African easterly waves (AEWs) are identified in numerical model analyses using an objective technique based on the 700-hPa streamfunction field. This method has been developed to (i) reduce the amount of manual data interpretation, (ii) reduce the likelihood of unrelated phenomena being identified as AEWs, and (iii) facilitate completely objective comparisons between AEWs with different structures on multiple scales, in order to describe their variability. Results show this method performs well when compared to methods of AEW identification used in previous studies. The objective technique is used to analyze all AEWs that originated over tropical North Africa during July–September (JAS) 2004. Results indicate that the “average” AEW in this period bears a close resemblance to composite structures from previous research. However, there is marked variability in the characteristics and ultimate fate of AEWs. Most AEWs of JAS 2004 are first identified east of the Greenwich meridian and develop as they move westward. Mature structures over the African continent varied, ranging from isolated potential vorticity maxima confined equatorward of the objectively defined African easterly jet to broad cross-jet structures symptomatic of both baroclinic and barotropic growth. As many as 80% of the cases fell into the second category. After leaving the West African coast, 45% of the AEWs in JAS 2004 were associated with tropical cyclogenesis in either the Atlantic or Pacific Ocean basins.

1. Introduction

African easterly waves (AEWs) are westward-propagating synoptic-scale disturbances that exist over Africa and the tropical North Atlantic during boreal summer (e.g., Burpee 1972). AEWs are important because they are known to modulate rainfall over Africa (see, e.g., Payne and McGarry 1977) and act as precursors to tropical cyclones in both the Atlantic and eastern Pacific Ocean basins (e.g., Avila and Pasch 1992; Frank 1970).

Synoptic studies of AEWs (e.g., Carlson 1969a,b) have demonstrated that AEWs commonly possess two distinct low-level relative vorticity centers, on the equatorward flank of the Sahara Desert near 20°N (in the region of a strong meridional temperature and moisture gradients) and in the rainy zone equatorward of the midtropospheric African easterly jet (AEJ). Pytharoulis and Thorncroft (1999) showed that relative vorticity centers generally propagate westward together along preferred northern and southern tracks as part of a single AEW, consistent with a baroclinic growth mechanism.

Evidence of AEW growth at the expense of the AEJ, via both barotropic and baroclinic mechanisms, has been presented by composite AEW studies (e.g., Reed et al. 1977; Thompson et al. 1979). Results from numerous idealized AEW simulations of varying complexity (e.g., Thorncroft and Hoskins 1994a,b) support these notions of dynamical growth on the AEJ.

A recent case study by Berry and Thorncroft (2005, henceforth BT05) proposed a three-stage conceptual model for AEW life cycles that built upon previous studies and emphasized the multiscale nature of AEWs. They suggested that AEWs developed as the result of intense mesoscale convective systems (MCSs) perturbing the unstable basic state that exists over the African
continent during boreal summer. On the basis of a potential vorticity (PV)–potential temperature analysis they suggested that the vorticity center moving westward along the northern track, termed “northern vortex” (and henceforth abbreviated NV), is part of the adiabatic (baroclinic) synoptic-scale structure of the AEW. Their conceptual model suggested that the NV baroclinically interacts with the zonally elongated midtropospheric PV strip that exists on the equatorward flank of the AEJ, near 10°N. They suggested that the diabatically generated subsynoptic-scale PV maxima (associated with MCSs embedded within the AEW) were superimposed upon the synoptic-scale baroclinic structure, resulting in a positive feedback between the AEW structure and mesoscale convection.

Discussion and interpretation of AEW developments ideally requires a consistent AEW reference point to be identified. Historically this has been quite challenging because the multiple scales involved are difficult to disentangle. Previous studies (e.g., Reed et al. 1977) have tended to use AEJ level trough and ridge axes, generally defined by a change in sign of the meridional wind field (i.e., \( v = 0 \, \text{m s}^{-1} \)), as the reference point (and implicitly as the definition) for an AEW. However, this diagnostic is not Galilean invariant and the distinction between AEWs and other phenomena of overlapping scale [such as a large mesoscale convective complex (MCC)] is not always obvious and could result in unrelated phenomena being identified as AEWs.

In this research we propose a new objective method of identifying AEWs. Following the methodology used by Hewson (1998) to objectively identify midlatitude fronts, we present a simple, accurate, and customizable way of identifying and plotting AEWs that can be applied to any gridded dataset. We then use this technique to document AEWs that occurred in July–September (JAS) 2004 over the African continent, for comparison with composite structures and conceptual models. AEW variability is also explored.

This paper is organized as follows: section 2 describes the objective identification of AEWs; section 3 then couples this technique with a rule-driven methodology for AEW tracking (currently applied manually); section 4 presents an analysis of AEWs during JAS 2004, including their ultimate fates; results are discussed and summarized in section 5; and ideas for future work are given in section 6.

2. Methodology

a. Background and definitions

It is desirable at the outset to define both a unique characteristic and a consistent reference point for the synoptic examination of AEWs. It is also highly advantageous for forecasting purposes to have a diagnostic that is easy to interpret and can be generated in real time with minimal computation from standard observed or modeled fields. Because of its familiar nature and deployment in previous studies, the core diagnostic chosen in this research is the position of the AEW trough axis.

