Electrically Active Hot Towers in African Easterly Waves prior to Tropical Cyclogenesis

KENNETH D. LEPPERT II
University of Alabama in Huntsville, Huntsville, Alabama

WALTER A. PETERSEN
Earth Sciences Office, NASA Marshall Space Flight Center, Huntsville, Alabama

(Manuscript received 1 May 2009, in final form 22 September 2009)

ABSTRACT

It has been hypothesized that intense convective-scale “hot” towers play a role in tropical cyclogenesis via dynamic and thermodynamic feedbacks on the larger-scale circulation. In this study the authors investigate the role that widespread and/or intense lightning-producing convection (i.e., electrically hot towers) present in African easterly waves (AEWs) may play in tropical cyclogenesis over the east Atlantic Ocean.

The 700-hPa meridional wind from the NCEP–NCAR reanalysis dataset was analyzed to divide the waves into northerly, southerly, trough, and ridge phases. The AEWs were subsequently divided into waves that developed into tropical storms (i.e., developing) and those that did not develop into tropical storms (i.e., nondeveloping). Finally, composites were created using various NCEP variables, lightning data gathered with the Zeus network and worldwide lightning location network (WWLLN), and brightness temperature data extracted from the NASA global-merged infrared brightness temperature dataset.

Results indicate that in all regions examined the developing waves seem to be associated with more widespread and/or intense lightning-producing convection. This increased convection associated with the developing waves might be related to the increased midlevel moisture, low-level vorticity, low-level convergence, upper-level divergence, and increased upward vertical motion found to be associated with the developing waves. In addition, the phasing of the convection with the AEWs as they move from East Africa to the central Atlantic shows some variability, which may have implications for tropical cyclogenesis.

1. Introduction

African easterly waves (AEWs) form over East/central Africa and move westward over West Africa, the Atlantic, and have even been known to travel as far west as the Caribbean and east Pacific regions (Burpee 1972). AEWs have a phase speed of about 8 m s$^{-1}$, a period of 3–7 days, and a wavelength of about 2500 km (e.g., Carlson 1969a; Burpee 1975; Renwick 1976; Norquist et al. 1977; Reed et al. 1977; Albignat and Reed 1980; Lau and Lau 1990; Thornicroft and Hodges 2001; Gu et al. 2004; Berry and Thornicroft 2005). The waves are most intense during the months of July–October (Carlson 1969a; Gu et al. 2004), achieve their greatest amplitude at around 700 hPa, and are often associated with convection. Thus, the waves are often identified by fluctuations in the 700-hPa meridional wind (e.g., Albignat and Reed 1980; Berry and Thornicroft 2005) or by tracking mesoscale convective complexes via satellite or radar data (e.g., Carlson 1969b; Frank 1970).

AEWs are important because they play a role in tropical cyclogenesis. Landsea (1993) showed that 57% of minor hurricanes (i.e., Saffir–Simpson category 1 and 2 hurricanes; Simpson 1974) and 83% of intense hurricanes (i.e., Saffir–Simpson category 3, 4, and 5) originated from AEWs occurring over the tropical Atlantic. Tropical cyclogenesis requires a preexisting low-level disturbance (Kurihara and Tuleya 1981), and AEWs often serve as that initial disturbance. Hence, study of these waves is important to understanding the process of tropical cyclogenesis in the Atlantic.

AEWs are often associated with convection at some point in their lifetime. How this convection relates to the various phases of the wave might have implications not...
only for further wave development but also for tropical cyclogenesis. Following Petersen et al. (2003), Petersen and Boccippio (2004, hereafter PB04) used the 700-hPa meridional winds from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset to divide AEWs into northerly, trough, southerly, and ridge phases and then the Tropical Rainfall Measuring Mission (TRMM) radar, lightning imaging sensor, and passive microwave data to examine the convective vertical structure and lightning as a function of wave phase for AEWs over West Africa. The conceptual model shown in Fig. 1 summarizes their findings. In Fig. 1, PB04 suggest that isolated convection with intense vertical development occurs in the ridge phase with continued intense vertical development in the northerly phase during a transition to much greater coverage of convection and precipitation. The precipitation structure and electrical activity of the trough phase seemed to indicate the presence of widespread, monsoonlike convection (e.g., Rutledge et al. 1992; Williams et al. 1992), while the southerly phase was associated with weaker, dissipating convection. Note that PB04 found that the greatest coverage and intensity (i.e., vertical development) of convection was observed to occur ahead of the wave trough as was also observed in several earlier studies (e.g., Burpee 1974; Thompson et al. 1979; Duvel 1990; Machado et al. 1993).

When convection occurs preferentially ahead of and within the wave trough a positive feedback process can ensue between the convection and wave dynamics. As a parcel of air moves westward through the trough axis it loses cyclonic vorticity. In this situation, conservation of potential vorticity dictates that increased divergence must occur, as shown in step 1 of Fig. 2 for a column of air west of the trough axis. Step 1 of Fig. 2 also shows the increased lower-level upward motion that could be forced as a result of the divergence at 700 hPa (Mass 1979). This enhanced upward motion is a large-scale condition favorable for enhanced convection (step 2 of Fig. 2). Latent heat released in association with the increased convection could result in the diabatic generation of potential vorticity as well as lead to the height of pressure surfaces beneath (above) the heating to descend (rise; step 3, Fig. 2). These changing heights of pressure levels could set up pressure gradients that result in greater low- (upper) level convergence (divergence), which could, in turn force greater upward motion near the level of heating (Aubert 1957). Enhanced synoptic-scale upward motion and low- (upper) level convergence (divergence) could further create a large-scale environment favorable for more convection. In addition, the enhanced low-level convergence could lead to an increase in vorticity (step 4, Fig. 2) via the divergence \[ \nabla \cdot (\mathbf{V} \cdot \nabla) \] term in the vorticity equation. This enhanced vorticity could then feedback to the larger

Fig. 1. Conceptual model of convection as a function of easterly wave phase developed by PB04. Note that the various colors within the clouds of the diagram are meant to represent various nonspecific radar reflectivity values, and the cloud and rain areas are simply meant to illustrate the text of the figure.
synoptic-scale wave helping to amplify it (as shown in step 5 in Fig. 2) and/or aid its westward propagation. The amplification of the wave can then lead to a further decrease in vorticity and greater 700-hPa divergence as air exits the wave trough to the west, intensifying the entire process shown in Fig. 2. Thus, when increased convection and its accompanying increased cyclonic vorticity occur just ahead of and in the trough, as is often observed for AEWs, a wave can intensify and perhaps become more favorable for development into a tropical cyclone.

