Evolution of African Easterly Waves in Potential Vorticity Fields

BRYCE TYNER AND ANANTHA AIYYER

Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, North Carolina

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ABSTRACT

The evolution of African easterly waves (AEWs) leading to tropical cyclones (TCs) in the Atlantic during 2000–08 is examined from isentropic potential vorticity (PV) and Lagrangian streamline perspectives. Tropical cyclone formation is commonly preceded by axisymmetrization of PV, scale contraction of the wave, and formation of a closed circulation within the wave. In these cases, PV associated with the synoptic-scale wave is irreversibly deformed and subsumed within the developing vortex. Less commonly, filamentation of the PV leads to separation and independent propagation of the wave and the TC vortex. In an example presented here, the remnant wave with a closed circulation persisted for several days after separation from the TC. A second TC did not result, consistent with several past studies that show that a midtropospheric closed gyre is not sufficient for TC genesis. Sometimes, an AEW and a weak TC remain coupled for a few days, followed by the dissipation of the TC and the continued propagation of the wave. Merger of tropical and extratropical PV anomalies is also often observed and likely helps maintain some waves. The results of this study are broadly consistent with recent Lagrangian analyses of AEW evolution during TC genesis.

1. Introduction

African easterly waves (AEWs) are one of the most common precursors to tropical cyclones (TCs) in the Atlantic. Approximately 60% of all Atlantic TCs and 80% of major hurricanes form in association with AEWs (e.g., Pasch et al. 1998). While only a fraction of all AEWs are involved in tropical storm formation, it is apparent that they satisfy one of the necessary conditions for cyclogenesis: a preexisting cyclonic circulation (e.g., Gray 1968). In the top-down view of TC genesis, midlevel cyclonic circulations form within the large-scale stratiform precipitation region of a mesoscale convective system (e.g., Bister and Emanuel 1997; Simpson et al. 1997). These midlevel vortices then merge, increasing the horizontal scale of the cyclonic potential vorticity (PV) anomaly. Stretching of the midlevel PV anomaly allows for downward penetration of cyclonic PV. The result is cyclogenesis at the surface. In the bottom-up view, TC genesis results from an aggregation of vorticity produced within horizontally small-scale, intense spontaneous updrafts occurring within a weak surface-based cyclonic circulation (e.g., Kieu and Zhang 2009; Tory et al. 2006b,a; Hendricks et al. 2004).

TC genesis from an AEW is typically envisioned as a process wherein a synoptic-scale wave transforms into a mesoscale vortex. The formation of a closed circulation within the AEW trough represents an important step. Shapiro (1977) defines the trigger for TC genesis as the point when the nonlinear vorticity advection associated with an initially quasi-linear neutral wave begins to dominate the evolution. This nonlinear vorticity advection occurs as the wave scale contracts, leading to a tightening of the vorticity gradient. Studies examining other ocean basins also found an important role of confluence-induced contraction of the zonal wave scale in the process of TC genesis (e.g., Sobel and Bretherton 1999; Kuo et al. 2001; Li et al. 2003).

The intertropical convergence zone (ITCZ) breakdown pathway is another route to closed circulations, developing from amplifying waves in an unstable environment. Guinn and Schubert (1993) and Ferreira and Schubert (1997) used a shallow-water barotropic model to examine ITCZ breakdown in the eastern Pacific. In their simulations, an initially zonal strip of cyclonic PV anomaly is unstable to perturbations that amplify via barotropic instability and irreversibly deform the PV strip into a series of eddies. Ferreira and Schubert (1997)
focused on eastern Pacific storms but also recognized the applicability of this mechanism to the Atlantic. However, Magnusdottir and Wang (2008) found that ITCZ breakdown was relatively rare in the Atlantic. Nevertheless, observations often show quasi-linear strips of PV connecting multiple AEWs. While this is different from the in situ development that occurs over eastern Pacific, the ensuing development of eddies and pooling of PV can lead to TC genesis.

An additional path to formation of a closed circulation within neutral waves has been proposed by Dunkerton et al. (2009, hereafter DMW09). In a Lagrangian framework, DMW09 suggest that TC genesis is preceded by the formation of a closed gyre within a critical layer, or a so-called marsupial pouch. This critical layer forms when the wave enters a region where its propagation speed matches the environmental flow. DMW09 suggest that the formation of the closed gyre helps buffer the air within the wave from the intrusion of dry air and preconditions the region for deep convection. The closed gyre formation is most applicable to neutrally propagating waves that have left their initiation region of the unstable African easterly jet (AEJ). However, DMW09 speculate that disturbances forming from ITCZ breakdown may also be consistent with this marsupial paradigm.

