Radar Observations of Convective System Variability in Relationship to African Easterly Waves during the 2006 AMMA Special Observing Period

ROSANA NIETO FERREIRA AND THOMAS RICKENBACH

Department of Geography, East Carolina University, Greenville, North Carolina

NICK GUY

Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

EARLE WILLIAMS

Parsons Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Manuscript received 29 July 2008, in final form 19 June 2009)

ABSTRACT

A radar-based analysis of the structure, motion, and rainfall variability of westward-propagating squall-line mesoscale convective systems (SLMCSs) in Niamey, Niger, during the African Monsoon Multidisciplinary Activities (AMMA) 2006 special observing period is combined with an analysis of 700-mb (hPa) winds and relative vorticity to study the relationship between SLMCSs and African easterly waves (AEWs). Radar results show that SLMCSs were the most important rainmakers in Niamey and accounted for about 90% of the rainfall despite being present less than 17% of the time. Analysis of the 700-mb synoptic-scale flow revealed that during the 2006 West African monsoon season the African easterly jet vacillated between about 10° and 15°N on time scales of 1–2 weeks. AEWs followed the jet as it vacillated north and south, thereby producing two preferred paths for AEWs propagating past Niamey’s longitude, a northern track along 8° – 16°N and a southern track along 2° – 6°N. It was found that Niamey SLMCSs occurred westward of the trough of AEWs propagating along either track. The properties of SLMCSs must then be placed in the context of their location relative to these two AEW tracks, rather than in the trough and ridge pattern of a single AEW track. Radar analysis further indicated that although the total amounts of rainfall produced by SLMCSs occurring in both African easterly jet latitude regimes were similar, significant structural differences occurred between the two groups of systems. SLMCSs that formed to the west of AEW troughs propagating along the northern track had a significantly larger mean stratiform rain fraction in an environment of lower convective available potential energy when compared with the SLMCSs that occurred to the west of the troughs of AEWs in the southern track. The authors conclude that AEWs that propagated farther north provided a more favorable environment for stratiform rain production in Niamey SLMCSs than those AEWs located farther south. These results may be helpful to studies of the two-way interaction between AEWs and convection in West Africa.

1. Introduction

African easterly waves (AEWs) have long been recognized as the most important synoptic-scale features of the West African summer monsoon. Although their origins, structures, energetics, and interactions with convection have been the subject of numerous studies, there are still gaps in our understanding of these important synoptic-scale features. In particular, understanding the complex interaction of AEWs with convection is a problem that remains elusive. Burpee (1974) was first to notice that whereas rainfall occurs preferably to the west of the trough in AEWs located to the south of 12.5°N, north of that latitude in the Sahel region rainfall shifts to the region to the east of the AEW trough, where southerly winds import moisture from the south, allowing convection to form in what is normally a dry region. Since then,
while many studies have reported that convective systems tend to occur in the low-level convergent region to the west of AEW troughs (e.g., Carlson 1969; Payne and McGarry 1977; Aspliden et al. 1976; Fink and Reiner 2003; Reed et al. 1977), others report finding no relationship between AEWs and convective system formation (Rowell and Milford 1993) or that convective systems preferentially occur in the moist southerly wind region to the east of the trough (e.g., Laing et al. 2008). In part, the discrepancy between these studies may be related to the differences in the datasets used, the periods of time studied, and, most importantly, the choice of region of study. In fact, several studies report on the regional character of the AEW modulation of convection such as a strengthening in the coupling between AEWs and convection as the waves propagate westward through tropical Africa, variations in the location of convection within the AEW between the Sahara–Sahel region and regions farther south (Burpee 1974; Duvel 1990; Mathon et al. 2002), or structural differences in AEWs between land and ocean locations. A more recent study by Kiladis et al. (2006) shows that West African convection tends to occur in the region of northerly winds located to the west of the troughs of AEW that are propagating near 10°N. Their study also shows that West African convection occurs in the region of southerly winds located to the east of AEW troughs that are propagating along 20°N, implying that the spatial relationship between convection and AEW trough location is different for AEWs that propagate along different latitudes.

Previous studies (e.g., Thorncroft and Hodges 2001) have established that over West Africa AEWs propagate along two distinct tracks on the northern and southern sides of the African easterly jet (AEJ). Thorncroft and Hodges (2001) developed a 20-yr climatology of AEW tracks over Africa and the adjoining Atlantic Ocean. They found two separate AEW tracks over the continent, one at 850 mb (hPa) in the dry Saharan air to the north of the AEJ, and a second one at 600 mb in the rainy zone on the southern side of the AEJ. Other studies have suggested that the AEW track on the southern side of the jet is composed of two maxima: one near 12°N and a second one near 3°N (Diedhiou et al. 1999; Kiladis et al. 2006).

Propagating convective systems are the most important rainmakers in the African Sahel, producing about 80% of the total rainfall in that region (e.g., Dhonneur 1981). In the rainier regions farther south, the rainfall contribution from propagating convective systems decreases to 50% of the annual rainfall in Benin (Fink et al. 2006), and to somewhere between 16% and 32% of the annual rainfall farther south near 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) with the role of locally generated convection increasing farther south in the core of the ITCZ. Previous work also suggests that the contribution of AEWs to the formation of squall lines is larger in the Sahel than farther southward (Fink and Reiner 2003). These observations make the Sahel a good choice of location to study the relationship between AEWs and propagating convective systems. A better understanding of the organization, propagation, and diurnal-to-intraseasonal variability of rainy systems in the African Sahel could represent an important contribution to understanding the relationship between AEWs and convection during the West African monsoon season. During the summer of 2006, the African Monsoon Multidisciplinary Activities (AMMA) special observing period provided a wealth of information regarding the onset, development, and intraseasonal variability of the monsoon season over the Sahel region of West Africa (Redelsperger et al. 2006). The aim of the AMMA program was to provide a better understanding of the West African monsoon system on daily to interannual time scales. Observations from the Massachusetts Institute of Technology (MIT) scanning C-band weather radar deployed near Niamey, Niger (13.5°N, 2.2°E) during AMMA documented the structure, motion, and precipitation of convective cloud systems from July to September 2006 during the monsoon season.