Favorable conditions for tropical cyclogenesis include some nonzero value of the Coriolis force, weak vertical wind shear, SSTs > 27°C, below-normal sea level pressure, above-normal low-level vorticity, and above-normal precipitable water (e.g., Gray 1968; Landsea et al. 1998; Bracken and Bosart 2000). A closed synoptic-scale circulation is difficult to develop without the influence of the Coriolis force, and weak vertical shear helps to prevent latent heating, released as a result of convection, from being dispersed. On the other hand, some shear is required to facilitate intensification. For example, Tuleya and Kurihara (1981) and Kerns and Zipser (2009) found that weak easterly shear is preferred for development. A deep, warm oceanic mixed layer and attendant warm SSTs help provide the energy required for genesis and intensification. Through fluxes of sensible and latent heat, warm SSTs also increase the equivalent potential temperature ($\theta_e$) in the boundary layer, decrease stability, and create an environment more favorable for convection. In addition, low sea level pressure and high moisture values provide an environment favorable for moist convection, which provides the latent heating required for genesis and intensification (Kurihara and Tuleya 1981).

There are several ways that convection may aid the process of tropical cyclogenesis. One such way proposed by Ritchie and Holland (1997) involves a top-down approach to low-level vortex development. They showed that the many midlevel, convective-scale vortices created by convection can interact and merge. This merger creates one larger, warm-core cyclonic circulation called a mesoscale convective vortex (MCV) that often forms at midlevels in the stratiform regions of mesoscale convective systems (MCSs). As more and more smaller vortices merge with the MCV, the circulation increases in size and deepens, eventually developing down to the surface.

Rogers and Fritsch (2001) used a modeling study to investigate how the redevelopment of convection within an MCV could lead to the downward development of a cyclonic circulation at the surface. They found that the

![Fig. 2. Conceptual model of how the decrease in cyclonic vorticity as air moves westward through a trough axis can lead to divergence near 700 hPa and low-level upward motion (step 1), creating an environment favorable for convection (step 2). Increased synoptic-scale, low-level convergence, upper-level divergence, and upward motion (all conditions that provide a favorable large-scale environment for further convection) could occur as a result of latent heating associated with the convection (step 3; P0 and P1 represent constant pressure surfaces). In addition, the enhanced low-level convergence could lead to the increase of vorticity (step 4), which could then help to amplify the synoptic-scale wave (step 5). This is discussed further in the text.](image-url)
redevelopment of convection caused the magnitude of the warm-core vortex to increase as a result of diabatic heating. The increased magnitude of the warm anomaly caused the heights of pressure surfaces beneath the anomaly to decrease which, in turn, caused the low-level wind field to adjust. The adjustment of the wind field resulted in increased surface convergence and the development of a cyclonic circulation near the surface. Successive convective bursts within the boundaries of the original MCV further intensified the developing cyclone. Rogers and Fritsch (2001) ran their model for an MCV over land, but suggest how a similar process could work to develop an MCV over water into a tropical cyclone.

In contrast to the top-down hypothesis of tropical cyclogenesis other studies have suggested a bottom-up method where an initial increase in low-level vorticity develops upward. Convective “hot towers” (e.g., Simpson et al. 1998; Hendricks et al. 2004; Montgomery et al. 2006) have been hypothesized to play a role in such bottom-up development. Simpson et al. (1998) suggested that subsidence warming around strong hot towers contributes to the development of tropical cyclones due to warming-induced hydrostatic surface pressure falls and a resultant intensification of the disturbance. Hendricks et al. (2004) performed a numerical simulation of Hurricane Diana (1984) and found that the preferred convective structures before the development of Diana were deep convective towers possessing strong positive vertical vorticity. Montgomery et al. (2006) suggested that these towers acquire large values of vorticity due to the tilting and stretching of preexisting vorticity by strong hot tower updrafts.

In model simulations of Diana described by Hendricks et al. (2004), the vorticity-rich convective towers experienced several mergers and axisymmetrization, helping to concentrate low-level vorticity and intensify the storm. Montgomery et al. (2006) suggest that a population of many growing, merging, and decaying towers acts as a quasi-steady diabatic heating rate that feeds back to the large-scale circulation. In order for the circulation to remain in thermal wind balance a secondary radial circulation develops with inflow near the surface. Both Hendricks et al. (2004) and Montgomery et al. (2006) suggest that this near-surface inflow encourages vortex merger, the concentration of low-level vorticity, and the intensification of the cyclone. A recent observational study by Houze et al. (2009) of Hurricane Ophelia (2005) seems to support the hot tower route to tropical cyclogenesis.

A distinction can be made between “thermodynamic hot towers” (i.e., deep convective towers that reach the tropopause; Simpson et al. 1998) and “electrically hot towers” (i.e., deep convective towers that are associated with much lightning; Williams et al. 1992). Chronis et al. (2007) showed that enhanced electrical activity in deep cumulonimbus (i.e., electrically hot towers) associated with AEWs over the eastern Atlantic might be related to tropical cyclogenesis. Price et al. (2007) showed that enhanced lightning associated with convection in East Africa may also be related to tropical cyclogenesis in the Atlantic. Electrically active convection requires strong updrafts and the development of considerable condensed water mass (i.e., large graupel, small crystals, and supercooled liquid water) in the mixed-phase region of the storm (e.g., Rutledge et al. 1992; Williams et al. 1992; Zipser 1994; Carey and Rutledge 2000; Petersen and Rutledge 2001; Petersen et al. 2005). Because lightning is intrinsically coupled to a robust development of updraft and the mixed phase in cumulonimbus clouds (e.g., Carey and Rutledge 1996; Petersen et al. 1999; Deierling and Petersen 2008) it is reasonable to hypothesize that observations of lightning might help to reveal where the strongest convection is occurring (i.e., electrically and thermodynamically hot towers) and the likelihood of development via processes related to the previously discussed hot towers.