Observations often show that an AEW does not entirely transform into a vortex. Often, thinning of the trough leads to its breakdown similar to midlatitude cutoff cyclones, an analogy that has also been noted by Lindzen (1974) and DMW09. Once cut off, the propagation paths of the TC and the residual wave are usually different. The AEW continues to follow the waveguide set by the background PV gradient, while the TC path is determined by the environmental steering current. After separation, most of the waves are observed to eventually decay. However, National Hurricane Center (NHC) storm reports occasionally indicate that a wave can continue on and possibly even lead to the formation of another TC (storm reports are available online at http://www.nhc.noaa.gov/pastall.shtml). For example, the storm reports for Franklin and Gert (2005) suggest that the same wave was the precursor to both storms. Occasionally, the storm reports also designate a decayed tropical storm as an open wave. The potential to survive the TC formation process and the apparent elasticity in reverting back to a wave state are intriguing flavors of AEW evolution that need to be better documented in order to improve our understanding of the role of the wave in TC genesis.

The studies described above indicate that the role of AEWs in the process of TC genesis and the fate of the incipient waves after TC genesis is not fully understood. The evolution of the synoptic-scale AEWs prior to, and immediately after, TC genesis is the focus of this study. We use isentropic PV instead of the streamlines that are traditionally used to describe the waves. Isentropic PV is conserved for adiabatic and frictionless flow, and thereby serves as a good tracer of synoptic-scale disturbances. Routine examination shows that despite localized nonconservation, AEWs can be clearly tracked in isentropic PV fields. Under the assumption that frictional effects are secondary, nonconservation of isentropic PV can be directly linked to convection (e.g., Brennan and Lackmann 2005). Isentropic PV has effectively been used as a tool to understand the process of TC genesis in several prior studies (e.g., Davis and Bosart 2001). A coherent maximum in PV can be associated with a closed circulation under the assumption of a suitable balance condition. Thus, the development of subsynoptic circularly symmetric PV patches within a parent wave is consistent with the description of a closed gyre in a wave-following frame. The PV view does not necessitate the estimation of the wave phase speed that the Lagrangian approaches require, which can often have significant uncertainties in their derivations (e.g., DMW09). Furthermore, the action at a distance property of PV can be used to infer the potential for existence of a closed circulation at multiple levels.

The specific objective of this study is to examine the evolution of AEWs from an isentropic PV perspective and a wave-following Lagrangian framework. The results show that in most cases, axisymmetrization of PV, scale contraction of the wave, and formation of a closed circulation precedes TC formation. The parent wave is irreversibly deformed and subsumed within the developing vortex. Less commonly, the wave and TC cleanly separate and the remnant wave survives for an extended period of time.

2. Data

The primary data used here are the Global Forecast System (GFS) final analysis fields and the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA; TRMM product 3B42; Huffman et al. 2007). Both datasets are on 1° latitude-longitude grids. While there are inherent limitations with the use of the GFS final analysis dataset over the tropical Atlantic, a routine inspection of the data used in this study suggests relatively smoothly varying fields over the Atlantic. Furthermore, several past studies have successfully used this dataset for describing various mesoscale and synoptic processes involved in TC genesis (e.g., Snyder et al. 2010; Montgomery et al. 2010). Tropical cyclone tracks as well as time of TC genesis...
were taken from the International Best Track Archive for Climate Stewardship (IBTrACS; Knapp et al. 2010).

We focus on tropical storms that met the following criteria: 1) clear AEW source of origin and 2) minimal baroclinic and upper-level forcing. A total of 51 storms were chosen for this study. These cases are broadly consistent with the nonbaroclinic origin TCs classified in McTaggart-Cowan et al. (2008). We also include some cases categorized as weak tropical transition by the authors on the basis of subjective inspection of the data.

Throughout the paper, isentropic PV is shown either on the 315-K surface or averaged over the 310–320-K layer. The 315-K level corresponds to roughly 650 hPa in the tropics and about 600 hPa in the subtropics; as such, it is an ideal surface to examine both the AEW circulation and the equatorward intrusion of PV from the midlatitudes. The 310–320-K layer-averaged plots are included to show that the results are robust when examined from other isentropic surfaces.

