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Radar-observed squall line propagation and the diurnal cycle of convection in Niamey, Niger, during the 2006 African Monsoon and Multidisciplinary Analyses Intensive Observing Period

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[1] Surface radar observations near Niamey, Niger, during the African Monsoon Multidisciplinary Analyses (AMMA) campaign in 2006 documented the structure, motion, and precipitation of cloud systems during the monsoon season. These unique observations for that part of the Sahel were combined with satellite rain estimates and infrared satellite imagery to study the diurnal cycle of rainfall in Niamey, Niger. This study confirms the bimodal structure of the diurnal rainfall cycle in Niamey during AMMA, seen by previous studies of West African rainfall. Radar analysis of squall line mesoscale convective systems (SLMCS) and non-MCS isolated convection clearly demonstrated that the nocturnal maximum was associated with the observed arrival time of westward propagating SLMCS. Satellite imagery suggested that these SLMCS formed in elevated terrain to the east of Niamey the prior afternoon. Radar observations showed that local isolated convection produced the smaller afternoon maximum. Early in the monsoon season, locally generated convection produced an afternoon diurnal rainfall maximum that was delayed by several hours compared to midseason when African easterly wave (AEW) activity was much greater. We suggest that the observed greater mean convective inhibition early in the season, perhaps tied to the absence of large-scale forcing from AEW, played a role in the delayed initiation time.

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1. Introduction

[2] Tropical and summer midlatitude convection over land generally displays a strong diurnal cycle with an afternoon maximum in rainfall associated with locally generated convection forced by solar heating of the surface. However, many tropical and midlatitude locations show longitudinal variations in the diurnal rainfall cycle, which complicate the simple model of local solar heating. Such longitudinal variations have been shown to be associated with propagating convective systems from preferred genesis regions of convection, for example orographic forcing on the lee side of the Rocky Mountains of the United States [*McAnelly and Cotton*, 1989; *Carbone et al.*, 2002], or sea breeze forcing along the northeast coast of Brazil [e.g., *Silva Dias and Nieto Ferreira*, 1992; *Cohen et al.*, 1995; *Negri et al.*, 2000; *Rickenbach*, 2004]. These studies illustrated the importance of distinguishing between locally forced convection and propagating convective systems when constructing diurnal composites of rainfall, leading to a more complete picture of rainfall variability at a particular location.

[3] Propagating convective systems are important features of the West African Sahel rain climatology [*Hamilton et al.*, 1945; *Aspliden et al.*, 1976; *Fortune*, 1980; *Chong et al.*, 1987; *Lebel et al.*, 1997; *Futyan and Del Genio*, 2007], producing about 80% of the total rainfall in that region [e.g., *Dhonneur*, 1981]. West African convective systems contain a large fraction of stratiform precipitation [*Schumacher and Houze*, 2006], consistent with the presence of mesoscale circulations known to be associated with propagating systems in West Africa [*Roux et al.*, 1984; *Chalon et al.*, 1988]. In the rainier regions to the south the rainfall contribution from propagating convective systems decreases to 50% of the annual rainfall in Benin [*Fink et al.*, 2006] to somewhere between 16% and 32% of the annual rainfall in the Guinean Coast [e.g., *Acheampong*, 1982]. Those results suggest that propagating convective systems dominate rainfall production on the northern edge of the West African Intertropical Convergence Zone (ITCZ) [*Mohr*, 2004], where the African Easterly Jet steers systems westward [*Chong et al.*, 1987], with the role of locally generated convection increasing

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further south in the core of the ITCZ. *Rowell and Milford* [1993] inferred from satellite imagery that these systems were organized as squall lines which, in agreement with *Aspliden et al.* [1976], commonly formed in the afternoon over elevated terrain in the eastern Sahel region of Africa.

[4] In the Sahel, previous studies [*Shinoda et al.*, 1999; *Mathon et al.*, 2002] used rain gauge data to show that the climatological diurnal cycle of rainfall in and around Niamey, Niger (13.5°N latitude, 2.2°E longitude), in the northern Sahel region of West Africa includes a strong early morning peak (0300–0600 LT) as well as a weaker late afternoon peak (1500–1800 LT). They hypothesized, but did not demonstrate, that squall lines arriving in Niamey in the early morning might account for the nocturnal maximum, while the afternoon mode may have been associated with local convection formed from daily solar heating. *Laing et al.* [2008] used geostationary satellite data in the Sahel region to show that the timing of the diurnal maximum in cloud cover at a given location occurred increasingly later with increasing west longitude, consistent with westward propagation.

