Tropical Cyclogenesis Initiated by Lee Vortices and Mesoscale Convective Complexes in East Africa

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LONG-TERM GOALS

To understand precursors leading to the development of Atlantic tropical cyclones:

1) the formation of a mesovortex (MV), a mesoscale convective complex (MCC), and African Easterly Waves (AEWs) to the lee of the Ethiopian Highlands (EH)

2) the propagation and evolution of the AEW with MCC and MV across the African continent.

OBJECTIVES

The scientific objectives of this effort are based on answers to the following fundamental questions:

(1) What mechanisms are responsible for the formation a pre-tropical cyclone (TC) MCC and MV at the lee side of the Ethiopian Highlands?

(2) How do the AEW and the pre-TC MV/MCC relate?

(3) What are the maintenance mechanisms of the pre-TC MCC and MV as they propagate across the African continent?

APPROACH

(A) Numerical Modeling: To answer the first question, we perform realistic numerical simulations of the environment of a land-based tropical disturbance (an AEW comprised of an MCC and an MV) in the vicinity of the EH. The disturbance is a precursor to the eventual genesis of Hurricane Alberto of 2000 (Hill and Lin 2003). We use the COAMPS® model, provided by the Marine Meteorological Division of the Naval Research Laboratory, and the MM5, provided by Penn State University (PSU) and the National Center for Atmospheric Research (NCAR). Realistic simulations are performed using two nested domains with 12-km and 4-km grid spacing, respectively, over a period of 72 h beginning at 00 UTC 27 July 2000.

To answer the 2nd and 3rd questions, we also utilize the NCAR Regional Climate Model v.3 (RegCM3) to study the formation and maintenance of the AEW associated with the pre-Alberto system. Realistic simulations are performed with 50-km and 30-km grid resolutions covering all of

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North Africa. The simulations are performed for 336 h starting at 00 UTC 25 July 2000. Several sensitivity tests are performed to help identify the mechanisms responsible for the generation and maintenance of the AEW, MCC, and MV, including experiments with flat terrain, no PBL, and no moisture effects.

(B) Observational and Global Model Data Analysis: METEOSAT satellite data provides the best means for verifying the existence of MCCs and, to a lesser extent, MVs associated with pre-TC disturbances over North Africa. Given the scarcity of tropospheric sounding observations from Africa, the realistic simulation results are verified against global model analyses, such as NOGAPS analyses, EOM analyses, and NCEP Reanalysis data. The analyses are also used to investigate the formation and maintenance mechanisms of the AEWs. The EOM analyses with grids spaced every 0.5625º are studied most extensively. NCEP reanalysis data are further used to study of the climatology and the larger scale environmental factors contributing to the formation and maintenance of AEWs.

WORK COMPLETED

(1) A paper entitled "Origin and Propagation of a Disturbance Associated with an African Easterly Wave as a precursor of Hurricane Alberto (2000)" has been accepted for publication by Monthly Weather Review. The work detailed in this paper is described in items 2 and 3 below.

(2) RegCM3 Numerical Modeling. The RegCM3 was used specifically to study the pre-Alberto AEW and surrounding AEWs. Sensitivity tests were performed to study the impact of the EH on the pre-Alberto AEW. Ms. Robertson and Mr. Hill contributed to this task.

(3) Data Analyses. (a) We have analyzed METEOSAT data and traced the formation and propagation of eastern Atlantic tropical cyclones from an area of 5-15°N and 30-40°E surrounding the EH during 1990 to 2001. To understand the convective cycle of pre-TC MCCs, we carried out further analysis of the incipient disturbances of Hurricanes Alberto, Isaac, and Joyce of 2000. Ms. Robertson and Mr. Hill each contributed to this task. (b) We have made extensive analysis of the pre-Alberto and pre-Isaac systems using the EOM data. Ms. Robertson contributed to this task.

(4) A paper entitled "Control parameters for track continuity and deflection associated with tropical cyclones over a mesoscale mountain" was published by the Journal of Atmospheric Science. The work detailed in this paper helps in the understanding of the effects of orography on the formation of a secondary vortex on the lee side of a mesoscale mountain. This study was co-sponsored by a UCAR/NSF cooperative agreement (AWARE program).

(5) Other realistic numerical modeling. Simulations have been conducted, using the COAMPS and MM5 models, to study the generation of the pre-Alberto AEW near the EH. Mr. Hill contributed to this task.