This paper presents the results of a radar-based analysis of the structure, motion, and rainfall variability of propagating convective systems combined with National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data and satellite precipitation data to study the relationship between propagating systems and AEWs near Niamey during the 2006 monsoon season. The goal is to place the organization and characteristics of propagating mesoscale convective systems into the context of the structure, location, and variability of AEWs. This study builds on past work by taking advantage of the unique asset of the surface radar deployed during AMMA. A companion study of radar-observed convective systems and the diurnal cycle of rainfall is presented in Rickenbach et al. (2009).

The paper is organized as follows. Section 2 discusses the three main datasets used in this study and the methodology used for the quality control and analysis of the MIT radar observations. Section 3 compares the 2006 Niamey monsoon season with the climatology. Statistics of convective system organization and rainfall, including
convective and stratiform rain fractions, are presented in section 4. Section 5 relates propagating convective systems to the passage of AEWs through Niamey’s longitude. A summary of the main findings and directions for future work are presented in section 6.

2. Datasets and methodology

Three main datasets are used in this study. Data from the MIT C-band weather radar, which operated during the AMMA special observing period (SOP), were used to study convective system structure and rainfall variability during the 2006 monsoon season near Niamey, Niger (13.5°N, 2.2°E). The NCEP–NCAR reanalysis and Global Precipitation Climatology Project (GPCP; Adler et al. 2003) precipitation datasets were used to study the relationship between the convection organization and propagation as seen by the radar and the propagation of AEWs across West Africa during the 2006 monsoon season.

Radar reflectivity and Doppler radial velocity data were collected by the MIT scanning radar during 5 July–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 to a range of 150 km (see Fig. 1 for radar location), was constructed from 15 individual 360° scans, each at increasing elevation angles. Reflectivity volumes were collected at 10-min intervals during the ROP and required about 8 min of scanning to complete. These volumes documented the three-dimensional structure of precipitation as convective systems formed and moved through the domain. Radar files in native format were interpolated onto a stationary Cartesian grid (Oye 1994) centered at the radar location, with 1-km horizontal and vertical spacing.

Nonmeteorological echo from ground clutter and anomalous echo propagation was extensive at times and had to be removed from the entire dataset. This was accomplished by using the National Aeronautics and Space Administration (NASA) Tropical Rainfall Measuring Mission (TRMM) Satellite Validation Office’s quality control software package (Kulie et al. 1999). A detailed description of the implementation of MIT radar data quality control for the 2006 AMMA SOP is presented in Guy (2008). That study showed that if not removed, the anomalous echo would introduce a 60% bias to the three-month total rainfall, thus making clutter removal a crucial step in the radar data processing. We have made available the entire Cartesian quality-controlled radar volume dataset for 2006 [in network common data form (netCDF) format] at the AMMA data archive. Analyses presented in Guy (2008) determined that the radar reflectivity values were well calibrated.

Animation of radar reflectivity constant-altitude plan position indicator (CAPPI) maps at 1-km altitude every 10 min for July–September 2006 enabled the subjective determination of system organization, as well as a quantitative estimate of system motion. The mesoscale convective system (MCS) was the basis used to characterize convective organization. From the radar perspective, an MCS is defined as a group of convective cells with a contiguous region of radar echo of at least 100 km in the horizontal dimension, generally with an associated homogeneous stratiform radar echo (Houze 1993). In this study, MCS events were defined to begin when a contiguous convective echo of at least 100-km 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 radar domain, or completely dissipated within the domain. In Niamey from July to September 2006, MCS organization generally took the form of large propagating squall lines (hereinafter termed SLMCs), which formed beyond the radar range 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) are presented in Fig. 2, which shows two CAPPI maps, separated by several hours, for typical events in each of the three categories. The first example shows the SLMC that passed through Niamey on 8 September, which accompanied the AEW that produced Hurricane Helene a few days later upon reaching the Atlantic Ocean. The well-defined leading edge of this nocturnal SLMC propagated from east to west between midnight and sunrise, passing over the radar location at 0500 UTC, with a large trailing stratiform region that persisted until local noon (Niamey local time = UTC + 1 h). The nonsquall MCS of 24 August formed from dense convection in the midafternoon (1400 UTC), which displayed neither discernable linear structure nor propagation and decayed to stratiform by early evening. The example of non-MCS isolated convection on 8 July showed scattered cells forming in the midafternoon (1500 UTC), becoming more widespread several hours later, and then decaying. The timing and general evolution of the cases shown in Fig. 2 were typical of each category (Rickenbach et al. 2009).