While examination of the unfiltered wind field for the location of the AEW trough axis can be sufficient for individual case studies, the significant amount of manual intervention sometimes required to differentiate between synoptic-scale AEW trough axes and localized circulation centers [e.g., those associated with MCSs (see BT05)] renders it inappropriate for objective tracking over an extended period. The use of a temporal bandpass filter (see, e.g., Mekonnen et al. 2006) facilitates simple identification of AEWs, but as computation requires either a long time series (including from periods in the future) or some crude assumptions, it cannot be employed reliably in real time.

As a solution, we suggest that AEW trough axes should be defined based on streamfunction \( \psi \). Streamfunction has the distinct advantage that the elimination of the divergent flow reduces noise associated with individual MCSs and offers a smoother field that presents fewer technical difficulties for the computation of objective AEW trough axes. Maximum perturbations associated with AEWs have been observed to occur near the level of the AEJ (e.g., Reed et al. 1977; i.e., near 650 hPa). We define AEW trough axes on the basis of \( \psi \) at 700 hPa, as this is the closest standard atmospheric level. Note also that the midlatitude counterpart of \( \psi \) is geopotential height, and that synopticians invariably use geopotential height to identify troughs in midlatitudes.

For orientation, an example of the 700-hPa \( \psi \) field over tropical North Africa during September 2004, as computed from output from a global model, is shown in Fig. 1. Recalling that the zonal \( (u_\phi) \) and meridional \( (v_\phi) \) components of the nondivergent wind \( (V_\phi) \) are given by

\[
 u_\phi = -\frac{\partial \psi}{\partial y} \quad \text{and} \quad \psi
\]

\[
 v_\phi = \frac{\partial \psi}{\partial x}
\]

reveals that the nondivergent wind in the Tropics is essentially the counterpart of the geostrophic wind in the extratropics. Figure 1 shows a large-scale anticyclone between 20° and 30°N, west of the Greenwich meridian, marking the upper portion of the Saharan heat low circulation (see, e.g., Thornicroft and Black-
On the equatorward flank of this midlevel anticyclone (between 10° and 20°N) a zonally elongated band of enhanced $\psi$ gradient can be observed, denoting the approximate location of the AEJ. The signature of an AEW is a wavelike perturbation to this intense gradient that moves westward with time. The position of a trough axis is marked by a poleward displacement of the $\psi$ contours and a ridge by an equatorward displacement. Two prominent troughs can be seen in Fig. 1 (labeled “T”). The streamfunction field can in fact be used, in isolation, to compute diagnostic quantities that enable AEWs, and indeed AEJs, to be plotted objectively (in line segment format). Table 1 lists all the identifying equations and inequalities that are required; their origins will now be described.

Nondivergent wind components for the time shown in Fig. 1 are plotted in Fig. 2a. Using these wind components, we compute “streamfunction vorticity” ($\xi_\psi$), defined as

$$\xi_\psi = \nabla_h \times \mathbf{V}_\psi,$$

where $\nabla_h$ is a standard horizontal gradient operator and the computed streamfunction vorticity is implicitly a vertical component. This quantity is displayed in Fig. 2b (positive values only), superimposed on the source $\psi$ field. From the streamfunction vorticity the position of a trough or ridge can be simply defined as

$$-\mathbf{V}_\psi \cdot \nabla_h \xi_\psi = 0,$$

that is, the point where the advection of the streamfunction vorticity by the nondivergent wind is equal to zero. This concurs with synoptic reasoning, wherein positive vorticity advection lies ahead of a trough axis and negative vorticity advection behind. However, this definition of trough and ridge lines is only mathematically correct for idealized two-dimensional waves (i.e., where $\mathbf{V}_\psi$ is a function of only one horizontal direction). Those that occur over tropical North Africa are not of this type, as Fig. 2a clearly shows. This is because a large contribution to the total streamfunction vorticity comes from horizontal shear across the AEJ. The advection of streamfunction vorticity due to the westward propagation of AEWs is obscured by the advection of streamfunction vorticity associated with relatively small fluctuations in the position or nature of the AEJ. A simple solution is achieved by partitioning the streamfunction vorticity into that due to the shear of the nondivergent wind (referred to here as “streamfunction shear vorticity”) and that due to the curvature
of the nondivergent wind field (henceforth referred to as “streamfunction curvature vorticity”), that is,

\[ \xi_\psi = \xi_\text{Shear} + \xi_\text{Curvature}. \]

Note again that each term in (5) is implicitly a vertical component, computed solely from the horizontal non-

divergent wind field. The two components of stream-

function vorticity, for the source \( \psi \) field, are shown in

Fig. 2c (positive values only). The AEW trough and

ridge axes are then redefined to be where

\[ -\nabla_\psi \cdot \nabla_h \xi_\text{Curvature} = 0. \]

