

## On African easterly waves that impacted two tropical cyclones in 2004

Melinda S. Peng,<sup>1</sup> Bing Fu,<sup>2</sup> Timothy F. Hogan,<sup>1</sup> and Tim Li<sup>2,3</sup>

Received 17 February 2005; revised 20 March 2006; accepted 1 May 2006; published 3 June 2006.

[1] The U. S. Navy Operational Global Atmospheric Prediction System (NOGAPS) daily analysis fields are used to study the African easterly waves to show how they impacted two tropical cyclones. Danielle and Earl (2004) formed approximately at the same time in the Atlantic. A three to eight day band-pass filter is applied to the daily global analysis fields to reveal the characteristics of the African easterly waves related to the two cyclones. The time-filtered 850 mb vorticity shows that African easterly waves reaching the formation locations of Danielle and Earl on and about 14 August 2004 bear similar structures, indicating a unique situation in which one train of the easterly wave is responsible for the genesis of two tropical cyclones located one-wavelength apart. In addition, using piecewise time-filtered analysis for different latitude bands, it is demonstrated that the movements of both cyclones are significantly modulated by the propagation of the easterly waves, even during Danielle's poleward movement for more than ten-degrees latitude. **Citation:** Peng, M. S., B. Fu, T. F. Hogan, and T. Li (2006), On African easterly waves that impacted two tropical cyclones in 2004, *Geophys. Res. Lett.*, 33, L11807, doi:10.1029/2006GL026038.

### 1. Introduction

[2] African easterly waves (AEWs) have been identified as the main precursors of tropical cyclones (hurricanes) in the Atlantic. In the past, studies of weather phenomena are hampered by lack of data over open oceans, especially in the tropics. Most studies on AEWs and the formation of tropical cyclones in earlier days relied mainly on satellite images. *Carlson* [1969b] identify three easterly waves within two weeks that finally developed into Atlantic tropical cyclones. *Simpson et al.* [1968] investigate Atlantic tropical disturbances during the 1967 hurricane season and point out that about 50% of the 61 disturbances are associated with the AEWs. With the advancement of remote-sensing technology, more Atlantic storms are identified as being generated within the AEWs [*Landsea et al.*, 1998]. In addition, significant improvement on the quality of the global atmosphere analysis has been achieved through improvements of satellite retrievals, data assimilations, and numerical models. *Thorncroft and Hodges* [2001] track vorticity centers in the European Centre for Medium-Range Weather Forecasts analyses and find positive corre-

lation between the AEW activity south of 15°N and the Atlantic tropical cyclone activity near the African west coast. *Gareth and Thorncroft* [2005] divide the AEW life cycle into three phases: the initial convective event over elevated terrain, baroclinic growth near the African easterly jet, and the final development with maintained convection in the coast. The PV anomalies embedded within the AEW merge with one another and developed a significant PV feature that left the West African coast and finally led to the rapid tropical cyclogenesis of Hurricane Alberto in 2000.

[3] Significant improvement on the predictions of tropical cyclones has been achieved for NOGAPS [*Peng et al.*, 2004]. Our examination indicates that all named tropical cyclones can be identified in the NOGAPS analysis for the 2003 and 2004 period. In this study, we apply a 3 to 8 day band-pass filter to the NOGAPS daily analysis fields to study the AEW associated with two tropical cyclones, Danielle and Earl, developed simultaneously in the Atlantic in 2004. We also demonstrate that the movements of these two cyclones are closely associated with the propagations of the AEWs. A brief history of Danielle and Earl is given in section 2. The data used and the filtering procedure are described in section 3. Results are presented in section 4 and the summary given in section 5.

### 2. Synoptic History of Danielle and Earl

[4] According to the analysis of the National Hurricane Center (NHC), cyclonic circulation in the easterly waves that spawned Danielle already possessed tropical cyclone characteristics over the African continent. More deep convection developed after the wave reached the warm Atlantic waters. It was estimated that Danielle became a tropical storm at 00UTC 14 August (Figure 1). Danielle underwent a period of rapid intensification to become a hurricane at 00 UTC 15 August and reached its maximum intensity of 95 kts at 1800 UTC 16 August while moving northwestward toward a weakness in the subtropical ridge eroded by a mid-to upper-level trough. Strong vertical shear brought by this trough also weakened Danielle as it moved poleward and finally Danielle degraded to a tropical storm by 1200 UTC 18 August.

