7.1 INVESTIGATE THE FORCING MECHANISMS LEADING TO THE FORMATION OF THE AFRICAN EASTERLY WAVES PRECEDING THE GENESIS OF TC DEBBY (2006)

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1. Introduction

African Easterly Waves (AEWs) are the dominant synoptic-scale atmospheric disturbances that occur in West Africa and the tropical North Atlantic during the summer (Reed et al. 1977; Thorncroft and Hodges 2001; Kiladis et al. 2006). These waves, which propagate westward, are important because they are linked with convective rainfall, the variability of which can have devastating societal impacts in Africa. They are also noted for being precursors to the generation of hurricanes in the Atlantic Ocean. Earlier studies reported that about 60 % of the TCs and non-major hurricane formation in the Atlantic Ocean are related to the propagating AEWs (Russell et al. 2017). Thus, it is important to understand the origin and processes responsible for the formation of the AEWs disturbance over East Africa is essential in improving the forecast of Atlantic hurricanes. Several mechanisms have been proposed in the past to explain the origin and formation of AEWs. Lin et al. (2013) – hereafter L13, proposed a conceptual model (see Fig. 1) to illustrate the origin of the pre-Debby (2006) AEWs. According to their conceptual model, the AEWs originated from the initiation of the cyclonic vortex from the southwest Arabian Peninsula. The Arabian High aids easterly waves propagating from a genesis area along the southern coast of the Arabian Peninsula into east Africa and interacting with the topography. However, they didn't explain what happens when the vortex formed from the Arabian Peninsula interacts with Ethiopian Highlands (EH). Apart from this, diabatic heating has also been proposed to explain the generation and growth of AEWs disturbance (e.g., Hsieh and Cook 2005; Ross and Krishnamurti 2007; Thorncroft et al. 2008), which is found to be one of the major energy sources of the AEWs. The goal of this study is to examine and understand the collective impacts of several forcing mechanisms, such as the thermal and mechanical forcing, responsible for the formation of the AEWs disturbance preceding the genesis of hurricanes in the Atlantic basin. Firstly, how is the vortex formed from the Arabian Sea coupled with convection generated by the EH terrain? What are the mechanical forcing impacts? Secondly, what are the impacts of Diabatic Heating on vortex? Is thermal force strengthening the vortex intensity?

Understanding the processes and interactions between these features is essential to better predict the formation and growth of the AEWs disturbance over Africa continent. Our approach is to conduct a sensitivity study of the forcing of the topography and diabatic heating.

2. Methodology and Numerical Model Experimental Design

To investigate the impacts of topography and diabatic heating on the evolution of AEWs over West Africa, we perform numerical simulations using the Advanced Weather Research and Forecasting model (WRF-ARW) Version 4.4 (Skamarock et al. 2021). This study employs two one-way interactive doubly nested domains with a horizontal grid spacing of 16 km and 4 km. A Mercator projection map is utilized for these two domains. The 16 km domain (D1) stretches from the Arabian Sea to the eastern Atlantic, covering the whole African continent and some parts of southwest Asia. The 4 km nested domain (D2) only covers some parts of northeastern Africa, including Ethiopia, Eritrea, Sudan, Yemen, the southern part of Saudi Arabia, etc. The domain configuration and topographic features from D2 are shown in Figure 2. The D1 domain is designed to focus on the synoptic features of the evolution of AEWs over Africa. We focus more on the innermost domain, D2, to investigate how topography (such as EH and AS) and diabatic heating affects the evolution of AEWs, and the related initiation and development of MCSs over West Africa. Each domain has 50 vertical grid levels with a domain top height of 50 hPa.

The WRF initial and boundary conditions are from the 5th generation European Center for Medium-Range Weather Forecasting reanalysis data (ERA5 2019). The topography data used in this study are Global Multi-Resolution Terrain Elevation Data 2010 (GMTED2010) provided by the U.S. Geological Survey (Danielson and Gesch 2011). The D1 domain is initialized by ERA5 data at 0000 UTC 08 August and ran to 0000 UTC 24 August 2006, a total of 16 days of simulation time, while domain D2 simulation is initialized at 0000 UTC 10 August and integrated to 0000 UTC 18 August 2006, a total of 8 days of simulation time. We refer to this simulation as the control (CNTL) case for the rest of this study. In addition to the CNTL case simulation, to differentiate the mechanical and thermal forcing, we also conduct four sets of sensitivity experiments by removing specific topography and turning off/on latent and sensible heating. Each test will investigate the impact of each force and how it impacts the vortex propagates westward. First, we remove 50% of the terrain of the Ethiopian Highlands (MTN50). Second, we remove the whole terrain (NMTN). Third, turn off only latent heating (NLHT) from the

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Microphysics and then finally no diurnal heating (NDHT) by turning off surface layer and boundary layer physics. These experiments are performed to analyze the response of the MCSs and AEWs activity due to changes in the topography and diabatic heating. Note that we use both 16 km and 4 km domains to conduct those four sensitivity experiments. These sensitivity experiments are summarized in Table 1.