[5] The rain gauge and satellite data sets used in these previous works could not directly observe the organization and motion of the precipitation within convective systems. During the summer of 2006 the African Monsoon Multidisciplinary Analyses (AMMA) Intensive Observing Period (IOP) provided a wealth of information regarding the onset and development of the monsoon season over the Sahel region of West Africa [*Redelsperger et al.*, 2006]. The Massachusetts Institute of Technology (MIT) scanning C-band weather radar deployed near Niamey during AMMA provided for the first time in this region a direct sampling of the structure, motion, and precipitation of convective cloud systems from during the monsoon season (July to September). R. Nieto Ferreira et al. (Radar observations of convective system variability in relationship to with African easterly waves during the 2006 AMMA IOP, submitted to *Monthly Weather Review*, 2008) (hereinafter referred to as NF2008) used this data set to show that squall line mesoscale convective systems (SLMCS), composed of a line of convection with a trailing region of stratiform rain [*Leary and Houze*, 1979; *Johnson and Hamilton*, 1988], were the primary rainmakers during AMMA IOP 2006. NF2008 showed that SLMCS occurred in both the troughs and ridges of African easterly waves, with those in troughs having significantly more stratiform rain.

[6] This study applies a radar-based analysis of the organization and motion of convective systems introduced by NF2008 to the roles played by propagating SLMCS and local isolated convection on the observed diurnal cycle of rainfall near Niamey during the 2006 monsoon season. The goal of this work is to confirm the existence of a bimodal structure to the diurnal rainfall cycle in Niamey during AMMA and to investigate its origin using surface radar data, infrared satellite observations of clouds, Tropical Rainfall Measuring Mission (TRMM) satellite rain estimates, and radiosonde measurements. We will demonstrate that the nocturnal maximum was associated with propagating SLMCS that formed in elevated terrain to the east of Niamey while local isolated convection led to the afternoon maximum. The paper is organized as follows. Section 2 discusses the data sets used in this study and the methodology used for analysis of the MIT radar observations. Diurnal rainfall composites and statistics of convective system propagation and region of origin are presented in section 3. A summary of the main findings and directions for future work are presented in section 4.

2. Data Sets and Methodology

[7] Observations of convective systems from the MIT C-band weather radar, which operated during the 2006 AMMA Intensive Observing Period, are used to classify and study the propagation and diurnal rainfall signal of convective systems during the 2006 monsoon season near Niamey, Niger (13.5°N, 2.2°E). Meteosat infrared satellite imagery provided a satellite perspective on convective system propagation.

[8] Radar reflectivity data was collected by the MIT radar during 5 July to 27 September 2006 (the radar observing period, or ROP), recording a total of over 11,250 volumes. Each radar reflectivity volume, representing a three-dimensional view of the troposphere out to 150 km horizontal radius, was constructed from 15 individual 360° scans at increasing elevation angles. Reflectivity volumes were collected every 10 min during the ROP. These volumes documented the three-dimensional structure of precipitation as convective systems formed and moved through the radar domain. A comparison of MIT radar reflectivity values with the TRMM precipitation radar during overpass times where significant convection was present indicated a mean bias of 1 dB*Z* (MIT radar lower than TRMM), which is within the uncertainty introduced in comparing platforms of different beam geometries. Sphere calibrations performed with the MIT radar during AMMA also suggested a 1 dB*Z* bias of measured signal compared to the theoretical return from a metallic sphere, which is a good agreement (B. Russell et al., Radar rain gauge comparisons on squall lines in Niamey, Niger for the AMMA, submitted to *Quarterly Journal of the Royal Meteorological Society*, 2008). Other details of the radar processing and quality control are given by NF2008 and *Guy* [2008]. Constant altitude plan position indicator (CAPPI) reflectivity maps at 1 km height were converted to rainfall rates in order to produce time series of radar-derived rainfall, as described by NF2008. Because errors in radar based rainfall retrieval can be significant [*Atlas et al.*, 1999], our results emphasize relative differences and time variation in rainfall rather than absolute rainfall amounts.

[9] Animation of radar reflectivity of the 1 km CAPPI maps every 10 min for July–September 2006 enabled the subjective determination of system organization, and a quantitative estimate of system motion. An MCS is defined [*Houze*, 1993, 2004] from a radar viewpoint as a group of convective cells with a contiguous region of radar echo of at least 100 km in horizontal dimension, generally with associated homogeneous stratiform radar echo. For each CAPPI map, radar echo associated with convective cells was identified and distinguished from the homogeneous weaker echo of stratiform rain using an automated convective-stratiform separation algorithm [*Steiner et al.*, 1995; *Rickenbach and Rutledge*, 1998]. An MCS event was defined to begin when contiguous convective echo of at least 100 km in length entered the radar domain, or formed within the radar domain. Event termination occurred when all radar echo associated with the MCS either propagated out of the

