Energy Transformation and Diabatic Processes in Developing and Nondeveloping African Easterly Waves Observed during the NAMMA Project of 2006

ROBERT S. ROSS AND T. N. KRISHNAMURTI
Department of Meteorology, The Florida State University, Tallahassee, Florida

S. PATTNAIK
Indian Institute of Tropical Meteorology, Pune, India

A. SIMON
Department of Meteorology, The Florida State University, Tallahassee, Florida

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ABSTRACT

This paper provides an understanding of essential differences between developing and nondeveloping African easterly waves, which was a major goal of NAMMA, NASA’s field program in the eastern Atlantic, which functioned as an extension of the African Monsoon Multidisciplinary Analysis (AMMA) program during 2006.

Three NAMMA waves are studied in detail using FNL analysis: NAMMA wave 2, which developed into Tropical Storm Debby; NAMMA wave 7, which developed into Hurricane Helene; and NAMMA wave 4, which did not develop within the NAMMA domain. Diagnostic calculations are performed on the analyzed fields using energy transformation equations and the isentropic potential vorticity equation.

The results show that the two developing waves possess clear and robust positive barotropic energy conversion in conjunction with positive diabatic heating that includes a singular burst of heating at a particular time in the wave’s history. This positive barotropic energy conversion is facilitated in waves that have a northeast–southwest tilt to the trough axis and a wind maximum to the west of this axis. The nondeveloping wave is found to have the same singular burst of diabatic heating at one point in its history, but development of the wave does not occur due to negative barotropic energy conversion. Such conversion is facilitated by a northwest–southeast tilt to the trough axis and a wind maximum to the east of this axis.

The conclusions about wave development and nondevelopment formulated in this research are viewed as important and significant, but they require additional testing with detailed observational- and numerical-based studies.

1. Introduction

African easterly waves (AEWs) are known to play a significant role in the development of Atlantic tropical cyclones. Avila et al. (2000) found that on average 62% of all Atlantic tropical depressions develop from AEWs. From June through October of the 1996 season Avila et al. tracked 62 AEWs. Only 12 of these waves developed into tropical depressions, but all 12 of these became named systems. It is evident that a majority of AEWs never develop beyond the wave stage, but that the ones that do develop become a very important source of Atlantic tropical cyclones. The genesis of tropical cyclones from AEWs has been the subject of considerable interest and debate in recent years. There is great interest in understanding the essential difference(s) between developing and nondeveloping AEWs. This was a major scientific objective of the 2006 NAMMA project, which was NASA’s field program in the eastern Atlantic, functioning as an extension of the African Monsoon Multidisciplinary Analysis (AMMA) program, thus yielding the acronym NAMMA for NASA-AMMA.

To formulate the genesis problem, we may ask to what extent each of the following areas determines the
development or nondevelopment of AEWs: 1) the large-scale environment surrounding the wave, 2) the synoptic-scale wave structure and dynamics, 3) the convective and mesoscale processes and their interactions, and 4) the cloud microphysics, including the impacts of cloud condensation nuclei (CCN) in the form of Saharan dust.

The most studied large-scale environmental influence on tropical cyclogenesis from AEWs in recent years has been the Saharan air layer (SAL). The studies by Karyampudi and Carlson (1988), Karyampudi et al. (1999), and Karyampudi and Pierce (2002) taken together suggest that the SAL can be a positive influence on tropical cyclogenesis in some cases, but may render a negative influence in other cases. Dunion and Velden (2004) found that the SAL suppresses the intensification of tropical cyclones that it engulfs but that those tropical cyclones that emerge from its influence can rapidly develop into strong hurricanes. The negative influences on development include increased stability from the low-level temperature inversion, increased vertical wind shear induced by the midlevel African easterly jet (AEJ), and dry air intrusion into the tropical cyclone circulation.

Synoptic-scale wave structure and dynamics and their relationship to tropical cyclogenesis have been studied by many investigators. Studies by Thorncroft and Hodges (2001), Hopsch et al. (2007), Ross and Krishnamurti (2007), and others have shown that there are two tracks for AEW disturbances and that both tracks can be instrumental in tropical cyclone formation, although the southern track is normally more prolific than the northern track. A forthcoming composite study by Hopsch et al. (2010) based on 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) data for the period 1979–2001 highlights the structural differences between developing and nondeveloping AEWs. Dunkerton et al. (2009) defined the concept of a critical layer within the easterly wave, where the wind speed matches the phase speed of the wave, allowing air parcels to remain within the easterly wave, where the wind speed matches the phase speed of the wave, allowing air parcels to remain within the wave form where they are protected from potentially hostile environmental influences such as the SAL. Development occurs near the wave’s vorticity maximum at the intersection of the wave trough axis with the latitude location of the critical layer. It should be emphasized that this concept defines where development will occur.
if it occurs, but cannot state \textit{whether} development will occur or not.

In the area of convective and mesoscale processes, interest has focused on the role of mesoscale convective vortices (MCVs) and their interaction with so-called vortical hot towers. MCVs may occur anywhere in the troposphere but those that build upward from lower to midlevels are generally thought to be most related to tropical cyclogenesis. Multiple MCVs may occur, either formed in situ or transported from upstream, and mergers of potential vorticity centers associated with MCVs are common. On the convective scale, Hendricks and Montgomery (2004) and Montgomery et al. (2006), using numerical simulations, have described how vortical hot towers, small-scale cumulonimbus towers possessing intense cyclonic vorticity in their cores, are the preferred structures for transforming an MCV into a surface-concentrated warm-core tropical depression.

The role of cloud microphysics including the impacts of CCN in the form of Saharan dust has been much discussed within the context of tropical cyclogenesis and tropical storm intensification. Recent papers by Zhang et al. (2007, 2009) found no clear-cut relation between the dust and tropical cyclone intensity. This was because cause and effect relationships were complicated by nonlinear feedbacks between microphysical processes and storm dynamics.