For each CAPPI map, the radar echo associated with convective cells was distinguished objectively from the
homogeneous weaker echo of stratiform rain. The relative amount of convective cell versus stratiform rainfall and rain area not only describes the system organization, but is also related to the way in which latent heat is distributed vertically in the troposphere (Houze 1989), which in turn determines the impact of the convective system on the synoptic-scale circulation. Thus, the convective–stratiform radar echo separation serves as a descriptor of system interaction with the environment. An objective convective–stratiform separation algorithm (Steiner et al. 1995; Rickenbach and Rutledge 1998) was applied to each CAPPI map to produce time series of the rain area and intensity by rain type.

Radar reflectivity was converted to rainfall at each point on each CAPPI map to produce time series of radar echo area and rainfall over the radar domain. Separate time series were constructed for the convective, stratiform, and total rain rate and echo area. Sauvageot and Lacaux (1995) derived a reflectivity–rainfall ($Z-R$) relationship using drop size distribution measurements at the Niamey airport, about 2 km from the MIT radar site. Their $Z-R$ relation, $Z = 364 R^{1.36}$, was applied at each pixel on the CAPPI maps. Given that errors in radar rainfall retrieval from the variability of $Z-R$ relationships, even at a single location, are known to occur (i.e., Atlas et al. 1999), our results emphasize the relative differences in the horizontal and temporal variations of the rainfall rather than the absolute rainfall amounts.

The synoptic-scale flow over northern Africa during the 2006 monsoon season was characterized using wind data from the NCEP–NCAR reanalysis at 2.5° × 2.5° horizontal resolution (Kalnay et al. 1996). Previous studies have demonstrated not only that this dataset is adequate for describing intraseasonal-to-interannual synoptic-scale variability over West Africa but also that it is consistent with the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyses for
Fig. 2. CAPPI radar reflectivity map pairs showing examples of the three modes of organization (two maps for each example). SLMCS at (a) 0401 and (b) 1041 UTC 8 Sep 2006, a nonsquall MCS at (c) 1401 and (d) 1851 UTC 24 Aug 2006, and non-MCS isolated convection at (e) 1511 and (f) 1731 UTC 8 Jul 2006.
that region (e.g., Diedhiou et al. 1999; Sultan and Janicot 2003). During the 2006 monsoon season, NCEP–NCAR reanalyses in the Sahel benefited from the assimilation of twice-daily radiosonde data in at least five locations along the Sahel\(^1\) (J. Woollen, NCEP, 2009, personal communication), making the flow in and around Niamey all the more realistic. Examples of individual soundings from the Niamey airport (less than 2 km from the MIT radar site) for a SLMCS case are shown in Rickenbach et al. (2009).

The daily GPCP precipitation dataset was used to study the synoptic-scale characteristics of the precipitation variability in Niamey during the 2006 monsoon season. The GPCP 1° horizontal resolution daily dataset is available from 1997 to the present and represents a combination of rain gauge data with precipitation information from various satellite instruments to produce a global precipitation dataset (Adler et al. 2003).

The absolute values of rain estimates for GPCP and radar do not agree well, differing by nearly a factor of 2 for the seasonal rain total (GPCP high). Given the differences in measurement instruments and techniques, it is well known that there are significant differences between satellite-based and radar-based rainfall estimates (Ebert and Manton 1998; Rickenbach 1999). However, the difference between absolute values is not important to this study, which is concerned only with the time variability of the rainfall and not the absolute rainfall values. The two datasets are in good agreement when it comes to the relative changes in the spatial and temporal distributions of the rainfall intensity.

3. The 2006 monsoon season in Niamey

Given the strong interannual-to-interdecadal variability in rainfall (e.g., Fontaine et al. 1995) and African easterly wave activity in the African Sahel (Thorncroft and Hodges 2001), a brief overview of the rainfall and AEW activity in Niamey during the 2006 monsoon season in Niamey is relevant to establish whether the convection organization and AEW interactions presented in this study are occurring during a dry, normal or wet Sahel monsoon season.

The rainy season in the African Sahel usually begins in mid-May and lasts until October with most of the precipitation occurring in July and August (Sultan and Janicot 2003). The 1997–2007 May–October average precipitation for the 3° × 3° GPCP box centered in Niamey\(^2\) (13.5°N, 2.5°E, hereinafter referred to as Niamey GPCP rainfall; see Fig. 1 for box location) was 453 mm with a standard deviation of 70 mm. The 2006 May–October GPCP rainfall in Niamey totaled 410 mm, or about 10% below average.\(^3\) A delayed monsoon onset (Janicot et al. 2008) and a drier month of June most likely contributed to the slightly drier 2006 monsoon season in Niamey. During the AMMA SOP, however, Niamey rainfall was average.

Because of their role in organizing convection in the African Sahel (e.g., Fink and Reiner 2003), it is also important to establish how AEW activity during the 2006 monsoon season in Niamey compares to the climatology. The analysis of section 4 concentrates on AEWs that propagate along the southern side of the AEJ since those waves are the ones that have been shown to be associated with convection to the south of 15°N (e.g., Thorncroft and Hodges 2001).

The relative vorticity has been routinely used to track AEWs (e.g., Reed et al. 1988; Thorncroft and Hodges 2001). A subjective analysis of the time–longitude 6-hourly NCEP–NCAR reanalysis 700-mb relative vorticity averaged for the 5°–15°N band [not shown here, but very similar to the one shown in Janicot et al. (2008)] was used to track AEW passage through Niamey during May–October 2006.\(^4\) Following Thorncroft and Hodges (2001), AEWs were defined as westward-propagating features of positive relative vorticity that propagated farther than 10° of longitude for a period of at least 2 days and had maximum relative vorticity of at least 0.5 \(\times 10^{-5}\) s\(^{-1}\). According to this definition, 31 AEWs crossed the longitude of Niamey (2.5°E) during May–October 2006 (Fig. 3). Of those, 24 AEWs crossed the longitude of Niamey (2.5°E) during the AMMA ROP. The number of AEWs that emerged from the west coast of Africa into the Atlantic Ocean during May–October 2006 was 29, which falls slightly above the climatological average of 27 AEWs emerging off the African coast between 10° and 15°N found in Thorncroft and Hodges (2001).\(^5\) In 2006 the most active month in terms of AEW numbers was August (Fig. 3).