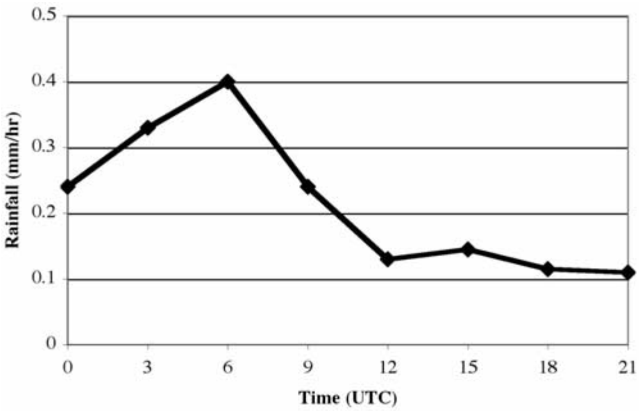

Figure 1. Diurnal variation of rainfall from July–September 2006, within a 3° × 3° region centered on the radar location, from TRMM 3B-42 data.

radar domain, or completely dissipated within the domain. In Niamey during July–September 2006, MCS organization generally took the form of large propagating squall line MCSs (SLMCS), which formed beyond the radar domain to the east and generally moved westward into the radar domain. Nonsquall MCSs were rare and short-lived (a few hours), often forming and decaying within the radar domain. When MCS events were not present, convection was organized as isolated convective cells, which formed and decayed locally. Examples of these three modes of organization (SLMCS, nonsquall MCS, and non-MCS isolated convection) and summary statistics of their relative occurrence and rainfall are presented by NF2008.

[10] For the present study, animations of CAPPI images at 1 km above ground level were analyzed to determine the dates, propagation speed, direction of motion, and time of arrival at the radar of SLMCS. Radar data has the advantage that it provides a more direct means of identification of SLMCS, and with greater temporal resolution, compared to the more commonly available visible and infrared satellite imagery of cloud tops. This is because radar directly senses the location and organization of precipitation within convective and stratiform clouds. In addition, the rapid update cycle of radar volume scans (every 10 min) allows the determination of the speed of relevant echo features, such as the leading edge of a squall line. The mean squall line speed and direction was found for each SLMCS event by manual tracking of the squall line leading edge in successive CAPPI images.

[11] Time series of the TRMM 3B-42 precipitation data set, a high-resolution product blended from microwave, infrared and gauge data sets, was used for an independent comparison with the radar-derived diurnal variation of rainfall. The 3-hourly, 0.25° × 0.25° data set was averaged over a 3° × 3° region inclusive of the radar coverage. Diurnal rain composites from 3B-42 were constructed for the period July–September 2006.

[12] The daily Global Precipitation Climatology Project (GPCP) precipitation data set was used to study the origin of large precipitating systems to the east of Niamey. The GPCP 1° horizontal resolution daily data set is available from 1997 to present and represents a combination of rain gauge data with precipitation information from various satellite instruments to produce a global precipitation data set [*Adler et al.*, 2003]. In the vicinity of Niamey, GPCP and rain gauge precipitation for 2.5° box averages over several years agreed to within 0.5 mm d^{-1} (GPCP higher), with the lowest bias along the Sahel region [*Nicholson et al.*, 2003]. GPCP composites 2 days prior, 1 day prior, and the day of SLMCS arrival in Niamey were constructed covering all of West Africa, as described by NF2008.

[13] Radiosonde data at from the Niamey Airport site, about 2 km from the radar location, were used to estimate convective inhibition (CIN) on undisturbed days during radar operation. The CIN analysis was used to examine mechanisms of the timing of rainfall diurnal maxima from locally generated convection. CIN values were determined [*Williams and Renno*, 1993] from 1200 UTC soundings on days when no mesoscale convection was present within 150 km from the radar site.

3. SLMCS Propagation and the Diurnal Cycle of Rain

[14] Most convective systems in Niamey during July–September 2006 were determined by NF2008 to be SLMCS, which formed beyond the radar range to the east and propagated westward into the radar domain. During the AMMA ROP, 28 SLMCS were observed by the radar (NF2008). In good agreement with previous studies [*Dhonneur*, 1981; *Mathon and Laurent*, 2001; *Nesbitt et al.*, 2006], NF2008 showed that on average, SLMCS produced 82% of the total rainfall according to the MIT radar. Nonsquall MCSs were rare and short-lived (a few hours), often forming and decaying within the radar domain. These systems contributed little to rainfall totals (NF2008) and are not explored further in this paper. When MCS events were not present, convection was organized as isolated convective cells, which formed and decayed locally. Typical examples of each of these three modes of organization (SLMCS, nonsquall MCS, and non-MCS isolated convection) are presented by NF2008.