(6) The following relevant preprints have been submitted to the 11th AMS Conference on Mesoscale Processes: (a) Convective and orographic aspects in the formation of a pre–cyclogenic African easterly wave near the Ethiopian Highlands, by C. M. Hill and Y.-L. Lin; (b) Effects of the landfall location and approach angle of a cyclone encountering a mesoscale mountain range, by Y.-L. Lin, L. C. Savage III, and C. M. Hill.

RESULTS

Based on analysis of METEOSAT imagery, 23 of 34 eastern Atlantic tropical cyclones had origins from incipient disturbances that developed at lee side of the EH over the period of 1990-2001, including Alberto and Isaac in 2000. Of the 23 identified tropical cyclones, 16 attained hurricane status ($V \geq 33$ m s^{-1}) and 10 attained major hurricane status ($V \geq 50$ m s^{-1}).

Based on satellite imagery and EOM data, we have identified 7 stages in a cycle of MCC development with the pre-Alberto AEW. Figure 1 depicts the AEW forming over the lee of EH and propagating across the African continent to the eastern Atlantic Ocean. The average propagation speed of the associated MCCs was found to be about 11.6 ms^{-1}.

The 7 stages of the convective cycle are identified as Genesis I, Lysis I, Genesis II, Lysis II, Genesis III, Lysis III, and Genesis IV. The MCCs that developed with the pre-Alberto AEW were measured by: (i) areas with cloud top temperatures less than or equal to –52ºC; (ii) meridional and zonal axes of the cloud coverage were measured; and (iii) the total convective coverage was calculated by multiplying the meridional and zonal lengths. Based on the EOM relative humidity (RH) fields (not shown), we hypothesize that the genesis and lysis stages of the MCCs are dominated by the low-level moisture supply over the African continent. Low-level moisture is advected from the Congolese rain forests by a seasonal eastward extension of the West African Monsoon.

To investigate the lifecycle and maintenance of the pre-Alberto system, Robertson and Lin (2004) studied the environmentally and orographically induced vertical moisture flux during the pre-Alberto period. NCEP surface RH (Fig. 2) and streamlines were compared with the track and convective lifecycle of the pre-Alberto system. The orographic and the general vertical moisture fluxes are calculated by $(\boldsymbol{V}_H \cdot \nabla h)q$ and wq, respectively, where $\boldsymbol{V}_H$ is the horizontal wind vector, h is the terrain height, q is the mixing ratio, and w is the vertical velocity. We found that vertical moisture flux is initially induced orographically, and moisture is entrained into the pre-Alberto system at the beginning of the G-I and G-III periods. As the system moves westward, vertical moisture flux is controlled more by the synoptic environment, such as by the effects of surface heating.

To investigate the synoptic-scale environmental effects on the associated AEW of the pre-Alberto system, we used the RegCM3, which is specified by: $\Delta x = \Delta y = 30$ km; 18 σ-levels; 312×110 horizontal grid points; $\Delta t = 60$ s; 336-h simulation starting on 00 UTC 25 July 2000; Grell cumulus parameterization scheme and Holtslag et al.'s PBL scheme. Results of the RegCM3 control simulation clearly show signals of the pre-Alberto AEW. From this simulation, we have analyzed the relative vorticity (Fig. 3), specific humidity, T, surface p, geopotential height, 6-h rainfall accumulation, w, streamlines, cloud water mixing ratio, meridional wind, and PV fields at various heights. We are currently in the process of analyzing and comparing the sensitivity tests with the real case control simulation.

Based on Hovmöller plots of meridional wind (Fig. 4), vorticity and other fields for the pre-Alberto AEW from EOM analyses (not shown), we found a wave structure associated with the MV and that two to three other vortices were embedded within the wave across the African continent. The origin of the waves seems to be consistent with that of the MV, i.e. at the lee of the EH. Thus, we hypothesize the AEW is generated by influence of the EH and that MVs tend to form within regions of maximum vorticity within the AEW.