3.Results

3.1 Model Verification

Combining satellite observations, reanalysis data, and numerical model simulations using the WRF model, have been examined to verify our model simulated results. Figures 3 and 4 show the Outgoing Longwave Radiation (OLR) at 700 hPa level for Satellite (left panel), L13 (middle panel), and our CNTL-D1 simulated (right panel) results from 0000UTC 11th to 16th August 2006. The local OLR minima, as denoted by the concentrated blue areas in the horizontal belt, are used as a proxy of Mesoscale Convective Systems (MCS). It can be seen that the convective cloud clusters over northern EH, Red Sea, and Asir mountains are captured by the CNTL case at 8/11/06Z by comparing with satellite and L13. These cloud clusters propagate downstream of the EH terrain after one day of propagation, which is also captured well with the satellite as well as L13. This propagation continues over the African continent for the next couple of days. In general, our CNTL case is able to capture major features of the pre-Debby MCS/cloud clusters and AEW.

3.2 Impacts of Mechanical and Thermal Forcing

In order to investigate the mechanical and thermal forcing, we focus more on the D2. From the OLR analysis, in CNTL case, we do see that the westward propagating meso vortex (MVs) interact with the EH terrain at approximately 8/12/00Z, as shown in Fig. 5. When MVs interact with the EH terrains, they splitted and flow around the mountains. However, in NLHT case, we do not see any such kind of interactions, which implies obvious impact of latent heating. In MTN50 case, we do see the interaction as well as splitting clusters but not as strong as CNTL case. In NMTN case, there is no interaction as all mountains are removed from the physical domain. Figure 6 shows that after one day of propagation, the splitted cloud clusters merged in the lee side of the EH terrain in the CNTL case. In MTN50's case we do see this merging process, but it is not as organized as the CNTL case. However, there are no merging steps in the NLHT and NMTN cases. Once the cloud clusters are merged, there exist two modes of disturbance, one is a stationary mode and other is a propagating mode. The stationary mode corresponds with the generation of moist convection over the EH triggered by diurnally variant sensible heating over the mountains. The propagating mode corresponds with the generation and propagation of MVs and MCSs from the lee side of the EH (see Fig. 7).

From our terrain and diabatic heating sensitivity experiments, the results show that the presence of substantial topography in eastern Africa, such as the Ethiopian Highlands and Darphur Mountains, plays a key role in modifying and/or changing the convective cloud clusters structures through convective initiation produced by combined mechanical and thermal forcing in the region. It is found that,

a) NMTN case mimic observation better except faster.
b) Mechanical forcing blocked the vortex so that the vortex splitted into several clusters upstream side of the EH terrain.
c) In the NMTN case, Vortex easily moves across the highlands.
d) Th propagation speed of the meso vortex has also increased as we removed the mountain.
e) The collective disturbance propagates westward (downstream) across the African continent.
f) The advection, splitting, and merging processes among the convective cloud clusters can be seen clearly in the figure.

The relative strength of these forcing depends on several factors, which may be represented by the orographic Froude number (U/Nh, where U is the mean wind speed, N the buoyancy frequency and h the mountain height) and the thermal Froude number (U/Nd, where d is the heating or cooling height) (see Lin 2007, p. 195).

4. Summary and Conclusion

In this study, we aimed to investigate the impacts of mechanical and thermal forcing while MVs from the Arabian Peninsula interacts with the EH terrain, which later organized downstream side of the terrain and produced the pre-Debby AEWs. Outgoing Longwave Radiation analysis shows how convective systems came in bursts and sustained its development. The advection, blocking, splitting, and merging processes among the convective cloud clusters can be seen clearly from the terrain sensitivity experiments while the MVs interact with the EH terrains. Flattened topography also causes an increase in surface temperature over the EH. The increase in temperature is also associated with the reduction of topographic uplift. Diabatic Heating strengthens the vortex intensity, which is concluded from the NLHT case. The relative strength of these forcing depends on several factors, which may be represented by the orographic Froude number (U/Nh) and the thermal Froude number (U/Nd). Thus, require further investigation.

The findings of this study provide important insights into the physical processes that govern the formation and evolution of the AEWs and their subsequent influence on the development of hurricanes in the Atlantic Ocean, which can be useful for improving seasonal forecasting and predicting the behavior of these storms.

5. Acknowledgements

This research is supported by the National Science Foundation (NSF) Award #260394. We also acknowledged the NCAR Computational and Information Systems Laboratory (CISL) for their support of the computing time on the Cheyenne supercomputer (Projects UNCT0005 and UNCT0001).