Exploring essential difference(s) between developing and nondeveloping waves, primarily from the viewpoint of synoptic-scale structure and dynamics, is the focus of the current paper. This will be accomplished through the intensive study of three NAMMA waves: wave 2, which developed into Tropical Storm Debby within the NAMMA domain; wave 7, which developed into a depression within the NAMMA region and which later became Hurricane Helene beyond the NAMMA region; and wave 4, which remained a nondeveloping wave as it traversed the NAMMA domain. These waves will be examined through the use of National Centers for Environmental Prediction (NCEP) final (FNL) analyses on a 36-km grid over the region 0°–30°N, 10°E–45°W. This study does not address the potential roles of the following factors in the development of the three waves studied: the large-scale environment surrounding the wave including the SAL, the interactions of convective and mesoscale processes, or cloud microphysics including CCN in the form of African dust.

The concepts developed in this paper may prove to be useful in field experiments designed to study developing versus nondeveloping waves by deploying research aircraft. In these experiments it is necessary to be able to pick out in advance the waves that are expected to develop versus those that are not expected to develop. This paper describes a potentially useful synoptic-scale “signature” that can distinguish between these two types of waves. With reliable evidence that a wave is very likely to be a “developer,” the critical-layer concept of Dunkerton et al. (2009) could then be used to define where within the wave form the development is very likely to occur. In short, the results of the present study could answer the \textit{whether} question, and the critical-layer concept could answer the \textit{where} question, both critical pieces of information for the deployment of the research aircraft.
2. Methodology

a. Energetics calculations

The dynamical aspects of the waves will be treated using energetics calculations based on the work of Norquist et al. (1977). The focus will be on the baroclinic conversion of eddy available potential energy to eddy kinetic energy and the barotropic conversion of zonal kinetic energy to eddy kinetic energy. We seek to understand the role of these two important energy conversions in wave development.

The baroclinic energy conversion, $C_E$, and the barotropic energy conversion, $C_K$, respectively, are expressed as

$$C_E = -\frac{1}{g} \int_{100}^{p_r} R \frac{[\omega \cdot T]}{\rho} dp$$

and

$$C_K = -\frac{1}{g} \int_{100}^{p_r} [u'v'] \frac{\partial[u]}{\partial y} dp - \frac{1}{g} \int_{100}^{p_r} [u'^2] \frac{\partial[v]}{\partial y} dp$$

$$\quad - \frac{1}{g} \int_{100}^{p_r} [u'\omega'] \frac{\partial[u]}{\partial p} dp - \frac{1}{g} \int_{100}^{p_r} [v'\omega'] \frac{\partial[v]}{\partial p} dp.$$ (2)
In the above expressions, $\{\}$ represents a zonal average of the quantity () and $[\cdot]$ represents a meridional average of the zonal average (area mean). A prime indicates a deviation from a zonal average. When $CE$ is positive, this represents a gain of eddy kinetic energy at the expense of eddy available potential energy that occurs when warm air rises and cold air sinks. A positive value of $CK$ represents an increase in eddy kinetic energy at the expense of the zonal kinetic energy that occurs when the eddy momentum flux is down the mean momentum gradient. Norquist et al. (1977) found that the first term in Eq. (2) was one or more orders of magnitude larger than the remaining terms and this result was confirmed in the present study. Thus, only results from the calculation of this first term will be presented.

When one carries out the vertical integrations and the area means in Eqs. (1) and (2), one number is obtained representing the energy conversions over a large volume. It is impossible to access the energy conversions at the levels where the AEWs are most developed, as well as spatially within the waves. It was important in the current study to be able to visualize the energy conversions over a map area and at key levels in the vertical; for example, 850 hPa, where baroclinic conversions tend to be largest, and 600 hPa, where barotropic conversions are normally largest for AEWs. To accomplish this, the vertical integrals were removed, as were the area means. Thus, the expression used to map the 850-hPa baroclinic conversions and the 600-hPa barotropic conversions, respectively, over the 36-km horizontal grid becomes

$$-\frac{R}{P} \omega' T'$$  \hspace{1cm} (3)

$$-u' \nu' \frac{\partial[u]}{\partial y}.$$ \hspace{1cm} (4)

### b. Diabatic calculations

The Ertel isentropic potential vorticity (IPV) equation as utilized by Krishnamurti et al. (2000) is the basis for the diabatic calculations performed in this study. This equation has the form

$$\frac{\partial}{\partial t} \zeta_{p\theta} = -V \cdot \nabla \zeta_{p\theta} \frac{\partial \zeta_{p\theta}}{\partial t} + \xi_{p\theta} \frac{\partial}{\partial \theta} \frac{\partial}{\partial t}$$

$$+ \left[ V \frac{\partial}{\partial t} \left( \frac{\partial (V \times k)}{\partial \theta} \right) \right] g \frac{\partial \theta}{\partial p} - V \cdot (F \times k) \times \frac{\partial}{\partial p}.$$ \hspace{1cm} (5)

The left-hand side of the equation represents the local rate of change of the potential vorticity on an isentropic surface (IPV). This change is due to five processes represented by the five terms on the right-hand side of the equation: horizontal advection, vertical advection, vertical differential of heating, horizontal differential of heating, and friction. The friction term is not included in the calculations of this study. The total diabatic heating is considered to be the sum of terms 2–4 on the right-hand side of the equation, i.e., vertical advection, vertical differential of heating, and horizontal differential.
of heating). The vertical advection term is included as a diabatic heating term because if $\frac{d\theta}{dt}$ is positive (negative), this would represent diabatic heating (cooling). All the terms were calculated on pressure surfaces, after transform equations were used to convert from the $\theta$ to the $p$ coordinate system. This was necessary because all variables from the FNL analyses were available at constant pressure levels. These pressure levels were distributed from 1000 to 100 hPa, with an interval of 50 hPa.