We have worked toward producing more accurate simulations of the generation of the pre-Alberto AEW with the COAMPS and MM5 models. Simulations from both models begin at 00 UTC 27 July 2000 and are run for 72 hours with a time step of 15 s. The coarse domain is set with 253 × 229 grid points, spaced every 12 km, and uses the Kain-Fritsch cumulus parameterization scheme. The nested domain is set with 283 × 283 grid points, spaced every 4 km, with uses no CP scheme. The COAMPS model uses NOGAPS 1.0º analyses for initialization and boundary conditions, one-way nesting, the Rutledge-Hobbs microphysical parameterization scheme, a TKE-based PBL scheme, and is structured with 42 vertical σ-levels. The MM5 uses EOM 1.125º analyses for initialization and boundary conditions, two-way nesting, the Goddard MP scheme, the Blackadar PBL scheme, and is structured with 45 vertical σ-levels. From the COAMPS and MM5 models, a wave of convective origin is simulated over northern Ethiopia (Fig. 5). The MV of the pre-Alberto AEW, as observed from satellite data, is thought to arise from within the convection. The simulated convection is less vigorous than convection observed from satellite data, which may explain the absence of a discernible MV within the simulated convective wave. Each model also simulates a larger cyclonic wave over southern Sudan between 7 and 10ºN; this feature appears to be a quasi-stationary lee trough. Within the MM5 simulation, a more amplified lee trough is depicted and combines with the convectively generated wave to produce the pre-Alberto AEW over southern Sudan (Fig. 6). Through a comparison between model results and with satellite data, the development of the pre-Alberto AEW appears to take place in four stages:

1) cellular convection develops in the local afternoon over the higher mountain peaks of the EH

2) growing convective cells conglomerate into an MCC during the local nighttime near the lee slopes of the EH

3) an MV develops from the remnants of the MCC

4) the convectively-generated MV combines with a pre-existing lee trough to form the AEW.

IMPACT/APPLICATIONS

Prediction of the formation and sustenance of the MCC/MV systems and the associated AEWs over the African continent are essential in understanding and predicting the eventual formation of tropical cyclones over the eastern Atlantic Ocean.

RELATED PROJECTS

UCAR/NSF AWARE project (P.I.: Dr. Y.-H. “Bill” Kuo) on effects of orography on TC track deflection and rainfall distribution associated with the passage of tropical cyclones over a mesoscale mountain.

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(1) Hill, C. M. and Y.-L. Lin, 2003: Initiation of a mesoscale convective complex over the Ethiopian Highlands preceding the genesis of Hurricane Alberto (2000), Geophys. Res. Lett., **30**, No. 5, 1232.

(2) Robertson, K. E. and Y.-L. Lin, 2004: The Maintenance of a MCC across northern Africa: a case study and analysis relating to surface moisture variables and fluxes. 26th Conf. on Hurricanes and Tropical Meteorology, Amer. Meteor. Soc., Miami Beach, FL, 288-289.

PUBLICATIONS

(1) Lin, Y.-L., K. E. Robertson, and C. M. Hill, 2005: Origin and propagation of a disturbance associated with an African easterly wave as a precursor of Hurricane Alberto (2000). Mon. Wea. Rev. [IN PRESS]

(2) Lin, Y.-L., S.-Y. Chen, and C. M. Hill, 2005: Control parameters for track continuity and deflection associated with tropical cyclones over a mesoscale mountain. J. Atmos. Sci., **62**, 1849-1866. [PUBLISHED]

(3) Hill, C. M., and Y.-L. Lin, 2005: Convective and orographic aspects in the formation of a pre–cyclogenic African easterly wave near the Ethiopian Highlands. 11th Conf. on Mesoscale Processes, Amer. Meteor. Soc., Albuquerque, NM [IN PRESS]

(4) Lin, Y.-L., L. C. Savage III, and C. M. Hill, 2005. Effects of the landfall location and approach angle of a cyclone encountering a mesoscale mountain range. 11th Conf. on Mesoscale Processes, Amer. Meteor. Soc., Albuquerque, NM [IN PRESS]