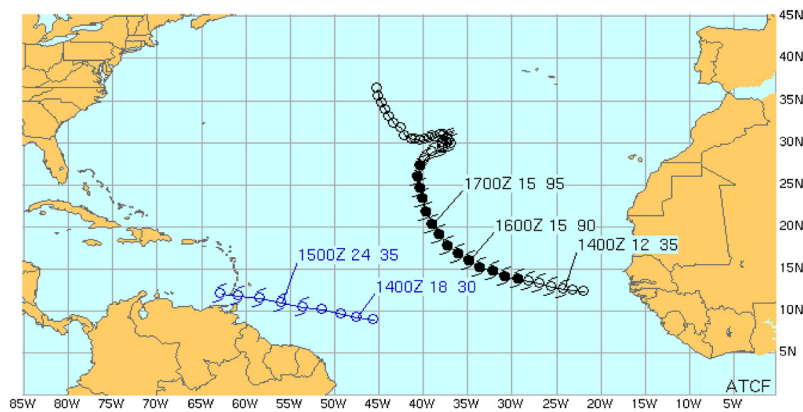
[5] Earl was a short-lived tropical storm. It formed from a tropical wave that moved from Africa to the eastern Atlantic Ocean. The wave developed into a tropical depression on 13 August and was estimated to have strengthened to Tropical Storm Earl on 14 August. During its short-lived period, Earl moved quickly forward in a straight west and slightly north direction (Figure 1).

[6] In the following, we present our analysis showing that one AEW is responsible for the genesis of both Danielle and Earl. Due to the near simultaneous formation of Danielle

<sup>1</sup>Naval Research Laboratory, Monterey, California, USA.

<sup>2</sup>Department of Meteorology, University of Hawaii at Manoa, Honolulu, Hawaii, USA.

<sup>3</sup>Also at International Pacific Research Center, Honolulu, Hawaii, USA.



**Figure 1.** Best tracks of Hurricane Danielle (shown in black) and Earl (shown in blue) in 2004 as determined by the National Hurricane Center. Open circle indicates tropical depression and open hurricane symbol indicates tropical storm. Positions of the cyclones are marked every 6 hours.

and Earl on 14 August, this date is used as the reference point for both storms.

### 3. Data and Methods

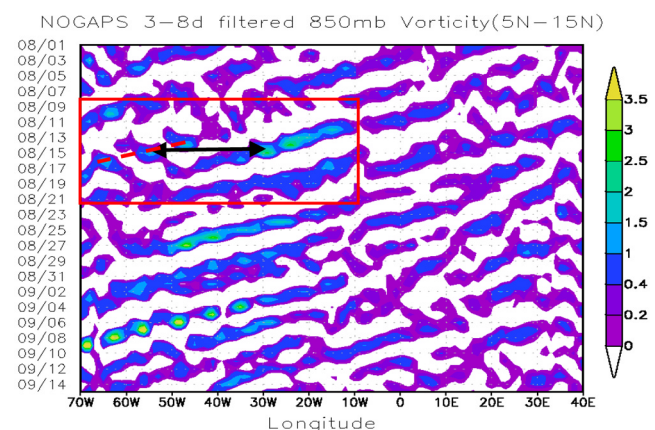
[7] The data used for this study are the daily operational global analysis fields from NOGAPS [Hogan and Rosmond, 1991]. NOGAPS is a global spectral model with 239 triangular truncation (half-a-degree resolution) and 30 vertical levels. An update cycle is carried out continuously in which the model integrates and assimilates observation data using a 3D variational method [Daley and Barker, 2001] every 6 hours. The resolution of the analyzed data we used is one degree longitude/latitude.