This contour is plotted on the source \( \psi \) field in Fig. 2d. To differentiate between AEW troughs and ridges, masks must be used to eliminate unwanted lines (i.e., AEW ridges) shown in Fig. 2d. In Fig. 2e, one mask is applied to obscure lines wherever the streamfunction curvature vorticity is below a (positive) threshold value, resulting in only trough lines being displayed. Because there will be instances where the curvature of the non-
divergent wind field reaches a local minimum yet is still positive (or conversely reaches a local maximum, yet is

still negative), a further masking diagnostic is required, to remove spurious lines that are not removed by the

streamfunction curvature vorticity mask:

\[ \nabla_\psi \cdot \nabla_h ( -\nabla_\psi \cdot \nabla_h \xi_\text{Curvature} ) > K, \]

where \( K \) is greater than or equal to zero for plotting troughs (for ridges the inequality sign would be reversed and \( K \) would be less than or equal to zero). Figure 3 illustrates how this works—note that the three solid black lines that cross the \( \psi \) contours (labeled 1, 2, and 3) would all be retained as AEW trough axes after applying the streamfunction curvature vorticity mask, because the streamfunction curvature is everywhere positive. We wish to retain only the trough axes labeled 1 and 3. Equation (7) yields negative values only along line 2, because of the opposition of the plotted vectors here, so would successfully remove this line segment when used as a mask. This mask has been applied (using the recommended threshold from Table 1) in deriving Fig. 2f. We have also obscured trough lines in regions where \( u_\psi \) is greater than 0 m s\(^{-1}\), since we are interested in synoptic systems embedded in easterly flow. In this research we focus on the position of AEW trough axes, for brevity and because of their well-
documented association with disturbed weather (e.g., Reed et al. 1977).

Note also that lines along which streamfunction shear vorticity \( \xi_\text{Shear} \) equals zero denote the cores of non-
divergent wind speed maxima or minima.\(^1\) Jet cores

\(^1\) This was essentially the method used to identify and plot jet stream cores on two of the figures in Hewson (1998) (albeit with shear vorticity used rather than streamfunction shear vorticity).

---

### Table 1. Summary of identifying equation and inequalities used for the objective identification of (a) AEW trough axes and (b) AEJ axes.

<table>
<thead>
<tr>
<th>Name</th>
<th>Equation/inequality</th>
<th>Recommended value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(a)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advection of streamfunction curvature vorticity</td>
<td>(-\nabla_\psi \cdot \nabla_h \xi_\text{Curvature} = 0)</td>
<td></td>
<td>Primary diagnostic used to mark AEW trough and ridge axes</td>
</tr>
<tr>
<td>Mask A1</td>
<td>(\xi_\text{Curvature} &gt; K_{1T})</td>
<td>(K_{1T} = 0.5 \times 10^{-5} \text{ s}^{-1})</td>
<td>Streamfunction curvature vorticity mask to exclude AEJ ridges axes or weak systems</td>
</tr>
<tr>
<td>Mask A2</td>
<td>(\nabla_\psi \cdot \nabla_h ( -\nabla_\psi \cdot \nabla_h \xi_\text{Curvature} ) &gt; K_{2T})</td>
<td>(K_{2T} = 0 \text{ m s}^{-3})</td>
<td>Removes “pseudoridge” axes in nondivergent flow that is highly cyclonically curved</td>
</tr>
<tr>
<td>Mask A3</td>
<td>(u_\psi &lt; K_{3T})</td>
<td>(K_{3T} = 0 \text{ m s}^{-1})</td>
<td>Removes trough axes in westerly flow</td>
</tr>
<tr>
<td><strong>(b)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind speed extrema</td>
<td>(\xi_\text{Shear} = 0)</td>
<td></td>
<td>Marks nondivergent wind speed maxima/minima based on streamfunction shear vorticity</td>
</tr>
<tr>
<td>Mask B1</td>
<td>(\nabla_\psi \cdot [ (\nabla_\psi \xi_\text{Shear} ) \times k ] &gt; 0)</td>
<td>(K_{1J} = 0 \text{ s}^{-2})</td>
<td>Obscures nondivergent wind speed minima</td>
</tr>
<tr>
<td>Mask B2</td>
<td>(</td>
<td>\nabla_\psi</td>
<td>&gt; K_{2J})</td>
</tr>
</tbody>
</table>
(i.e., wind speed maxima) are isolated by using the following graphical mask:

\[ \mathbf{V}_\psi \cdot \left[ (\nabla \zeta_{\text{Shear}}) \times \mathbf{k} \right] > 0, \quad (8) \]

where \( \mathbf{k} \) is the unit vector perpendicular to the earth's surface (and the \( \times \) \( \mathbf{k} \) operator effects a 90° clockwise rotation of the preceding vector). Effectively this mask detects whether streamfunction shear vorticity is positive to the left or right of the nondivergent wind vector. If it is positive to the left, the extremum must be a maximum, the inequality will be positive, and the jet axis will be retained. If it is positive to the right, the extremum must be a minimum, the inequality will be negative, and the (anti) jet will be erased. Equation (8) is applied as a graphical mask to the streamfunction shear vorticity field in Fig. 2c (black contours, only positive values shown), resulting in an objective jet axis, which is denoted in Figs. 2d–f as a dashed line. Although we will not directly address the nature of the AEJ axis in this research, the point at which it intersects the AEW trough axis [i.e., where Eq. (6) is satisfied and where \( \zeta_{\text{Shear}} \) equal zero] is used as a convenient, fully objective AEW feature point for tracking purposes (as in the methodology of Hewson 1997).