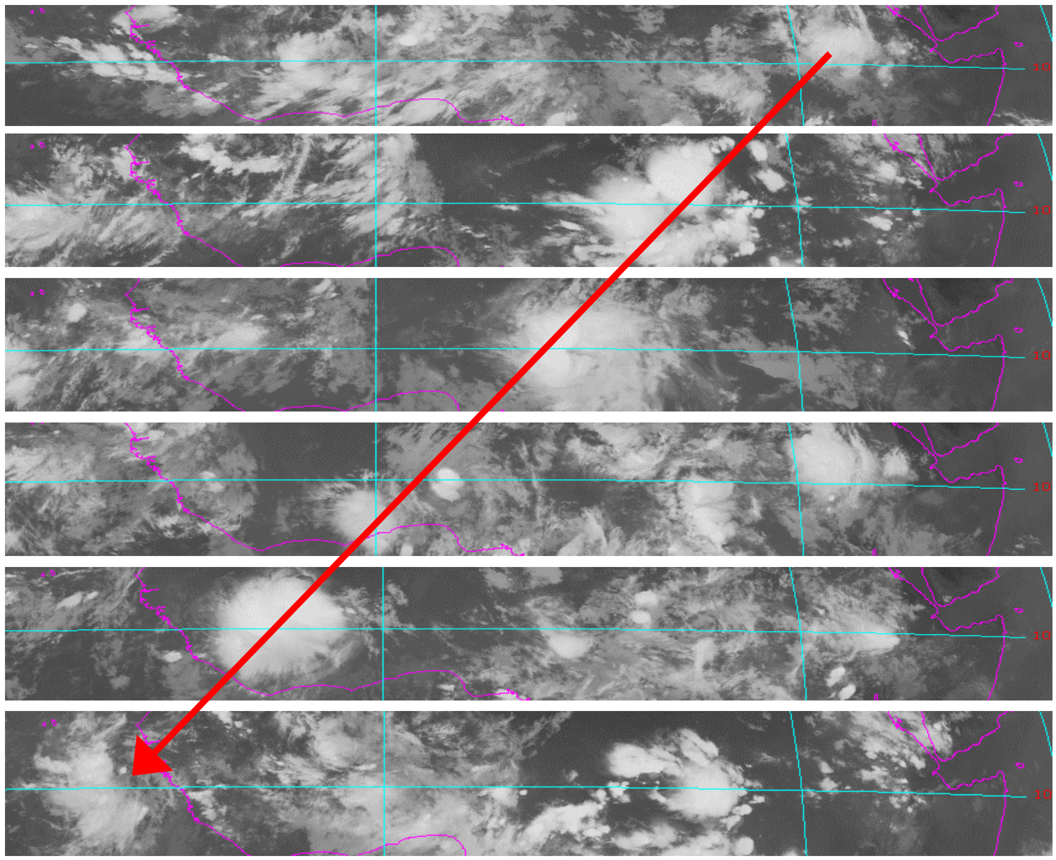

Figure 1. Pre-Alberto MCC/MV system depicted by METEOSAT-7 IR imagery, which spans the period of 06 UTC 29 July 2000 through 12 UTC 03 August 2000. Latitude line is 10°N. Longitude lines are 0° and 30°E. Imagery provided by EUMETSAT © 2003.

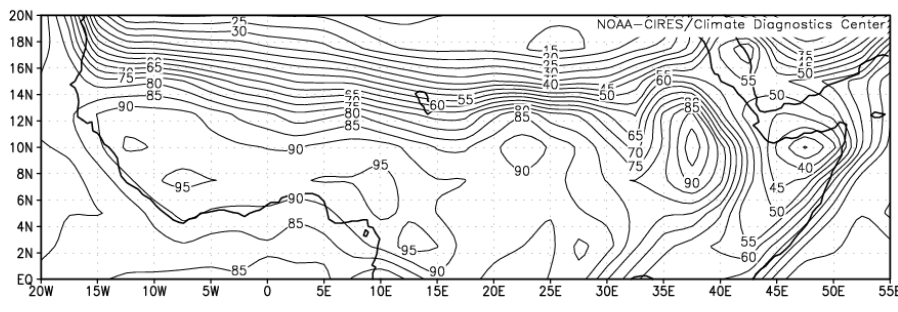

Figure 2. NCEP monthly mean surface RH (%) averaged for July-August 2000.