[8] To extract AEWs from full-spectrum disturbances, a band-pass filter is applied. A 3 to 8 day period is chosen following previous studies on the characteristics of AEWs [Carlson, 1969a; Burpee, 1972]. The time filtering is carried out for every grid point time series using the technique by Christiano and Fitzgerald [2003], originally designed for applications on economic data. The program reads in periodic data for the whole year of 2004, transforms them into Fourier series and then retains signals with a specified range of frequency. The derived 850 mb vorticity is the main field we examined.

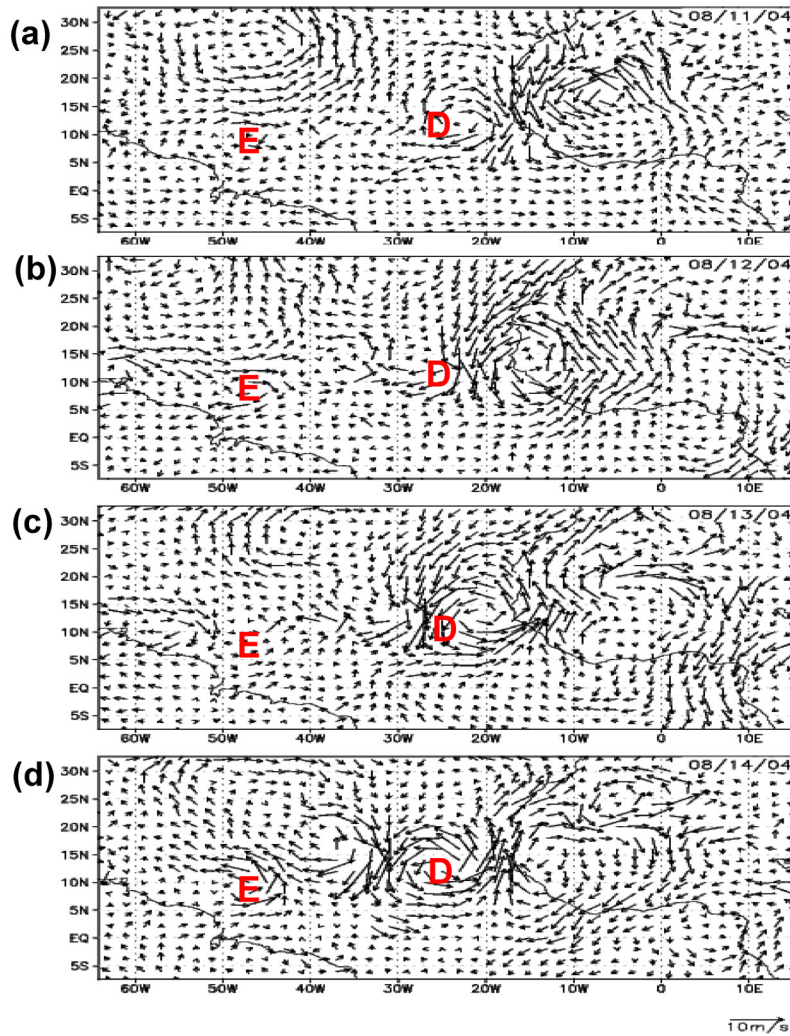
### 4. Results

[9] To explore the characteristics of the easterly wave and its relation with the two cyclones, we apply a local time filter to the data and extract out waves with periods between 3 to 8 days. The filtered 850 mb vorticity from the NOGAPS analyses, averaged between 5°N and 15°N, is plotted as a function of time and longitude from 1 August to 15 Sep in Figure 2. The figure shows the propagation of wave crests from east to west with time, represented by positive vorticity associated with the cyclonic circulation. The formation of Danielle and Earl on 14 August is indicated by the two local maxima at 47°W and 25°W, respectively. The filtered and unfiltered fields (not shown) are similar except the filtered one has clearer wave signals. In addition, the unfiltered field is dominated by the persistence of cyclonic vorticity between 20°E and 30°E that is