[15] Before turning to the radar results, we present in Figure 1 an independent estimate of the diurnal composite of rain, using the TRMM 3B-42 data set. The data were averaged from July–September 2006 within a 3° × 3° region centered on the radar location, representing the radar area. Figure 1 established the early morning maximum for the Niamey region during AMMA and also suggested a weak secondary maximum in the midafternoon. The origin of these features will be explored next using radar observations.

[16] Monthly time series of rainfall derived from the CAPPI radar reflectivity maps for July–September are shown in Figure 2. Generally, rain maxima exceeding about 0.6 mm h^{-1} (the tallest peaks) in the time series are associated with SLMCS events passing through the radar area. It is clear from these time series that SLMCS occurred on average every 2–4 days. Power spectra of the rain time series (not shown) indicate significant variability at those periods. NF2008 discuss the connection of this variability timescale with African easterly waves. It is crucial to note, for the interpretation of diurnal rainfall variation shown in Figure 1, that SLMCS do not occur every day. Instead, when they occur, these systems arrive at the radar area at a consistent time of day. Figure 3 shows a histogram of the

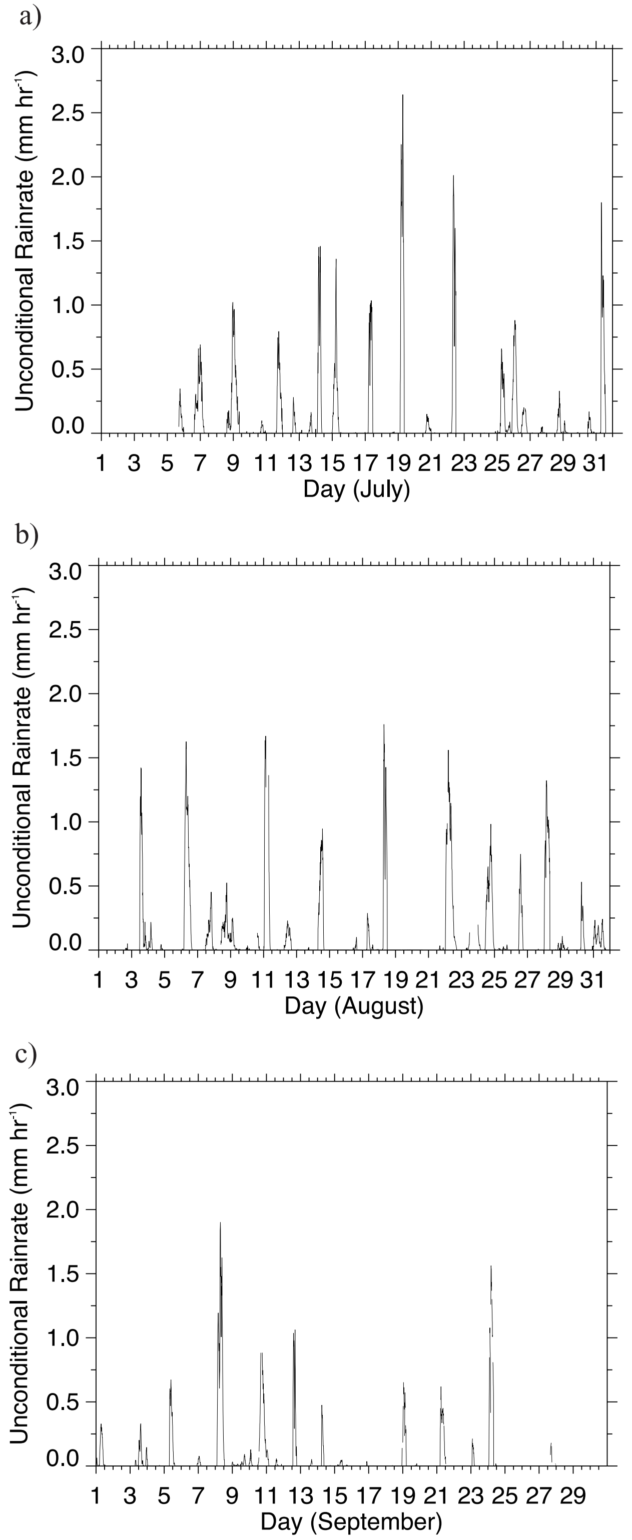

Figure 2. Time series of radar-derived rain rate for (a) July 2006, (b) August 2006, and (c) September 2006. Units are mm h^{-1}.

time of arrival at the radar of the leading edge of all SLMCS sampled by the radar during the ROP. Note that in Niamey, local time is UTC + 1 h. SLMCS have a systematic early morning time of arrival to Niamey, with 83% of these systems arriving between 0000 UTC and 0900 UTC (while none of them arrive between 1500 and 0000 UTC).

