6A.5 A NUMERICAL STUDY ABOUT THE IMPACTS OF DRY AIR ON TROPICAL CYCLONE FORMATION

Cody L. Fritz* and Zhuo Wang
Department of Atmospheric Sciences
University of Illinois at Urbana-Champaign
Urbana-Champaign, Illinois

1. INTRODUCTION

Dry air intrusion is one of the factors that affect tropical cyclone formation, particularly, over the North Atlantic, where the basin is subject to frequent Saharan dust outbreaks and large-scale subsidence. The impact of the Saharan Air Layer (SAL) on tropical cyclone activities over the Atlantic has attracted a lot of attention in recent years, but the mechanisms are not well understood.

Using GOES Satellite imagery and GPS dropsonde data, Dunion and Velden (2004) suggested that the SAL suppressed tropical cyclone activity over the Atlantic. Evan et al. (2006) reported an inverse relationship between the North Atlantic tropical cyclone days and the atmospheric dust cover based on a statistical analysis. The negative influences of the SAL on tropical cyclone intensification were disputed recently by Braun (2010). He showed that comparisons between strengthening and weakening storms provide little evidence for significant negative SAL impact. Positive influences of dry air on tropical cyclone development have been proposed by some earlier studies. Karyampudi and Carlson (1988) and Karyampudi and Pierce (2002), for example, suggested the SAL promotes strong baroclinicity along its southern border, strengthens the midlevel easterly jet, and enhances convective precipitation in the equatorial zone, which is favorable for the maintenance and intensification of tropical wave disturbances.

A majority of the tropical cyclones over the Atlantic originate from tropical easterly waves (e.g., Landsea 1993). The impacts of dry air on tropical cyclone formation thus need to be studied in the context of these synoptic-scale waves. A new framework for tropical cyclone formation within tropical waves was recently proposed by Dunkerton *et* al. (2009) (hereafter DMW09). DMW09 demonstrated that the critical layer of a tropical easterly wave, which forms from the nonlinear interaction of the wave with the mean flow, is the preferred location for tropical cyclone formation. The cat's eye in the wave critical layer is a region of weak strain/shear deformation and provides a favorable environment for deep convection and vorticity aggregation in the lower troposphere. This was named the "marsupial paradigm". The closed circulation within the wave critical layer is also called the "wave pouch". Wang (2012) showed that the thermodynamic conditions near the pouch center are particularly favorable for genesis.

The marsupial paradigm provides a framework to systematically examine the dynamic and thermodynamic evolution of precursor disturbances. The objective of our study is to understand how dry air may affect tropical cyclone formation through the analysis of numerical model simulations in the marsupial framework, particularly with regards to how dry air may get into a wave pouch and influence the moist convection near the pouch center. The pre-genesis evolution of Tropical Storm Fay (2008) and the post-storm evolution of Tropical Storm Gaston (2010) are simulated using the Weather Research and Forecasting (WRF) model.

* *Corresponding author and address*: Cody L. Fritz, Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign, Urbana, IL 61801.
E-mail: Fritz7@illinois.edu

2. SYNOPTIC OVERVIEW OF FAY (2008) AND GASTON (2010)

Tropical Storm Fay (2008) developed from a tropical easterly wave that departed the African coast on 06 August 2008. Fay was classified as a tropical depression at 1200 UTC 15 August 2008, and upgraded to a tropical storm six hours later. Prior to genesis, the pre-Fay disturbance encountered dry air from the northwest. However, the dry air did not seem to intrude to the center of the circulation, and convection near the pouch center remained vigorous and became better organized on August 14-15. Our simulation focuses on the pre-genesis evolution of Fay.

Another storm examined in this study is Gaston. Gaston was a short-lived storm that developed from an African Easterly Wave (AEW) on 01 September 2010. Despite warm sea surface temperatures (SSTs) (28-31°C) and moderate wind shear as indicated by the NHC observational analysis, Gaston (2010) quickly weakened to a tropical depression within 24 hours and then was downgraded to a remnant low. The remnant low continued moving westward but did not re-intensify. Our simulation focuses on the post-storm stage of Gaston, or the ex-Gaston disturbance. It thus can be regarded as a non-developing wave.