likely associated with the origin of AEWs in the eastern Africa. The filtered 850 mb wind fields from the 11th to the 14th of August are depicted in Figure 3. The genesis positions of both cyclones on the 14th are marked by “D” and “E” for Danielle and Earl, respectively. The filtered wind fields show clearly a wave propagating from western Africa to the easterly Atlantic. The leading cyclonic circulation downstream of point “D” was not well-organized on the 11th (Figure 3a) but it became more intense and organized on the 12th (Figure 3b). This weak cyclonic circulation moved downstream and formed Earl on the 14th. On the other hand, the second cyclonic circulation behind (to the east of) the anticyclonic flow, is much stronger on the 11th. This cyclonic circulation further intensified as it moves out of Africa and its scale contracted and became Danielle on the 14th (Figures 3b–3d). From these daily time sequences, it is clear that there were coherent waves propagating through the genesis sites of Danielle and Earl. Note that on the 12th, both future genesis



**Figure 2.** Time-longitude plot of the filtered 850 mb vorticity ( $10^{-5}\text{s}^{-1}$ ) averaged within the 5°N–15°N latitudinal band from August 1st to Sep 15th between 70°W to 40°E. Positive values indicate cyclonic vorticity and negative vorticity are not plotted. Red arrow line points to the genesis of Danielle on the right and Earl on the left, on 14 August 2004.



**Figure 3.** Band-pass filtered (3–8 days) 850 mb wind field on (a) August 11th, (b) August 12th, (c) August 13th, and (d) August 14th. “D” and “E” denotes the genesis location for Danielle and Earl on August 14th, respectively.

locations of Earl and Danielle were in the anticyclonic circulation of the easterly wave. Figures 3b and 3d indicate that the distance between the two cyclone genesis locations is approximately one wavelength of the easterly wave passing through them and the period of the wave is about 4 days. Due to the large distance ( $\sim 2500$  km) between Danielle and Earl, there was no mutual interaction between them.

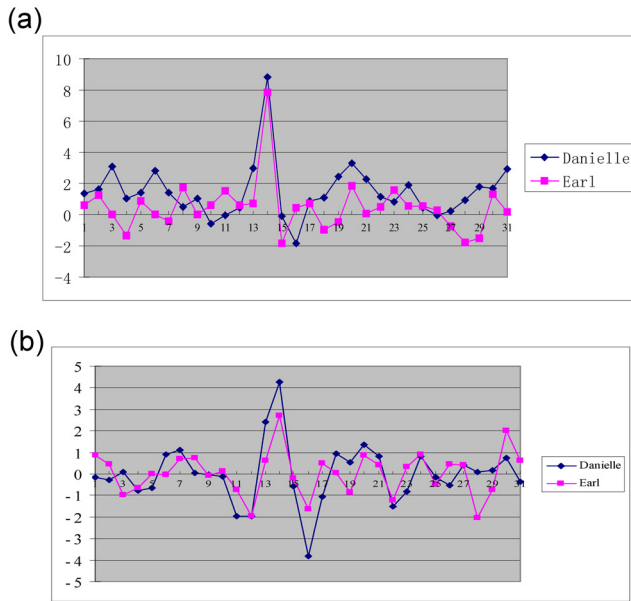
[10] The time sequence of the 850 mb vorticity, averaged within a four by four degree longitude/latitude box centered at the genesis locations of Danielle and Earl (Figure 2), are depicted in Figure 4 for both the unfiltered and filtered data. For the unfiltered data (Figure 4a), the vorticity became very large at both locations on 14 August, corresponding to the rapid development of Danielle and Earl simultaneously. Prior to it, the time sequences from the unfiltered data at these two locations do not show clear wave signals or any relation between them. With the 3 to 8 band pass filter applied (Figure 4b), the time sequences of the 850 mb vorticity show an in-phase propagation of the AEWs at these two locations. These analyses indicate that two tropical cyclones formed within a single train of easterly wave with their genesis locations one-wavelength apart. For

all the tropical cyclones we examined for 2003 and 2004, no similar case was found, indicating this is rather unique.

[11] After the formation of Danielle and Earl on the 14th, the AEW continued moving past these two locations until early September so that the two locations remained as active regions for more tropical cyclone genesis. Two hurricanes, Frances (August 25th) and Ivan (Sep 3rd), formed at or upstream of these two locations.