It should be noted that the units for the terms on the right-hand side of Eq. (5) are not actual heating units. But since terms 2–4 on the right-hand side of the equation represent processes that change the IPV through diabatic heating, these terms, and only these terms, will be referred to as “diabatic heating” terms.

3. Results

a. NAMMA wave 2: Tropical Storm Debby

This system was studied at 6-hourly intervals beginning at 0000 UTC 20 August 2006 through 0000 UTC 24 August 2006 using the FNL analyses. The National Hurricane Center (NHC) classified the system as a wave until 1200 UTC on 21 August, when it became a tropical
depression. It remained a depression until 1200 UTC on 23 August, when it became Tropical Storm Debby. Figure 1 shows the wind flow at 700 hPa at four times: 1200 UTC 20 August (wave), 1200 UTC 21 August (just formed depression), 1200 UTC 22 August (depression), and 1200 UTC 23 August (tropical storm). Note the northeast–southwest-tilted wave trough line in Figs. 1a and 1b with a distinct wind maximum ahead of the trough line, and the depression and storm center locations (marked with an X), respectively, in Figs. 1c and 1d.

1) ENERGY CONVERSIONS

Figure 2 demonstrates very clearly that positive barotropic energy conversion (conversion of zonal to eddy kinetic energy) was a very prominent feature of the dynamics of the developing NAMMA wave 2. Note the designations of “wave,” “depression,” and “storm” in Fig. 2. In Fig. 2a there is a strong positive energy conversion to the south of the AEJ in the wave stage, with a declining conversion in the depression stage, and a negligible conversion in the tropical storm stage. An unanticipated, and somewhat surprising, result is that there is a positive conversion to the north of the AEJ (positive south wind), and hence the wind speed values on the ordinate are positive, but it is understood that these values represent easterly winds in this region.

Next, we will interpret the energy conversion results shown in Fig. 2 using maps of $u'$ and $v'$, along with meridional profiles of $[u]$ in conjunction with expression (4) above. Figure 3, based on FNL analysis at 1200 UTC 21 August 2006 (see timeline in Fig. 2), shows a very prominent region of positive barotropic energy conversion to the east of the northeast–southwest-tilted trough. This is in a region where $u'$ is positive (south wind), $u'$ is positive (minimum in easterly wind component), and $\partial[u]/\partial y$ is negative (negative $[u]$ increasing northward). With the minus sign in front of expression (4), this produces a positive energy conversion. A secondary region of positive barotropic energy conversion exists well to the west of the wave trough line where an easterly wind maximum (negative $u'$) combines with northerly winds (negative $v'$) again in a region where $\partial[u]/\partial y$ is negative. This dipole pattern of positive energy conversion was seen repeatedly in this study. Another feature mentioned in connection with Fig. 2, the positive barotropic energy conversion to the north of the AEJ, can also be discerned in Fig. 3, although the signal is much stronger at later synoptic times. To reduce the number of figures, we will use Fig. 3 to demonstrate how a positive energy conversion can occur to the north of the jet. In this figure note the positive conversion near 17°N and 18°W. From the meridional profile of $[u]$ (Fig. 3, bottom right), it is evident that this region of energy conversion is to the north.
of the easterly wind maximum near 14°N. Thus, the sign of $\partial u/\partial y$ is positive, while $u'$ is positive (south wind) and $u'$ is negative (maximum in the easterly wind component). With the minus sign in front of expression (4), this produces a positive energy conversion. Thus, because of the particular configuration of the wind field to the north and south of the jet, the zonal kinetic energy of the jet is being converted into eddy kinetic energy of the wave.

Another possible source of wave energy is the conversion of eddy available potential energy to eddy kinetic energy, or the baroclinic energy conversion process represented by expression (3). Eddy kinetic energy is produced when warm air rises ($\omega' < 0$, $T' > 0$) and/or cold air sinks ($\omega' > 0$, $T' < 0$). Figure 4 shows this energy conversion based on FNL analyses for NAMMA developing wave 2 (Debby) at 850 hPa, where this conversion tends to be largest, over the same period as for the barotropic energy conversions at 650 hPa shown in Fig. 2 (i.e., 0000 UTC 20 August–0000 UTC 24 August 2006). In contrast to the barotropic energy conversions, which were universally positive for this developing wave, the baroclinic conversions are characterized by regions of both positive and negative conversion across the system as it transitions from wave to depression to storm stage. Negative conversions dominate positive conversions throughout the period of study. Positive
conversions remain nearly zero until the late depression/early storm stage, when they become larger, but these larger values are countered by larger negative values. The message from Fig. 4 seems to be that wave energy (eddy kinetic energy) was not able to grow in this developing wave due to baroclinic conversions because positive conversions tend to be countered by negative conversions, and the positive values are very small, for the most part, allowing negative conversion values to dominate.

An example of the inhibiting effects on the development of the baroclinic conversions is presented in Fig. 5 based on FNL analysis, where maps of $T'$, $\omega'$, $\omega'T'$, and the baroclinic conversion term (3) are shown for 850 hPa at 0000 UTC 21 August 2006 when NAMMA wave 2 was in the wave stage, just as the wave becomes a depression according to NHC classification (see timeline in Fig. 4). It is immediately clear that the baroclinic energy conversion process is acting as a brake on the development of this wave, given the impressive bull’s-eye of negative conversion located at the