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Table 1

Case	Key Features	Remarks
CNTL	Real control case. 2 nested domains with Δx = 16 km (D1), 4 km (D2).	Capture the synoptic scale features of the AEW preceding the genesis of TC Debby.
NLHT	No Latent Heating case. Same as CNTL except turned off Latent Heat from the Microphysics.	Reduce the strength of the vortex. Hence thermal forcing helps to strengthen the vortex intensity
MTN50	Same as CNTL except for 50 percent of the Ethiopian Highlands terrain is removed.	The blocking effect was reduced as the mountain was removed.
NMTN	Same as CNTL, except the Ethiopian Highlands terrain is removed.	No blocking effect. Vortex moves faster than CNTL and Observed.
NDHT	No Diurnal Heating case. Same as CNTL except turned off surface layer and boundary layer physics.	Reduce the strength of the Vortex.

Figure 1

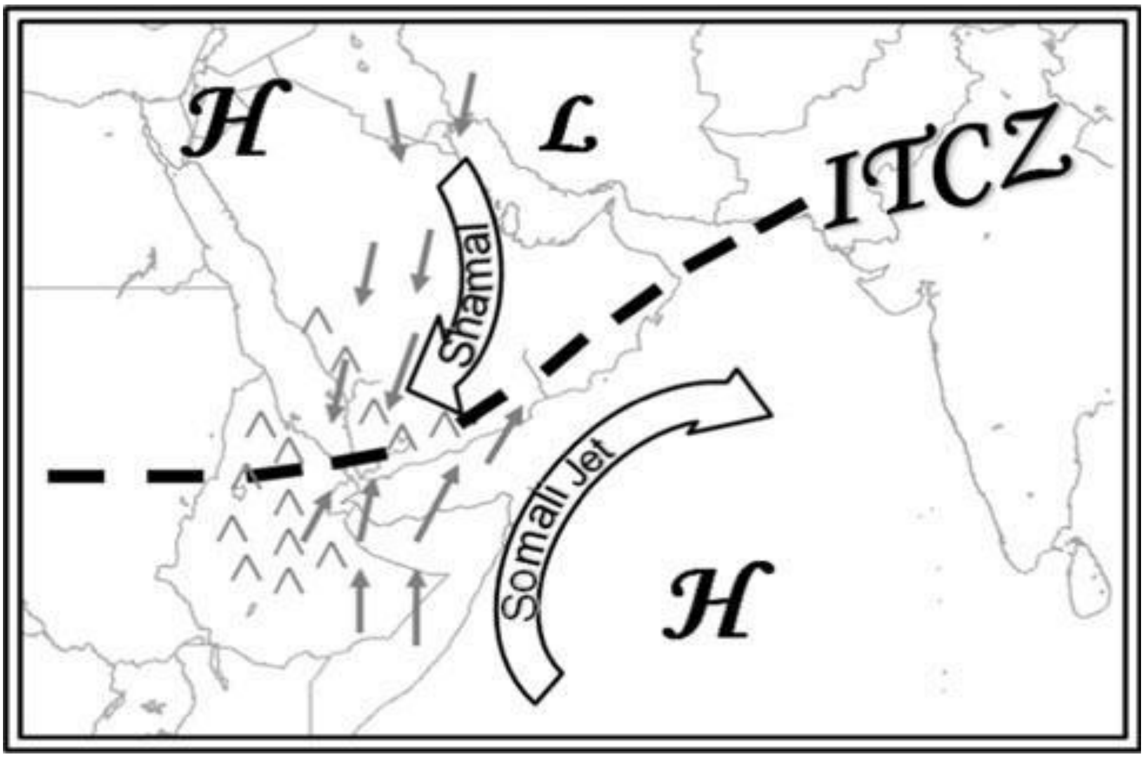

Figure 1: A conceptual model of the generation of cyclonic vorticity perturbations and convective cloud clusters preceding the pre-Debby (2006) AEW–MCS system. The sources of the convective cloud clusters and vorticity perturbations were attributed to the cyclonic convergence of northeasterly Shamal wind and the Somali jet, especially when the Mediterranean High shifted toward east with high pressure ridge extended farther to the southeast and the Indian Ocean high strengthened and its associated Somali jet penetrated farther to the north. Figure is taken from Lin et al. (2013).

