^2 to about 20% at 5000 km^2 . The top 10% of cloud cluster areas contributed more than 70% of the rainfall, and the top 1% (>20 000 km^2) contributed about 35% of the total rainfall.

Reflecting the cumulative frequency distributions of

MCS minimum PCT, rainfall contributions with respect to minimum PCT had significant regional differences. Although the median minimum PCT for the study regions was 228–238 K, 200 K was in the 10th percentile in the oceanic regions and the 25th percentile in the four continental regions. The cumulative frequency distribution of the four continental regions had broader distributions compared to the oceanic regions. The oceanic distributions peaked sharply at 200 K but peaked at 175 K in the four continental regions. In the oceanic regions, over half of the rain was contributed by the fewer than 20% of cloud clusters colder than 210 K. In the four continental regions, 70%–80% of the rain was contributed by the 20%–30% of cloud clusters colder than 200 K, with nonnegligible contributions from a small number of cloud clusters colder than 120 K. Sub-Saharan Africa had the largest contribution from cloud clusters colder than 120 K.

The ice-scattering signature is linearly related to but does not directly measure rain rate, introducing uncertainty into the calculation of rain volumes. However, the methodology was appropriate for estimating relative contributions to tropical rainfall. The results of this study were unambiguous and consistent with previous related studies. MCSs with minimum brightness temperatures colder than 200 K dominated rainfall totals in all of the study regions. Such MCSs represented less than or equal to 20% of the population of cloud clusters but contributed greater than or equal to 70% of the rain. Because there appears to be a circumscribed range of sizes and intensities of systems most responsible for tropical rainfall, work on improving weather and climate models can focus on finding the most efficient parameterizations to reflect these ranges.

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