\[ \text{FIG. 8. (a) Isentropic potential vorticity (10}^{-8} \text{ kg}^{-1} \text{ m}^2 \text{ s}^{-1} \text{ K}) at 600 \text{ hPa based on FNL analysis at 0000 UTC 21 Aug 2006. (b) Total diabatic heating [sum of second, third, and fourth terms on right-hand side of Eq. (5); }10^{-12} \text{ kg}^{-1} \text{ m}^2 \text{ s}^{-2} \text{ K}] at 600 \text{ hPa based on FNL analysis at 0000 UTC 21 Aug 2006 when NAMMA wave 2 was in the wave stage (see timeline in Fig. 6). (c) Same as in (a) but at 1200 UTC 21 Aug 2006. (d) Same as in (b) but at 1200 UTC 21 Aug 2006, just as the wave becomes a depression according to NHC (see timeline in Fig. 6). The wave trough axis is indicated by a northeast–southwest-sloping boldface line. Positive values are indicated by solid contour lines and negative values are indicated by dashed contour lines.} \]
center of the 850-hPa vortex just off the West African coast. Surrounding this negative conversion is a ring of much weaker positive conversion. The negative conversion is produced by rising cool air (note negative $\omega'$ in bottom-left panel, negative $T'$ in top-right panel, and positive $\omega'T'$ in bottom-right panel in Fig. 5). With a minus sign in front of the expression for baroclinic conversion in (3), the conversion is negative, or eddy kinetic energy is being converted into eddy available potential energy. The ring of weak positive conversion surrounding the negative conversion results from a ring of sinking cool air (positive $\omega'$ in bottom-left panel in the presence of negative $T'$ in the top-right panel in Fig. 5).

It is evident that the main contributor to the negative baroclinic conversion is the $T'$ parameter. The rising air along the trough axis and within the cyclonic vortex (Fig. 5, bottom left) is cooler in relation to the surrounding air (Fig. 5, top right). This rising, relatively cooler, air produces the negative baroclinic energy conversion. But this is also a region of active convection (to be shown later). So why would this not be a relatively warmer region, due to convective heating, which would then produce, along with rising motion, a positive baroclinic conversion? The answer lies in the fact that the 36-km grid is on a scale larger than the scale of the convective towers. On this larger scale, the cloudy, rainy area is cooler than the surroundings, but on the smaller scale we would expect to see relatively warmer air in the convective towers as compared to the region outside these towers. We would, therefore, expect a positive energy conversion on the scale of the convective towers, whereas we are seeing a negative conversion on the larger scale. Looking at this issue from another perspective, suppose that the calculations were done on a 1-km grid that resolved both the rising warmer air in the relatively smaller regions occupied by convective towers and the sinking cooler air in the relatively larger regions occupied by saturated downdrafts between the towers. Then, if these calculations were averaged and expressed on a 36-km grid, we would expect to get the same negative energy conversion results presented here. In other words, the effects on the scale of the 36-km grid represent an average of all the effects occurring on the scale of the 1-km grid. A similar negative baroclinic energy conversion will be seen in the two remaining waves, to be discussed later. This discussion drives home...
the point that the present study is focused on a scale larger than the cloud scale.

2) DIABATIC HEATING EFFECTS

The diabatic heating effects shown here are based on the sum of three terms on the right-hand side of the IPV Eq. (5): the second term, which represents the vertical advection of IPV; the third term, which represents the vertical differential of heating; and the fourth term, which represents the horizontal differential of heating. Figure 6 shows this diabatic heating averaged over the 800–400-hPa layer for the period 0000 UTC 20 August 2006–0000 UTC 24 August 2006 based on FNL analyses. A very prominent “burst” of heating is seen at 0000 UTC 21 August while the system is still in the wave stage. The diabatic heating gradually decreases after this time as the system develops into a depression and then into Tropical Storm Debby. The Meteosat 10.5-μm infrared satellite images in Fig. 7 provide visual confirmation of a rapid development of organized convection coincident with the “burst” of heating shown in Fig. 6. Figures 7a–f correspond to the first five plotted points in Fig. 6. The satellite imagery adds credibility to the calculations of the diabatic heating and offers the hope that forecasters might be able to use such rapid development of organized convection as a proxy for quantitative determinations of diabatic heating, which are not readily available in the forecast environment.

A mapping of the diabatic heating at 600 hPa is shown in Fig. 8 based on the FNL analysis at 0000 UTC 21 August 2006, when the system is in the wave stage (at the time of the peak in the burst of heating), and at 1200 UTC 21 August 2006, when the system had just become a depression (see timeline in Fig. 6). Figures 8a and 8c show the IPV at the two times, and Figs. 8b and 8d show the total diabatic heating at the two times. In Fig. 8b the burst of heating mentioned above is seen as a bull’s-eye pattern centered on the wave trough axis, with a maximum value of 240 units. At this time the IPV in Fig. 8a has a maximum value of 100 units in the wave trough axis. By 12 h later, the IPV has grown to a maximum value of 160 units in the wave trough axis, while the diabatic heating maximum, still centered in the trough axis, has diminished to 40 units. It is reasonable to conclude that the wave’s development, as measured by a sharp increase in IPV, is due in part to the very strong heating in the wave trough axis during this period.

It is now very important to review an earlier result discussed in conjunction with Figs. 2 and 3. In those figures it was seen that the barotropic energy conversion was also a maximum at these critical times in the wave’s development into a depression. For example, note Fig. 2a where the barotropic conversion was seen to be a maximum during the times being considered here (0000 UTC 21 August and 1200 UTC 21 August). Note Fig. 3 (top left), which shows a very prominent maximum in the barotropic energy conversion just upstream of the trough axis. Figure 3 is for 1200 UTC 21 August when the system had just been classified as a depression.

In summary, the results presented here for NAMMA wave 2 indicate that the wave was able to develop due
to robust contributions from positive barotropic energy conversions in conjunction with robust diabatic heating. Overall, the baroclinic energy conversions were diagnosed as an inhibiting effect on wave development.

b. NAMMA wave 7: Hurricane Helene

The system was studied using FNL analyses at 6-hourly intervals beginning at 1200 UTC 10 September 2006 through 1200 UTC 14 September 2006. NHC classified this system as a wave until 1200 UTC 12 September, when it became a tropical depression. It became Tropical Storm Helene at 0000 UTC 14 September, and Hurricane Helene at 1200 UTC 16 September, well beyond the NAMMA domain. This system is depicted in Fig. 9 using 700-hPa wind flow at four times: 1200 UTC 11 September (wave), 1200 UTC 12 September (depression), 1200 UTC 13 September (depression), and 1200 UTC 14 September (tropical storm). As with the previously discussed wave that developed into Tropical Storm Debby, this developing wave also shows the same northeast–southwest-tilted wave trough axis with the wind maximum ahead of the trough line. Even after the system becomes a
tropical depression (Figs. 9b and 9c) and a tropical storm (Fig. 9d), this same tilt and wind maximum structure are maintained.