The PV maxima associated with AEWs are identified using an algorithm that 1) searches isentropic PV fields for local maxima that exceed 0.2 potential vorticity units (PVU; 1 PVU = \(10^{-6} \text{m}^2\text{Ks}^{-1}\text{kg}^{-1}\)), and 2) ensures that at least one closed PV contour of value 0.1 PVU less than the central maximum can be drawn. These criteria help eliminate some of the noise in the PV field throughout the tropics and produce results consistent with other studies that have objectively identified AEWs (e.g., Hopsch et al. 2007). For each identified AEW, the PV is bilinearly interpolated to a cylindrical grid, with the local PV maximum as the center of the grid. A quantitative estimate of axisymmetry of the PV patches is then obtained by taking the ratio of the largest to smallest axis of the PV patch after projecting the data onto a cylindrical frame. The axes are measured for the contour that is \(e^{-1}\) of the maximum PV at the center. This aspect-ratio-based definition of axisymmetry is based on a similar definition in previous studies (e.g., Melander et al. 1987). Values closer to 1 denote a more axisymmetric vortex compared to larger values. Similar results were obtained when we used an alternate definition based on the azimuthal variance of PV at set distances from the wave pouch center, wherein symmetric vortices have near zero PV variance (not shown).

Isentropic PV framework also allows us to explore the process of PV thinning associated with AEWs. A useful diagnostic is the Okubo–Weiss filamentation time (Weiss 1991), which is defined as the \(e\)-folding time scale of the growth rate of the quasi-horizontal isentropic PV gradient (Rozoff et al. 2006). Since PV thinning is associated with an increase in PV gradient, this diagnostic provides a succinct way of identifying areas of rapid change in AEW structure. These rapid changes occur in such processes as breakdown of a quasilinear PV strip and separation of the TC and wave. In a recent study, Tsai et al. (2010) derived a version of the Okubo–Weiss filamentation time for three-dimensional divergent flow constrained by material conservation of isentropic PV. Adapting their formulation and neglecting the effect of Earth’s curvature (given the proximity to the equator), the filamentation time is written as

\[
\tau_{fil} = 2\left\{ \delta + (S^2 - \zeta^2)^{1/2} \right\}^{-1} \text{ for } S^2 > \zeta^2, \tag{1}
\]

where \(\delta\), \(S\), and \(\zeta\) refer to divergence, total deformation, and relative vorticity on an isentropic surface respectively. As noted in Tsai et al. (2010), the formulation is defined only for strain-dominated regions, and small values of this diagnostic indicate rapid increase in PV gradient and potential for cutoff low formation. Tsai et al. (2010) examined three cases of PV filamentation of upper-level troughs, including one in the tropics. While the applicability of the filamentation time defined above is questionable when nonconservative processes are present, some insight in AEW evolution can be gained in areas away from active convection. Small values of filamentation time highlight strain-dominated regions, wherein the PV associated with the AEW is expected to thin.

### 3. Results

#### a. Subjective classification of wave evolution

In animations of PV fields, AEWs exhibit a complex and rich array of structures ranging from distinct PV maxima associated with AEW troughs to quasi-linear PV strips that connect multiple AEWs. The broad range of AEW evolution during TC genesis is subjectively classified into three categories, based upon PV and streamline evolution.

- **Type A**: The PV associated with the wave contracts in horizontal scale through axisymmetrization and the wave is irreversibly deformed. The wave merges with the TC circulation or the remnants of the wave are short lived. The TC genesis is followed by a change in the speed and direction of the TC relative to the initial propagation direction of the wave. Of the 51 storms considered here, 42 were classified as type A (Table 1). An idealized schematic of this evolution is shown in Fig. 1a.

- **Type B**: The wave and TC-vortex separate and the wave evolves independently, as seen in both isentropic PV and wave-following streamlines. Filamentation of the PV leads to separation of the TC from the wave, akin to a cutoff low formation in the midlatitudes. Typically, the TC acquires a rapid poleward motion while the remnant wave continues to propagate westward.
This behavior is less commonly seen, as only six cases in our dataset fit this description (Table 1). The idealized schematic of this evolution is shown in Fig. 1b.

- Type C: The wave and TC propagate together for a period followed by dissipation of the TC and continued evolution of the wave. The system maintains primarily a westward direction of propagation. Only three cases of this hybrid wave–TC evolution were identified (Table 1), and the idealized schematic of this evolution is shown in Fig. 1c.