Therefore, this paper pursues two goals related to electrically active convective hot towers and tropical disturbance intensification. The first is to determine how convection, specifically electrically hot towers, phases with AEWs and how the phasing changes as the waves move from East Africa to the Atlantic Ocean. The second goal will be to determine how this phasing influences tropical cyclogenesis. The paper is organized as follows. Section 2 describes the methodology along with a description of data sources that were used. In section 3, the main results are given, and a summary and conclusions are presented in section 4.

2. Methodology

First, we performed an analysis of AEWs by partitioning the waves into phases based on NCEP–NCAR reanalysis (Kalnay et al. 1996) 700-hPa meridional wind data for a grid box stretching from 50°W to 30°E and from 5° to 15°N, outlined by the solid white line in Fig. 3. (This figure also provides an example of the distribution of IR brightness temperatures and lightning locations associated with an AEW valid for 1800 UTC 11 September 2006. The MCS located along the west coast of Africa within the analysis domain is associated with the wave that eventually developed into Hurricane Helene.) The waves were analyzed for the months of July–November of 2004, 2006, and 2007. Similar to Machado et al. (1993), Petersen et al. (2003), and PB04 the waves were divided into northerly, trough, southerly, and ridge
phases. However, the method used here to divide the waves into these phases was unique. First, meridional wind anomalies were calculated by subtracting the mean at each longitude from the appropriate \( v \)-wind values. Next, a bandpass filter was applied to the \( v \)-wind anomalies in order to isolate the 3–7-day signal of AEWs. Then the filtered anomalies were normalized by the standard deviation at each longitude. Finally, the wave phases were identified using the \( \pm 0.75 \) standard deviation threshold. Normalized anomalies greater than 0.75 were classified as the southerly phase, and those less than –0.75 were classified as the northerly phase. For a given day, the normalized anomalies between northerly (southerly) and southerly (northerly) phases were classified as troughs (ridges).

After the various wave phases were identified, the AEW troughs were subsequently divided into developing (i.e., waves that eventually developed into tropical storms) and nondeveloping waves (i.e., waves that never developed into tropical storms) via information provided by the National Hurricane Center (NHC) storm reports (NHC 2008). Any of the other three wave phases found within three data points \( (7.5^\circ) \) east or west of the developing wave troughs were considered to be part of the developing wave. All other wave phases outside of this range near developing troughs were considered to be part of nondeveloping waves. To determine conditions favorable for development Kerns and Zipser (2009) examined developing and nondeveloping vorticity maxima, whereas other studies (e.g., McBride and Zehr 1981; McBride 1981) looked at the differences between developing and nondeveloping cloud clusters. We sought to emulate some of the methodology of these studies but examined waves instead of vorticity maxima or cloud clusters.

Reed et al. (1977) and Shapiro (1978) provide some early examples of how compositing analyses have been used in the study of AEWs, and we followed some of their methodology in our approach by creating composites of divergence, IR brightness temperatures, lightning, omega, specific humidity, and vorticity for developing and nondeveloping waves. (Note that all calculations were done with a spatial resolution of 2.5\( ^\circ \) by 2.5\( ^\circ \) and a temporal resolution of 1 day. All variables that were composited were taken directly from their respective data sources, except for divergence and vorticity, which were calculated with fourth-order finite differencing using reanalysis meridional and zonal wind components.) The composites were created for the developing and nondeveloping waves over the entire analysis grid box. Then the grid box was divided into four longitude bands indicated by the dashed white lines in Fig. 3. The first band stretched from 50\( ^\circ \)W to 33\( ^\circ \)W over the central Atlantic, the second band from 33\( ^\circ \)W to 16\( ^\circ \)W over the east Atlantic, the third band from 16\( ^\circ \)W to 7\( ^\circ \)E over West Africa, and the final band stretched from 7\( ^\circ \)E to 30\( ^\circ \)E over central Africa. Note that the West African coast lies approximately along 16\( ^\circ \)W near the northern part of the

![Fig. 3. CG lightning locations and IR brightness temperatures valid for 1800 UTC 11 Sep 2006. The lightning locations are for strikes that occurred between 1800 and 1900 UTC. The analysis domain is outlined by the solid white line and the dashed white lines within the analysis domain indicate the longitude bands over which composites were created.](image-url)
analysis domain, but bends toward the east in the southern part as shown in Fig. 3. Composites of developing and nondeveloping waves were created for each longitude band. Next, individual cases were examined to determine if patterns observed for each of the composites existed in individual cases. Finally, the Student’s t test was used to determine if the results of the composites and cases were statistically significant. For this test to be valid the data must be distributed normally about its mean, and all the data used, except the lightning data, have an approximately normal distribution about their respective means. Thus, for this test the 3-yr average of each composited variable (excluding lightning) was calculated at each vertical level over the entire domain and for each longitude band. The developing and nondeveloping composite averages were then compared to the appropriate 3-yr average while the cases were compared to the appropriate 1-yr average (valid over the entire analysis domain) to determine if the composite (case) averages were significantly different from the 3-yr (1 yr) mean.

Data for the IR composites was taken from the National Aeronautics and Space Administration (NASA) global merged IR brightness temperature dataset (Liu et al. 2009). This is a global dataset (60°N–60°S) with 4-km resolution that incorporates measurements from several different geostationary satellites including the (Geostationary Operational Environmental Satellites) GOES-8, GOES-10, (Meteorological Satellites) Meteosat-5, Meteosat-7, and the Geosynchronous Meteorological Satellite (GMS). The data for the lightning composites was taken from the Zeus network (Chronis and Anagnostou 2006) for 2006 and worldwide lightning location network (WWLLN; Rodger et al. 2006) for 2006 and 2007. The Zeus network consists of ten very low frequency (VLF) receivers in Europe and Africa that record the radio noise emitted by primarily cloud-to-ground lightning strikes. The lightning location is retrieved via the arrival time difference (ATD) triangulation technique. The WWLLN is made up of 25 VLF receivers that provide coverage for most of the earth. Flash location retrieval is similar in principal to that of Zeus. More information on how the WWLLN operates can be found in Dowden et al. (2002).