1) ENERGY CONVERSIONS

Figure 10 shows clearly that positive barotropic energy conversion was an important aspect of the dynamics of developing NAMMA wave 7, just as it was for developing NAMMA wave 2. Figure 10 shows that barotropic conversion was important throughout the period of study of this system and that the conversion was larger in the depression stage than in the wave stage. In contrast, for NAMMA wave 2 the barotropic conversion was larger in the wave stage.

The energy conversion results depicted in Fig. 10 will now be interpreted using maps of the parameters in the barotropic conversion expression (4) above. Figure 11, based on FNL analysis at 0600 UTC 11 September 2006 (see timeline in Fig. 10), shows a prominent region of positive barotropic energy conversion to the east of the northeast–southwest-tilted wave trough. This is in a region of positive $\nu'$ (south wind), positive $u'$ (minimum in easterly wind component), and negative $\partial[u]/\partial y$ (negative $u$ increasing northward). With the minus sign in front of expression (4), this produces a positive energy conversion. There is a more expansive region of positive barotropic conversion to the west of the wave trough axis where an easterly wind maximum (negative $u'$) combines with northerly winds (negative $\nu'$) again in a region where $\partial[u]/\partial y$ is negative. All of these diagnoses pertaining to the production of positive barotropic energy conversions are identical to those presented in section 3a(1) for developing NAMMA wave 2, including the dipole nature of the conversion pattern.

As indicated in Fig. 10, positive barotropic energy conversion was important throughout the period of study of this system. Detailed interpretations of this conversion, as presented in Fig. 11, were conducted for 1200 UTC 12 September 2006, when the system became a depression, and for 1200 UTC 14 September 2006, after the system became Tropical Storm Helene (see timeline in Fig. 10). In both cases the patterns were found to be identical to those shown in Fig. 11 including the dipole nature of the positive conversion pattern. These additional results will not be shown here for the sake of brevity.

Next, we will consider the importance of baroclinic energy conversion, as represented by expression (3) above, for the dynamics of NAMMA wave 7. Figure 12 shows this conversion at 850 hPa over the same period as for the barotropic energy conversion at 650 hPa shown in Fig. 10 (i.e., 1200 UTC 10 September–1200 UTC 14 September 2006). As with the previous discussion of developing NAMMA wave 2, the baroclinic conversions for this developing wave demonstrate regions of both positive and negative conversion across the system as it evolves from wave to depression to storm stage. There is
a definite positive maximum at 0600 UTC 11 September and 1200 UTC 11 September while the system is still a wave, but this is more than offset by a marked negative maximum at the same times. Beyond those times, the positive conversion is unremarkable and for the most part is more than offset by negative conversion. The message from Fig. 12 seems to be the same as the message from Fig. 4 for NAMMA wave 2; that is, the baroclinic conversion cannot be viewed as a dynamical factor that would increase the eddy kinetic energy of the wave because positive energy conversions tend to be small and when they become large they are offset by large negative conversions. In fact, for many of the times considered, the negative conversions are dominant, indicating that the baroclinic conversion may act primarily as a braking action on wave growth.

2) DIABATIC HEATING EFFECTS

The total diabatic heating effects for NAMMA wave 7 are shown in Fig. 13 for the period 1200 UTC 10 September 2006–1200 UTC 14 September 2006.
based on FNL analysis. Total heating is defined as the sum of the second, third, and fourth terms on the right-hand side of Eq. (5). Figure 13a presents the mean heating for the layer 800–400 hPa, while Fig. 13b shows the heating at each level in the layer (800, 600, and 400 hPa). There is a remarkable similarity between Figs. 13a and 6 for NAMMA wave 2. Both show a singular burst of heating during the wave stage of the system. In Fig. 13a, the heating quickly rises to a maximum at 0600 UTC 11 September and at 1200 UTC 11 September, and just as quickly dissipates beyond these times in the depression and storm stages. It is interesting to note that this maximum burst in heating occurs at all three levels defining the 800–400-hPa layer (Fig. 13b).

The Meteosat water vapor images (6.2 μm) in Figs. 14a–c provide visual confirmation of a rapid development of organized convection, followed by a demise of that convection in Fig. 14d. These panels in Fig. 14 correspond to plotted points 3, 4, 5, and 6, respectively, in Fig. 13a (0000 UTC 11 September–1800 UTC 11 September), which depict the rapid development of the burst of heating followed by an equally dramatic decay of that heating. As with the satellite imagery for NAMMA wave 2 (the Debby wave) shown in Fig. 7, the satellite imagery in Fig. 14 conforms very nicely to the calculated diabatic heating and adds credibility to those calculations.

Fig. 14. Meteosat water vapor satellite images (6.2 μm) for NAMMA wave 7 (Helene wave): (a) 0000 UTC 11 Sep, (b) 0600 UTC 11 Sep, (c) 1200 UTC 11 Sep, and (d) 1800 UTC 11 Sep 2006. The system is in the wave stage in all depictions, and the maximum heating seen in Fig. 13 occurs with the system as seen in (b) and (c).

