

# Initiation of a mesoscale convective complex over the Ethiopian Highlands preceding the genesis of Hurricane Alberto (2000)

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[1] A tropical disturbance, which would later become Hurricane Alberto (2000), was traced back in time as a mesoscale convective complex (MCC) to the Ethiopian Highlands (EH), where the MCC first developed. Meteosat-7 imagery indicates that the MCC develops during the late afternoon and evening of 28 July 2000, and that a mesovortex (MV) was evident on the morning of 29 July 2000. A preliminary mesoscale model simulation features the development of two areas of maximum relative vorticity in the middle troposphere, with the maturation of one of the vorticity maxima into a significant MV. The higher-level vorticity center of the simulated MV tracks westward and is nearly collocated with the vortex signature in satellite imagery, while the lower-level center remains near the lee side of the EH. The vortex signature in satellite imagery was traceable to the cyclogenesis stage over the eastern Atlantic Ocean. **INDEX TERMS:** 3329 Meteorology and Atmospheric Dynamics: Mesoscale meteorology; 3314 Meteorology and Atmospheric Dynamics: Convective processes; 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; 9305 Information Related to Geographic Region: Africa. **Citation:** Hill, C. M., and Y.-L. Lin, 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, 2003.

## 1. Introduction

[2] In the course of tropical cyclone research, interest has been raised with regard to the development of Atlantic tropical cyclones from disturbances of African origin [e.g., Erickson, 1963; Gray, 1968; Simpson *et al.*, 1968; Carlson, 1969; Laing and Fritsch, 1993]. Erickson [1963], Simpson *et al.* [1968], and Carlson [1969] were all able to show that some tropical cyclones developed from disturbances that were first observed in the western and central Sahel in Africa. Laing and Fritsch [1993] were able to trace three tropical cyclones backward in time over western Africa from mesoscale convective complexes (MCCs, as defined by Maddox [1980]), which previously developed and organized over the African Sahel.

[3] The influence of orography has been observed in the development of lee vortices and, subsequently, to tropical cyclones. In one such case, the vortex that led to the genesis of Hurricane Guillermo (1991) was found to have initially developed on the lee (west) side of the Sierras Madre mountain range in Central America [Bister and Emanuel, 1997; Farfán and Zehnder, 1997]. Frank [1970] briefly

mentions the possibility that easterly waves (known predecessors of tropical cyclones) may develop downstream of the Ethiopian Highlands (EH) as a result of orographical influence on easterly flow, present throughout the depth of the troposphere. Hence, the generation of some tropical cyclones can be preceded by the development of disturbances (e.g. lee vortices, easterly waves) initiated by the influence of orography. Three hurricanes began as disturbances over the African continent during the 2000 hurricane season: Alberto, Isaac, and Joyce. Hurricane Alberto was a long-lived tropical cyclone with a peak, internal maximum sustained wind speed of  $57 \text{ m s}^{-1}$  [Beven, 2000]. Although Hurricane Alberto never directly affected any land area, our hypothesis of its convective origin over the EH and the observation of its rapid cyclogenesis over the eastern Atlantic Ocean served as bases in choosing this tropical cyclone as the main focus for this paper.

[4] After beginning the work detailed in this paper, we happened upon a similar study involving the origination of an easterly wave system from a mesoscale convective system (MCS) near the EH in August 1995 [Wegiel and Herbster, 1998]. A resultant mesovortex (MV) is said to have been found in association with the MCS. The presence of an MV has been found to be instrumental in the development and organization of new MCSs or MCCs as part of a distinct mesoscale system, or disturbance, capable of periodically regenerating moist convection while over land [Fritsch *et al.*, 1994]. Furthermore, the easterly wave system noted in August 1995 is linked to the later development of Hurricane Luis over the eastern Atlantic Ocean (Wegiel and Herbster, unpublished). In our study, we 1) use satellite data in an attempt to identify pre-cyclone disturbances organizing from MCCs that originate over the EH during the hurricane season of 2000, and 2) examine the kinematics associated with the developing "Alberto" disturbance, as it was observed with satellite data, using a preliminary mesoscale model simulation.