Over the entire region of study the detection efficiency of each lightning detection network is approximately constant, but the detection efficiency of the Zeus network (Chronis and Anagnostou 2006) is much greater than that of the WWLLN (Rodger et al. 2006), hence the number of lightning strikes found in the Zeus dataset is greater than that found in the WWLLN dataset. However, this work focuses on the relative amount of lightning strikes between various waves, wave phases, regions, etc., and not on the specific number of strikes. Conclusions drawn by using just one detection network or the other are identical. Thus, it is reasonable to conclude that despite more strikes being recorded in the Zeus dataset, the relative patterns are not affected by the combination of data from the two networks in the composite analysis. However, to account for the differences in detection efficiency between the networks, lightning flash count anomalies normalized by the standard deviation (i.e., a mean and standard deviation were calculated for all the data from each network within the entire analysis domain and each longitude band, and the anomaly was calculated by subtracting the appropriate mean from each data value) were used for the composite averaging and analysis instead of actual lightning flash counts. Normalized lightning anomalies (NLAs) were also used for individual cases to facilitate a better comparison between cases that utilize data from either one network or the other.

3. Results

a. Case study analysis

To gain a better understanding of the differences in the characteristics of convection between developing and nondeveloping waves several individual cases were examined. Two such cases, one developing and one nondeveloping, will now be presented similar to the case examined in Simpson et al. (1967). The developing case is for the wave that eventually became Hurricane Helene in 2006, and the nondeveloping case is for a wave that could be traced through the entire analysis domain between 12 and 22 August 2004. An example of a lightning location/brightness temperature plot for the nondeveloping wave is given in Fig. 4 valid for 1800 UTC 14 August 2004. The wave is indicated by the thick white line, but the amplitude of the wave is exaggerated. The phases of the wave are divided by the thin vertical white lines and labeled “R” for ridge, “N” for northerly, “T” for trough, and “S” for the southerly phase.

Figure 5a shows the lightning anomaly normalized by the standard deviation for both cases, and Fig. 5b shows the same except for brightness temperatures. Table 1 provides the average fraction of a 2.5° by 2.5° box covered by brightness temperatures less than 240 K and less than 210 K as a function of wave phase. The table also includes an index for how much of the area covered by cold clouds (i.e., area covered by a brightness temperature of less than 240 K) is covered by deep convective clouds (i.e., area covered by temperatures less than 210 K). The index was calculated by dividing the 210-K areal threshold by the 240-K areal threshold. Hence, information from Table 1 and Fig. 5 for the developing case reveals that isolated (i.e., relatively small coverage
of brightness temperatures below 240 K), vertically developed convection (i.e., presence of deep, strong updrafts, a robust mixed phase, a relatively high amount of lightning, and a relatively high coverage of brightness temperatures less than 210 K), some of which is in the form of electrically hot towers, occurred in the ridge phase. Convection with less vertical development but broader cold cloud coverage (i.e., greater coverage by brightness temperatures <240 K) appears to be associated with the northerly phase. The trough was associated with the most widespread (i.e., relatively large coverage of brightness temperatures less than 240 K) convection and exhibited slightly more vigorous (i.e., more lightning) convection than that associated with the northerly phase. The southerly phase appears to be associated with decaying, isolated convection.

Several studies indicate an upscale “cascade” of energy from the smaller convective scale to the larger synoptic scale (e.g., Simpson et al. 1998; Hendricks et al. 2004; Montgomery et al. 2006). Thus, assuming that more widespread and/or intense convection is associated with developing waves, as opposed to nondeveloping waves, how does this increased convection affect the larger scale? The aggregate effect of the convection could affect the larger scale in several ways. First, latent heating associated with the robust mixed phase of electrically active convection could result in larger-scale convergence (divergence) below (above) the heating (e.g., Mapes and Houze 1995) that could then force greater upward motion near the level of heating, as described in more detail in section 1 with regard to step 3 of Fig. 2. Figure 6a shows vertical profiles of omega for each wave phase of the developing case, and Fig. 6b shows the same for the nondeveloping case. The developing case clearly shows greater upward motion, especially at higher levels, in all wave phases. The ridge associated with the developing case seemed to be associated with increased upper-level
upward motion as a result of enhanced mid- to upper-level latent heating. Despite the fact that the upper-level (i.e., 600 hPa) upward motion in the developing ridge is greater than that in the nondeveloping ridge, it is still far less than that observed in the other developing wave phases. Perhaps wave dynamics (forcing; i.e., large-scale subsidence) in the ridge prevent intense large-scale upward motion from developing in the upper region of the ridge. Another possible explanation is that the sample size in the ridge phase was simply too small to provide accurate results. In fact, an application of the Student’s t test revealed that the ridge sample size was not large enough for its omega values to be significant even at the 90% level.

Another effect of convection on the large-scale could be to moisten the atmosphere, especially at mid- and upper levels, as a result of transport from the surface to higher levels in convective updrafts. This mid- and upper-level moistening of the atmosphere can help to inhibit the development of strong evaporatively cooled downdrafts that can transport air to the surface with lower values of \( \theta_e \) that could, in turn, inhibit tropical cyclogenesis (Rotunno and Emmanuel 1987). An analysis of profiles of the specific humidity anomaly (not shown; the anomaly was calculated by subtracting the appropriate mean at each longitude from each data point) does, indeed, reveal that the developing case has more midlevel (i.e., \( \sim 700 \) hPa) moisture than the nondeveloping case in the northerly and trough phases. In fact, the anomaly in the trough of the developing case is more than twice that of the nondeveloping case. Despite this greater moisture at midlevels for the developing case, the nondeveloping profiles still show anomalies that are significantly greater than the mean at the 95% level on various pressure levels. More discussion on this is given in section 3b.