[12] By tracking local vorticity maxima along the wave crest in Figure 2, it is easy to see that hurricanes not only usually formed in the cyclonic regions of the AEWs, they often move with the propagation of the waves. The movement of Earl is examined first as it moved fairly straight westward. Following the crest of positive vorticity that passed the genesis point of Earl, there are two additional local maxima located at  $55^\circ\text{W}$  and  $65^\circ\text{W}$  on 15 and 16 August, respectively. These are the longitudes where Earl moved to in the next two days as indicated in Figure 1. Note that the strength of Earl weakened considerably after 18 UTC 15 Sep so that its position on 00 UTC 16 Sep is not depicted in its best track in Figure 1. The movement of Earl following the propagation of the easterly wave where it was

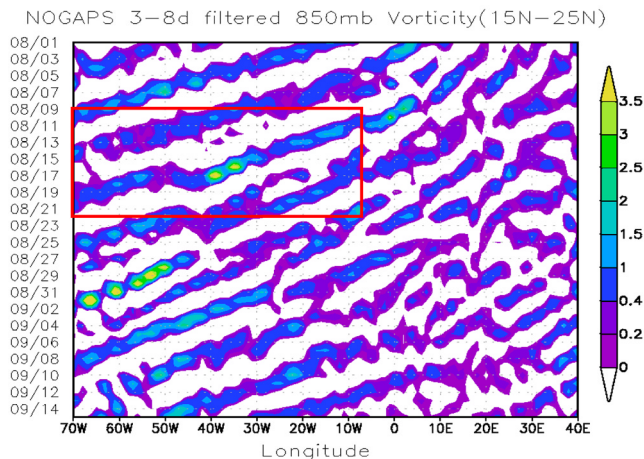




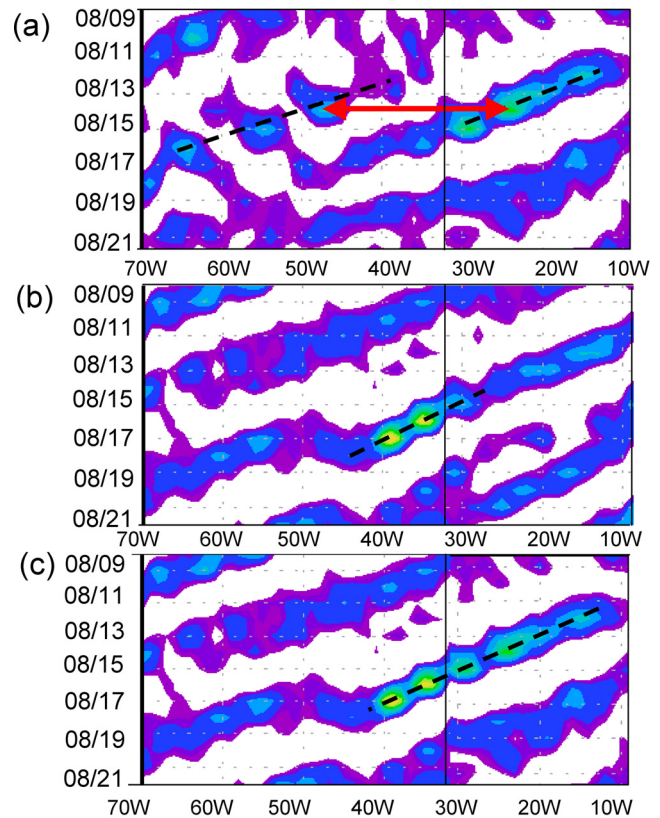
**Figure 4.** Time sequence of the 850 mb vorticity for the 4-degree box average centered at the location of the formation of Danielle (blue line) and Earl (pink line) from August 1st to 31st: (a) unfiltered and (b) 3–8 day band pass filtered.

imbedded is a well known feature [e.g., *Gareth and Thorncroft*, 2005]. Next, we examine the movement of Danielle and its relation to the easterly wave.