The diagnostics described above have been generated for JAS 2004 using 1° × 1° National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) operational analyses (which have a temporal resolution of 12 h). By generating multiple maps in which the minimum curvature vorticity threshold for plotting AEW trough axes was modified, it was determined that displaying AEW trough axes only in regions where the streamfunction curvature vorticity (\( \zeta_{\text{Curvature}} \)) exceeded 0.5 \( \times \) 10^{-5} s^{-1} gave the best overall compromise between retaining weaker systems and reducing noise. Note that because of the ubiquitous presence of MCSs over tropical North Africa, this threshold is probably sensitive to the GFS physics and assimilation schemes; hence the same threshold will likely produce different results in different models. To discriminate between tropical and (predominately eastward moving) extratropical systems, AEW trough axes were only displayed in regions where the zonal component of the nondivergent wind (\( u_\psi \)) had to be greater than 8 m s^{-1}. The threshold value recommended for each masking diagnostic is given in Table 1.
b. Examples

Figure 4 shows two Hovmöller diagrams of the AEW troughs plotted over two more conventional methods of AEW identification/tracking in order to illustrate the usefulness of the technique we are promoting. In the full 700-hPa meridional wind field (Fig. 4a) for September 2004, synoptic-scale westward-moving features do not become well defined until they are near 0°W, whereas the overlaid 700-hPa trough axes indicate the presence of the same feature farther to the east. In fact, the 700-hPa AEW trough axes are more consistent with the 2–6-day bandpass filtered meridional wind field at 700 hPa for the same period, shown in Fig. 4b. Note that in most cases, despite the latitudinal averaging (which would act to mask smaller AEW trough axes), the AEW trough diagnostic gives approximately the same result as the 2–6-day filtered meridional wind. We feel this performance justifies that the AEW trough diagnostics are a useful and reliable tool for detecting AEWs in real time. Recall also that unlike the bandpass method, the new trough diagnostic method requires data for only one time, rendering it much more useful in any forecasting context.

Figure 5 shows AEW trough and AEJ axes diagnostics (for the same analysis time as shown in Fig. 1) superimposed on Meteosat infrared imagery of tropical North Africa and the eastern Atlantic Ocean. It can clearly be observed that there are two meridionally oriented AEW trough axes over the African continent (labeled on the figure), centered approximately on 10°–15°N. These features are associated with enhanced cloudiness near the 700-hPa trough axes, consistent with previous observations (e.g., Payne and McGarry 1977; Kiladis et al. 2006). Sequences of these maps (see discussion section) indicate that the labeled trough axes all intersect the AEJ at some point over Africa (con-
3. Application of the methodology to study AEW behavior

To begin to track objectively identified features, in this case manually, it was necessary to first discriminate further between AEW trough axes and other weak, short-lived, or unrelated features that occasionally appear on plots. This is done by imposing some further restrictions in our analysis. AEWs exhibit unique characteristics (i.e., are synoptic-scale phenomena that grow via barotropic or baroclinic processes, move westward with time, etc.) and the restrictions are designed to reflect this. Beginning on 1 July 2004 and ending on 30 September 2004, using both 0000 and 1200 UTC analysis times, and examining by eye, trough axes were counted as AEW trough axes only if they fulfilled the following criteria:

(i) were generated over the African continent,
(ii) were observable for at least 24 h (i.e., three consecutive analyses),
(iii) were at least 500 km in meridional extent over the African continent at some point during their life cycle,
(iv) intersected the objective AEJ axis at some point during their life cycle, and
(v) could be coherently followed as a westward-moving feature.

For each AEW, the trough axis is used as the sole reference for synoptic analysis. The horizontal tilts of the AEW trough axes are examined for consistency with barotropic growth, and the presence and position of NVs west of the trough axes are sought as an indication of baroclinic growth. On the basis of the analysis presented in BT05, in this study an AEW is determined to possess an NV if a 925-hPa relative vorticity maxima, exceeding \(2 \times 10^{-5} \text{s}^{-1}\), can be coherently tracked moving westward with the 700-hPa trough axes for at least 12 h (i.e., two consecutive analysis times) over the African continent. To differentiate between relative vorticity centers moving in the preferred northern (dry) and southern (moist) tracks (cf. Thorncroft and Hodges 2001), a coherent relative vorticity center is only counted as an NV if its center lies poleward of the objectively diagnosed AEJ axis.

As noted by BT05 in their case study, the westward progression of the AEW trough axes is not always consistent with systems growing dynamically on the AEJ and move westward over the course of several days.

![Fig. 4](http://journals.ametsoc.org/mwr/article-pdf/135/4/1251/4230236/mwr3343_1.pdf)
smooth, with marked acceleration, deceleration, or even retrogression sometimes occurring in response to the diabatic generation of subsynoptic-scale PV maxima by embedded deep convection. This behavior presents an obstacle to calculation of AEW trough speed for comparison with values from previous studies. To address this, a “smooth track” for each AEW was generated. This was achieved by noting the longitude of the point at which the AEW trough and AEJ intersected at every analysis time. A linear regression line was plotted through these longitudes, which then defines the AEW smooth track, from which the AEW speeds are calculated. Because it is well documented that the speed of AEWs is different over the land and ocean (e.g., Reed et al. 1977), this operation is performed only over the African continent (east of 15°W).