As described in section 1, it is hypothesized that hot towers can tilt and stretch low-level ambient vorticity, thereby helping to increase the synoptic-scale vertical vorticity at low and midlevels after some merger of the incipient convective-scale vortices. The vertical profiles of vorticity in Figs. 7a,b of the developing and nondeveloping cases, respectively, show that the developing case, which seems to be associated with more widespread and vertically developed convection (i.e., electrically hot towers), does, indeed, have greater midlevel (i.e., \( \sim 700 \) hPa) and low-level vorticity than the nondeveloping case in all phases.

b. Developing versus nondeveloping composites over the entire analysis domain

Composites as opposed to case studies can be used to gain a better understanding of the expected patterns and structures associated with developing versus nondeveloping waves; hence, composites of 23 developing waves (552 data points classified as developing trough) and 81 nondeveloping waves (1602 data points classified as nondeveloping trough) over various spatial domains and wave phases were created and examined. Figure 8a depicts the average IR brightness temperature for each composite wave phase over the entire analysis domain (i.e., 50°W–30°E) of developing, nondeveloping, and all waves, and Table 2 presents the NLAs for each composite wave phase of developing and nondeveloping waves over various domains. The 3-yr grid average in Fig. 8a is simply an average of every grid point over the entire analysis domain for all 3 yr of study and is given as a reference. An examination of Fig. 8a and the NLAs valid over the entire analysis domain from Table 2 reveals that: 1) the developing waves are associated with cooler brightness temperatures and higher lightning flash counts than nondeveloping waves, perhaps indicating that, in general, the developing waves are associated with more intense, electrically active convection; and 2) the phase associated with the largest lightning
count and coldest brightness temperature in developing waves precedes that of the nondeveloping composite.

An analysis of Fig. 8a in addition to information contained in Tables 1 and 2 for developing waves over the entire analysis domain leads to the development of a conceptual model of how convection phases with developing waves, shown graphically in Fig. 9a. The ridge phase appears to be associated with isolated, very intense convective towers. A comparison between the NLA in the ridge and that in the northerly phase seems to indicate a decrease in the intensity of convection in the northerly phase (i.e., a transition in convective behavior), but the coverage of the 210-K threshold is also greater in that phase. This suggests that convection associated with the northerly phase is deeper (i.e., greater coverage of colder cloud tops) but not as vigorous (i.e., associated with a robust mixed-phase and high lightning counts) as the ridge phase. The developing trough phase has a temperature and NLA nearly identical to the northerly phase. Hence, the convection in the trough seems to be similar to the northerly phase. Finally, the brightness temperature and electrical activity associated with the southerly phase indicates more isolated convection than that found in the trough and convection that may be dissipating.

The conceptual model for the convection associated with the composite nondeveloping wave over the entire analysis domain is provided in Fig. 9b. Again, the lightning and brightness temperature data suggest that the ridge phase is associated with isolated, vertically developed convective towers, although not as vertically developed as for the developing waves. The nondeveloping northerly phase appears to be associated with less vigorous convection but a slightly greater coverage of cold cloud tops when compared to the ridge phase. The trough phase seems to be associated with yet more widespread cold cloudiness and less electrically active, monsoon-like convection. Finally, the nondeveloping southerly phase.

Table 1. The fraction of a 2.5° by 2.5° grid box (76 176 km²) covered by IR brightness temperatures less than or equal to 240 and 210 K for the wave phases associated with two cases and for developing and nondeveloping composite wave phases valid over various spatial domains. The developing case is for the wave that developed into Hurricane Helene in September 2006, and the nondeveloping case is for a wave that passed through the analysis domain between 12 and 22 Aug 2004. A 210/240 index is calculated by dividing the areal coverage of the 210-K threshold by that of the 240-K threshold and is an index for the coverage of deep convection. The bold numbers indicate the phase(s) that have the largest value(s).

<table>
<thead>
<tr>
<th>Brightness temperature thresholds</th>
<th>Developing</th>
<th>Nondeveloping</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>240 K</td>
<td>210 K</td>
</tr>
<tr>
<td>Cases</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ridge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northerly</td>
<td>0.157</td>
<td>0.039</td>
</tr>
<tr>
<td>Trough</td>
<td>0.173</td>
<td>0.033</td>
</tr>
<tr>
<td>Southerly</td>
<td>0.266</td>
<td>0.059</td>
</tr>
<tr>
<td>Northerly</td>
<td>0.135</td>
<td>0.019</td>
</tr>
<tr>
<td>Trough</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Southerly</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composite (50°W–30°E),</td>
<td></td>
<td></td>
</tr>
<tr>
<td>full analysis domain</td>
<td>Ridge</td>
<td>0.092</td>
</tr>
<tr>
<td>Northerly</td>
<td>0.125</td>
<td>0.021</td>
</tr>
<tr>
<td>Trough</td>
<td>0.124</td>
<td>0.020</td>
</tr>
<tr>
<td>Southerly</td>
<td>0.116</td>
<td>0.017</td>
</tr>
<tr>
<td>Composite (7°–30°E),</td>
<td></td>
<td></td>
</tr>
<tr>
<td>central Africa</td>
<td>Ridge</td>
<td>0.118</td>
</tr>
<tr>
<td>Northerly</td>
<td>0.165</td>
<td>0.034</td>
</tr>
<tr>
<td>Trough</td>
<td>0.141</td>
<td>0.028</td>
</tr>
<tr>
<td>Southerly</td>
<td>0.145</td>
<td>0.024</td>
</tr>
<tr>
<td>Composite (16°W–7°E),</td>
<td></td>
<td></td>
</tr>
<tr>
<td>West Africa</td>
<td>Ridge</td>
<td>0.099</td>
</tr>
<tr>
<td>Northerly</td>
<td>0.139</td>
<td>0.030</td>
</tr>
<tr>
<td>Trough</td>
<td>0.119</td>
<td>0.020</td>
</tr>
<tr>
<td>Southerly</td>
<td>0.077</td>
<td>0.013</td>
</tr>
<tr>
<td>Composite (33°–16°W),</td>
<td></td>
<td></td>
</tr>
<tr>
<td>east Atlantic</td>
<td>Ridge</td>
<td>0.087</td>
</tr>
<tr>
<td>Northerly</td>
<td>0.110</td>
<td>0.011</td>
</tr>
<tr>
<td>Trough</td>
<td>0.117</td>
<td>0.014</td>
</tr>
<tr>
<td>Southerly</td>
<td>0.117</td>
<td>0.015</td>
</tr>
<tr>
<td>Composite (50°–33°W),</td>
<td></td>
<td></td>
</tr>
<tr>
<td>central Atlantic</td>
<td>Ridge</td>
<td>0.036</td>
</tr>
<tr>
<td>Northerly</td>
<td>0.050</td>
<td>0.002</td>
</tr>
<tr>
<td>Trough</td>
<td>0.116</td>
<td>0.010</td>
</tr>
<tr>
<td>Southerly</td>
<td>0.113</td>
<td>0.012</td>
</tr>
</tbody>
</table>
phase is the preferred phase for the most electrically active convection out of all the nondeveloping wave phases and associated with a slightly greater coverage of cold cloud tops than the trough phase. Thus, nondeveloping waves indicate a preference for intense, widespread convection within and behind the wave trough, whereas developing waves show a preference within and ahead of the trough.