A mapping of the terms in the Ertel IPV Eq. (5) is shown in Fig. 15 based on FNL analysis for the 600-hPa level at 0600 UTC 11 September 2006, which is the time of the peak burst of heating seen in Fig. 13. Figure 15a shows the northeast–southwest-tilted wave trough axis with an IPV maximum of 120 units centered in this axis. Figure 15c depicts a horizontal advection pattern that is consistent with the positioning of the vorticity center, with positive (negative) advection downstream (upstream) from the vorticity center. Total diabatic heating is shown in Fig. 15b, and it is dominated by a very prominent center of positive heating (240 units) located near the wave trough axis. Finally, the total rate of change of IPV represented by the sum of first four terms on the right-hand side of Eq. (5) is depicted in Fig. 15d. This pattern looks almost exactly like the total heating pattern in Fig. 15b, indicating that diabatic heating is far more important than are horizontal advective processes in a dynamical understanding of the development of this wave at this time, as measured by IPV.

It is important to recall that positive barotropic energy conversion was also an important factor in the development of this wave. Figure 11 (top left) shows a dipole pattern of positive barotropic energy conversion at 0600 UTC 11 September 2006, the same time as the burst of diabatic heating was occurring, as just discussed.
To summarize, for the two most important developing systems to be studied during the NAMMA project (Debby and Helene), the analysis presented here indicates that the waves were able to develop due to robust contributions from positive barotropic energy conversion coupled with robust diabatic heating. In both cases the diabatic heating calculations were supported and confirmed by satellite imagery of organized convection. For both systems, the diagnosis presented here indicates that baroclinic conversion was, overall, an inhibiting effect on wave development. The findings in sections 3a and 3b above are remarkably similar, adding credibility to these statements. We will next consider a non-developing wave, which will be significant, both in its similarity to and in its difference from, the foregoing developing waves.
The fourth wave to be studied in the NAMMA project was a wave that did not develop in its transit across the NAMMA domain. There is a possibility that the wave may have eventually been involved in some way in the development of Hurricane Florence, but this development occurred far to the west over the Atlantic, with the depression forming at 39.4°W, the tropical storm forming at 46.1°W, and the hurricane forming at 65.3°W according to the NHC. In contrast, NAMMA wave 2 formed into a depression at 21.7°W and into Tropical Storm Debby at 28.1°W, and NAMMA wave 7 became a depression at 22.0°W and Tropical Storm Helene at 31.9°W. Nondeveloping wave 4 was studied using FNL analyses at 6-hourly intervals beginning at 1200 UTC 29 August 2006 through 1200 UTC 2 September 2006.

Figure 16 shows the wind flow at 700 hPa for the period 1200 UTC 29 Aug–1200 UTC 1 Sep 2006 for nondeveloping NAMMA wave 4. The wave trough axis is indicated by a boldface line in all panels. Note that the line near 21°N, 5°W in all panels is a geographical boundary and not a wave trough line.

c. NAMMA nondeveloping wave 4

The fourth wave to be studied in the NAMMA project was a wave that did not develop in its transit across the NAMMA domain. There is a possibility that the wave may have eventually been involved in some way in the development of Hurricane Florence, but this development occurred far to the west over the Atlantic, with the depression forming at 39.4°W, the tropical storm forming at 46.1°W, and the hurricane forming at 65.3°W according to the NHC. In contrast, NAMMA wave 2 formed into a depression at 21.7°W and into Tropical Storm Debby at 28.1°W, and NAMMA wave 7 became a depression at 22.0°W and Tropical Storm Helene at 31.9°W. Nondeveloping wave 4 was studied using FNL analyses at 6-hourly intervals beginning at 1200 UTC 29 August 2006 through 1200 UTC 2 September 2006. Figure 16 shows the wind flow at 700 hPa at four times: 1200 UTC 29 August, 1200 UTC 30 August, 1200 UTC 31 August, and 1200 UTC 1 September. Note that the orientation of the wave trough axis and the placement of the wind maximum are in sharp contrast to the previous two waves studied here, that is, the trough axis is oriented northwest–southeast (rather than northeast–southwest) and the wind maximum is located behind (rather than in front of) the trough axis.

1) ENERGY CONVERSIONS

Figure 17 demonstrates definitively that negative barotropic energy conversion (conversion of eddy kinetic energy to zonal kinetic energy) was a very prominent feature of the dynamics of this nondeveloping NAMMA wave 4. This “hand off” of kinetic energy from the wave to the zonal flow is, of course, consistent with the wave’s lack of development. For the first four times depicted, which would correspond to the period 1200 UTC 29 August–0600 UTC 30 August, there is both negative and positive barotropic conversion. This positive conversion occurs before the wave takes on the classic configuration that favors only negative conversion, that is, a wind maximum behind a northwest–southeast-tilted wave trough axis. Referring to Fig. 16a, it can be seen that the wave at these earlier times has the required tilt to the trough axis to promote only negative conversion, but the wind maximum is still extending from east of the trough.
axis, around the top of the trough axis, and into a position on the west side of that axis. This wind maximum to the west side of the trough axis allows for positive conversion to occur in that location, as will be demonstrated in the discussion of Fig. 18 below. However, beyond these first few times, negative barotropic conversion takes over as the wave evolves into the classic structure supporting that conversion, in terms of the tilt of the trough axis and the placement of the wind maximum (see Figs. 16b–d).

A very important feature in Fig. 17 is that the maximum value of the zonally averaged $u$-wind component increases with time throughout most of the period of study of this wave, a result that is consistent with, and supportive of, the conclusion that eddy kinetic energy of the nondeveloping wave is being converted into zonal kinetic energy of the AEJ. Wind speed values are shown as positive but it is understood that the winds are easterly in this region (AEJ).