Figure 2

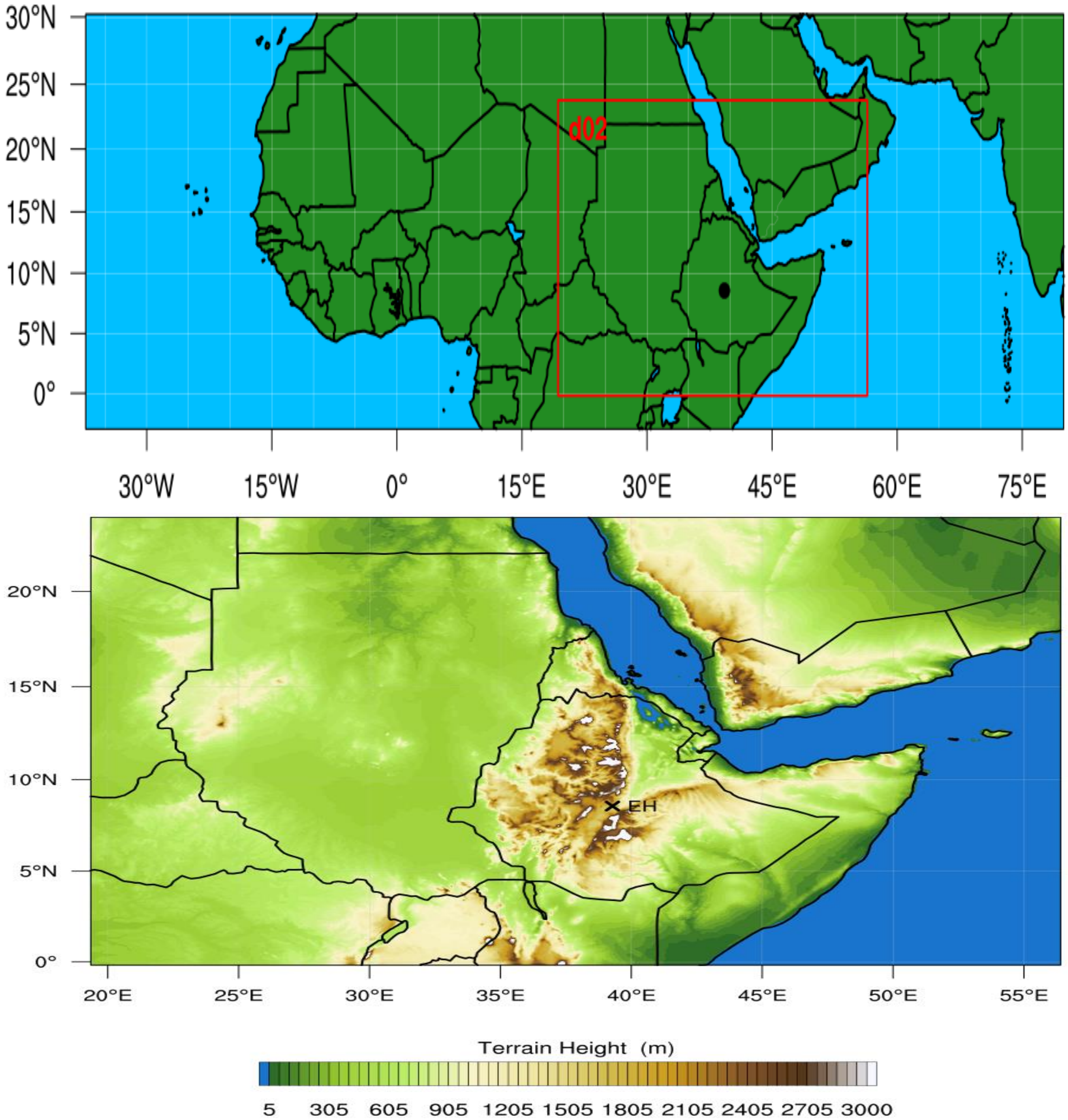

Figure 2: (top) Domain configuration of d01 and d02 with a horizontal grid spacing of 16 km and 4 km. (bottom) Terrain geometry of d02, which covers some parts of northeastern Africa, including Ethiopia, Eritrea, Sudan, Yemen, and the southern part of Saudi Arabia. The terrain height (shaded) is in m. Labels indicating major topographic locations: EH for the location of the Ethiopian Highlands.