FIG. 6. Vertical profiles of omega for each wave phase associated with (a) the wave that developed into Hurricane Helene in 2006 and (b) the nondeveloping wave that passed through the analysis domain between 12 and 22 Aug 2004. The average profile is an average of data valid over the entire analysis domain for each case’s respective year, and the horizontal dashed lines indicate ±1σ.

FIG. 7. As in Fig. 6, but for profiles of relative vorticity.
As explained in section 3a more widespread and/or vertically developed convection (i.e., greater coverage by electrically hot towers) associated with the developing waves could influence the larger scale in several ways. First, as observed from a comparison of the vertical profiles of omega for developing waves in Fig. 10b and for nondeveloping waves in Fig. 11b, more intense convection associated with a deeper ice phase (i.e., greater latent heating) and more lightning could lead to greater net upward motion on the larger scale, in particular at higher levels in the clouds, as well as greater upper-level divergence (Fig. 10a for developing profiles and Fig. 11a for nondeveloping profiles. (Values of divergence for all the developing wave phases, except the ridge, at 200 hPa are significantly greater than the mean valid at the 99.9% level, whereas the values for the nondeveloping waves are not significant even at the 90% level.) For a given low-level value of convergence (profiles of divergence below 300 hPa are almost identical between developing and nondeveloping waves), the combination of enhanced upward vertical motion over a deep layer and upper-level divergence could help to remove more mass from the column of air above a surface low pressure center associated with a developing tropical cyclone, thereby helping to deepen the low. This deepening low could then lead to increased surface wind speeds and an enhanced surface cyclonic circulation (i.e., tropical disturbance intensification).

**Fig. 8.** Average IR brightness temperatures for each composite wave phase over (a) the entire 50°W – 30°E domain, (b) central Africa between 7° and 30°E, (c) the east Atlantic between 33° and 16°W, and (d) the central Atlantic between 50° and 33°W. Only temperatures <270 K were used in the calculations. The 3-yr grid average is an average of all the data within each longitude band for all 3 yr of the study. The standard deviations associated with the grid average are 5.2, 4.9, 5.6, and 5.8 K, respectively. The key of (a) is valid for all parts of the figure.
Another effect of convection on the larger scale could be greater midlevel (~700 hPa) vorticity generation (Fig. 10d for developing and Fig. 11d for nondeveloping). Finally, electrically active convection could act to moisten the troposphere on the larger scale, especially at mid- and upper levels. A comparison of Figs. 10c and 11c (profiles of the anomaly of specific humidity for developing and nondeveloping waves, respectively) shows that the developing waves clearly have more moisture associated with them throughout the depth of the troposphere.

It is interesting to note that while the nondeveloping composite (Fig. 11c) is associated with (except for the southerly phase) moisture that is either near average or below average, the nondeveloping case discussed in section 3a was associated with a significant positive moisture anomaly at low and midlevels. The nondeveloping composite was created by averaging together all nondeveloping waves, including waves that could only be traced for a short period of time and more temporally coherent waves that could be traced across the entire analysis domain. The case discussed in section 3a was an example of the latter. Perhaps a reason for the discrepancy between the nondeveloping composite and the case presented in section 3a is because less organized waves, which held together for only a short time, dominated the nondeveloping composite, but waves that were better organized and long lived are fundamentally different than the less organized waves, especially in terms of the waves’ moisture distribution and longevity.

c. Developing versus nondeveloping waves for the central/East Africa box (7°–30°E)

The phasing of the convection with the waves in central Africa (box D in Fig. 3) is quite different from that of the entire analysis domain. An analysis of Fig. 8b (composite brightness temperatures as a function of wave phase over central Africa) and the NLAs (Table 2) for the same region reveal that developing waves over central Africa are associated with much cooler brightness temperatures and more lightning in all wave phases compared to nondeveloping wave phases. In particular, the data suggest that convection is organized into isolated but intense towers in the developing ridge, widespread and less intense but deeper (i.e., less lightning but greater coverage of the 210-K brightness temperature threshold) in the northerly phase, associated with a smaller coverage of cold cloud tops and more lightning in the trough, and has further increased lightning in the southerly phase. Despite the increased intensity in the trough and southerly phases, the coverage of the 210-K brightness temperature threshold (Table 1) decreases in both of these phases, indicating fewer and/or less coverage of the most intense, electrically active towers. In this case, the convection may be occurring in a more conditionally unstable environment conducive to isolated, but vertically developed convection. The nondeveloping waves show little variability in brightness temperatures or lightning among the various wave phases. Hence, the nondeveloping waves provide little indication of a preferred wave phase for convection.

Vertically developed, electrically active convection seems to occur preferentially behind the wave trough in southerly flow (and in the ridge) for the developing waves, but, as mentioned previously, convection in this region is not in a preferred location to strengthen the wave. We hypothesize that in central Africa the waves are seed disturbances, just beginning to develop and strengthen, so they are weaker here than in other regions. Therefore, a positive feedback interaction between convection and wave dynamics may not be as well defined or strong. Despite the preference for the most intense convection of the developing waves to occur in the ridge and southerly phase the vertical profiles of vorticity in those wave phases (Fig. 12a) show almost no increase in low-level values when compared to the profiles for the
nondeveloping waves (Fig. 12b). (Note that while enhanced convection over central Africa does not seem to have much of an effect on the vorticity of waves over that region it may still be contributing to the rate of change of vorticity and an enhancement of midlevel vorticity farther west as seen in Fig. 13c for profiles of vorticity for developing waves over West Africa.) Another possible explanation for why convection seems to occur preferentially behind the wave trough is due to the dynamics of the large-scale wave having an influence on the smaller-scale convection instead of the other way around. Perhaps the increase in low-level moisture ($\theta_e$) in the southerly phase (not shown) as a result of transport from the south helps to increase instability and provide an environment more favorable for intense convection behind the wave trough. In addition, the relative lack of moisture in the dry northerly phase may act to inhibit electrically active convection.
there. In this mode, the convection serves only as a response to the wave forcing and not as a direct positive feedback to the wave.