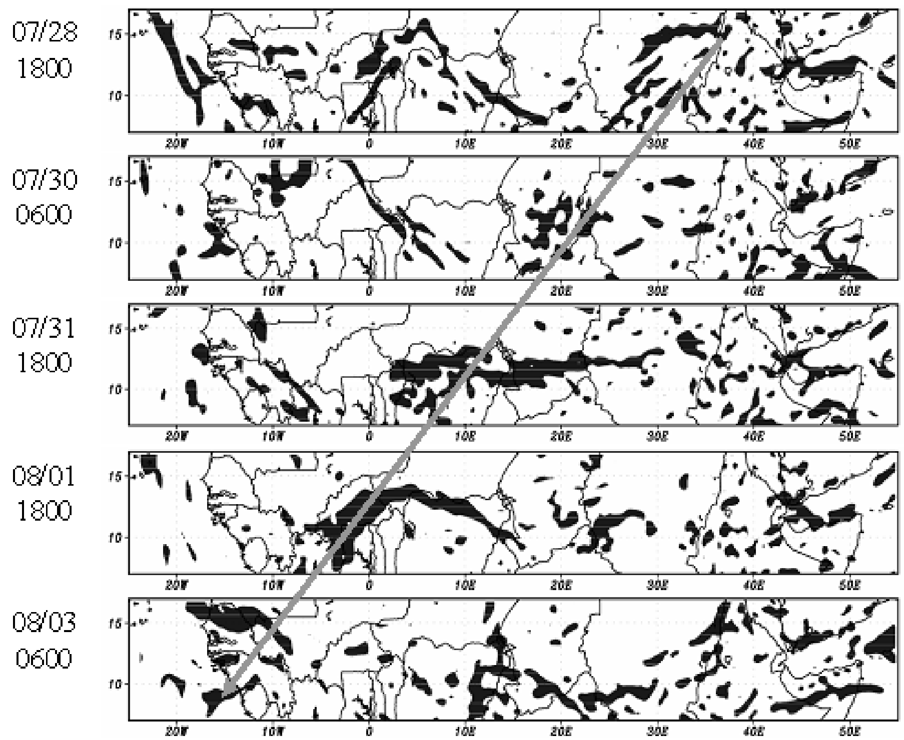

Figure 3. RegCM3 700-hPa relative vorticity, from the RegCM3 30-km real case model simulation, with regions of $\zeta \geq 10^{-5}\ s^{-1}$ shaded.

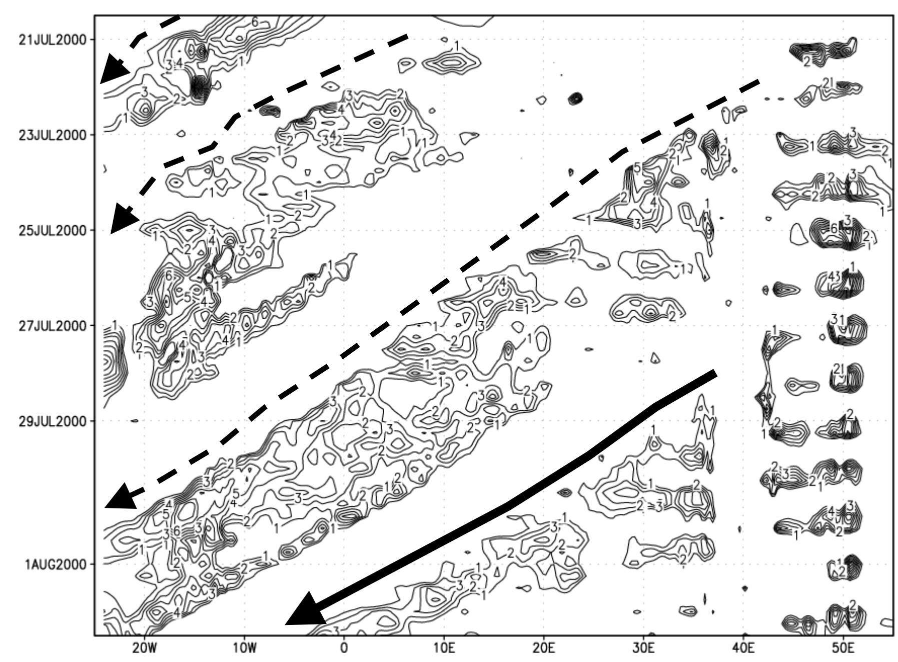

Figure 4. Meridional wind Hovmöller plot at 700 hPa for the RegCM3 control case simulation. Positive, or southerly, values are contoured at an interval of 1 ms^{-1}. Arrows represent AEWs; solid arrow represents pre-Alberto AEW.