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\(^1\) Time–pressure plots of meridional and zonal winds constructed from radiosondes and NCEP–NCAR reanalysis at Ndjamen, Chad; Niamey, Niger; Ouagadougou, Burkina Faso; Bamako, Nigeria; and Dakar, Senegal, are in excellent agreement (not shown).

\(^2\) A 3° × 3° box centered in Niamey (see Fig. 1 for averaging box location) was chosen because it covers approximately the area covered by the radar, therefore facilitating rain comparisons between the GPCP 1° daily dataset and the radar.

\(^3\) The same conclusion is reached if the 1979–2007 record from the 2° monthly GPCP dataset is used.

\(^4\) Similar results are obtained using the 600-mb level relative vorticity.

\(^5\) Janicot et al. (2008) tracked 27 AEWs in JAS 2006 using an objective analysis of the 700-mb relative vorticity curvature.
Hence, in terms of the total rainfall and the total number of AEWs, 2006 was an average monsoon season in Niamey, a result that is in line with Janicot et al. (2008). Therefore, it is plausible that the findings reported in sections 4 and 5 would be representative of a typical wet season in Niamey.

4. Statistics of convective system rainfall

The organization of convection and rainfall variability in Niamey is now analyzed using data from the MIT radar. This study focuses on SLMCSs since they are the main rainmakers in the Sahel and previous studies (e.g., Mathon et al. 2002; Fink and Reiner 2003) have linked them to AEW activity and structure. The relationship between SLMCSs and AEW activity and structure is examined in section 5.

a. Rain statistics and organization: Radar and GPCP

The question of how common SLMCSs were in 2006 and what portion of the total AMMA ROP rainfall they produced is now considered from the radar standpoint. During the AMMA ROP, 28 SLMCSs were observed by the radar. On average, SLMCSs occurred in the radar domain 17% of the time but produced 82% of the total rainfall [the latter consistent with Dhonneur (1981) and Nesbitt et al. (2006) for the Sahel region]. Non-MCS isolated convection episodes were the most common mode of rainfall production (present 80% of the time) and yet they accounted for only about 6% of the rain. These results were generally consistent with a similar accounting in the equatorial western Pacific (Rickenbach and Rutledge 1998). A summary of these radar statistics broken down by month is presented in Tables 1 and 2, which show that SLMCSs were slightly more common in August, when AEWs were more numerous (Fig. 3), than in July or September (differences of a few percent). However, SLMCSs accounted for much more of the total rain (87%) in September. Analysis of the radar data therefore shows that a relatively small number of SLMCS events produced most of the rainfall in Niamey.

For comparison, the GPCP dataset shows that about 91% of the total rainfall measured during the AMMA ROP occurred on days when an SLMCS passed through Niamey. Hence, the radar and GPCP estimates are consistent with each other and independently show that SLMCSs are the major contributor to the monsoon precipitation in this portion of the African Sahel. This is in line with previous work that showed that about 80% of the annual precipitation in the Sahel is produced by squall lines (Dhonneur 1981).

The linear correlation between the daily time series of GPCP rainfall and Niamey radar rainfall (not shown) is 0.74 for the ROP but decreases to 0.63 when only SLMCS cases are considered. The weaker correlation between radar and GPCP for SLMCS may be related to the fact that the heavy convective rainfall of the squall line sensed by the radar is much smaller in area than the large cold cloud-top area on which GPCP rainfall is based (Rickenbach 1999). Nevertheless, the good correlation between the radar and GPCP precipitation time series lends confidence to using both datasets together to study the intraseasonal rainfall variability in Niamey.

b. Convective–stratiform partitioning of rainfall

The convective–stratiform partitioning of the radar data (cf. section 2) gives additional insight into the link between SLMCSs in Niamey and AEWs to be discussed in section 5. For the 3-month ROP, although convective rain accounted for only 12% of the total area occupied by SLMCSs, it contributed 55% of the rainfall. This is lower than the 69% convective rain fraction for West Africa in June–August (JJA) for 1998–2000 estimated from the TRMM Precipitation Radar (Schumacher and Houze 2003). Sources of this discrepancy include interannual variability and the larger sample region of

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<tr>
<th>System Type</th>
<th>Jul</th>
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<tr>
<td>SLMCS (%)</td>
<td>79</td>
<td>81</td>
<td>87</td>
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<tr>
<td>Nonsquall MCS (%)</td>
<td>15</td>
<td>12</td>
<td>10</td>
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<tr>
<td>Isolated convection (non-MCS, %)</td>
<td>6</td>
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TRMM relative to the surface radar. In addition, we are focusing here on SLMCSs, while the TRMM estimate represents all rain, including that from small isolated convective cells, which would tend to raise the TRMM estimate of the convective rain fraction. In the month of July, SLMCSs were characterized by a higher convective rain fraction (58%) than in either August (53%) or September (52%). The lower convective rain fractions occur during August and September when a larger number of AEWs crossed Niamey’s longitude (Fig. 3). The relative contribution of convective and stratiform rain in an MCS is generally determined by the size of the area of stratiform rain (Houze 2004). Convergence and upward vertical motion are generally enhanced over a broad area upstream of an AEW trough (e.g., Reed et al. 1977), which would tend to favor the production of a larger SLMCS stratiform rain region (Houze 1989) and a larger stratiform rain fraction (see section 5). This idea is also consistent with a much larger rain contribution from SLMCS and a much smaller contribution from non-MCS isolated convection in September relative to other months (Table 2).