In each case the date of the event (used for reference and numbering purposes only) is defined as the date on which the smooth track of a particular system (or its extrapolation) crosses the Greenwich meridian.

4. Results of JAS 2004 synoptic analysis

In this section we present a summary of the synoptic analysis of the 3-month period JAS 2004, which we performed by combining the automated feature identification methods from section 2 with the manual tracking methods from section 3. First, to put the 2004 season into perspective, more conventional methods are used to compare JAS 2004 with the same period in previous years. Figure 6 shows a time series of the 2-6-day bandpass-filtered eddy kinetic energy (EKE) at 700 hPa (using horizontal wind components only) for each JAS from 1973 to 2004 (as a normalized deviation, defined as JAS anomalies divided by total JAS standard deviation). Values were calculated using 2.5° × 2.5° NCEP reanalysis data, averaged in two boxes, one near the West African coast (covering the area 5°–20°N, 0°–20°W) and one in central North Africa (covering the region 5°–20°N, 0°–30°E). Note that although the NCEP reanalysis data are available from 1948, only data from 1973 onward are used because of the availability of satellite data.

It can be seen in Fig. 6 that although normalized deviations of 2–6-day bandpass-filtered EKE are highly variable interannually, they are well correlated between the two boxes [correlation coefficient of 0.7 for the entire time series, consistent with the analysis of Mekonnen et al. (2006)]. The largest negative deviations in both boxes occur in years with well-documented El Niño events (e.g., 1982/83, 1997), and the largest positive deviations occur in years with La Niña events (e.g., 1988, 1999). Relative to the 1973–2004 mean, the 2–6-day bandpass-filtered EKE during JAS 2004 is slightly below the 1973–2004 average. Noteworthy features are that the JAS 2004 season continues a recent tendency of declining 2–6-day bandpass-filtered EKE values and is the first year since 1997 in which the JAS 2–6-day bandpass-filtered EKE has dropped below the 1973–2004 mean.

We will now present the results of the synoptic analyses made using the objective AEW trough identification as described in section 2. These results are divided into two sections: (a) AEWs over the African continent...
and (b) the fate of the AEWs after moving off the West African coast.

a. AEWs over the African continent

In the period 1 July–30 September 2004 a total of 31 systems, meeting the AEW criteria specified in section 2, were generated over the African continent. Using the first appearance of the 700-hPa trough axis in the GFS analysis as the genesis date, in July, August, and September 11, 12, and 8 AEWs began, respectively.

The average speeds of the individual AEWs, calculated using the method described in section 2, are displayed in Fig. 7. The average speed of all the 700-hPa AEW trough axes during JAS 2004 is 10.0 m s⁻¹, close to AEW phase speeds quoted in previous studies (e.g., Reed et al. 1977). The most notable result from Fig. 7 is the large range of AEW speeds during JAS (standard deviation 2.8 m s⁻¹), which has not been documented previously. The slowest AEW of JAS 2004 (which crosses the Greenwich meridian on 6 July) moved westward with an average speed of 5.5 m s⁻¹, whereas the fastest (two, which cross the Greenwich meridian on 14 and 16 July) had an average speed of 15.2 m s⁻¹. Figure 7 also indicates that there are several periods in which AEW speeds for consecutive waves are persistently high (e.g., early September) or low (e.g., late July). Preliminary analysis (not shown) indicates that these differences cannot be simply accounted for by variations in AEJ strength.

When compiling the speed statistics, we noted the longitude at which the 700-hPa AEW trough axes could first be detected in the GFS analyses, in order to provide further detail of the variability of AEWs. These results are presented in Fig. 8. It is clear that these results exhibit marked variability with a range of values that span tropical North Africa, from 34°E (Ethiopia) to 11°W (close to the West African coast). During August and September the region between 15° and 25°W, just downstream of the mountainous Darfur, Sudan, region, is the most common region in which trough axes are first detected, accounting for 11 of the 20 AEWs during these 2 months (cf. Mekonnen et al. 2006; BT05). The most probable starting position of AEW trough axes seems to progress farther and farther east as the season progresses. Further research is required to determine if this is part of the typical season cycle. However, one important implication of the variability, pertaining to forecasting for particular locations in
West Africa, is that warning times for AEW passage can vary greatly (i.e., by 1 or more days).

From examining the synoptic analyses for the 3-month period, we noted that most mature AEW structures over West Africa bore close resemblance to composite mature AEW structures (e.g., Reed et al. 1977; Burpee 1974; Kiladis et al. 2006). Most AEWs observed during this period exhibited a trough line in excess of 1000 km in meridional extent that, in general, tilted from northeast to southwest equatorward of the AEJ axis and from southeast to northwest poleward of the AEJ axis, a structure consistent with barotropic growth at the expense of the AEJ (W27 and W28 in Fig. 5 broadly have these features). Approximately 80% of the AEWs possessed an NV (as defined in section 3) that moved westward with the AEW, consistent with baroclinic growth on the low-level temperature and midlevel PV gradients. An example of two AEWs, exhibiting barotropic and baroclinic growth characteristics over the African continent, are shown in Fig. 9a.