Figure 3

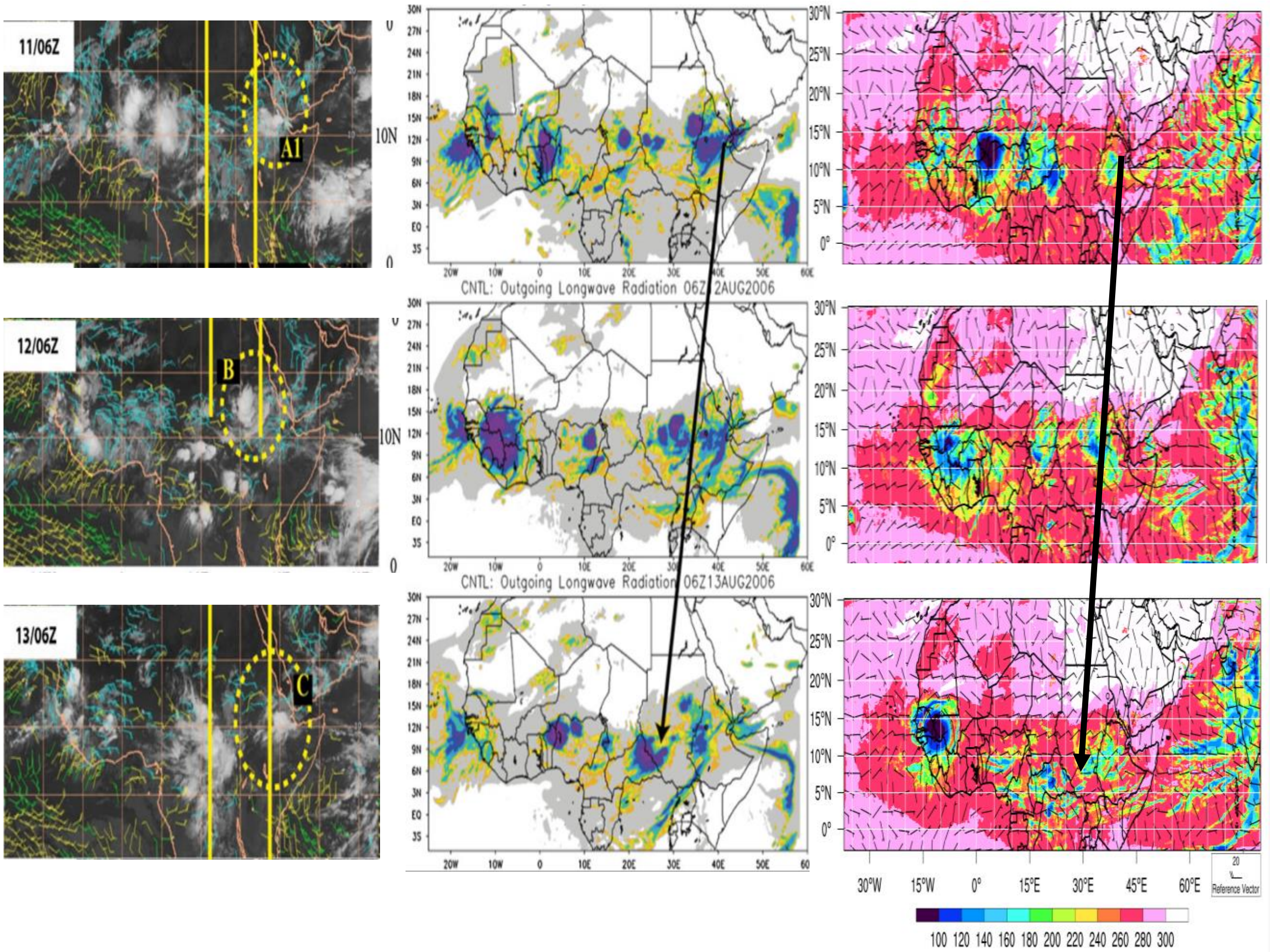

Figure 3: Comparison of Outgoing Longwave radiation (shaded; Wm^{-2}) among the Satellite (left panel), L13 (middle panel), and our CNTL-D1 simulated (right panel) valid at 08/11/06Z, 08/12/06Z, and 08/13/06Z. The local OLR minima, as denoted by the concentrated blue areas in the horizontal belt, are used as a proxy of Mesoscale Convective Systems.