## 2. Methodology

### 2.1. Analysis of Satellite Imagery

[5] In verifying the overall tracks of the pre-cyclone disturbances over the African continent, Meteosat-7 visible-wavelength (VIS) and infrared-wavelength (IR) data were examined. Starting with the visible image depicting "Alberto" as a tropical storm (1100 UTC 04 August 2000), more images were gathered for times prior to the cyclogenesis stage of "Alberto". Adopting the procedures for cloud analysis from Dvorak [1984] and Zehr [1992], the "Alberto" and "Isaac" disturbances were deemed to have retained sufficient cloud and circulatory structure to be

traced across the African continent. The position of an MV associated with the daily-regenerating MCC was estimated to the nearest  $0.5^\circ$  of latitude and longitude from each image. While both the VIS and IR data were used to verify the structural coherence of the “Alberto” and “Isaac” disturbances, the VIS data (of finer spatial resolution) best depict the signature of the mesoscale circulation. For brevity, the early VIS data depicting the “Alberto” disturbance will be presented in this paper.

## 2.2. Mesoscale Model Specifications

[6] The Mesoscale Atmospheric Simulation System (MASS<sup>®</sup>) [MESO, Inc., 1999], version 5.13, is used to simulate the environment during the observed development of the MCC and MV of the “Alberto” disturbance. For preprocessing the MASS model, a 45-km grid resolution was set in a domain of  $136 \times 86$  grid points. The model domain was specified, from southwest to northeast, at  $2^\circ\text{S}$ ,  $8^\circ\text{E}$  to  $32^\circ\text{N}$ ,  $63^\circ\text{E}$ . To set boundary conditions for every 12th hour, 00-hr analyses from the Navy Operational Global Atmospheric Prediction System (NOGAPS) were used, each with 15 vertical pressure levels. Terrain data from the Central Intelligence Agency, at 5-min resolution, and Biosphere-Atmosphere Transfer Scheme (BATS) land-use data were also used for preprocessing. The model time-increment was set to 60 s, and the total time integration set to 48 h starting from 00 UTC 28 July 2000. The MASS model employed the Kain-Fritsch cumulus parameterization scheme, and the moisture physics within the model were set to be diagnostically calculated. A total of 42 vertical  $\sigma$ -levels were interpolated in the MASS model.

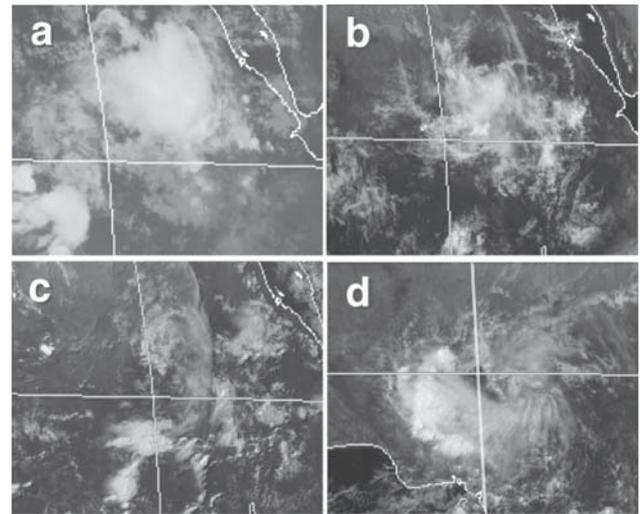
[7] The vertical  $\sigma$ -levels are translated to pressure coordinates in increments of 30 hPa. Due to space limitations, only model-simulated relative vorticity,  $\zeta$ , and wind fields at the 360- and 660-hPa levels, along with cross-sections of equivalent potential temperature,  $\theta_e$ , and the wind field will be shown in this paper for comparison with satellite observations.

## 3. Results

### 3.1. Satellite Imagery Analysis

[8] Meteosat-7 VIS imagery indicates that convection associated with the “Alberto” MCC develops during the early afternoon ( $\sim 1300$  LST) of 28 July 2000 over the EH (not shown). Convection continues to develop during the local afternoon and evening on 28 July 2000, likely in response to cumulative diurnal heating during the day and prevalent conditional instability. By 0000 UTC 29 July 2000, the convection has organized into an MCC to the west of the EH (Figure 1a), near the border between Ethiopia and Sudan. The intersecting lines in Figure 1a denote  $10^\circ\text{N}$ ,  $30^\circ\text{E}$ .