It was noted that most systems possessing an NV exhibited approximately equal meridional extent on either side of the AEJ axis, as demonstrated by the two AEWs in Fig. 9a. The 20% of AEWs (six cases) that did not possess a coherent NV were smaller, with the 700-hPa trough axis generally confined equatorward of the AEJ axis. To highlight the difference between these groups of AEWs, an example of an AEW that lacks an NV is shown in Fig. 9b. It is plausible that the dynamical processes at work in AEWs in this subset differ from those in the more common type of AEW. Confinement equatorward of the AEJ axis suggests that these AEWs are growing barotropically on internal PV gradients or are dominated by convection and its associated subsynoptic-scale PV maxima.

b. AEW fates

AEWs were tracked after moving off the West African coast using both the GFS analysis and satellite observations. Consistent with the high variability over the continent (as detailed in previous subsections) the behavior of AEWs (or their remnants) over the ocean is complex, with AEWs and their embedded PV maxima developing, splitting, and interacting with their environment. Fates have been divided into five categories that encapsulate the observed postcontinental AEW life cycles, including tropical cyclogenesis (in both the Atlantic and Pacific basins), dissipation/dispersion (within and beyond the central Atlantic), and movement into the extratropics.

In all, 28 of the 31 AEWs left the African continent during JAS 2004. The remaining three AEWs merged...
with the previous AEW over the African continent and could not be followed into the Atlantic basin as separate features. Table 2 presents the five categories and the total number of AEWs exhibiting each type of behavior. The most common AEW fate during JAS 2004 was associated with the genesis of an Atlantic tropical cyclone. In all, nine AEWs (29% of the JAS total) were later associated with Atlantic tropical cyclones, including Hurricane Ivan, the only category 5 Atlantic hurricane of the 2004 season. Note that in the case of Hurricane Lisa, the remnants of two AEWs were involved; thus both are counted [see National Oceanic and Atmospheric Administration (NOAA) Tropical Prediction Center (TPC) tropical cyclone report, http://www.nhc.noaa.gov/2004lisa.shtml, for more details]. Five of the six major (rated at category 3 or above)
Atlantic hurricanes of the 2004 season formed from AEWs. Of the tropical cyclones that formed from AEWs in the Atlantic basin, five (Charley, Earl, Frances, Jeanne, and Ivan) moved westward through the so-called main development region \[ \text{MDR; defined as from } \sim 10^\circ \text{N to } 20^\circ \text{N between the west coast of Africa and central America (after Goldenberg and Shapiro 1996)}, \] curved northward through the Caribbean Sea, and continued toward the United States. Each of the three remaining Atlantic tropical cyclones to form from AEWs (Danielle, Karl, and Lisa) moved northwestward after leaving the West African coast, in response to the southward extension, in the central North Atlantic, of a midtropospheric extratropical trough. Additionally, five AEWs (or their remnants) were associated with tropical cyclones in the East Pacific basin (corroborated by TPC reports), including Hurricane Javier, the strongest East Pacific tropical cyclone of 2004.

Figure 10 shows a sequence of maps of PV on the 315-K isentrope with the 700-hPa trough axes. These illustrate the development, from two consecutive AEWs (labeled W14 and W15), of tropical cyclones of both the “Cape Verde” type (Tropical Storm Earl) and

![Figure 9](http://journals.ametsoc.org/mwr/article-pdf/135/4/1251/4230236/mwr3343_1.pdf)
the northward-moving type (Hurricane Danielle). It is evident in Fig. 10 that the AEW precursors of both tropical cyclones are of comparable meridional scale in the eastern Atlantic, despite W14 being the less common type of AEW (i.e., lacking an NV and being confined equatorward of the AEJ) over the African continent. Perhaps consistent with its larger meridional extent over West Africa (not shown), W15 (the “Danielle” precursor) possesses the more intense 315-K PV maxima leaving the West African coast. W14 (the “Earl” precursor) moved westward along 10°N and the embedded subsynoptic PV maxima develop into a tropical storm near 60°W (Fig. 10e). Conversely, PV maxima embedded within W15 intensify shortly after leaving the West African coast and a tropical cyclone forms near 25°W (Fig. 10d). Note also that W16, the next AEW to leave the West African coast, merges with the developing tropical cyclone just offshore (Figs. 10c–f). A region of high PV can be observed moving equatorward near 40°W, between W14 and W15 (Figs. 10c–f), in association with the southward extension of an extratropical trough. Hurricane Danielle moved northward (consistent with steering flow induced by the large-scale trough) and eventually merged with the extratropical feature, losing its identity (not shown). This synoptic pattern is reminiscent of the extratropical transition of tropical cyclones observed in higher latitudes (see Jones et al. 2003). Because this sequence of events occurs in the middle of the Atlantic Ocean, it prevents the tropical cyclones from threatening highly populated regions farther west.