3. MODEL SIMULATIONS AND ANALYSIS DESCRIPTION

3.1 Numerical Model Simulation Description

The model used in this study is the Advanced Research Core of Weather Research and Forecasting model (WRF-ARW) version 3.2.1 (Skamarock *et* al. 2005). A high-resolution numerical model simulation was conducted for Tropical Storm Fay (2008) by adopting a four-grid nested domain with the horizontal grid spacing of 27-9-3-1 km and a two-grid nested simulation with the horizontal grid spacing of 27-9 km was adopted for ex-Gaston. The simulation for Fay was run 84 hours from 0000 UTC 13 until 1200 UTC 16. The evolution of ex-Gaston was simulated from 0000 UTC 04 September to 0000 UTC 07 September 2010. Initial and boundary conditions of both simulations were derived from the ERA-Interim 6-hourly data.

3.2 Budget Formulation

The water vapor budget equation in cylindrical coordinates can be written as

$$\frac{\partial \overline{q_v}}{\partial t} = -\overline{u}\frac{\partial \overline{q_v}}{\partial r} - \overline{w}\frac{\partial \overline{q_v}}{\partial z} - \overline{u'\frac{\partial q_v'}{\partial r}} - \overline{w'\frac{\partial q_v'}{\partial z}} + \overline{NC} + \overline{B_v} + \overline{D_v}$$

where q_v is the water vapor mixing ratio, the overbar denotes azimuthal average with respect to the pouch center and the prime denotes the asymmetric component with respect to the azimuthal average. The term on the left hand side (LHS) of the equation is the water vapor tendency in the wave co-moving frame of reference. The first two terms on the RHS are the radial (or horizontal) and vertical advection associated with the azimuthal-mean transverse circulation, and the third and fourth terms are radial and vertical advection by the asymmetric eddies. The other three terms, $\overline{NC}$, $\overline{B_v}$ and $\overline{D_v}$ represent the net condensation, the contribution from the planetary boundary layer parameterization, and the residual term, respectively.

4. TROPICAL STORM FAY

Water budget terms for pre-Fay are averaged over 24-48 h, a time period prior to the formation of the tropical depression. The azimuthally averaged water vapor budget fields are displayed in Fig. 1. The water vapor tendency field (Fig. 1a) shows general moistening near the pouch with areas of weak drying above the pouch center between 6-8 km altitude and beyond 150 km radii below the 4 km altitude. In particular, there is moistening tendency of about 1-2 g kg^{-1} day^{-1} near the pouch center between 1-4 km altitude.

The mean radial advection term and the mean vertical advection term are shown in Fig. 1b and Fig. 1c, respectively. The mean radial advection term shows a quadrature pattern below 8 km within the 200-km radius as the inflow converges moisture to the pouch center in the boundary layer and the weak outflow transports moisture outward above the boundary layer. The mean vertical motion transports moisture from the boundary to the free atmosphere, contributing to a negative tendency in the boundary layer and lower troposphere and positive tendency above.

The net condensation term represents the major moisture sink above the boundary layer (Fig. 1d). The maximum condensation occurs near the pouch center and peaks around 4 km. At radii larger than ~100 km, net condensation stronger than 3 g kg^{-1} day^{-1} is confined primarily above the freezing level (~3 km), and there is only weak drying below the freezing level (< 300m). This indicates that convective precipitation is dominant near the pouch center and that the contribution from stratiform precipitation increases at the large radii. The PBL term (B_v) contributes a strong positive tendency near the surface (not shown), similar to a mature storm (Braun 2006).

The eddy horizontal advection term (Fig. 1e) contributes to drying over the pouch center from 6-10 km and drying in the lower troposphere at radii larger than 300 km. The former represents the middle to upper level dry air intrusion, and the latter indicates lateral dry air entrainment at the pouch periphery. The eddy vertical advection term (Fig. 1f) contributes to negative tendency below 3 km and between 5-7 km and moistening between 8-11 km. Overall, the eddy terms are much weaker than the mean advection terms, indicating relatively weak pouch relative flow and asymmetric eddies, and the mean vertical motion plays the dominant role in moistening the free atmosphere.