The results tabulated above indicate that the most common post-TC genesis fate of AEWs is that of being subsumed within the developing storm or rapid decay soon after (type A). The observed frequency of parent wave decay is consistent with the qualitative results presented in DMW09, where the authors cite evidence of frequent wave decay during TC genesis in the NHC’s Tropical Prediction Center (TPC) surface analyses. Examination of PV fields suggests that merging of PV from breaking midlatitude troughs or from neighboring easterly waves are common sources of invigoration of a decaying wave after separation from the TC. It should be noted that the classification was made by subjective inspection of the fields and may be sensitive to the dataset characteristics, such as resolution and assimilation of observations.

b. Illustrative examples

1) Type A: DOLLY (2008)

Tropical Storm Dolly (2008) formed at 1200 UTC 20 July 2008 within an AEW that had emerged from the west coast of Africa about 9 days earlier. A 6° latitude range following the pre-Dolly wave was averaged and used to develop a Hovmöller diagram of 315-K PV and TRMM precipitation. Figure 2 shows that the AEW can be clearly tracked from the eastern Atlantic to the Caribbean Sea in both PV and TRMM precipitation. Increase in convection around 1200 UTC 16 July while located near 60°W is accompanied by an increase in the area-averaged PV following the wave. Another period of increase in 315-K PV and enhanced convection began around 0000 UTC 19 July, indicative of the TC genesis process that was already under way. From 16 to 19 July, the phase speed of the wave was held nearly constant at around 8.5 m s⁻¹.

Figure 3 shows the 315-K PV and 600-hPa streamfunction at selected times to illustrate the evolution of the pre-Dolly wave. On each panel, the localized PV maximum of interest is labeled. Salient features of the AEW evolution seen here are as follows:

- Seven days prior to TC genesis (Fig. 3a), the precursor to Dolly appears as an elongated PV strip. The streamfunction contours are nearly zonal. At this time, the pre-Dolly feature is part of a basinwide undulating PV strip that connects multiple AEWs.
- The subsequent sequence of charts show the breakdown of the PV strip in a manner consistent with Guinn and Schubert (1993) and Ferreira and Schubert (1997). However, in this case, the PV strip is not associated with an ITCZ that develops in situ, but is
instead associated with an AEW wave train that originated over North Africa. There is clear evidence of pooling of PV into distinct eddies connected to their neighbors by thin filaments.

• By 1200 UTC 17 July (Fig. 3d), three cyclonic gyres have resulted after the breakdown of the PV strip.
• The streamfunction field shows a gradual amplification of the trough axis and development of the pre-Dolly wave. By the TC genesis time at 1200 UTC 20 July (Fig. 3g), the PV within the pre-Dolly wave is much more axisymmetric compared to the associated PV shown in previous panels.
• 24 h later, shown in Fig. 3h, the trough has contracted further and the PV within the trough has increased.
• Merger of PV of midlatitude origin with AEWs is seen in several panels. In Figs. 3c–e, PV from an equatorward breaking and thinning midlatitude trough merges with the pre-Dolly wave.

Figure 4 shows the 310–320-K layer-averaged PV, TRMM precipitation, and streamlines in wave-following frame for the same times as in Fig. 3. The Lagrangian streamlines are calculated in a manner similar to DMW09, where the estimated wave phase speed is subtracted from the total flow. Wave phase speed is calculated from the Hovmöller diagram (Fig. 2) as noted earlier.

Key aspects of AEW evolution in this Lagrangian framework are as follows:

• Seven days prior to TC genesis (Fig. 4a), the circulation surrounding the elongated PV maximum is not associated with closed streamlines. The bulk of the precipitation is to the south of the PV strip, with a weak maximum just to the west of the wave pouch center. Diabatic generation of PV, with enhancement in the lower troposphere, is expected in areas of precipitation.
• 48 h later (Fig. 4c), a closed gyre can be seen in the streamlines. The gyre corresponds closely to the closed contours in the PV field. Saddle points in the streamlines can be seen both to the west and east of the gyre, and are associated with the stretching of the PV filaments connecting the gyres that formed from the breakdown of the original PV strip.
• As the PV continues to axisymmetrize over the next 96 h, precipitation shifts closer to the wave pouch center. The PV filament connecting the pre-Dolly gyre to its neighbors continues to thin, and even breaks on the eastern side. Over the days leading to the formation of the tropical depression, both PV and precipitation rates are observed to increase.