[17] The consistent time of arrival is reflected in the radar-derived rainfall monthly diurnal composites for SLMCS shown in Figure 4a. From these composites it is clear that most of the SLMCS rainfall in Niamey occurred in the morning, consistently each month, with a sharp peak at 0700 LT. Combined with the westward propagation of SLMCS (described in detail below) this diurnal phase locking suggests a common time and place of SLMCS origin east of Niamey, which is explored later. The amplitude was somewhat lower for September, likely because non-MCS isolated convection were present a larger fraction of time during that month when compared to July and August (NF2008), as the monsoon season approached its end.

[18] For comparison, monthly diurnal composites for non-MCS (local isolated convection) in Figure 4b showed afternoon maxima in rainfall, but with interesting month-to-month differences. In July the diurnal maximum occurred in the late afternoon, at 1700 UTC, while in August the maximum was 3 h earlier. We hypothesize that more African easterly wave (AEW) activity in August compared to July (NF2008), with an associated increase in large-scale forcing, provided a more conducive thermodynamic environment for the triggering of local convection during the diurnal heating maximum leading to an earlier diurnal rain maximum. To test this idea, we averaged values of convective inhibition (CIN) calculated from undisturbed days (no mesoscale convection present in the radar area) at 1200 UTC using soundings from the Niamey airport site located 2 km from the radar. The average CIN value for July was 209 J kg^{-1}, which is 30% higher than the August average of 158 J kg^{-1}. The higher mean CIN value in July represents a greater thermodynamic barrier for local triggering mechanisms to overcome, and is consistent with a delayed initiation time of afternoon convection in July compared to August.

[19] This result compares well to a similar analysis in tropical South America. The late afternoon diurnal maximum in isolated convective rain for July is in stark contrast to the "noon balloon" (0100–0200 LT) maximum in locally generated rainfall seen in the western Amazon Basin of

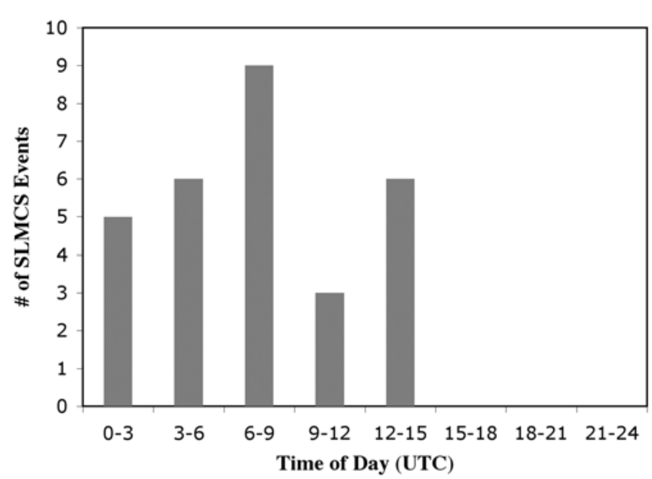

Figure 3. Histogram of the time of arrival (UTC) at the Niamey radar of the leading edge of SLMCS during the 2006 ROP. Local time equals UTC + 1 h.