5. SLMCSs and African easterly waves

Having established that the most important rain-makers in Niamey are SLMCSs, the characteristics of the synoptic-scale flow within which the SLMCSs form are now presented. AEWs are the most important mode of synoptic-scale variability in the West African monsoon circulation. During AMMA, the radar time series showed that SLMCS rain events affect Niamey every 2–5 days (Rickenbach et al. 2009), suggesting a link between SLMCS and AEWs. However, the phase relationship between AEWs and convection is still not generally well understood (see the introduction). In this section, Niamey SLMCSs are classified into two groups according to their location relative to nearby AEW troughs. Based on this classification, separate synoptic-scale flow composites will be presented for each group to analyze the different flow regimes associated with SLMCS passage through Niamey.

Climatologically, the summertime AEJ is strongest and located farthest north over West Africa where it is centered near 15°N (Janicot et al. 2008). East of Niamey, the AEJ bends southward becoming centered at 10°N to the east of Lake Chad. During July–September (JAS) 2006, the AEJ was located near 15°N over West Africa and had wind speeds about 2 m s\(^{-1}\) stronger than the climatology (Janicot et al. 2008). Previous studies have indicated the existence of distinct tracks of AEWs in West Africa, one at 850 mb along the northern side of the AEJ near 20°N, and a second one at 700 mb along the southern side of the AEJ near 10°N (e.g., Thorncroft and Hodges 2001; Fink and Reiner 2003; Kiladis et al. 2006). One way to highlight the overall activity and tracks of AEWs during the monsoon season is to calculate the variability (via the standard deviation) of the <10-day filtered daily 700-mb relative vorticity (Kiladis et al. 2006). The horizontal structure of the <10-day relative vorticity standard deviation during JJA of 2006 is shown in Fig. 4. The main AEW track on the southern side of the AEJ discussed in previous studies (e.g., Thorncroft and Hodges 2001; Kiladis et al. 2006) is represented by the band of high values of relative vorticity standard deviation along 8°–16°N (hereafter referred to as the northern track) that is best defined between 20°E and 5°W (inclusive of Niamey) but extends also into the Atlantic Ocean. A less well-known feature is the elongated band of high variability along 2°–6°N that extends from 20°E westward into the Gulf of Guinea (hereafter referred to as the southern track). A hint of this southern track of high <10-day variability is present in the long-term average of the 15-yr ECMWF Re-Analysis (ERA-15) shown in Kiladis et al. (2006, their Fig. 2c). Further evidence supporting the idea that the southern track is also associated with AEWs is presented below. It will also be shown below that SLMCSs occur in Niamey during times when AEW troughs are crossing 2.5°E on either of these two tracks.

For the purposes of this analysis, AEW troughs are defined as westward-propagating centers of positive <10-day filtered relative vorticity at the 700-mb level with relative vorticities in excess of \(1.5 \times 10^{-5} \text{ s}^{-1}\). A subjective analysis of daily plots of GPCP rainfall superimposed on the 700-mb NCEP–NCAR reanalysis filtered winds and relative vorticity was used to track the position of AEW troughs as they propagated westward.
across Africa during the ROP. The coordinates of the nearest AEW trough on the day when an SLMCS occurred in Niamey were recorded for use in the SLMCS classification outlined below. It was observed that AEWs followed two distinct tracks as they crossed that portion of Africa, one near 12°N, along the northern track, and another one much farther south near 5°N along the southern track. Those SLMCSs that occurred when an AEW trough was propagating near Niamey’s longitude along the northern track were classified as SLMCS-NT. Those that occurred when an AEW trough was propagating near Niamey’s longitude along the southern track were classified as SLMCS-STs.

Among the 28 SLMCSs that passed through Niamey during the AMMA ROP, 15 were classified as SLMCS-NTs (northern track) and 13 were classified as SLMCS-STs (southern track).

Based on the subjective classification of SLMCS-NTs and SLMCS-STs above, a composite analysis was performed to get a clearer picture of the synoptic-scale flow associated with SLMCS-NT and SLMCS-ST events. Figure 5 shows the 700-mb zonal wind and relative vorticity composites for the SLMCS-NT and SLMCS-ST events. The location of the radar is marked with a boldface circle. In each composite the AEJ is readily seen as a region of strong easterly winds that stretches inland from the West African coast. Although the intensity of the AEJ is similar in both composites, its latitudinal location is quite different, with the AEJ located farther northward during SLMCS-NT than during SLMCS-ST events. This is particularly true between 0° and 10°E where the AEJ is centered to the north of Niamey near 15°N during SLMCS-NT events and to the south of Niamey near 11°N during SLMCS-ST events. Figure 5 therefore suggests that the AEJ vacillated between 11° and 15°N over the course of the AMMA ROP. The time–latitude diagram of the 700-mb zonal wind averaged between 0° and 10°E (Fig. 6) confirms that the AEJ vacillated back and forth between about 10° and 17°N on time scales of 1–2 weeks throughout the 2006 monsoon season. This vacillation of the AEJ is superimposed on the seasonal migration of the AEJ in which the AEJ begins to migrate northward sometime in April, reaches its northermost position in August, and quickly migrates southward during September and October (not shown).