In the Lagrangian framework, closed gyre formation is consistent with axisymmetrization of PV and is associated with an increase in precipitation near the wave pouch center. Diabatic PV generation aids the axisymmetrization by increasing the PV anomaly, which further enhances the nonlinear PV advection and pooling of the PV within the gyre. Figure 5 shows the 310–320-K layer-averaged PV and filamentation time (24 h or less) computed using the layer-averaged winds. As previously mentioned, shorter filamentation times denote strain-dominated regions and are located outside the core PV anomaly. The shortest filamentation times are found on either side of the gyre, and are consistent with the stretching and thinning of PV on those time scales (e.g., Figs. 5c,d). During the process of TC genesis, filamentation times remain quite long or not defined, consistent with the PV anomaly becoming more axisymmetric and vorticity dominating the straining flow (e.g., Fig. 5g).

A period of axisymmetrization and increase in area-average PV and precipitation commences around 0000 UTC 15 July, as seen in the time series of 315-K PV and TRMM precipitation (Fig. 6). Initially, it appears that precipitation leads PV enhancement, but they appear to evolve nearly simultaneously after the gyre forms. After the formation of the closed gyre on 16 July, a period of nearly steady evolution is followed by a second round of axisymmetrization, enhanced PV, and precipitation.
commencing around 1200 UTC 18 July, leading up to and beyond the formation of the tropical depression at 1200 UTC 20 July.

A measure of vertical development of the wave is presented in a wave-following cross section of area-averaged relative vorticity and vertical velocity in Fig. 7. The peak vorticity is located at 600 hPa on 14 July. During this time, the strong upward vertical velocity is primarily confined to the upper troposphere. The formation of the closed gyre in the midtroposphere is associated with an increase in upward velocity over a deep column. As seen earlier with precipitation in Fig. 6, enhanced vertical velocity leads the increase in lower-tropospheric vorticity prior to the formation of the gyre and subsequently proceeds nearly in concert. The formation of the closed gyre, nearly 5 days prior to TC genesis, is also accompanied by generation of anticyclonic vorticity aloft. The vorticity column builds upward after the gyre forms. At the time of TC genesis, cyclonic vorticity spans much of the troposphere, from near the surface to about 300 hPa.

In summary, during the processes of TC genesis for Dolly, the precursor wave was deformed and axisymmetrized. After TC genesis, the wave did not propagate further, as the system underwent a complete transformation into a nonlinear vortex. In the Earth-relative frame, the wave contracted in scale, as evidenced by the streamlines and PV. After TC genesis, Dolly propagated more northward, consistent with the environmental steering current.

2) TYPE B: BERTHA (2008)

Bertha formed close to the West African coast from an AEW around 0600 UTC 3 July 2008. Using a 6° latitude range following the disturbance, the Hovmöller diagram in Fig. 8 shows the evolution of the AEW.
during and post TC genesis. Prior to TC genesis, a merging of two separate PV anomalies occurs between 2–3 July near 10°–20°W. The TC and the wave separate around 0000 UTC 4 July, soon after which the TC acquires rapid northward motion and moves out of the averaging latitudinal range of the Hovmöller plot. Subsequently, the wave begins to weaken and diabatic activity nearly ceases by 5 July. Despite this weakening of diabatic activity, the remnant PV continues to propagate westward and maintains its strength for over 96 h. The key features in the sequence of PV and streamfunction fields in the Earth-relative frame (Fig. 9) are as follows:
The precursor AEW appears as a strong PV anomaly associated with an AEW. In Fig. 9a, a closed contour in the Earth-relative streamfunction field can be seen. The streamfunction field shows an open wavelike structure 24 h later (Fig. 9b). At this time, there is a secondary PV anomaly just to the east of the primary anomaly.

By 3 July, the two PV anomalies within the AEW have merged and TC genesis has occurred (Fig. 9c). The AEW has a southwest-to-northeast tilt. A distinct PV filament continues to take shape over the next 24 h as the TC and remnant wave begin the process of separation (Fig. 9d).

Fig. 5. 310–320-K layer-averaged PV (\(\times10\) PVU, shaded), and filamentation time (contours; interval 6 h; only values less than or equal to 24 h shown). Each panel is 24 h apart, starting at 1200 UTC 14 Jul 2008. The white filled circle marks the position of the AEW. The location of the TC is noted by a white “X.”
Over the next couple of days, the separation between the two increases. Simultaneously, PV from a midlatitude trough (marked by the symbol T) is advected cyclonically around the TC and it eventually merges with the remnant AEW (Figs. 9f,g).