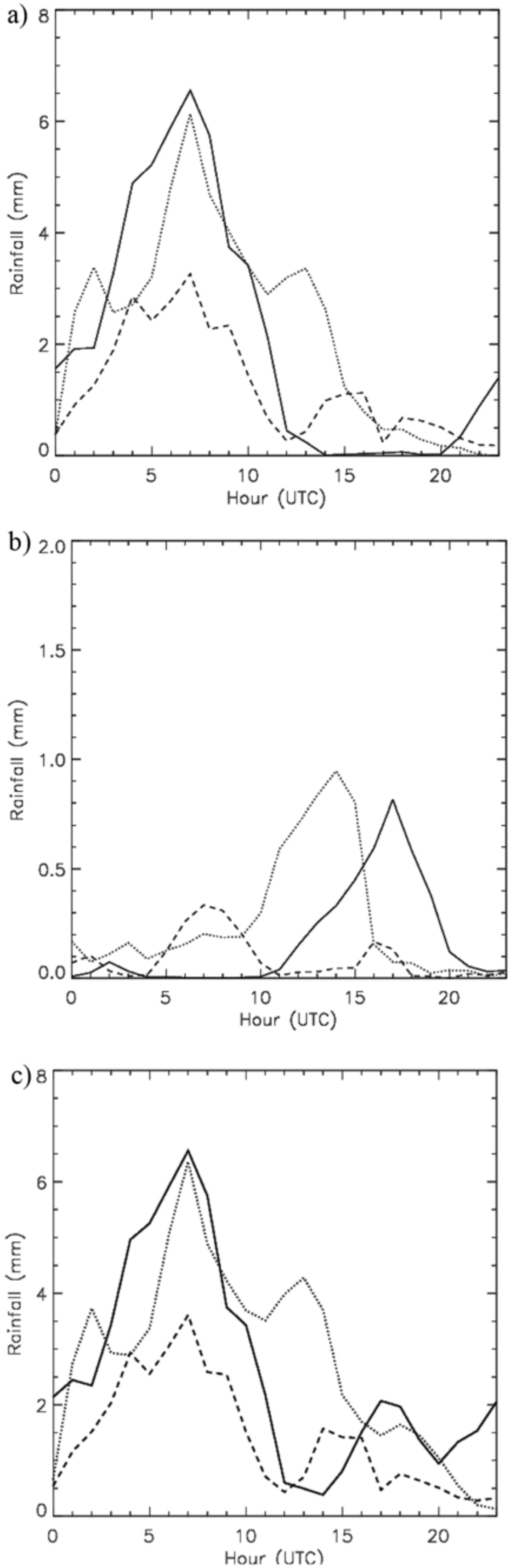

Figure 4. Monthly composite diurnal cycle of precipitation observed by the MIT radar for (a) SLMCS events, (b) non-MCS isolated convection, and (c) all rain events. Solid curve is July, dotted curve is August, dashed curve is September. Local time equals UTC + 1 h.

South America during a TRMM-related field campaign (TRMM–Large-Scale Biosphere-Atmosphere (LBA) Experiment in Amazonia [*Rickenbach et al.*, 2002; *Williams et al.*, 2002]). In undisturbed conditions during TRMM-LBA the mean CIN value was 40 J kg^{-1} [*Halverson et al.*, 2002], which was much lower than the Niamey July value and was consistent with the delayed convective initiation in West Africa. In September there is a weak additional rainfall maximum in the midmorning that is not present in the other months. Though non-MCS isolated convection was more common in September, it produced relatively less rainfall compared to SLMCS that month perhaps leading to a noisier diurnal composite. In summary, for all rain types combined (Figure 4c), the diurnal cycle of rainfall observed by the radar in Niamey during 2006 shows two main modes: a strong early morning peak associated with the nocturnal arrival of SLMCS, and a weak mid-late afternoon peak from locally generated convection. This bimodal structure to the radar-derived diurnal rainfall cycle is consistent with the TRMM 3B-42 result (Figure 1) and is in good agreement with previous studies for this region [e.g., *Shinoda et al.*, 1999].

[20] Further evidence to explain the nocturnal diurnal timing of SLMCS in Niamey came from the 6-hourly Meteosat infrared satellite imagery and superimposed MCS cloud top tracks [*Machado et al.*, 1998] available at the AMMA website (http://aoc.amma-international.org/animSOP/). These IR images were used to backtrack the origin of cloud features associated with each SLMCS that affected Niamey during the ROP. The location of SLMCS initiation, large-scale precipitation anomalies prior to and following SLMCS passage in Niamey, and important topographic features are presented in Figure 5. Figure 5 (middle) shows the approximate locations of formation of 25 of the 28 SLMCS 1 day prior (day −1) to their passage through Niamey during the ROP using a number that indicates the number of SLMCS origins and their genesis location. The remaining three SLMCS could not be tracked because of missing IR imagery. Backtracking the location of formation of the cloud shields of SLMCS events over Niamey revealed that all of the SLMCS observed by radar in Niamey during the 2006 monsoon season formed to the east of Niamey, as suggested earlier. The majority of these systems originated in the late afternoon of the previous day in elevated terrain between the longitudes of Niamey and Lake Chad, consistent with the results of *Fink and Reiner* [2003]. This result meshes well with the composite analysis of GPCP precipitation for the day prior to SLMCS arrival in Niamey (Figure 5, middle) which shows a large region of precipitation at approximately the same location. The day −2 GPCP composite (Figure 5, top) shows no significant rainfall anywhere in tropical Africa, consistent of the formation of SLMCS on day −1. On day 0 (Figure 5, bottom), Niamey is located on the northern fringe of a north-south elongated precipitation feature that has maximum values in excess of 14 mm d^{-1} just to the south of Niamey. Taken together, the day −2 through