Figures 18 and 19 will be used to interpret the barotropic energy conversions shown in Fig. 17. These figures provide the necessary parameters ($u'$, $v'$, meridional profile of $u$) to evaluate expression (4) above. Figure 18, based on FNL analysis at 0000 UTC 30 August 2006 (see timeline in Fig. 17), depicts negative barotropic energy conversion to the east of the northwest–southeast-tilted wave trough axis. This occurs with the classic setup for such conversion, with a negative $u'$ (maximum in easterly wind component), positive $v'$ (south wind), and negative $\partial[u]/\partial y$ (negative $[u]$ increasing northward). However, the maximum in the easterly wind component ($u' < 0$) extends into the region to the west of the wave trough axis, where it combines with northerly winds ($v' < 0$) and negative $\partial[u]/\partial y$, to produce the classic setup for positive barotropic conversion. However, by 1200 UTC 30 August 2006, as depicted in Fig. 19 using FNL analysis (see timeline in Fig. 17), the wave has undergone a transformation in wind structure that now favors only negative barotropic energy conversion. Note the prominent center of negative conversion to the east of the wave trough axis, with a disappearance of the positive conversion that had been seen to the west of the trough axis in Fig. 18. This transformation in energy conversion is due exclusively to the easterly wind maximum now being located only on the east side of the wave trough axis. This wind structure persists for the remainder of NAMMA wave 4’s traverse across the NAMMA domain (see Fig. 16) and produces the negative barotropic energy conversion seen for all remaining times in Fig. 17a.

Next, we consider baroclinic energy conversion for this nondeveloping wave. Figure 20 depicts this conversion at 850 hPa over the same period as for the barotropic energy conversion at 650 hPa shown in Fig. 17 (i.e., 1200 UTC 29 August–1200 UTC 2 September 2006). There are positive and negative conversions occurring throughout the period of study. There is once again, as in the two previous waves considered, an offsetting tendency in these conversions; that is, when the positive conversion gets large (small), the negative conversion tends to get large (small). Overall, it appears
that negative conversions dominate somewhat. The conclusion is that the baroclinic conversion is not indicated unambiguously as a dynamical factor that would either strengthen or weaken this wave because of the offsetting positive and negative conversion values at a given time.

2) DIABATIC HEATING EFFECTS

Total diabatic heating effects for nondeveloping NAMMA wave 4 are shown in Fig. 21 for the period 1200 UTC 29 August–1200 UTC 2 September 2006 based on FNL analysis. As in the two previous cases, total diabatic heating is defined as the sum of the second, third, and fourth terms on the right-hand side of Eq. (5). Figure 21a depicts the mean heating for the 800–400-hPa layer, while Fig. 21b depicts the heating at each level in the layer (800, 600, and 400 hPa). Remarkably, just as in the first two cases, there is a dramatic and singular burst of heating, at 0000 UTC 30 August and 0600 UTC 30 August. Compare Fig. 21a with Figs. 6 and 13a. After this brief burst, the diabatic heating gradually tapers off for the remainder of the timeline. This burst of heating is

\[ E = \frac{10^{-2}}{W \cdot kg^{-1}} \]
prominent throughout the layer, since Fig. 21b shows this peak in heating occurring at all three levels defining the layer.

A mapping of the diabatic heating at 600 hPa is shown in Fig. 22 based on FNL analysis for 0000 UTC 30 August 2006 at the time of the burst in heating, and for 1200 UTC 30 August 2006 just after the burst in heating (see timeline in Fig. 21). Figures 22a and 22c show the IPV at the two times, and Figs. 22b and 22d show the total diabatic heating at the two times. In Fig. 22b the burst of heating mentioned above is seen as a bull’s-eye pattern located to the west of the northwest–southeast-tilted wave trough axis for this nondeveloping wave, with a maximum value of 300 units. This is the largest heating seen in the three cases studied in this research. The maximum value of the IPV at this time (Fig. 22a) is 100 units, with the center positioned near the trough axis. By 12 h later (1200 UTC 30 August 2006), the diabatic heating has diminished drastically to a maximum of 80 units in two centers located to the west of the trough axis (Fig. 22d), and the maximum IPV has decreased to 80 units, now in two centers, one on either
side of the trough axis. Clearly, the wave is not developing as evidenced by the breakdown of the IPV into two weakened centers. Now refer to the barotropic energy conversion patterns for the wave at these two critical times in Figs. 18 and 19. At 0000 UTC 30 August 2006 (Fig. 18), even though the maximum diabatic heating is occurring at this time (Fig. 22b), the wave’s barotropic energy conversion pattern is ambiguous at best with a positive center west of the trough axis and a negative center east of the trough axis. This is not the strong and unambiguous positive conversion pattern seen with the two previous cases of developing waves (Fig. 3 for Debby and Fig. 11 for Helene). By 1200 UTC 30 August 2006 (Fig. 19), the wave’s barotropic energy conversion pattern is now clearly and strongly negative, at the same time that the heating has markedly decreased (Fig. 22d). This trend in the wave’s energy conversion and diabatic heating patterns is clearly not one that is favorable for development, and the wave continues to translate westward after this critical period as a nondeveloping wave (see Figs. 16c and 16d).

In summary, the results presented here for NAMMA nondeveloping wave 4 strongly suggest that the wave was not able to develop because, even though the wave exhibited extremely large diabatic heating (the largest of the three cases studied here) at a critical time in its life history, this occurred within the context of a dynamical pattern characterized by either ambiguous or strongly negative barotropic energy conversion. Baroclinic energy conversion was diagnosed as an ambiguous dynamical factor in the development or nondevelopment of this wave due to a pattern of offsetting positive and negative conversions.

4. Generalization of results

From all of the foregoing analysis and discussion, we may draw a general proposition that requires broad testing beyond the bounds of this current study. We have seen that the two waves that developed within the NAMMA domain, wave 2 (Debby) and wave 7 (Helene), possessed a northeast–southwest tilt to the wave trough axis with a wind maximum ahead of that axis, and that the one nondeveloping wave studied here possessed a northwest–southeast tilt to the wave trough axis with the wind maximum behind that axis. Our analysis has shown that the wind and wave trough structure, in the first instance, promotes positive barotropic energy conversion leading to wave development, and, in the latter instance, promotes negative barotropic energy conversion leading to the nondevelopment of the wave. Obviously, all of the NAMMA waves should be subjected to detailed observation-based and forecast-based analysis to assess the generality of this proposition. But as a quick check of this principle, the seven waves of NAMMA can be examined using 700-hPa wind flow to define the trough axis tilt and location of the wind maximum in relation to the trough axis. This information
can then be compared to a specification of whether each wave developed or not. Two waves developed within the NAMMA domain (defined here as extending to 45°W) and five waves did not develop within that domain.