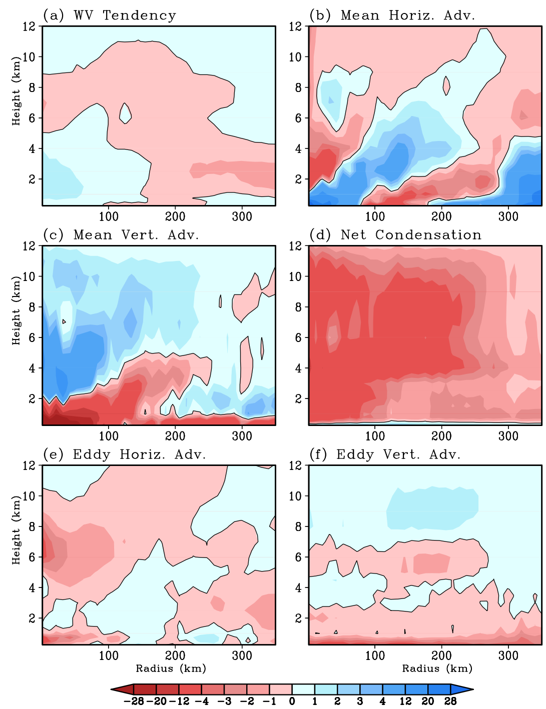

FIG. 1 Azimuthally averaged water vapor budget fields for Fay (2008) averaged between 24-48 h: (a) net water vapor tendency, (b) mean horizontal advection, (c) mean vertical advection, (d) net condensation, (e) eddy horizontal advection, and (f) eddy vertical advection. The units of the variables are g kg^{-1} day^{-1}.

To examine the dry air pathway and evolution, the HYSPLIT model was used (Draxler *et* al. 2009) to assess the 3-diminsional (3D) trajectories of dry air particles, and three scenarios during the evolution of Fay are examined: two at the tropical wave stage and one at the tropical storm stage.

In scenario 1 (Fig. 2a), the pathway of dry air in the upper troposphere (~7 km or 400 hPa) at the wave stage (1000 UTC 13 August 2008) is examined. The streamlines in the co-moving frame show that the wave is open with extremely dry air (~15% RH) ahead (west) of the wave trough axis. The time series of the pressure (not shown) along the trajectory of an air parcel initialized west of the low-level pouch center shows that the air parcel stays around its initial level before 42 h and then descends to near 650 hPa, suggesting that dry air is transported to near the pouch center from the upper troposphere.

In scenario 2, 30 hours prior to the formation of the tropical depression (0000 UTC 14 August), a dry air slot is wrapped around the wave pouch along its eastern periphery (Fig. 2b). The HYSPLIT trajectory model shows that an air parcel initialized in the dry air region at ~650 hPa stays at the wave pouch periphery and does not move to the pouch center region.

In a final scenario, (Fig. 2c), the trajectory is initialized at 1000 UTC 15 August (2 hours prior to the formation of the tropical storm), and the dry air entrainment along the northwestern periphery of Fay at the tropical storm stage is examined. Although the particle gets less than 100 km from the pouch center, it has become quite moist by then (RH of the particle increases from 35% to 80-90%).

The second and the third scenarios suggest that the dry air entrainment may suppress convection at the pouch periphery but may not affect convection near the pouch center.

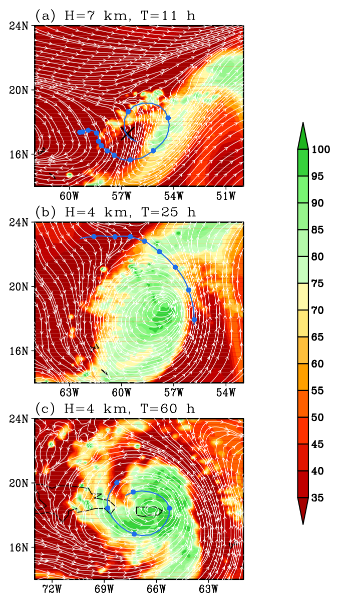

FIG. 2 Trajectory analysis of pre-Fay: forward trajectory and streamlines in the commoving frame of reference superimposed on relative humidity. The cross in (a) represents the pouch center at 4 km. The points along the trajectories in (a), (b), and (c) represent the position of the parcel every 6 hours.

5. NON-DEVELOPER – GASTON (2010)

The non-development of ex-Gaston (2010) is examined in this section. The time-height cross section (not shown) of RH shows presence of dry air above 7 km altitude throughout the simulation with RH as low as 40%, which is in contrast to the transient dry air intrusion in Fay. Moreover, analysis of the vertical profile of θ_e shows a mid-level minimum at 5-6 km altitude, which decreases from 1800 UTC 04 September to 0600 UTC 06 September by about 4 K. The mid-level θ_e remains below 340 K throughout the simulation, and the difference in θ_e between the surface (values around 357 K) and the 5-km level remains well above 15 K, while in pre-Fay the θ_e difference is reduced from 15.6 K to 4.9 K at 1200 UTC before genesis.

To analyze the cause for the drying in the middle troposphere we evaluate the evolution of dry air surrounding the wave pouch of ex-Gaston. A snapshot of RH at 3 km is shown in Fig. 3a. Ensemble trajectories are superimposed on the translated streamlines in Fig. 3a. The particles are released on 0800 UTC 05 September 2010 at the southern boundary of the wave pouch at 709 hPa, where RH is less than 35%. The air parcel trajectories have a bifurcation at the pouch separatrix: a few air parcels move eastward relative to the wave pouch, and most air parcels take a cyclonic route. All air parcels, except one, stay off the pouch center during the 40-hour trajectory evolution.