[9] Between 0000 UTC and 0800 UTC, on 29 July 2000, the convection is observed to dissipate as the newly formed disturbance begins a westward track. At 0800 UTC 29 July 2000 (Figure 1b), the loss of convection reveals surface outflow boundaries and even banding features near the former core of convection, indicative of circulation within the dissipating MCC. This result closely matches the finding by Hodges and Thorncroft [1997], in that most MCCs originating near the EH tend to track southwestward and dissipate within a day. The vortex signature is more evident at 1400 UTC 29 July 2000 (Figure 1c). By 1400 UTC 31

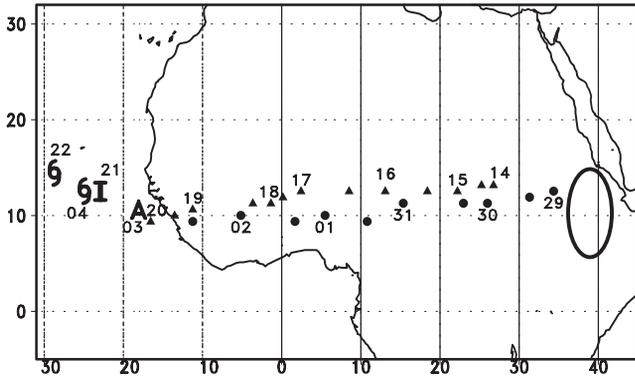


**Figure 1.** METEOSAT-7 IR satellite image for a) 0000 UTC 29 July 2000, and VIS satellite imagery for b) 0800 UTC 29 July 2000, c) 1400 UTC 29 July 2000, and d) 1400 UTC 31 July 2000. The latitude line in each image represents  $10^\circ\text{N}$ . The longitude lines are  $30^\circ\text{E}$  in (a), (b), and (c); and  $10^\circ\text{E}$  for (d). Satellite imagery provided by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT).

July 2000 the “Alberto” disturbance has tracked westward to a point just east of  $10^\circ\text{N}$ ,  $10^\circ\text{E}$ , with the circulation pattern being clearly evident (Figure 1d). In its review of tropical cyclone activity for the year, the National Hurricane Center (NHC) recognized that the disturbance identified on 30 July 2000 would later become “Alberto” [Beven, 2000]; hence no other images are presented here beyond this date. The vortex signature of the “Isaac” disturbance was first evident at 0800 UTC 14 September 2000 from a diminishing MCC, and was traceable to the time of cyclogenesis on 1400 UTC 21 September 2000 (not shown). The complete transcontinental tracks of the “Alberto” and “Isaac” disturbances to the cyclogenesis stage are summarized in Figure 2, which shows a trace of the MV positions estimated from VIS imagery.

### 3.2. MASS<sup>®</sup> Model Results

[10] A significant result from the model simulation of the “Alberto” disturbance is the development of mid-tropospheric MV immediately west, and downstream [relative to the African Easterly Jet (AEJ)], of the northern EH. At 0000 UTC 29 July 2000, two areas of maximum  $\zeta$  are featured directly above and to the lee side of the northern EH, with magnitudes of  $30 \times 10^{-5} \text{ s}^{-1}$  (area V1) and  $18 \times 10^{-5} \text{ s}^{-1}$  (area V2), respectively (Figure 3a). The V1 area over the EH is situated near  $10^\circ\text{N}$ ,  $38^\circ\text{E}$ , while the V2 area is located at the border of Sudan and Ethiopia near  $12^\circ\text{N}$ . Leading up to this time, the base of a monsoon trough over the EH has become chaotic and dispersed, suggesting the possible breakdown of associated synoptic-scale vorticity into smaller-scale eddies. These eddies could be a source for the simulated  $\zeta$  maxima in the EH region. By 0800 UTC 29 July 2000, the V2 area increases in magnitude to  $36 \times 10^{-5} \text{ s}^{-1}$  (Figure 3b) and becomes a strong MV, while the V1 area drifts eastward