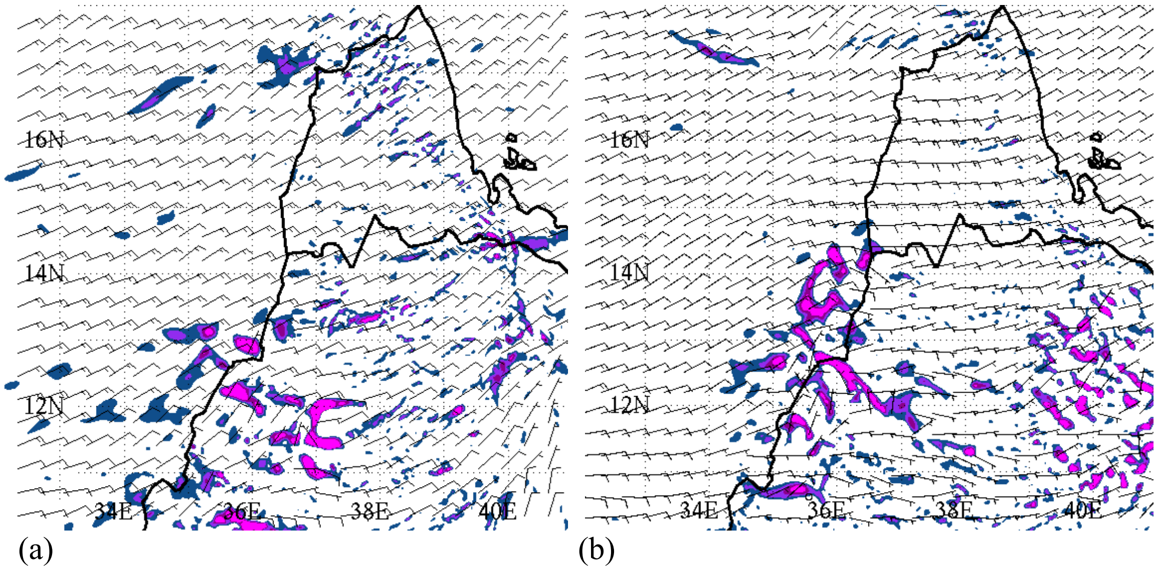

Figure 5. 600-hPa relative vorticity (s^{-1}) and wind ($m\ s^{-1}$) at 2200 UTC 28 July 2000 for a) COAMPS and b) MM5. Vorticity is shaded every $10^{-4}\ s^{-1}$ up to $4 \times 10^{-4}\ s^{-1}$.

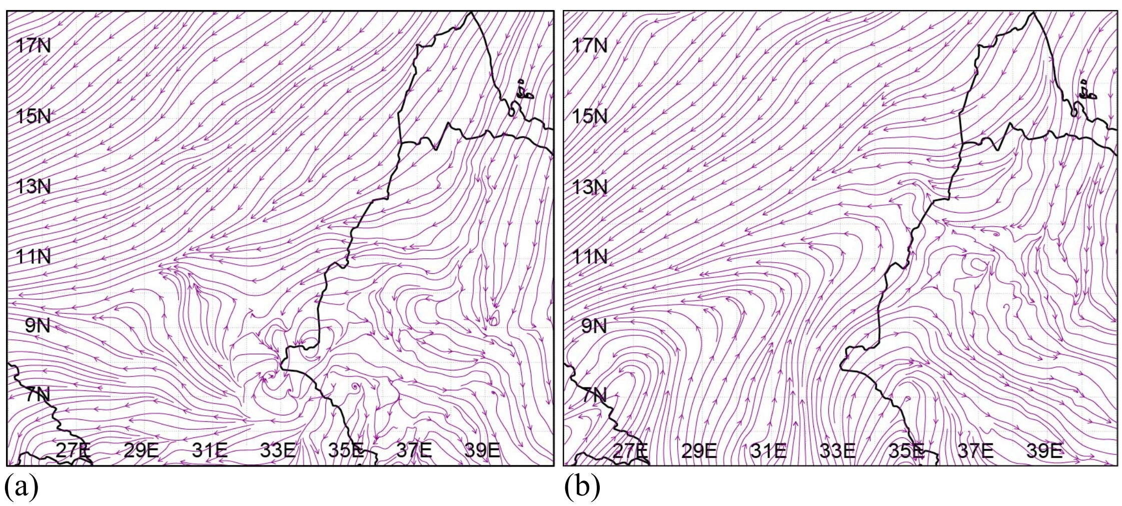

Figure 6. 12-km grid 700-hPa streamline field at 2200 UTC 28 July 2000 for a) COAMPS and b) MM5.