[13] After its formation, Danielle moved west by north-west until the 15th and it gradually recurved poleward afterward (Figure 1). From the 15th to the 18th, Danielle moved about 11 degrees west and 13 degrees north. The time-longitude plot of the easterly waves depicted in Figure 2 still shows a clear vorticity maximum on the 15th at the longitude where Danielle was. The wave crest associated with this positive vorticity then weakened considerably beyond this time. Note that the wave pattern depicted in Figure 2 is for the vorticity averaged within a latitudinal band between  $5^{\circ}\text{N}$ – $15^{\circ}\text{N}$ . By the 16th, Danielle



**Figure 5.** Same as in Figure 2 except for the  $15^{\circ}\text{N}$ – $25^{\circ}\text{N}$  latitudinal band.



**Figure 6.** The band filtered 850 mb in the zoomed regions as shown by the red boxed in Figures 2 and 5 for (a) the  $5^{\circ}\text{N}$ – $15^{\circ}\text{N}$  latitudinal band, (b) the  $15^{\circ}\text{N}$ – $25^{\circ}\text{N}$  latitudinal band and (c) patched figure of Figures 6a and 6b marked by the vertical thin line. In Figure 6c, the region to the left of the line comes from the left part of Figure 6b and the region to the right comes from the right part of Figure 6a to highlight a continued movement of Danielle and the propagation of the AEWs at different latitude bands.

has moved north of  $15^{\circ}\text{N}$ , out of the latitudinal band where the easterly waves are displayed in Figure 2. To see if the further movement of Danielle may still be associated with the AEWs north of  $15^{\circ}\text{N}$ , the time-longitude plot for the 3–8 day band pass filter is plotted for the latitudinal average in the  $15^{\circ}\text{N}$ – $25^{\circ}\text{N}$  band (Figure 5). The existence of the AEWs and their propagations in the  $15^{\circ}\text{N}$ – $25^{\circ}\text{N}$  latitudinal band are as clear as for the  $5^{\circ}\text{N}$ – $15^{\circ}\text{N}$  band. In Figure 5, one would not find the signals for Earl as Earl is out of this latitudinal band. The signal for Danielle is also very weak before the 15th. However, the vorticity maximum on the 16th and 17th denote the existence of Danielle within the easterly wave. By the 18th, Danielle has moved north of  $25^{\circ}\text{N}$  and is again out of the latitudinal band shown in Figure 5. Further examination of the filtered data north of  $25^{\circ}\text{N}$  shows little signal of the easterly waves and Danielle did not move further west (Figure 1).

[14] The tracking of Danielle in the AEW is displayed more clearly in Figure 6 within a smaller region outlined by the red boxes in Figures 2 and 5. Figure 6c is the combined figure of Figures 6a and 6b with the region left of the marked vertical line coming from Figure 6b and the region to right coming from Figure 6a. In this patched figure,

Danielle propagated smoothly with the easterly wave until the 18th (Figure 1). The continuity of the movement of Danielle in the patched figure indicates that Danielle was under the influence of the easterly wave, even as it recurved more than 10 degrees pole ward. The result above points out a new paradigm for Atlantic hurricane movement, that is, although primarily controlled by the basic steering flow, the hurricane track tends to co-locate with the cyclonic vorticity of the AEWs.

## 5. Summary

[15] By applying a 3–8 day band pass filter to globally analyzed atmospheric wind fields, we show a unique situation where two tropical cyclones, Danielle and Earl, developed simultaneously on 14 August 2004 in the Atlantic within the passage of one African easterly wave train. The characteristics of the waves bear very similar patterns prior to the formation of Danielle and Earl. The location of Earl is to the west of Danielle at a distance that is approximately one wavelength of the easterly wave. The movement of the two cyclones also followed the propagation of the easterly waves from east to west. This is not surprising for Earl, which moved west by northwest within a narrow latitudinal range. Using piecewise analysis of the easterly waves for different latitude bands, it is demonstrated that Danielle still rode with the westward propagating AEW even when it was recurving poleward. Another example, Hurricane Frances, was identified for the similar type of movement during the same period. The relation between the tropical cyclone movement and the AEWs at different latitudes, as revealed by our piecewise analysis, may occur commonly. In the future, we will extend our study to a broader database and to investigate the 3-dimensional dispersion characteristics of easterly waves [Tam and Li, 2006].