**Table 2. Fates of AEWs after leaving the West African coast.**

<table>
<thead>
<tr>
<th>Fate</th>
<th>No. of AEWs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlantic tropical cyclone</td>
<td>9</td>
</tr>
<tr>
<td>Pacific tropical cyclone</td>
<td>5</td>
</tr>
<tr>
<td>Absorbed into the extratropics</td>
<td>6</td>
</tr>
<tr>
<td>Dissipates within MDR</td>
<td>3</td>
</tr>
<tr>
<td>Dissipates outside MDR</td>
<td>5</td>
</tr>
</tbody>
</table>

![Fig. 10](image-url) Sequence of maps showing tropical cyclone formation from AEWs over the Atlantic Ocean. Potential vorticity on the 315-K isentrope, shaded according to the color bar in the bottom right of the image [potential vorticity units (PVU), 1 PVU = 1 K m² s⁻¹ kg⁻¹]. The 700-hPa AEW trough axes are shown as thick lines. Locations of tropical cyclones, based on TPC best track, are denoted by standard symbols. Systems are labeled as follows: W13, W14, W15, and W16 are AEW numbers 13, 14, 15, and 16; D = Danielle and E = Earl. The date and time is shown beneath each panel.
The northward movement shown by Hurricane Danielle and its precursor is also observed in nondeveloping AEWs; these exited the MDR through its northern edge. Table 2 indicates that a total of six AEWs during JAS 2004 exhibited this behavior. In each case, the synoptic situation was similar to that illustrated in the Hurricane Danielle case, with an extratropical trough located to the north and west of the AEW. In these cases the AEW and its embedded PV maxima were meridionally elongated during interaction with the extratropical feature and the moisture associated with the AEW was advected northward. It is plausible that in these events, this poleward transport of moisture into the predominantly dry extratropics may have important repercussions on the weather and climate in northwest Africa (see Knippertz et al. 2003) or even southwestern Europe. It is also possible that these poleward surges of moisture can mix with the very dry Saharan air layer, modifying its characteristics and perhaps affecting basinwide tropical cyclone activity (see Dunion and Velden 2004).

The remaining eight systems that left the African coast during JAS 2004 had less dramatic fates. Five AEWs weakened and became untrackable after moving through the MDR, dissipating beyond recognition over the Caribbean Sea, Central America, or the eastern Pacific. Three AEWs became untrackable within the MDR, weakening beyond recognition a few days after leaving the African coast.

5. Discussion and summary

a. Core diagnostics and their applications

We have presented an objective trough axis identification method that has not previously been applied in the context of AEWs, and our overall results compare favorably with previous (predominantly composite) studies that have documented AEW characteristics. The 700-hPa AEW trough axis based on $\psi$ (with the rules set out in Table 1a) was easier to interpret with less ambiguity than in equivalent analysis based upon other fields (e.g., meridional wind, relative vorticity). On most occasions, little or no manual intervention (e.g., joining a fractured trough axis to form a continuous line) was required when analyzing the daily maps. As demonstrated by the Hovmöller diagram in Fig. 4b and emphasized by daily maps (not shown) very little practical differences exist between subjective trough lines generated from the 2–6-day filtered 700-hPa meridional wind field and the objective method presented here. Therefore, we argue that objective AEW trough and AEJ axes based upon 700-hPa $\psi$ give a more concise (i.e., easier to interpret) representation of AEW activity than do other commonly used fields, with the added advantages that they are completely objective, automated, and can be derived in real time. Meeting with our aims set out in the introduction, the inherent objectivity and flexibility of this method would also permit different time periods and different gridded datasets to be meaningfully intercompared.

Although not explicitly discussed in this research (except in the objective calculation of AEW speeds), the AEJ axis location is also a useful diagnostic that we believe has further potential applications. For example, examination of the horizontal tilts of AEW trough axes relative to the AEJ axis gives some indication of energy exchanges between the AEW and the basic state. It was noted that on most occasions a distinct wavelike distortion of the AEJ axis (consistent with the wavelike wind field) could be observed in the vicinity of the AEW trough axes (see, e.g., Figs. 5 and 9a). In some cases this distortion of the AEJ axis could be seen prior to the appearance of the 700-hPa AEW trough axis, suggesting an application as a simple forecasting tool. However, it may also be that some thresholds on Table 1 could be relaxed to highlight weak (incipient) AEWs, albeit at the expense of adding more noise to the basic product.