As seen in Fig. 9h, the AEW and the TC have completely separated by 1200 UTC 8 July and the wave appears robust.

The sequence of TC formation and separation seen in Figs. 9d–f bears a similarity to the cutoff low formation in the midlatitudes via the cyclonic wave breaking process (e.g., Thornicroft et al. 1993). The PV associated with the AEW appears to wrap cyclonically in association with the accentuated southwest-to-northeast tilt.

In the Lagrangian wave-following frame there exists a closed circulation surrounding the large PV anomaly just off the West African coast (Fig. 10a). Precipitation is broadly centered within the gyre. About 30 h after TC genesis (Fig. 10d), the closed circulation associated with the tropical storm and the PV of the remnant wave have...
begun to separate. At this time, there is precipitation associated with the remnant wave. In the remaining panels, the focus is on the remnant wave. As the PV of midlatitude origin wraps around the TC and merges with the wave, the circulation amplifies (Figs. 10f,g). In fact, by 1200 UTC 8 July, a closed gyre has formed again in association with the wave (Fig. 10h). The wave continues to propagate toward the west-northwest for several days while maintaining the closed gyre (not shown). Notably, however, there is no significant convective activity associated with this wave. This is consistent with the results described in DMW09, where the authors observed several cases of waves with closed gyres in the wave-relative framework devoid of convection. The wave eventually merges with an extratropical system in the Gulf of Mexico. Thus, despite the formation of a second gyre that remains coherent for 2–3 days, a second TC does not result.

The filamentation time for Bertha (2008) is shown in Fig. 11. As was the case in Dolly (2008), the shortest filamentation times are found on the eastern and western sides of the AEW PV anomaly. Unlike Dolly (2008), however, the filamentation time scales are much shorter, with values as low as 6–12 h present to the south of the main PV anomaly in Figs. 11b–d. The short filamentation times are consistent with the thinning of PV to the south of the main PV anomaly. This thinning PV structure is analogous to the filamentation resulting in the formation of cutoff lows in the midlatitudes, as described in Tsai et al. (2010). Following this period of filamentation of PV, the filamentation time scale becomes longer or no longer defined, shown in Figs. 11f–h. This is consistent with the dominance of vorticity over straining flow. The result is a more axisymmetric PV anomaly associated with the wave propagating to the west.

The events described above are further illustrated in the time series of area-averaged 315-K PV, rainfall, and the measure of axisymmetry following the AEW (Fig. 12). A closed gyre exists at the initial time (1200 UTC 1 July) and axisymmetrization and an increase in PV
occur while the wave is coupled to convection. After TC genesis, the remnant wave is rapidly deformed, as seen in the decrease in symmetry and reduction in area-averaged PV. However, soon thereafter, even as the precipitation within the wave continues to sharply decrease, the PV stabilizes. This occurs as a breaking trough from the extratropics merges with the wave. The formation of the second gyre is likely a result of this merger and subsequent axisymmetrization of the wave. The cross section of relative vorticity and vertical velocity in the wave-following frame (Fig. 13) further illustrates the evolution during and post-TC genesis. The TC genesis is preceded by deep convection within the wave, which leads to amplification of lower-

FIG. 10. 310–320-K layer-averaged PV (×10 PVU, shaded), 600-hPa streamlines (thin contours), and TRMM precipitation (mm h$^{-1}$, thick contours) in wave-following frame. Each panel is 24 h apart and has the wave as the center of the plot, starting at 1200 UTC 1 Jul 2008. The white filled circle marks the position of the AEW. The location of the TC is noted by a white “X.”
tropospheric vorticity. The separation of the wave and TC is marked by the discontinuity in vorticity around 1200 UTC 3 July. Following the separation, the vorticity in the remnant wave is mainly confined to the middle and upper troposphere. Merger with vorticity from upper-tropospheric vorticity of extratropical origin is evident between 5–7 July. As noted earlier, convective activity is absent, as seen in the lack of significant upward vertical velocity.

In summary, near the time of TC genesis, the parent wave and TC decoupled, leading to separate propagation characteristics. The wave continued to propagate to the west for several days, whereas the TC propagated more northward. Filamentation of PV allowed the wave...
to continue propagating, rather than subsuming within the TC circulation. The remnant wave’s circulation amplified and a closed gyre formed, in part due to merging with PV from a midlatitude system. However, the lack of convective coupling with the parent wave likely prevented a second case of TC genesis associated with the wave.