Our current understanding of the dynamics of AEW formation and propagation tells us that AEWs should follow the AEJ as it vacillates northward and southward. Previous studies have shown that combined barotropic–baroclinic instability can produce AEWs that propagate along the northern edge of an east–west-oriented belt of positive relative vorticity (e.g., Burpee 1972; Schubert et al. 1991; Nieto Ferreira and Schubert 1997). Such positive relative vorticity features stretching across Africa are present in the cyclonic shear region to the south of the AEJ in both composites shown in Fig. 5. This means that as the AEJ vacillates between 11° and 15°N, the latitude along which AEWs form and propagate necessarily shifts northward and southward in such a way as to remain on the southern side of the AEJ. This is dynamically consistent with the idea that AEW tracks vacillated north and south along with the AEJ during the AMMA ROP, as will be shown below.

Figure 7 shows the composite maps of GPCP rainfall and <10-day filtered 700-mb NCEP–NCAR reanalysis winds and relative vorticity for the day before (day −1),

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6 This classification did not change if the nonfiltered 700-mb relative vorticity is used instead.

7 Note that since Fig. 5 shows a time-averaged zonal wind and Fig. 6 shows a longitude band average of the zonal wind, the span of the AEJ vacillation derived from these two figures is slightly different.

8 Likewise, an east–west-oriented belt of negative relative vorticity is present in the anticyclonic shear region to the north of the jet.
the day of (day 0), and the day after (day +1) the passage through Niamey of SLMCS-NT events. Shaded rainfall contours, wind vectors, and black relative vorticity contours are significant to the 90% level according to a Student’s t test. The location of the radar is again marked with a boldface circle. On day −2 (not shown), no significant areas of rainfall are present near or to the east of Niamey. A N–S-elongated area of precipitation is first seen on day −1 (Fig. 7a), a few hundred kilometers to the east of Niamey in the region of elevated terrain in southern Niger and northern Nigeria (see Fig. 1), between 5°–15°N and 5°–10°E. On day 0 (Fig. 7b), Niamey is located on the northern edge of a mesoscale precipitation feature that extends several hundred kilometers to the south. The N–S elongation of the composite rain feature and westward displacement of the rain feature between days −1 and 0 are consistent with the signature of large westward-moving SLMCSs that originate in the afternoon in the region of elevated terrain in southeastern Niger and arrive in Niamey in the early hours of the morning of the next day (Fink and Reiner 2003; Laing et al. 2008). Rickenbach et al. (2009) discusses the origin and propagation of the 2006 Niamey SLMCS using 3-hourly infrared satellite imagery and radar data.

The relationship between AEWs and the SLMCS-NT passage in Niamey (day 0) is evident in Fig. 7b where an AEW trough (a 700-mb center of positive relative vorticity) is centered a few hundred kilometers to the SE of Niamey near 12.5°N, 5°E. Throughout the composite (Figs. 7a–c), the SLMCS-NT rainfall stays ahead of an AEW trough that is propagating westward along 12°N at
a speed of about 6.4 m s$^{-1}$, in good agreement with typical AEW speeds observed in previous studies (e.g., Reed et al. 1977). The SLMCS-NT therefore occur in a region that is dynamically favorable for convection, that is, in the low-level convergence and synoptic-scale ascent found ahead of AEW troughs. This is in agreement with the finding in Kiladis et al. (2006) that convection tends to occur ahead of the AEW trough in Niamey when the AEJ is located to the north of Niamey (their Fig. 3b).

The composite maps for the SLMCS-ST events (Fig. 8b) show a very different scenario. During SLMCS-ST events, Niamey was under the influence of a center of negative 700-mb relative vorticity associated with the anticyclonic shear on the northern side of the AEJ. Based on the analysis of the 700-mb relative vorticity in Niamey alone, this would seem to indicate that SLMCSs occurred almost equally often in the presence of anticyclonic (13 SLMCS events) or cyclonic (15 SLMCS events) vorticity centers at 700 mb. One might thus erroneously conclude that the SLMCSs occurred equally often in the ridges and troughs of propagating AEWs. Instead, careful analysis of the composite in Fig. 8b shows that in the SLMCS-ST cases AEWs were propagating along the southern track and therefore in those cases the AEW trough is present about 1000 km to the south-southeast of the radar near 5°N, 7.5°E, much farther south than the location of the AEW trough in the SLMCS-NT composites. During the period covered in the SLMCS-ST composite (Figs. 8a–c), the AEW propagates westward at a speed of 7.7 m s$^{-1}$, which is again in good agreement with typical AEW speeds observed in previous studies (e.g., Reed et al. 1977). Rainfall ahead of the AEW trough centered at 5°N, 7.5°E extends over a large area from 5°N to just northward of 15°N, inclusive of Niamey.9

The picture that emerges from the composites in Figs. 7 and 8 is consistent with the idea that the SLMCS-NTs and SLMCS-STs are associated with AEWs propagating across West Africa along different tracks. As shown in Figs. 4 and 6, while the SLMCS-NT composite describes a flow regime in which AEWs propagate along the northern track, the SLMCS-ST composite describes a flow regime in which AEWs propagate farther south along the southern track. The north–south shifts in the AEW tracks occur in tandem with north–south shifts in the location of the AEJ (Figs. 5, 7, and 8).