Figures 23b and 23g show that the two developing waves are NAMMA wave 2 (Debby) and NAMMA wave 7 (Helene), respectively. Both show the northeast–southwest tilt to the trough axis with the wind maximum to the west of that axis, as extensively discussed above. Our proposition holds so far. Now consider the non-developing waves. NAMMA wave 1 in Fig. 23a has the expected northwest–southeast tilt but it appears that a wind maximum can be located on either side of the trough axis. (This wave may have been involved in the formation of Tropical Storm Ernesto but this was not until 65.8°W.) NAMMA wave 3 in Fig. 23c has the prescribed northwest–southeast tilt to the trough axis but again a wind maximum can be identified on either side of this axis. NAMMA wave 4 in Fig. 23d was extensively discussed above, and it does show the northwest–southeast tilt to the trough axis with a wind maximum to the east of that axis. (This wave may have been involved in the formation of Tropical Storm Florence but this was not until 46.1°W.) NAMMA wave 5 in Fig. 23e has the signature of a developing wave according to our

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**FIG. 21.** (a) Maximum positive mean diabatic heating \((10^{-12} \text{ kg}^{-1} \text{ m}^2 \text{ s}^{-2} \text{ K})\) for the 800–400-hPa layer (mean of heating at the levels of 800, 600, and 400 hPa) based on FNL analysis at 6-hourly intervals from 1200 UTC 29 Aug to 1200 UTC 2 Sep 2006. (b) Same as in (a) but heating is shown at each of the levels at 800, 600, and 400 hPa that compose the mean in (a). In both instances the maximum mean positive diabatic heating values are based on inspection of maps of diabatic heating in the vicinity of the non-developing system.
proposition, with a definite northeast–southwest tilt to the trough axis and a wind maximum to the west of that axis. It looks much like the developing waves in Figs. 23b and 23g. So why did it not develop quickly within the NAMMA domain, waiting until 56.3°W to become Tropical Storm Gordon? According to NHC this wave did not develop for a week after exiting the African coast due to strong vertical wind shear. It appears that our proposition would have been verified had it not been for this wind shear. Another factor could have been a negative influence from the SAL, but this was not mentioned in the NHC narrative. Finally, NAMMA wave 6 in Fig. 23f verifies our proposition with a northwest–southeast-sloping boldface line. Positive values are indicated by solid contour lines and negative values are indicated by dashed contour lines.

![Fig. 22](image-url)

FIG. 22. (a) Isentropic potential vorticity ($10^{-8}$ kg$^{-1}$ m$^2$ s$^{-1}$ K) at 600 hPa based on FNL analysis at 0000 UTC 30 Aug 2006. (b) Total diabatic heating [sum of second, third, and fourth terms on right-hand side of Eq. (5); $10^{-12}$ kg$^{-1}$ m$^2$ s$^{-2}$ K] at 600 hPa based on FNL analysis at 0000 UTC 30 Aug 2006 (see timeline in Fig. 21). (c) Same as in (a) but at 1200 UTC 30 Aug 2006. (d) Same as in (b) but at 1200 UTC 30 Aug 2006 (see timeline in Fig. 21). The wave trough axis for this nondeveloping wave is indicated by a northwest–southeast-sloping boldface line. Positive values are indicated by solid contour lines and negative values are indicated by dashed contour lines.
The seven waves of NAMMA depicted with 700-hPa wind vectors 1 day after the NHC-defined date of passage across the west coast of Africa: (a)–(g) waves 1–7. Developing waves are (b) Debby and (g) Helene. All others are nondeveloping within the NAMMA domain [i.e., (a) and (c)–(f)].
5. Concluding remarks

This research has addressed a major scientific objective of the NAMMA project, which was to understand the essential difference(s) between developing and non-developing AEWs. Three NAMMA waves were studied extensively using FNL analysis: NAMMA developing wave 2 (Debby), NAMMA developing wave 7 (Helene), and NAMMA nondeveloping wave 4. It has been found that the two developing waves possessed robust positive barotropic energy conversion produced by a northeast-southwest-tilted trough axis and wind maximum ahead of this axis. A singular and impressive burst of diabatic heating also occurred in these two cases, supported by satellite imagery showing concurrent rapid development of organized convection. The nondeveloping wave, remarkably, exhibited the same singular and impressive burst of diabatic heating but did not develop due to negative barotropic energy conversion produced by a northwest-southeast-tilted trough axis and wind maximum behind that axis.

The conclusion from this research, which requires further testing, is that strong diabatic heating is a necessary but not sufficient condition for wave development. What is needed in conjunction with this heating is robust positive barotropic energy conversion. Together these two factors constitute the necessary and sufficient conditions for development, assuming that the large-scale environment within which the wave is embedded is not hostile. Another conclusion was that baroclinic energy conversion was not a clear and definitive factor that could explain either the development or nondevelopment of the waves studied.

A quick accounting of all seven NAMMA waves using 700-hPa wind flow gave a favorable confirmation of the conclusions concerning the role and nature of barotropic energy conversion in wave development, with a few exceptions. As previously stated, detailed studies of additional waves using analysis and model output is needed to confirm or negate the viewpoints, propositions, and conclusions presented here. It would be of particular interest to determine how well the operational and/or research models used to forecast tropical cyclogenesis are able to capture the processes that are shown here to be important for genesis.

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