3) TYPE C: EARL (2004)

The NHC storm report indicates Earl formed on 13 August 2004 from an AEW that moved off the coast of West Africa on 10 August. After propagating across the Atlantic for several days, the wave moderately strengthened. NHC classified the system a depression at 1800 UTC 13 August. Over the next 24 h, the system continued to slowly strengthen, and NHC classified the system a tropical storm at 1800 UTC 14 August. By 1800 UTC 15 August, the system began to weaken, and the official NHC forecast designated it as an open wave on 16 August. The remnant wave eventually crossed into the eastern Pacific and was the precursor to the formation of Hurricane Frank on 23 August.

FIG. 12. Time series of 315 K PV ($\times 10$ PVU, thick black line), TRMM rainfall (mm h$^{-1}$, dashed black line), both averaged within a 3° box following the pre-Bertha wave, and axis ratio for the gyre within the wave (thick gray line). Dashed vertical lines mark significant events during the evolution of the wave.

FIG. 13. Vertical structure of relative vorticity (s$^{-1}$, shaded) and vertical velocity (Pa s$^{-1}$, contours) averaged within a 3° box following the pre-Bertha wave.

FIG. 14. Hovmöller diagram of 315-K PV ($\times 10$ PVU, shaded) and TRMM precipitation (mm h$^{-1}$, contours) averaged over a 6° latitude range following the pre-Earl wave. Tick marks denote 0000 UTC for each day. Time and location of TC genesis is indicated by an “x”.
Fig. 14 shows this evolution of the AEW during and post-TC genesis. After TC genesis, the system continues to propagate westward, in the initial direction of the AEW. The elasticity displayed in the evolution for Earl is of significant interest. Key observations of the PV and streamfunction fields in the Earth-relative frame are enumerated below.

- The 310–320-K layer-averaged PV and 600-hPa streamfunction fields in the Earth-relative frame for Earl (Fig. 15) show an initially weak but coherent AEW that moves westward and axisymmetrizes during and after TC genesis (Figs. 15b,c).
- Even though the system is no longer designated a TC, the parent wave remains coherent and crosses Central America on 18 August (Fig. 15e). While the streamfunction fields clearly show the wave, the PV is deformed (Fig. 15f). The deformation of PV is consistent with the climatological results of waves crossing Central America presented in Kerns et al. (2008).
- At 36 h later, the PV has amplified and has become more axisymmetric (Fig. 15g). About 18 h prior to the formation of Frank, even the Earth-relative streamfunction field exhibits a closed contour (Fig. 15h). The wave-following view (Fig. 16a) shows the existence of a closed circulation 24 h prior to TC formation.
- As seen in subsequent panels (Figs. 16b–h), a closed gyre exists for most of the wave lifetime except for a couple of days during its passage over the Central American highlands. Throughout this evolution, the wave remains coupled to convection, as seen in the precipitation within the gyre.

The time series of PV, precipitation, and axisymmetry (Fig. 17) shows the complex evolution of this AEW. Formation of the closed gyre is preceded by an increase in precipitation and area-averaged 315-K PV. Axisymmetrization continues after TC formation in association with an increase in wave-averaged PV. Even after the decay of the TC around 0000 UTC 16 August, the gyre persists for over a day until the time the wave begins to cross into the eastern Pacific. The rapid loss of axisymmetry and decrease in area-averaged PV reverses after the remnant wave reaches the eastern Pacific. The gyre is reestablished around 1800 UTC 19 August, and the PV strengthens as precipitation rate increases. Frank forms approximately 84 h after the reestablishment of the gyre. The filamentation time (Fig. 18c) around the time of TC genesis is undefined near the PV anomaly. This continues for the next 24 h, as the rotational flow continues to dominate over straining flow. However, as the tropical cyclone weakens, the filamentation time increases significantly on the periphery of the PV anomaly (Fig. 18d). The PV associated with the tropical cyclone thins, consistent with the evolution to a much weaker system. This weaker, open wave propagates to the west over the next several days, with long or...
undefined filamentation times on the periphery of the PV anomaly (Figs. 18e–h).