d. Developing versus nondeveloping waves for West Africa (16°W–7°E)

The lightning (Table 2) and brightness temperature thresholds (Table 1) associated with the waves over West Africa (box C in Fig. 3) indicate phasing of convection with the developing waves that agrees very well with the conceptual model of PB04 (Fig. 1). Isolated convection with intense vertical development is indicated in the ridge phase, whereas more widespread cold cloudiness with much lightning occurs in association with the northerly phase. The developing trough is associated with more shallow (i.e., relatively small coverage of the 210-K brightness temperature threshold) but widespread, monsoonlike cloud cover and convection, and the southerly phase appears to be associated with more scattered, dissipating convection. The averages for the nondeveloping wave phases indicate near-average brightness temperatures and lightning strikes for each wave phase with hardly any indication of a preferred phase for convection.

FIG. 10. Composite analysis of vertical profiles of (a) divergence, (b) omega, (c) specific humidity anomaly, and (d) vorticity for each developing wave phase between 50°W and 30°E. The average profiles are valid over the entire analysis domain for all 3 yr of the study. The dashed horizontal lines indicate ±1σ and the key below (d) is valid for all parts of the figure.
In concert with the increased convection of the developing waves, as opposed to the nondeveloping, and for reasons discussed in section 3a the developing waves have greater vorticity (Fig. 13c for developing profiles and Fig. 14c for nondeveloping profiles) at midlevels, a much greater moisture anomaly (Fig. 13b for developing profiles and Fig. 14b for nondeveloping profiles) throughout the depth of the troposphere, and greater upper-level upward vertical motion (Fig. 13a for developing profiles and Fig. 14a for nondeveloping profiles). Thus, the increased convection associated with the developing waves in West Africa seems to be coupled or at least occurs coincident with transformations of the waves and the environment around the waves into something more favorable for tropical cyclogenesis.

e. Developing versus nondeveloping waves over the east Atlantic (33°–16°W)

Over the ocean, convection is typically less vertically developed in terms of updraft magnitude and mixed-phased precipitation development, so lightning occurrence over the ocean is less than over land (e.g., Zipser 1994; Petersen and Rutledge 2001; Christian et al. 2003; Williams 2005), and, not surprisingly, this is also observed in the east Atlantic (box B in Fig. 3). An analysis of lightning (Table 2) and brightness temperatures (Fig. 8c) in association with information from Table 1 reveals that for the developing ridge phase convection seems to be concentrated into isolated, vertically developed towers. Cold cloudiness associated with the nondeveloping ridge
phase is more widespread than the developing ridge, but much less electrically active. In the northerly phase, convection is relatively weak in both the developing wave and nondeveloping wave, but the convection associated with the developing case appears to be more widespread than in the nondeveloping case. In the transition from the northerly phase to the trough phase the coverage of cold cloud tops and vertical development of convection increase in both the developing and nondeveloping waves with slightly more intense convection occurring in the developing trough than in the nondeveloping trough. Both the developing and nondeveloping waves show a preference for the most intense convection in the southerly phase, but the developing southerly phase is associated with more lightning than the nondeveloping southerly phase. In addition, the transition from trough to southerly phase appears to be associated with little change in the coverage by cold cloudiness in both developing and nondeveloping waves.

The greater vertical development of convection associated with developing waves might be responsible for the observations of greater upper-level upward vertical motion (Fig. 15b), higher moisture anomaly throughout the troposphere (Fig. 15c), greater low-level convergence, and greater upper-level divergence (Fig. 15a) when compared to the profiles of nondeveloping waves (Figs. 16b,c,a, respectively). The updrafts of the hot towers associated with the developing waves might also be helping to increase low- and midlevel vorticity as seen in a comparison of vertical profiles of vorticity for developing waves (Fig. 15d) and profiles for nondeveloping waves (Fig. 16d).

Over land strong convection ahead of and/or within the trough phase seems to occur preferentially with wave intensification. Once the wave leaves the West African coast the large-scale region of anomalously high low-level vorticity thus developed is beneficial for tropical cyclogenesis (e.g., Gray 1968). The observation that the most widespread and intense convection associated with developing waves in the east Atlantic seems to occur principally in the trough and southerly phases may be related to the increase in the low-level vorticity over a relatively large region. Weaker convection associated with the nondeveloping waves may not allow for the development of a large region of above-normal low-level vorticity. In fact, as seen in Fig. 16d, the presence of convection in the nondeveloping trough and southerly phases (i.e., nondeveloping phases with the most intense convection) does not seem to have much of an effect on the low- and midlevel vorticity.

f. Developing versus nondeveloping waves over the central Atlantic (50°–33°W)

Convection over the central Atlantic (box A in Fig. 3) would be expected to have relatively little vertical
development and lightning when compared to locations over land or even near coastal locations. Indeed, this is observed in the composite lightning data for this region with very little lightning in any wave phase. Hence, for clues related to the differences in convection between the varying wave phases over the central Atlantic we rely primarily on the brightness temperature composites (Fig. 8d) and areal coverage of brightness temperature thresholds found in Table 1 to provide information on differences in the coverage of cold cloud tops and, by proxy, convection. For developing waves, the cold cloudiness achieves its greatest spatial extent in the trough and achieves its smallest extent in the ridge, which would be expected with a wave nearing development into a tropical depression. The second greatest coverage of cold cloud tops occurs in the southerly phase, and the second smallest coverage occurs in the northerly phase. For the nondeveloping waves, cold cloudiness is most widespread in the southerly phase, with the next most widespread coverage occurring in the trough, and the least widespread cold cloudiness occurring in association with the ridge and northerly phases. The greater preference for cold cloud to occur in the southerly phase of both developing and nondeveloping waves than in the northerly phase might

![Composite analysis of vertical profiles of (a) omega, (b) specific humidity anomaly, and (c) vorticity for each developing wave phase between 16°W and 7°E. The average profiles are valid between 16°W and 7°E for all 3 yr of the study. The dashed horizontal lines indicate ±1σ, and the key below (c) is valid for all parts of the figure.](image)
be related to moisture transport. The profiles of the specific humidity anomaly for both developing waves (Fig. 17c) and nondeveloping waves (Fig. 18c) indicate relatively large anomalies associated with the southerly phase at low levels. The increased low-level moisture associated with the southerly phase as a result of transport from the south (perhaps from the ITCZ) might be better able to support moist convection than the drier northerly phase.