Figure 4

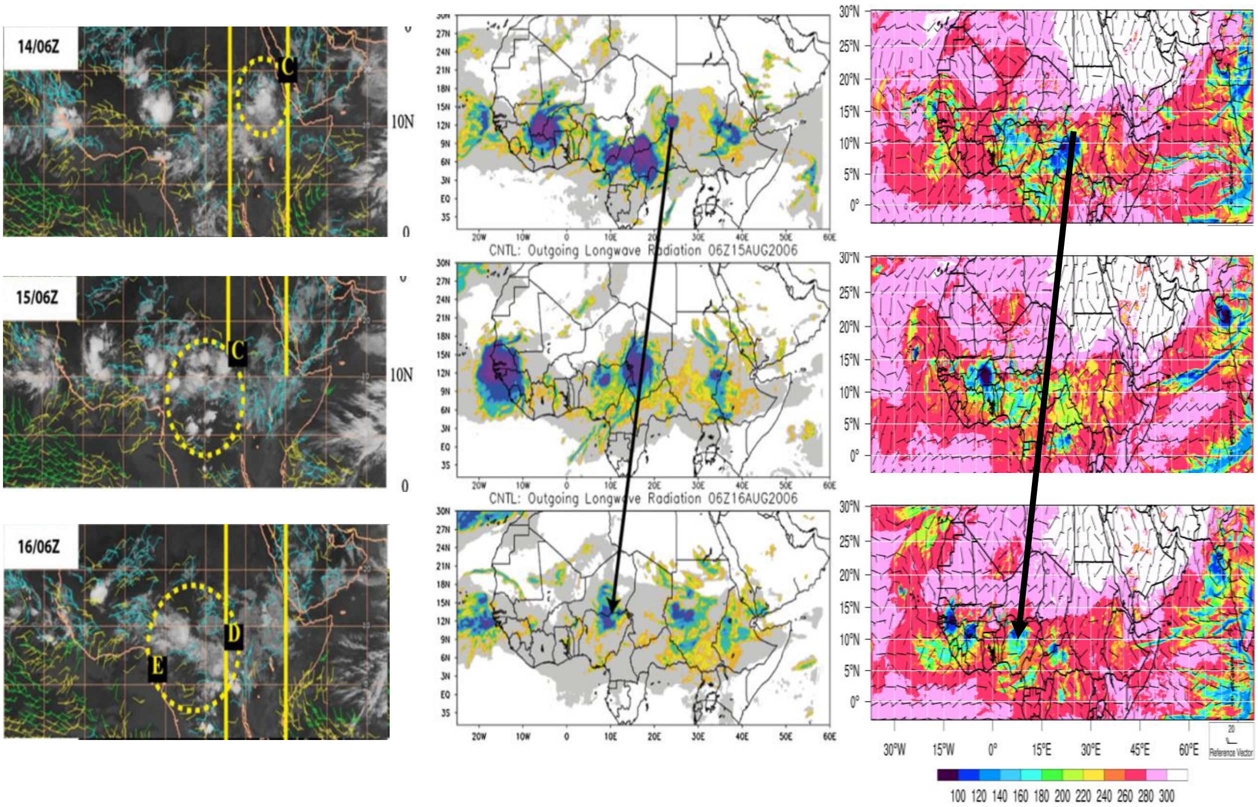

Figure 4: Same as Figure 3 except valid at 08/14/06Z, 08/15/06Z, and 08/16/06Z.

Figure 5.