This evolution is consistent with the cross section of vorticity and vertical velocity (Fig. 19). The main feature of interest here is the initial downward building of relative vorticity until the closed gyre forms in the lower troposphere. After this, the enhanced relative vorticity remains in the lower troposphere, while deep convection exists nearly throughout the lifetime of the wave. The only exception to this occurs during the passage over Central America. The vorticity recovers quickly after reaching the eastern Pacific on 19 August, as seen in the deep cyclonic vorticity column with anticyclonic vorticity in the upper troposphere.

In summary, for Earl, the wave and TC appeared to coexist and propagate together for several days after TC genesis. The wave-following streamline analysis suggests the closed circulation during and after TC genesis.
opened up several days later. This is consistent with the NHC storm report, which suggests the tropical cyclone degenerated back into an open wave. After the wave crossed Central America and reached the Pacific, the closed circulation redeveloped. Convective coupling ensued, and a second TC named Frank formed in the eastern Pacific.

4. Discussion and conclusions

This study examined the evolution of AEWs undergoing TC genesis from isentropic PV and Lagrangian streamline perspectives. Only tropical, nonbaroclinic AEWs were considered. In isentropic PV fields, the evolution of AEWs is rich and varied, ranging from isolated PV maxima to quasi-linear PV strips associated with AEWs. Merging of PV with neighboring waves and with midlatitude disturbances is also observed and is likely a mechanism for the maintenance of AEWs over the Atlantic. Typically, the PV associated with the AEW begins to axisymmetrize several days prior to the formation of the TC. This is confirmed visually as well as using a metric of axisymmetry diagnosed from the wave-centered PV distribution. Once a TC forms within a parent wave, three outcomes are possible for the synoptic-scale wave:

- The wave is deformed and axisymmetric. In these cases, the wave ceases to propagate further and is subsumed within the TC. In this situation, there is a complete transformation from a quasi-linear wave to a nonlinear vortex. In the Earth-relative frame, the streamfunction associated with the wave sharpens as the wave shrinks in scale. This outcome is the most common.
- The wave and TC decouple, leading to separate propagation. This scenario may be similar to midlatitude wave breaking and wrap-up of low PV around the deformed trough, leading to a cutoff low, while the remnant wave continues to propagate. NHC storm reports occasionally indicate that the remnant wave can continue and possibly even lead to the formation of another storm. In the case illustrated here, the remnant wave continued to propagate for several days after separation from the TC, but did not lead to a second TC. About 10% of cases considered in this paper exhibit this evolution.
- The wave and TC can coexist and propagate together for some time after TC genesis. In the case described here, the TC decays and the wave survives to eventually lead to a second TC. This outcome is believed to be relatively uncommon in the Atlantic, as only 3 of the 51 analyzed storms exhibited this evolution.

Axisymmetrization of PV is consistent with formation of a closed gyre in the Lagrangian wave-relative frame. In all three cases shown here, the formation of a closed gyre occurs several days prior to the official declaration of a tropical depression. While the role of diabatic process was not explicitly diagnosed, it is likely that PV generation in the lower troposphere accelerated the axisymmetrization.

In light of the recently proposed marsupial paradigm for TC genesis by DMW09, the analysis presented here suggests the following:

- Our results are broadly consistent with those of DMW09 and Wang et al. (2010), in that TC genesis is commonly preceded by the formation of a wave-relative closed circulation in the midtroposphere several days in
advance. This is reflected in the axisymmetrization of PV within the AEW and represents a transition from a wavelike to a vortexlike structure.

- It is also seen here that the existence of a closed circulation does not guarantee TC genesis. In the case of the remnant wave after formation of Bertha (2008), a closed gyre exists for several days without further development. The quasi-neutral wave persists through PV merger, but the circulation is confined to the middle troposphere and does not have a significant convective signal associated with it. This observation is consistent with the marsupial paradigm, in that the role of the closed gyre only becomes significant if convective initiation occurs. Without convective initiation,
the role of the pouch in promoting convective organization to the point of TC genesis is limited.

- The closed gyre is not confined to a single level but typically covers a significant part of the lower troposphere, as the vortex scale shrinks horizontally and is stretched vertically.

- DMW09 suggested a potential for a cooperative relationship between the closed gyre and the synoptic-scale wave. In this relationship, the larger-scale wave provides a sheltered environment for the vortex, which in turn helps maintain the wave through diabatic feedback. While this is likely during the initial stages of the formation of the closed gyre, once convective activity is well established, the deformation of the parent wave is accelerated as TC genesis ensues.

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**REFERENCES**