Interestingly, the differences in the AEW regimes captured by the NCEP–NCAR reanalysis are reflected in the precipitation structure of the SLMCS. While the radar and GPCP datasets agree that the total rainfall amounts in Niamey during SLMCS-NT and SLMCS-ST events are similar, there are significant differences in the mode of delivery of the rainfall (i.e., the convective–stratiform rainfall partitioning) between the two types of SLMCSs. In the 2006 monsoon season, SLMCS-NT events had a significantly larger mean stratiform rain fraction (47%) than did the SLMCS-ST (35%; see Table 3). This

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9 The difference between the AEW composites shown in Fig. 7 and those shown in previous studies stems from differences in sampling methods. Previous AEW composites (e.g., Burpee 1974; Fink and Reiner 2003) have been produced by dividing each AEW into eight wave phases and then averaging meteorological fields within each wave phase. This method produces a clear “wave looking” feature by eliminating the blurring effects of differences in propagation speeds, wavelengths, and locations of AEWs. The composites presented in this study, however, are necessarily centered on the time of passage of SLMCSs in Niamey, since the basis of this investigation is the position of Niamey SLMCSs within the AEW structure. This compositing technique does not eliminate the blurring effects of differences in phase and wavelength of propagating AEWs and in the end produces a less clear wave-looking signal.
result suggests that AEW troughs present at Niamey’s latitude during SLMCS-NT events favor stratiform rain production in SLMCSs, while the environment during SLMCS-ST events is more hostile to stratiform rain. An analysis of the Niamey airport\textsuperscript{10} soundings that were launched in the undisturbed environment that preceded squall-line passage in Niamey shows a significant difference in the convective available potential energy (CAPE) that supports SLMCS-NT and SLMCS-ST events, with the CAPE being lower prior to the passage of SLMCS-NT (1296 J kg\textsuperscript{-1}) than SLMCS-ST (1825 J kg\textsuperscript{-1}) events.

The large-scale environment in which an SLMCS forms can impact its stratiform area both thermodynamically and dynamically. Lower CAPE values imply weaker convective updrafts, less convective rainfall, and, for a given amount of stratiform rain, a higher stratiform rain fraction (Donner et al. 2001). Cyclonic circulation in the lower troposphere, for example in an AEW trough, can lead to midlevel ascent and increased relative humidity (Reed et al. 1977), both of which favor the maintenance and longevity of stratiform rain (Petersen et al. 2003). For SLMCS-NT, we find low CAPE and a high stratiform rain fraction where the cyclonic vorticity of the AEW trough region is centered just east of Niamey, consistent with this framework. For SLMCS-STs, the AEW is well south of Niamey, so that the dynamic forcing that favors a stratiform rain area is absent. The CAPE is significantly higher in this regime, likely due to greater solar heating of the surface away from the cloud-covered trough. Both of these factors are consistent with the observed lower stratiform rain fraction in SLMCS-STs, implying that convective processes dominate rain. These results suggest that the higher stratiform rain fraction for SLMCS-NT is related to low CAPE and favorable cyclonic circulation in the wave trough. Analysis of the sounding low-level humidity (below 900 mb) did not reveal statistically significant differences between the low-level moisture in which the two groups of SLMCS formed, likely since winds near the surface were generally southerly regardless of the AEW track location.

\begin{table}
\centering
\caption{SLMCS in Niamey during the 2006 monsoon season. SLMCS-NT (northern AEW track) and SLMCS-ST (southern AEW track) number and convective–stratiform rain partition.}
\begin{tabular}{lcc}
\hline
 & SLMCS-NT & SLMCS-ST \\
\hline
No. of cases & 15 & 13 \\
Stratiform rain fraction (%) & 47 & 35 \\
Convective rain fraction & 53 & 65 \\
\hline
\end{tabular}
\end{table}

There were also significant differences in the average westward propagation speed of the SLMCS-NTs and SLMCS-STs, with the SLMCS-NT speed (15 m s\textsuperscript{-1}) being slower than the SLMCS-ST speed (19 m s\textsuperscript{-1}). The SLMCSs therefore propagate westward at speeds that are much faster than the average speed of the AEW troughs in the SLMCS-NTs (6.4 m s\textsuperscript{-1}) and SLMCS-STs (7.7 m s\textsuperscript{-1}) calculated using Figs. 6 and 7. This result is in agreement with previous studies (e.g., Reed et al. 1977; Fink and Reiner 2003; Laing et al. 2008; Berry and Thornicroft 2005).

The working hypothesis is that the SLMCS-NTs, being located just ahead of AEW troughs near Niamey, were embedded in an environment of lower CAPE, and stronger low-level convergence and synoptic-scale ascent (typical of AEW troughs), that favored stratiform rain production, as suggested earlier. The SLMCS-ST events, on the other hand, occur far northward of the AEW trough and therefore are embedded in an environment that is not as favorable for stratiform rain production. A more detailed study of the synoptic-scale circulation and environment associated with the two AEW tracks will be necessary to explain the variability in convection described here.

6. Summary

Radar observations near Niamey, Niger, during the AMMA SOP documented the structure, motion, and rainfall variability of cloud systems during the 2006 monsoon season. These unique observations for that part of the Sahel were combined with GPCP satellite rain estimates and NCEP–NCAR reanalysis winds to study the interaction between SLMCSs and AEWs during the 2006 West African monsoon. In terms of rainfall totals and AEW activity, the GPCP and NCEP–NCAR reanalysis data indicate that 2006 was an average monsoon year in Niamey. Therefore, the convective system organization, structure, and rainfall variability, as well as AEW variability, shown in this study may be considered typical for the region.