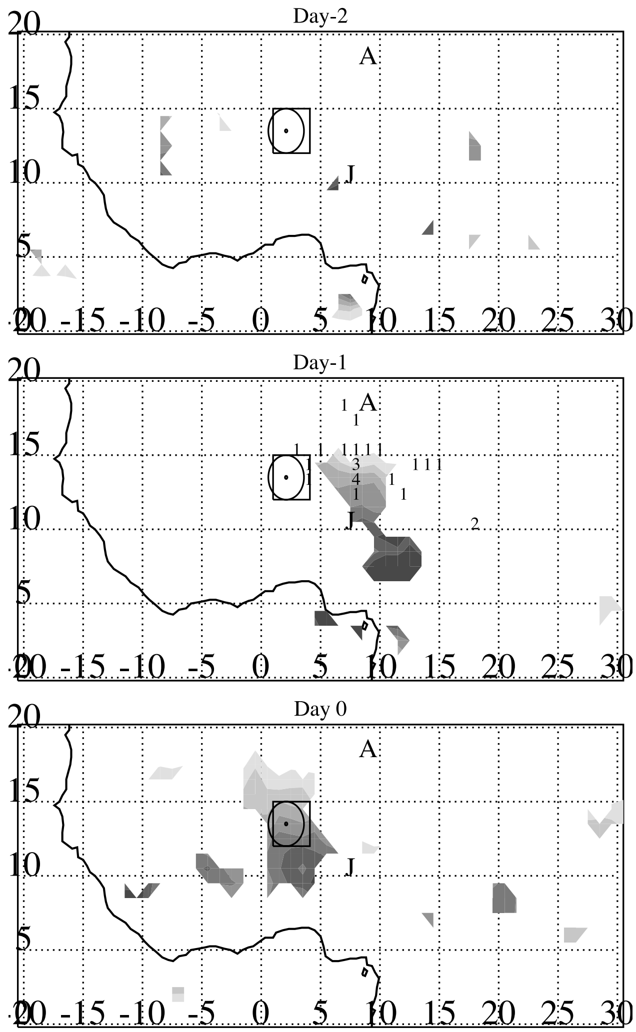

Figure 5. Composite of GPCP precipitation for (top) 2 days prior to (day −2), (middle) day prior to (day −1), and (bottom) the day of (day 0) an SLMCS event in Niamey. Shading represents GPCP precipitation anomalies contoured every 2 mm d^{-1}, starting at 2 mm d^{-1}. Only results that are significant to the 90% level according to a Student's t test are shown. The positions of SLMCS event formation that affected Niamey on day 0 are marked with a number that indicates the number of SLMCS formations in that location. The location of the Aïr Mountains and the Jos Plateau are marked with "A" and "J," respectively. The MIT radar area is denoted by a circle centered in Niamey, Niger. The TRMM 3B-42 diurnal rainfall composite was determined in the 3° × 3° box near the radar area.

day 0 GPCP composites (Figure 5) indicated that most of the SLMCS that reach Niamey at night form the previous day over the elevated terrain of the Aïr Mountains and the Jos Plateau (Figure 5). Moreover, the time of formation of these systems (not shown) is in line with results of previous studies that have shown that squall lines form preferentially between 12 and 18 Z across equatorial Africa, often in the lee of mountainous regions [*Rowell and Milford*, 1993; *Laing et al.*, 2008].

[21] A histogram of the speed of propagation of SLMCS as they passed through the radar domain is shown in Figure 6. All but one of the SLMCS observed by the radar propagated at speeds in excess of 10 m s^{-1}, with most systems propagating faster than 15 m s^{-1}, which is generally consistent with previous satellite studies [*Fortune*, 1980; *Payne and McGarry*, 1977; *Fink and Reiner*, 2003; *Laing et al.*, 2008] and radar analyses [*Lebel et al.*, 1997] over West Africa. The directional histogram in Figure 7 shows that 20 of the 28 SLMCS observed by the radar propagated through Niamey from east-to-west, the same systems that formed the previous afternoon in mountainous terrain 600 km to the east. Space-to-time conversion based on their speed and location of origin 600 km to the east was consistent with a nocturnal arrival time in Niamey. In fact, the vast majority of systems that propagated through Niamey had a strong easterly propagation component and only one of these systems propagated into Niamey from the north. These results confirm previous satellite-based results on the direction of organized convection propagation over equatorial Africa [*Aspliden et al.*, 1976; *Rowell and Milford*, 1993; *Hodges and Thorncroft*, 1997; *Laing et al.*, 2008].