Moreover, Fig. 3a reveals pockets of isolated dry air near the pouch center. The vertical cross-section going through a dry air pocket along 17.5N (Fig. 3b) reveals a deep structure of the dry air extending from 9 km all the way down to 3 km. This suggests that the dry air source may come from the upper troposphere. To confirm this, we employed ensemble backward trajectories that were initialized at 0800 UTC September 05 2010, starting within the dry air pocket (highlighted by a box in Fig. 3a). The trajectory analysis (figure not shown) shows that a large number of particles originate above their initial pressure level and most of these particles have lower RH. The backward trajectory analysis confirms that dry air is transported downward and contributes to the mid-level drying near the pouch center.

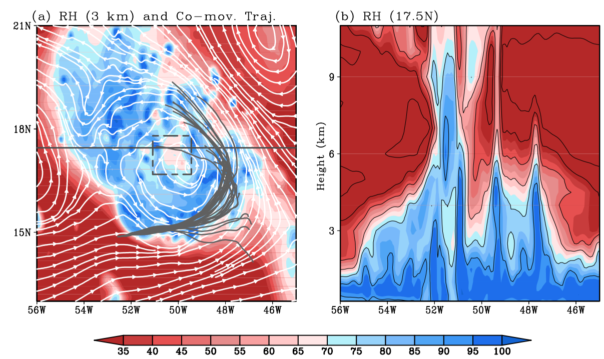

FIG. 3 (a) 3 km relative humidity and storm relative streamlines for Gaston (2010) at 0800 UTC 05 September 2010; (b) vertical cross section of RH along 17.5N (contour intervals are set to 15%). The box in (a) highlights a pocket of dry air near the pouch center. The line in (a) highlights the cross section location shown in (b). Ensemble forward particle trajectories (gray) and streamlines are both shown in a wave co-moving framework. The forward trajectories have a runtime of 40 hours.

To further examine the potential impacts of dry air on the evolution of Gaston, the water budget terms are averaged over 31-36 h, a time period when drying takes place above the boundary layer and equivalent potential temperature decreases in the middle troposphere. As shown in Fig. 4a, the mixing ratio decreases near the pouch center from 1 km to 12 km, with the maximum drying of about 2-4 g kg^{-1} day^{-1} occurs from 2-8 km. Figure 3a also shows a drying tendency of 2-6 g kg^{-1} day^{-1} at radii larger than 200 km below 5 km.

The mean horizontal advection term is shown in Fig. 4b. It contributes to moistening between 20-250 km radii in the boundary layer, and drying tendency is dominant above the boundary layer. Compared to pre-Fay, the overall pattern is much noisier.

The mean vertical advection term (Fig. 4c) contributes to drying in a thin layer near the surface, and areas of drying tendency are also found above 1 km, in particular from 3-10 km over the pouch center, which is in contrast to the strong and prevailing moistening induced by the vertical advection term in pre-Fay. The transverse circulation (not shown) suggests that this is associated with the downward motion below 6 km over the pouch center.

Figure 4d shows that the net condensation at multiple radii has two maxima, one around 8 km and the other around 4 km altitude. The former indicates possible contribution by stratiform processes. Net evaporation is present near the pouch center and at several other radii, contributing to a positive tendency.

The eddy horizontal advection term (Fig. 4e) contributes to drying above 5 km within the 200 km radius and drying below 5 km near the pouch periphery. The former can be attributed to the pouch-relative flow in the middle-upper troposphere, where a closed circulation is absent, and the latter represents lateral dry air entrainment due to the pouch relative flow and mesoscale eddies. The eddy vertical advection terms (Fig. 4f) contribute to drying below 3 km at most radii with a magnitude slightly smaller than the mean vertical advection term. It also contributes to moistening about 2-4 g kg^{-1} day^{-1} above 7 km at radii between 100-220 km.