Over the central Atlantic few, if any, intense hot towers would be expected to exist in the shallow convection generally found over the ocean, although a few less intense towers might exist. Nevertheless, the convection that does exist in this region might still be able to have an influence on the larger scale, especially at lower levels. For example, the greater coverage of convection in the developing trough and southerly phase might help to moisten the midlevels (Figs. 17c and 18c) and increase low-level vorticity (Fig. 17d for developing profiles and Fig. 18d for nondeveloping profiles). The increased coverage of convection (cold cloudiness) in the developing trough and southerly phase might also help to increase low-level convergence (Fig. 17a for developing profiles and Fig. 18a for nondeveloping profiles) and increase upward vertical motion at midlevels (Fig. 17b for developing wave omega profiles and Fig. 18b for nondeveloping profiles) due to latent heat release. It is interesting to note the difference between the shape of the omega profiles of the developing waves over the east Atlantic (Fig. 15b) and over the central Atlantic (Fig. 17b). Over water, far from any land, very little deep

**Fig. 14.** As in Fig. 13, but for nondeveloping waves.
convection would be expected to exist; only shallow convective and stratiform precipitation regions generally exist. Hence, there is only one midlevel peak in the omega profiles over the central Atlantic. Closer to the coast over the east Atlantic, some deep, intense convection might exist in addition to the shallow convection and stratiform regions. Hence, there are two peaks in the omega profiles over that region.

4. Summary and conclusions

AEWs cross the coast of West Africa every ~5 days during the months of July–October and often form the necessary precursor disturbance for tropical cyclogenesis. These waves are often associated with convection, and several hypotheses have been offered in the literature describing how convection within AEWs can help lead to cyclogenesis. Thus, the purpose of this study was to examine the phasing and potential role of electrically active, convective hot towers in tropical cyclogenesis.

It was found that, in general, developing waves are associated with more intense and/or widespread convection (i.e., greater frequency of occurrence of electrically hot towers) than nondeveloping waves. This seems to remain true even as the phasing of the convection with the waves changes as the waves move from East Africa to

**Fig. 15.** As in Fig. 10, but between 33° and 16°W. The average profiles are valid between 33° and 16°W for all 3 yr of the study.
The increased convection associated with the developing waves might influence the larger scale by increasing low-level convergence, upper-level divergence, upward motion, midlevel moisture, and low-level vorticity, which all would help create an environment more favorable for cyclogenesis.

The developing composite valid over the entire analysis domain indicates that convection tends to occur in and ahead of the wave trough where it can interact with the wave dynamics in a positive feedback to intensify the wave, and, perhaps, make it more favorable for further development into a cyclone over the Atlantic while the nondeveloping composite shows a preference for convection behind the wave trough where the positive feedback is not as likely to occur. The phasing of the convection with the waves also seems to show some regional variation as the waves move from East Africa to the central Atlantic (which may have implications for tropical cyclogenesis) as summarized in Fig. 19. Figure 19 shows where the coolest average brightness temperature and highest NLA occur as a function of wave phase for different regions across Africa and the Atlantic for developing and nondeveloping waves. The convection associated with the developing waves seems to have its greatest coverage (i.e., lowest average brightness temperature) in the northerly phase over land and in the trough over the ocean. The most vertically developed convection (i.e., highest NLA) occurs in the ridge over central Africa, the northerly phase over West Africa, the southerly phase over the east Atlantic, and the trough
over the central Atlantic. For the nondeveloping waves the convection with the greatest vertical development and most coverage occurs in the northerly phase over Africa. Over the east (central) Atlantic the most widespread convection occurs in the trough (southerly phase) and most vertically developed occurs in the southerly phase (ridge). Thus, while the phasing of the convection with the waves changes some as the waves move over land or over water, the greatest change occurs as the waves move from over land to water. Also, note that Fig. 19 is qualitative, and that the actual lightning count and brightness temperature averages as well as coverage of certain brightness temperature thresholds can provide much greater insight into the specifics of how the phasing of convection with the waves changes as the waves move across Africa and the Atlantic.

An examination of a developing case and a nondeveloping case reveals reasonably good agreement between the developing composite and its respective case, but less agreement between the nondeveloping composite and its respective case despite the fact that both cases seemed to be representative of their respective wave category. More cases should be examined to see if patterns observed in the developing composite are generally seen in individual cases. Perhaps the reason for the differences between the nondeveloping case and
the composite is related to different structures between nondeveloping waves that were strong and coherent enough to maintain their identity across the entire analysis domain and those that were less organized. Cases should be examined for both types of nondeveloping waves to determine any significant differences.

For much of this research it was hypothesized that the smaller convective scale may be affecting the larger scale. But, several observations associated with the various cases and composites could, instead, be a result of the influence of the larger scale on the convective scale. For example, observations of greater upward vertical motion and low- (upper-) level convergence (divergence) may be a result of latent heat release associated with convection or they may foster a large-scale environment more favorable for convection. Some numerical modeling work of AEWs, convection, and tropical cyclogenesis should be done to better determine which scale is having the most effect on the other.

Other future work that could be done is to expand the analysis to the west Atlantic, Caribbean, Gulf of Mexico, and east Pacific regions to see if relationships observed in the east Atlantic apply to these other regions as well.

Acknowledgments. The authors gratefully acknowledge funding from Dr. Ramesh Kakar under a subaward to NASA Grant NNX07AT03G. We would also like to acknowledge previous fruitful discussions with our collaborators: Dr. E. Williams, Dr. T. Chronis, and
Dr. E. Anagnostou. In addition, Dr. D. Cecil and two anonymous reviewers provided excellent recommendations for improving the manuscript.

REFERENCES