b. AEWs of July–September 2004

In the course of our synoptic analysis of each of the AEWs that developed over Africa during JAS 2004, we noted a tendency for the appearance of a 700-hPa trough axis to be preceded by a westward-moving region of convection (generally composed of several long-lived regenerating MCSs) upstream of the first 700-hPa AEW trough position. In most cases this convection was located within the synoptic-scale AEW over West Africa. Although difficult to quantify on the basis of Meteosat imagery alone, we crudely estimate a convective “precursor” to AEW development can be observed upstream of the first trough position in over 80% of the AEWs of JAS 2004. In all cases where a convective precursor is believed to exist, this convection is initiated over elevated terrain east of 15°E, particularly the Ethiopian and Darfur mountain ranges. This casual observation of a link between subsynoptic-scale regions of convection and the initiation of AEWs is entirely consistent with earlier hypotheses of AEWs being initiated in central or eastern Africa and growing as they move westward, supported by barotropic and baroclinic energy exchanges (e.g., Carlson 1969a; Mekonnen et al. 2006; BT05; Kiladis et al. 2006).
Figure 11 shows the life cycles of two consecutive large amplitude AEWs from September 2004 that have continental histories typical of those observed during JAS 2004. The first frame of this figure (Fig. 11a) shows an intense region of convection near 15°N, 35°E, just west of the Ethiopian highlands. Animations of satellite imagery (not shown) indicate that this convective burst was not present 12 h previously. This region of convection can be coherently followed on subsequent frames moving westward across tropical North Africa and on into the Atlantic Ocean (Fig. 11f). An AEW trough line becomes defined within the cloud mass approximately 1 day after the initial convection (Fig. 11b) and is located within an area of locally high 315-K PV. This AEW trough line moves westward with the region of convection and is designated W27 after meeting all the tracking criteria. When the AEW is near 15°E, a coherent NV develops at low levels near the northern tip of the trough line (indicated by a cross on Fig. 11), moving coherently with the AEW trough line to the west coast. With continued westward progression, intense subsynoptic-scale 315-K PV maxima develop in the vicinity of the AEW trough (see, e.g., Figs. 11d,e). Over the ocean, these 315-K PV maxima further intensify, merge, and
The life cycle of the second AEW (W28) is very similar to the first; an intense subsynoptic-scale convective burst occurs near 30°E (Fig. 11c) and can be followed moving westward on subsequent images. Within this region of convection the AEW trough line and subsynoptic PV maxima develop. North of the AEJ axis an NV develops and moves westward with the other components of the AEW to the West African coast (see Figs. 11c–h). Over the ocean the trough axis associated with W28 becomes ill defined, but the embedded subsynoptic-scale PV maxima can still be coherently followed, where they are associated with the formation of Hurricane Lisa (not shown). These examples demonstrate how the AEW trough axis diagnostic, if deployed with another appropriate field (in this case 315-K PV), highlights the multiple scales associated with AEWs (as shown by, e.g., BT05).

Over West Africa the majority of AEWs during JAS 2004 were characterized by 700-hPa trough axes that were tilted NE–SW equatorward and SE–NW poleward of the AEJ axis and, in most circumstances, possessed a low-level NV downstream of the trough axis (see Fig. 9a). These structures are consistent with AEWs extracting energy from the basic state via both baroclinic and barotropic interactions (as in Thornicroft and Hoskins 1994a). The small subset of systems that lacked a coherent NV was confined equatorward of the jet axis and was noted as generally exhibiting an upshear (NE–SW) tilt south of the AEJ axis. Because the 700-hPa AEW trough axes only existed in the rainy zone south of the AEJ axis, and did not extend to the baroclinic zone on the southern fringe of the Sahara, it is suggested that these systems are dominated by barotropic energy exchanges and/or diabatic processes.

Consolidating our experience of the AEWs during JAS 2004, and following BT05, it is our conjecture that there exists a continuum of structures, ranging from synoptic-scale baroclinic waves, dominated by Rossby wave dynamics (amplifying on the basic state that exists over the African continent), to synoptic-scale phenomena that are dominated by convective processes and only weakly dynamically coupled to the basic state. We suggest that AEWs have their origins as discrete forcings (typically MCSs over central and eastern Africa) that couple to the basic state and amplify. The synoptic structures that develop downstream (i.e., the AEWs) are functions of the nature and location of the initial forcing and the basic state, both of which can be modified by other AEWs, localized convection, or even remote forcings (e.g., extratropical troughs, equatorial waves).

The examination of the AEW life cycles after leaving the West African coast has also uncovered some intriguing results. Perhaps most significantly, it was found that 14 of the 31 AEWs (45%) were associated with tropical cyclones in either the Atlantic or Pacific basins. Previous studies (e.g., Frank 1970) have indicated that a much smaller percentage of AEWs (of order 10%) are typically expected to be associated with tropical cyclones. It is likely that much of this disparity is related to two factors: (i) we have focused on only the 3 central months of the 6-month Atlantic hurricane season (June to November) and (ii) we have implemented our objective method, which we believe to reduce the potential for MCSs to be incorrectly identified as AEWs. Another possibility is that the rate at which AEWs transition into tropical cyclones in JAS was for some reason anomalously high in 2004. An additional notable aspect of postcontinental AEW life cycles documented in this research is the transition of some AEWs (or their remnants) into the extratropics via the northern edge of the MDR. There is little discussion of this behavior in the literature, although it is implied by tropical cyclone tracks that curve northward over the central Atlantic Ocean. It is suggested that the most likely reason for these observed tracks is the influence of a pseudostationary midlevel trough (peaked near 700 hPa) in the central and eastern Atlantic basin (as highlighted by Carlson 1969b).

6. Future work

In light of the above results, it is suggested that future research should focus on developing applications of our objective AEW identification method. The technique itself has scope for “expansion,” by coupling it with an automated tracking routine to allow the analysis of AEW variability over a long time period (cf. Thornicroft and Hodges 2001; Aiyyer 2003). The objective methods may also be applied to analyses and forecasts from different global models, in order to objectively intercompare performance in representing and predicting AEWs (or the AEJ) over North Africa and the Atlantic. Armed with such comparative information, forecasting of AEWs and associated weather over Africa becomes more tractable, bringing not only local socioeconomic benefits but providing also an important input to daily planning during upcoming field campaigns, such as the African Monsoon Multidisciplinary Analyses (AMMA) program.

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