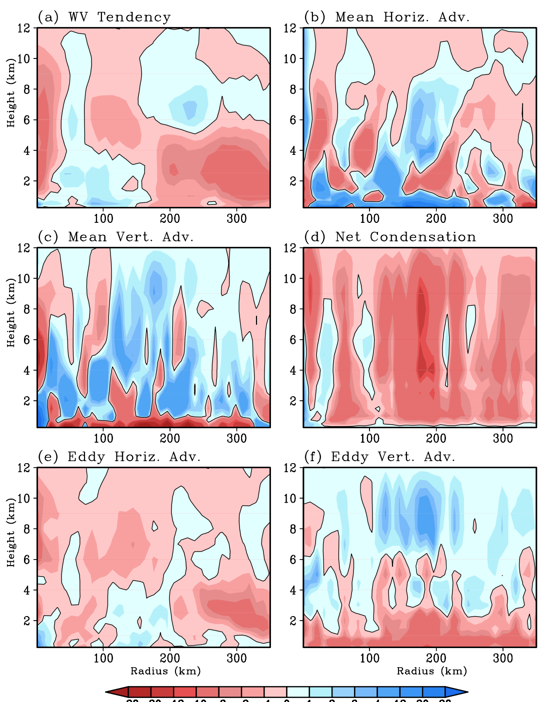

FIG. 4 Same as Fig. 1 except for the simulation of ex-Gaston. Each term is averaged over 31-36 h.

6. CONCLUSIONS AND DISCUSSION

In this study, ex-Gaston (2010) and pre-Fay (2008) were simulated using the WRF model to examine the impacts of dry air on the storm evolution. Both ex-Gaston and pre-Fay were subject to the impacts of dry air during their lifetime, but the former failed to re-develop after being downgraded to a remnant low, and the latter developed into a tropical storm despite lateral dry air entrainment in the middle troposphere and transient dry air intrusion at the upper levels.

Three-dimensional trajectory analysis suggests that dry air entrained at the pouch periphery does not penetrate to the pouch center due to weak mid-level inflow in the model simulation of pre-Fay. On the other hand, ex-Gaston is subject to the persistent impacts of middle- to upper-level dry air intrusion, and the model simulation shows a decrease in the mid-level equivalent potential temperature near the pouch center due to drying, which is consistent to the observation. Backward trajectory analysis based on the simulation of ex-Gaston indicates downward transport of dry air from the middle-to-upper troposphere, where a well-defined wave pouch is absent.

The water vapor budget analysis shows the low-level inflow converges moisture within the wave pouch in the boundary layer, and the mean vertical moisture transport plays the dominant role in moistening the free atmosphere in both storms. The analysis from ex-Gaston confirms the contribution of downward transport of dry air to mid-level drying. When convection is suppressed by the mid-level drying, the moisture supply to the middle troposphere is reduced, which further enhances the mid-level drying. Also, in both storms, the eddy horizontal advection term indicates dry air entrainment at the pouch periphery.

REFERENCES

Braun, Scott A., 2010: Reevaluating the Role of the Saharan Air Layer in Atlantic Tropical Cyclogenesis and Evolution. Monthly Weather Review, 138, 2007-2037.

Braun, S.A., 2006: High-Resolution Simulation of Hurricane Bonnie (1998). Part II: Water Budget. J. Atmos. Sci., 63, 43–64.

Draxler R., Stunder B., Rolph G., Stein A., Taylor A., 2009, HYSPLIT4 user's guide, Ver. 4.9, http://www.arl.noaa.gov/docments/reports/hysplit user guide.pdf.

Dunion, J.P., and C.S. Velden, 2004: The Impact of the Saharan Air Layer on Atlantic Tropical Cyclone Activity. Bull. Amer. Meteor. Soc., 85, 353–365.

Dunkerton, T. J., Montgomery, M. T., and Wang, Z, 2009.: Tropical cyclogenesis in a tropical wave critical layer: easterly waves, Atmos. Chem. Phys., 9, 5587-5646.

Evan, A. T., J. Dunion, J. A. Foley, A. K. Heidinger, and C. S. Velden, 2006: New evidence for a relationship between Atlantic tropical cyclone activity and African dust outbreaks, Geophys. Res. Lett., 33, L19813, doi:10.1029/2006GL026408.

Karyampudi, V. M., and H. F. Pierce, 2002: Synoptic-scale influence of the Saharan air layer on tropical cyclogenesis over the eastern Atlantic. Mon. Wea. Rev., 130, 3100–3128.

Karyampudi, V. M., and T. N Carlson, 1988: Analysis and numerical simulations of the Saharan air layer and its effect on easterly wave disturbances. J. Atmos. Sci., 45, 3102-3136.

Landsea, Christopher W., 1993: A Climatology of Intense (or Major) Atlantic Hurricanes. Mon. Wea. Rev., 121, 1703–1713.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang, and J. G. Powers, 2005: A Description of the Advanced Research WRF Version 2. NCAR technical note 468+STR, 88 pp.

Wang, Z., 2012: Thermodynamic Aspects of Tropical Cyclone Spin-up. J. Atmos. Sci., accepted.