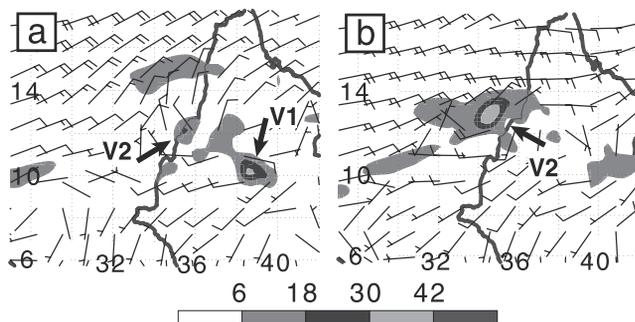


**Figure 2.** Mesovortex and cyclone center estimated positions of “Alberto” (circles) and “Isaac” (triangles) from METEOSAT-7 VIS images for 0800 UTC 29 July 2000 through 1400 UTC 04 August 2000 and for 0800 UTC 14 September 2000 through 1400 UTC 22 September 2000. Land-based estimated positions of Alberto (Isaac) for 0800 UTC are labeled below (above) by the successive day of the month. Following westward, each system center position is estimated for the alternating times of 0800 UTC and 1400 UTC. Only positions for 1400 UTC are plotted over the Atlantic Ocean. Letter labels represent cyclogenesis stage. Oval represents the approximate area of Ethiopian Highlands.

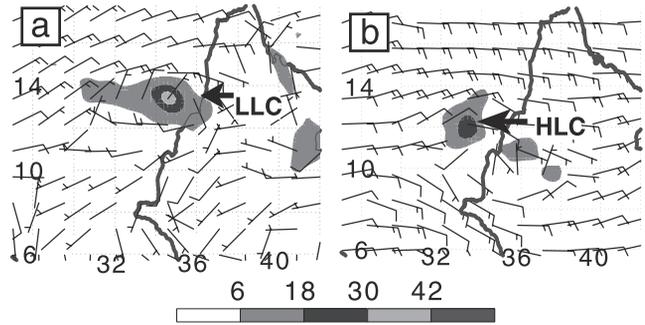
and dissipates. Six hours later, the MV essentially maintains its position and intensity (Figure 4a).

[11] Cross-sectional analysis indicates that the  $\zeta$  maxima develop vertically from near the 700-hPa level to as high as the 300-hPa level (not shown). While the V1 area is stacked vertically, the MV (V2 area) is slanted about  $0.5^\circ$  southward with height. As a result of increasing vertical wind shear, the higher-level center (HLC) of this simulated MV separates from the lower-level center (LLC) and begins a definitive westward track by 1400 UTC 29 July 2000; Figure 4 shows the HLC as reflected at the 360-hPa level. According to Figures 4a and 4b, the LLC is left behind by the HLC near the lee side of the EH, with the HLC being  $0.5^\circ$  west and  $1.7^\circ$  south of the LLC.

[12] The main source from which low-level moisture contributes to MCC development over the EH is southern Sudan, with the Red Sea being a secondary source (Figure



**Figure 3.** MASS-simulated 660-hPa relative vorticity ( $10^{-5} \text{ s}^{-1}$ ) and wind ( $\text{m s}^{-1}$ ) for a) 0000 UTC 29 July 2000, and b) 0800 UTC 29 July 2000. Vorticity is shaded every  $12 \times 10^{-5} \text{ s}^{-1}$ . V1 and V2 designate areas of maximum relative vorticity.

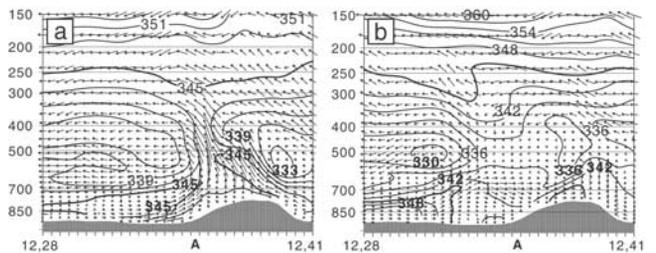


**Figure 4.** Same as Figure 3, except for 1400 UTC 29 July 2000 at a) 660-hPa, and b) 360-hPa. LLC and HLC designate the lower- and higher-level vortices, respectively.