A subjective analysis of radar reflectivity maps was used to classify rainy days in Niamey according to the organization of precipitation systems. A total of 28 SLMCSs passed through Niamey during the ROP. Intervals of 2–5 days between SLMCS passages through Niamey suggest a link between SLMCSs and AEWs. According to both radar and GPCP estimates, SLMCSs were the most important rainmakers in Niamey, producing about 90% of the ROP rainfall despite being present only about 17% of the time. Convective–stratiform partitioning of the radar CAPPI showed that although convective rain occupied only 12% of the total

\textsuperscript{10} Four-times-daily radiosonde data from the Niamey airport were obtained from the University of Wyoming (information online at http://weather.uwyo.edu/upperair/sounding.html).
SLMCS area, it accounted for 55% of the total rainfall produced by SLMCSs. The stratiform rain fraction was higher later in the season during August–September when more and stronger AEWs crossed 2.5°E (Niamey’s longitude), possibly producing synoptic-scale dynamic forcing that favored stratiform rain production.

The relationship between SLMCSs and AEWs was explored by using the NCEP–NCAR reanalysis and GPCP rainfall data. Analysis of the standard deviation of the <10-day filtered relative vorticity for JJA 2006 shows the presence of two AEW tracks to the south of 16°N across West Africa. Whereas the northern track is a well-known feature of the West African monsoon, the weaker southern track at 2°–6°N has not received as much attention in the literature. During the 2006 monsoon season, SLMCS events occurred in Niamey almost equally often during times when AEWs were propagating along the northern track (15 events) or southern track (13 events). While SLMCS-NT events were located to the west of an AEW trough propagating along the northern track, SLMCS-ST events were located to the west of the trough of an AEW propagating along the southern track.

A closer analysis of the GPCP rainfall and NCEP–NCAR reanalysis 700-mb winds and relative vorticity revealed details of the synoptic-scale flow associated with the northern and southern AEW tracks. Throughout the 2006 West African monsoon season, the AEJ axis vacillated between about 10° and 15°N on intra-seasonal time scales. Dynamical constraints related to the formation and propagation of AEWs require that AEWs remain to the south of the main AEJ axis and vacillate between the northern and southern AEW track regimes on time scales of 1–2 weeks. A preliminary analysis of the <10-day filtered relative vorticity standard deviation plots for 1979–2008 suggests that there is strong interannual variability in the locations and strengths of the AEW tracks in West Africa, with a few years displaying the two tracks while most years have a single AEW track. Future work on this subject will involve a closer examination of AEW track variability on intraseasonal-to-interannual time scales and a study of the mechanisms involved in producing the vacillation of the AEJ. Any relationship between the AEJ vacillation and intraseasonal modes of variability previously studied in Africa (e.g., Mathews 2004; Mounier et al. 2008) also remains to be investigated.

Analysis of the radar and sounding data independently showed significant differences in the structures and environments of SLMCS-NTs and SLMCS-STs. Even though the total rainfall amounts produced by SLMCS events in the different AEW regimes were nearly the same, SLMCS-NT events had a significantly larger mean stratiform rain fraction and lower CAPE than did the SLMCS-ST events. The lower CAPE values associated with SLMCS-NTs, and their locations west of the AEW trough, provide a favorable thermodynamic and dynamic environment for stratiform rain production in SLMCS-NTs. It is hypothesized that this occurs through reduced convective rainfall via weaker buoyancy and enhanced synoptic-scale lifting favoring stratiform rain to the west of the trough. The SLMCSs that form to the west of the AEW troughs that are propagating much farther south of Niamey form in an environment that is less favorable for stratiform rain production. Future work will examine this result in more detail.

The AEJ and AEW vacillation shown in this study is perhaps yet another factor that helps explain different outcomes of studies of the SLMCS and AEW phase relationship discussed in the introduction. Analysis of the 700-mb relative vorticity in Niamey shows that about half of the SLMCSs at Niamey are associated with positive relative vorticity, while the other half are associated with negative vorticity at 700 mb. At first glance, this result seems to indicate that SLMCSs showed no preference for occurring in association with the presence of a trough or ridge at 700 mb, as some previous studies have concluded. However, the properties of SLMCSs must therefore be placed within the context of the SLMCS location relative to the northern and southern AEW tracks, rather than in the trough and ridge pattern of a single AEW track.

An important outstanding issue in tropical Africa is the two-way interaction between the AEWs and convection. While AEWs produce favorable synoptic-scale conditions for the formation and maintenance of convective systems, the role of latent heat release by convective systems in the formation and maintenance of the AEJ and AEW activity cannot be neglected (e.g., Thornicroft and Hoskins 1994; Nieto Ferreira and Schubert 1997; Berry and Thornicroft 2005). Interestingly, a N–S-elongated region of convection that extends northward of 15°N is observed in the GPCP rainfall data ahead of AEW troughs propagating along the northern and southern AEW tracks. The similarities in the rain fields associated with these two AEW tracks raise interesting questions about the role of AEWs in forcing convection as well as the role of convection in forcing the AEJ. Analysis of the structural and energetic differences between AEWs in the two tracks may be helpful in understanding the interactions between AEWs and convection.

Acknowledgments. We appreciate the hard work and effort of all those who planned and participated in the AMMA SOP field campaign. AMMA is a French-led international effort funded by agencies in France, the
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