[16] This finding expands the scope of the influence of easterly waves on the formation and movements of tropical cyclones. It also highlights the importance of proper simulations of AEWs for the prediction of tropical cyclones in numerical models. Note that most of the cyclonic circulations within AEWs do not form tropical cyclones. Satellite images show that the genesis sites for Danielle and Earl have convective activity locally prior to their genesis. Mechanisms leading to the formation of tropical cyclones within the AEWs have been previously investigated [Burpee, 1972; Hill and Lin, 2003]. However, many aspects

of TC genesis remain unclear. The time evolution of the circulations associated with the easterly wave shown in Figure 3 suggest that the formations of Danielle and Earl may be through the intensification and scale contraction of the easterly waves. The investigation of detailed genesis mechanisms requires high-resolution model simulation and is beyond the scope of the present study.

[17] **Acknowledgments.** This research is sponsored by the Naval Research Laboratory and the Office of Naval Research under program element 62435N, project number BE-435-003. We thank Ping Liu at IPRC for providing the code for the time filtering.

## References

- Burpee, R. W. (1972), Characteristics of North African easterly waves during the summers of 1968 and 1969, *J. Atmos. Sci.*, **31**, 1556–1570.
- Carlson, T. N. (1969a), Some remarks on African disturbances and their progress over tropical Atlantic, *Mon. Weather Rev.*, **97**, 716–726.
- Carlson, T. N. (1969b), Synoptic histories of three African disturbances that developed into Atlantic hurricanes, *Mon. Weather Rev.*, **97**, 256–276.
- Christiano, J., and T. J. Fitzgerald (2003), The band pass filter, *Int. Econ. Rev.*, **44**, 435–465.
- Daley, R., and E. Barker (2001), *NAVDAS Source Book: NRL Atmospheric Variational Data Assimilation System*, Nav. Res. Lab., Mar. Meteorol. Div., Monterey, Calif.
- Gareth, J. B., and C. D. Thorncroft (2005), Case study of an intense African easterly waves, *Mon. Weather Rev.*, **133**, 752–766.
- Hill, C. M., and Y. Lin (2003), Initiation of a mesoscale convective complex over the Ethiopian Highlands preceding the genesis of Hurricane Alberto (2000), *Geophys. Res. Lett.*, **30**(5), 1232, doi:10.1029/2002GL016655.
- Hogan, T. F., and T. E. Rosmond (1991), The description of the Navy Operational Global Atmospheric Prediction System's Spectral Forecast Model, *Mon. Weather Rev.*, **119**, 1786–1815.
- Landsea, C. W., G. D. Bell, W. M. Gray, and S. B. Goldenberg (1998), The extremely active 1995 Atlantic hurricane season: Environmental conditions and verification of seasonal forecasts, *Mon. Weather Rev.*, **126**, 1174–1193.
- Peng, M. S., J. A. Ridout, and T. F. Hogan (2004), Recent modifications of the Emanuel convective scheme in the Naval Operational Global Atmospheric Prediction System, *Mon. Weather Rev.*, **132**, 1254–1268.
- Simpson, R. H., N. L. Frank, D. Shideler, and H. M. Johnson (1968), Atlantic tropical disturbances 1967, *Mon. Weather Rev.*, **96**, 251–259.
- Tam, C.-Y., and T. Li (2006), The origin and dispersion characteristics of the observed tropical summer synoptic-scale waves over the Western Pacific, *Mon. Weather Rev.*, in press.
- Thorncroft, C. D., and K. Hodges (2001), African easterly wave variability and its relationship to Atlantic tropical cyclone activity, *J. Clim.*, **14**, 1166–1179.

B. Fu and T. Li, Department of Meteorology, University of Hawaii at Manoa, 2525 Correa Road, HIG 350, Honolulu, HI 96822, USA.

T. F. Hogan and M. S. Peng, Naval Research Laboratory, 7 Grace Hopper Ave., Stop 2, Monterey, CA 93943–5502, USA. (melinda.peng@nrlmry.navy.mil)