5a). The highest vertical velocity at point A ( $\sim 35.5^\circ\text{E}$ ) is superposed with a narrow column of near neutral stability ( $\partial\theta_e/\partial z \sim 0$ ), similarly found with developing tropical cyclones. Apart from the core of high  $\theta_e$ , the 700- to 400-hPa layer of  $\theta_e$  is as many as 18 K lower than the layer immediately above the surface, indicating the prevalence of conditional instability downstream of the EH. By 1400 UTC 29 July 2000, the vertical structure of the columns of upward air motion and high  $\theta_e$  has been disrupted within the 600- to 400-hPa layer (Figure 5b). The upper-level (lower-level) maxima of upward air motion and high  $\theta_e$  have moved with the HLC (LLC); the columns of vertical air motion and  $\theta_e$  are no longer in phase. Low-level moisture advection is confined merely to the downstream (west) side of the disturbance and the upward forcing of the moist air is no longer supported by the EH.

#### 4. Conclusions

[13] Satellite imagery shows that an MCC first develops over Ethiopia on 28 July 2000 and becomes a disturbance with a discernable vortex signature 29 July 2000. The “Alberto” disturbance traverses the Sahel of Africa over a five-day period and emerges over the Atlantic Ocean on 03 August 2000, when it is designated as a tropical depression. The “Isaac” disturbance was similarly traced during the period of 14 September 2000 to 21 September 2000. More work will be needed to pinpoint the vortex signature of the “Joyce” disturbance, as this system was more often devoid



**Figure 5.** Cross-sections of MASS-simulated equivalent potential temperature (K) and tangential circulation for a) 0000 UTC 29 July 2000, and b) 1400 UTC 29 July 2000. Cross-sections span the vertical plane from  $12^\circ\text{N}$ ,  $28^\circ\text{E}$  to  $12^\circ\text{N}$ ,  $41^\circ\text{E}$ . Equivalent potential temperature is contoured every 3 K. Point A represents  $12^\circ\text{N}$ ,  $35.5^\circ\text{E}$ .

of accompanying clouds, making the backward trace of this system difficult.

[14] Analysis of the satellite imagery suggests the presence of an MV on 29 July 2000, as the convection of the MCC is dissipating. The MASS model simulates the development of two areas of maximum  $\zeta$  at the 660-hPa level, with the maturation of one of the  $\zeta$  maxima into a significant MV. An increase of vertical wind shear causes this MV to separate into higher- and lower-level centers; the HLC was approximately collocated with the vortex signature observed in satellite imagery at 1400 UTC 29 July 2000. With the simulated MV being vertically split, neither the HLC nor the LLC was present throughout a sufficient depth of the troposphere to initiate and organize new convection in the afternoon and evening of 29 July 2000. Convection was not observed to redevelop in association with the vortex signature until the local, early daylight hours of 30 July 2000 near 10°N, 28°E. It was during this day that the NHC tropical cyclone report [Beven, 2000] first noted the existence of the “Alberto” disturbance. Our future work will include a study of the evolution of the disturbance after 29 July 2000, as well as of other pre-cyclone disturbances such as “Isaac” and “Joyce”.

[15] Possible contributing processes in the development of the mid-tropospheric MV associated with the “Alberto” disturbance include the orographic generation of lee vorticity downstream of the EH, vortex initiation within deep convection, dispersion of synoptic-scale vorticity from the monsoon trough, and divergence downstream of an easterly monsoon jet in the upper troposphere. Analysis of the exact processes leading to MV development will be another point of future study.

[16] In summary, the complementary development of both the initial MCC and the associated MV near the EH can be considered the beginning stage of a dynamically-sustained disturbance (as opposed to simply an easterly wave), readily capable of developing into a tropical cyclone as it emerges into the more favorable environment over the eastern Atlantic Ocean. The model used in this study was able to produce a significant mid-level MV at the lee of the EH, near where Meteosat-7 VIS imagery first depicted the vortex signature of “Alberto”. This vortex was traceable to the stage of cyclogenesis over the eastern Atlantic Ocean.

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