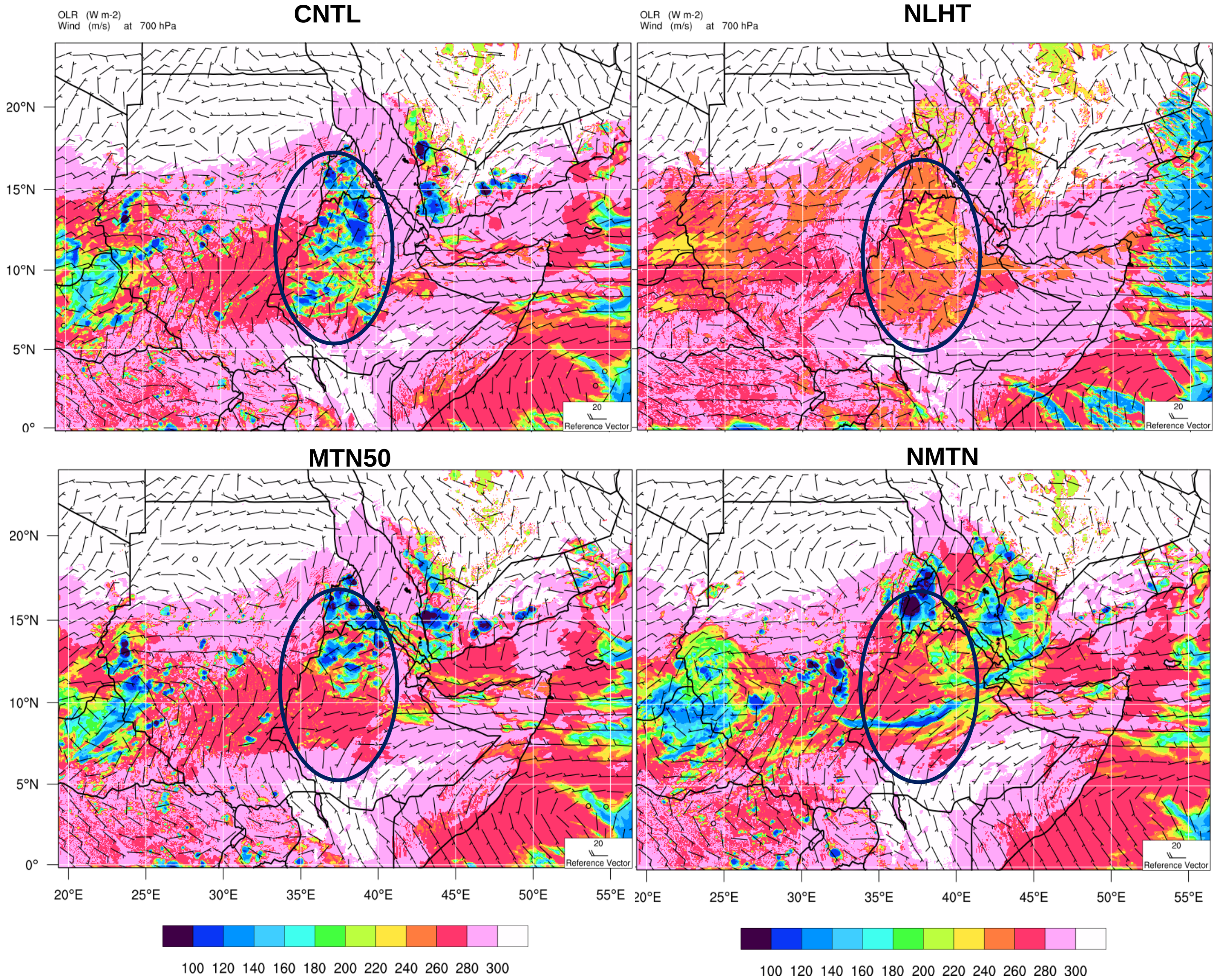

Figure 5: Blocking and Splitting stage: The D2 Outgoing Longwave radiation at 700hPa for the CNTL, NLHT, MTN50, and NMTN cases valid at 08/12/00Z, 2006. The westward propagating MVs interact with EH terrains.

Figure 6.