[22] The arrival time of SLMCS to Niamey does not appear to be phase locked with AEW. NF2008 showed that at the time the squall line MCSs passed through Niamey, 57% of them were located at or ahead of an AEW trough (with the remaining 43% ahead of or in an AEW ridge). Though many SLMCS are in and ahead of the trough, the numbers do not suggest systematic phase locking with the diurnal formation and propagation of SLMCS.

4. Summary

[23] Radar observations near Niamey, Niger, during the AMMA IOP documented the structure, motion, and rainfall variability from cloud systems during the 2006 monsoon season. This study confirms the bimodal structure of the diurnal rainfall cycle in Niamey during AMMA using TRMM satellite and surface radar data, a result seen by previous studies of West African rainfall. Radar observations,

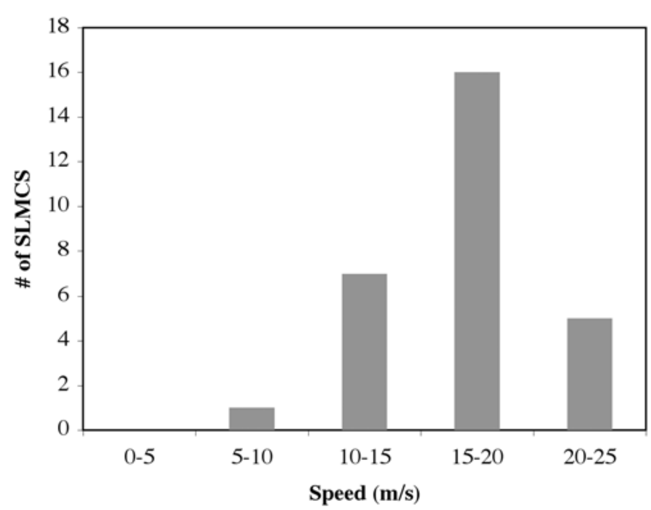

Figure 6. Histogram of the eastward speed of propagation of SLMCS through the Niamey radar.

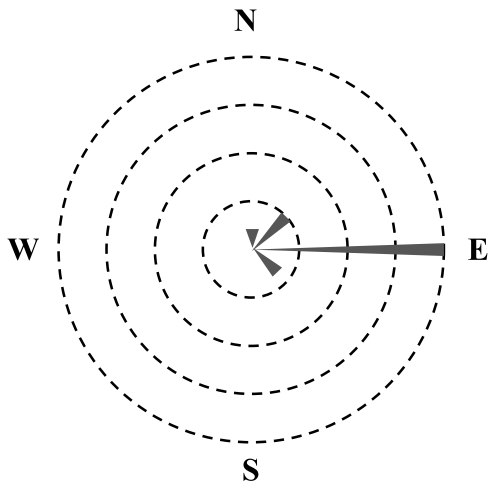

Figure 7. Histogram of the direction of propagation of SLMCS that propagated through Niamey during the AMMA ROP. Triangular bars show the number of SLMCS events in eight coordinate directions (N, NE, E, SE, S, SW, W, NW). Dashed circles denote the number of events in each category. The innermost dashed circle represents the 5 events contour, and contour interval is 5.

unique in this part of the Sahel, allowed an investigation into the origin of this bimodal feature. Analysis of SLMCS and non-MCS isolated convection confirmed that the nocturnal maximum was associated with propagating SLMCS that formed in elevated terrain to the east of Niamey the prior afternoon, while local isolated convection led to the smaller afternoon maximum. Early in the monsoon season, locally generated convection produced an afternoon diurnal rainfall maximum that was delayed by several hours compared to midseason when AEW activity was much greater. We suggest that the observed greater mean convective inhibition early in the season, perhaps tied to the absence of large-scale forcing from AEW, played a role in the delayed initiation time.

[24] Animations of radar CAPPI were used to classify rainy days in Niamey according to the organization of precipitation systems. A total of 28 SLMCS passed through Niamey during the ROP. Of these 28 SLMCS, 20 arrived at Niamey during the early morning, traveling westward across the radar domain. This consistent early morning time of arrival points to a common time and place of origin for SLMCS to the east of Niamey. A subjective analysis infrared satellite imagery show that these westward propagating precipitation systems originated over elevated terrain in southern Niger hundreds of kilometers to the east of Niamey.

[25] Future work will focus on examining the mechanisms of formation and maintenance of SLMCS in Niamey, using individual case studies of SLMCS combining radar and satellite data with sounding and NCEP reanalysis data.

[26] **Acknowledgments.** We appreciate the hard work and effort of all those who planned and participated in the AMMA field campaign. On the basis of a French initiative, AMMA is an international effort funded by agencies in France, the United Kingdom, the United States, Africa, and the European Union. We thank Richard Barnhill for performing the TRMM 3B-42 data analysis.

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