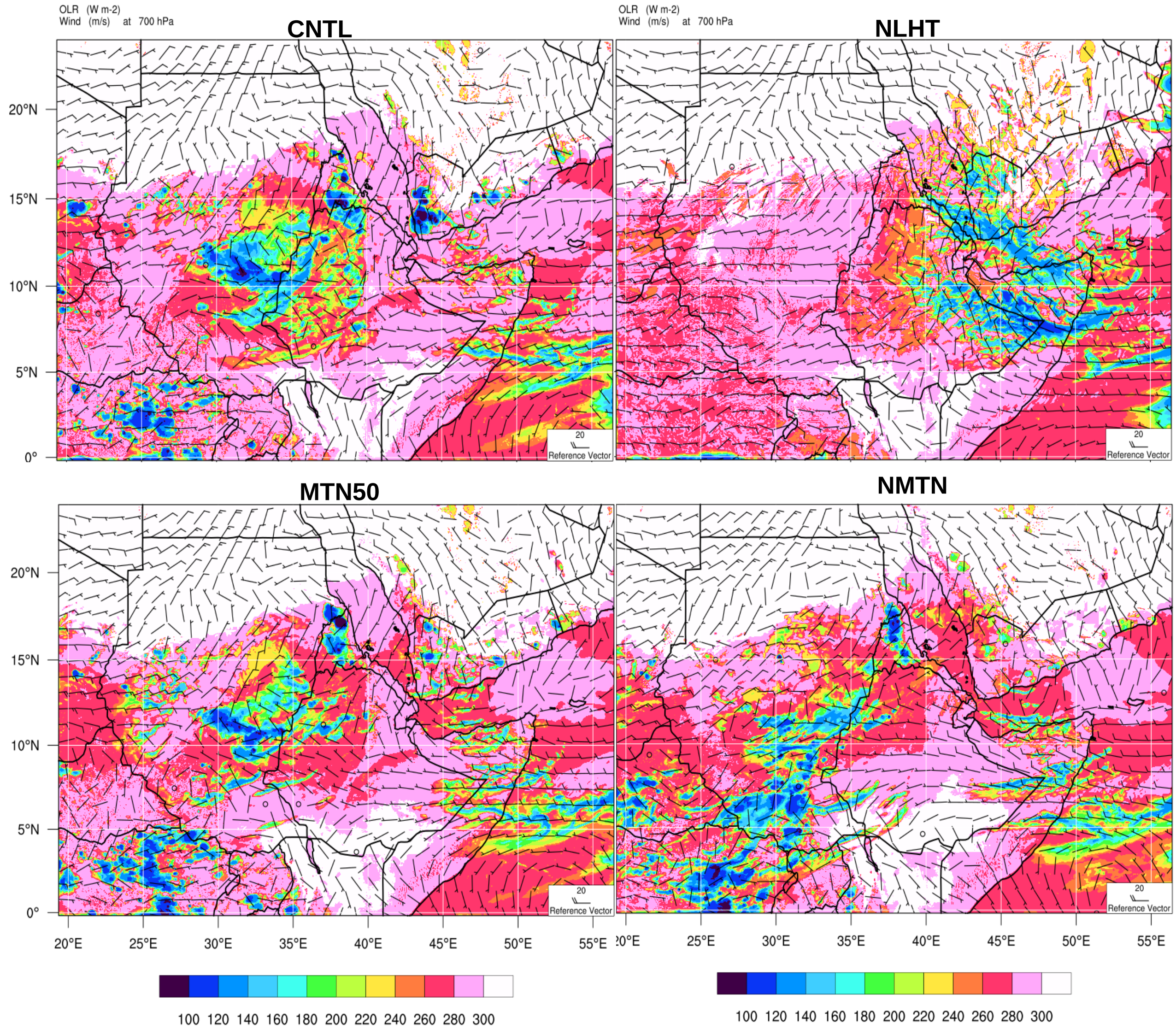

Figure 6: Merging Stage: The splitted cloud clusters merged the downstream side of the EH terrain. The D2 OLR valid at 08/13/00Z, 2006.

Figure 7.

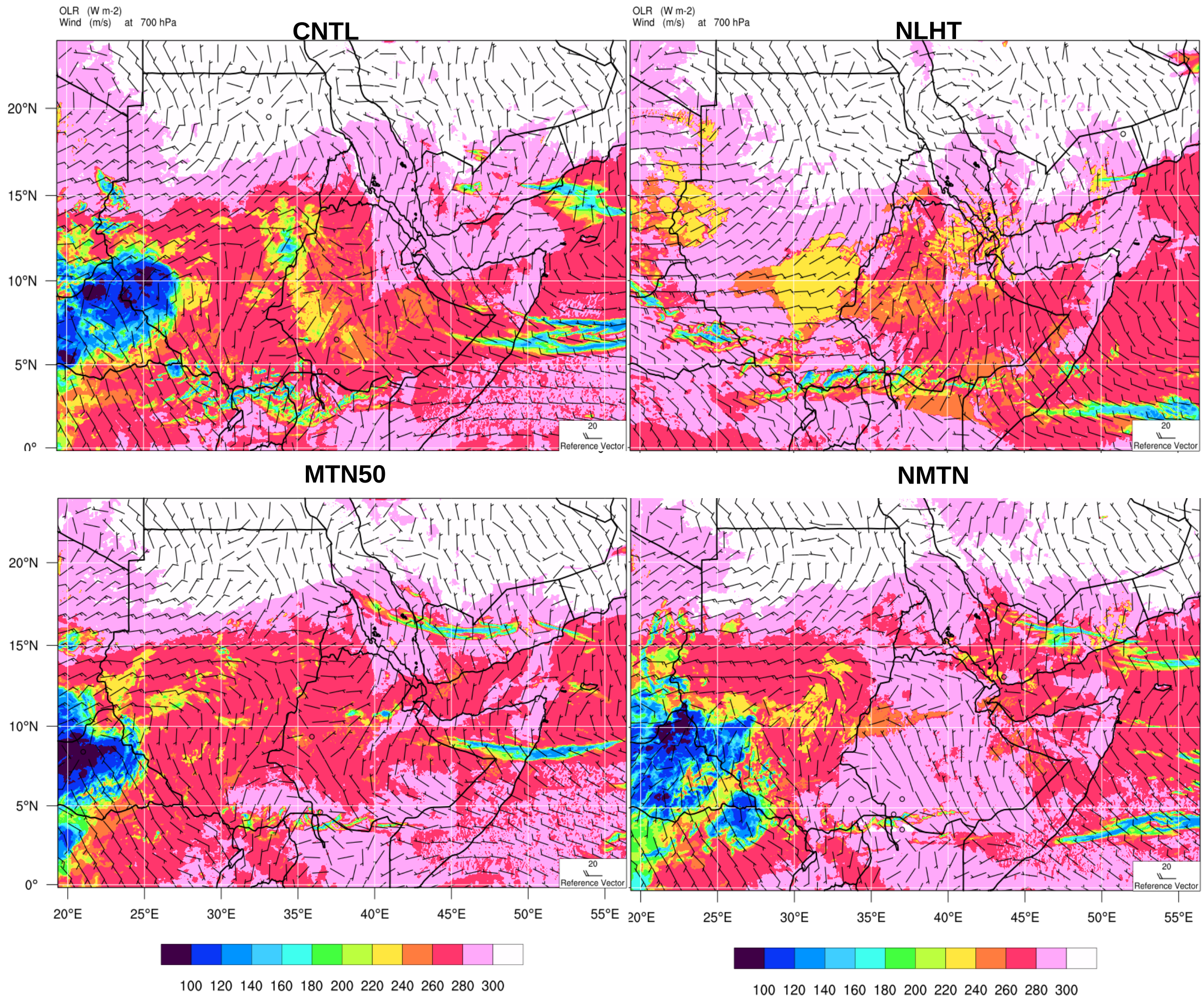

Figure 7: Same as figure 5 except valid at 08/15/00Z, 2006. The organized convective cloud clusters move westward.