P3.500 Numerical Studies of Lower Boundary Forcing on Tropical Storm Fay (2008) over Southern Florida

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1. Introduction

The physical processes of how tropical cyclones maintain or re-intensify over land is still not well understood and poorly predicted. For instance, Tropical Storm Fay (2008) produced damaging winds and rain across most of Florida with heavy rains, both transient and sustained, which resulted in flash flooding which caused the most damage with this storm. Rain ahead and behind Tropical Storm Fay's center of circulation caused major flooding of roadways, homes, and destroyed property through its path.

Previous studies have shown that tropical cyclones extract energy from the underlying ocean surface, and can form and be maintained over waters of 26°C or greater (e.g., Wu et. al 2005). Research has shown once tropical cyclones have crossed or become near SST that there is a reduction of oceanic heat; the reduction of SST comes from the tropical cyclone's center of circulation using the stored energy from SST in the form of heat fluxes (e.g., Zhu and Zhang 2005). Tuleya (1994) and Shen et al. (2002) described wet, oceanic like land conditions as favorable for TC maintenance or intensification over land. Emanuel et al. (2008) further noted that warm core vortices could re-intensify over land in an environment of high latent heat fluxes caused by the wetting of hot, sandy soils by rainfall ahead of the storm's vortex.

When tropical cyclones cross-land surfaces there is a reduction of heat, drag coefficient, and all ingredients that help maintain and intensify tropical cyclones. Land surfaces can reduce the drag coefficient of a tropical cyclone by half once it has crossed land, which in turns reduces the wind speed of tropical cyclones. For instance, Lake Okeechobee has a surface area of 730 square miles and the average depth is 9 feet deep making it the largest lake in the southeastern United States. The lake and its surrounding area contain unique land surfaces (i.e., swamp, agriculture and farmland) that may affect the intensity of land falling tropical cyclones.

The main goal of this study is to advance our understanding on how and in what manner TS Fay intensified after landfall. This study will provide better planning and execution of societal and industrial responses at appropriate time scale of evacuation strategies. The objectives of this research include: 1) to understand the role of regional high sea surface temperature over the west coast of Florida and Lake Okeechobee water temperature in terms of the intensification changes after Fay made landfall; 2) to apply the tropical cyclone bogus scheme of the Weather Research and Forecasting (WRF-ARW) model for better gauging winds and precipitation distributions.

In Section 2 the numerical model and experiment design are the synoptic and mesoscale conditions are outlined. Section 3 provides the results, divided into the regional climatology and case study features. Section

4 is a comparative discussion and summary with suggestions for further work.

2. Numerical Model and Experiment design

Numerical simulations were performed using the WRF-ARW version 3.2. The advanced research WRF dynamical core is based on an Eulerian solver for the fully compressible, non-hydrostatic Navier-Stokes equations. Variables are solved in the scalar-conserving flux form. The vertical coordinate is a mass-based terrain-following coordinate, and the horizontal/vertical grid staggering is done on an Arakawa C-grid. The Runge-Kutta third-order time scheme, as well as fifth and third-order positive-definite advection schemes are adopted in the horizontal and vertical directions, respectively. A time-split integration scheme is used on a shorter time-step for the acoustic and gravity-wave modes. Detailed information about the WRF model may be found at: www.wrf-model.org.

A triple-nested simulation of the WRF-ARW model is configured with grid spacing of 30 km (102 x 73), 10 km (133 x 133) and 3.3 km (121 x 211) for domains 1, 2 and 3, respectively. Figure X shows the configuration of the nested domain. The top of the atmosphere in the model is located at 50 hPa, and a total of 28 unequally spaced terrain-following levels in the vertical were employed. The lowest level was about ten meters above ground level. The initial and the time-dependent lateral boundary conditions are both derived from the National Center for Environmental Prediction Operational Model Global Tropospheric Analysis data (FNL, 1.0x1.0 degree) and the Real-Time Global, Sea Surface temperature analyses (i.e., RTG_SST Analysis, 0.0823 degree). A 72-hr simulation is conducted starting at 0600 UTC 19 August 2008, which allowed enough spin-up time for the model results to be reasonably evaluated throughout the duration of the evolution of TS Fay.

The atmospheric radiation scheme accounts for longwave (i.e., RRTM; Mlawer et al. 1997) and Dudhia shortwave transfers and interactions with the atmosphere, clouds, and the surface. The Yonsei University (YSU) planetary boundary layer scheme (Hong et al. 2006) was used. Cumulus scheme (Kain-Fritsch) was only used on domains 1 and 2. The WRF Single-Moment 3-Class microphysical parame-terization was used as well as the Noah Land-surface model. The discussions to follow will concentrate on the inner most 3.3 km resolution domain results, since in this paper we are most interested in the features of the change of intensity and structure of TS Fay that can best be resolved at this resolution.

The first sensitivity experiment is designed to evaluate the sensitivity of SST. In this experiment the SST of the entire domain 3 increased 1 degree (i.e., SST+1). The second experiment is to evaluate the possible contribution from high SST during TS Fay. Thus, we conducted a simulation with SST at 26 degree C in domain 3 (i.e., SST26). In the TCBOG experiment, the WRF-ARW bogussing scheme is applied. It can remove an existing tropical storm, and may optionally bogus in a Rankine vortex for the new tropical storm.

3. Results

a. Control Experiment

The control experiment was setup without changing the predetermined setup to analyze how the WRF model would handle the initialization, movement and intensity of Tropical Storm Fay. The WRF model captured the overall movement and structure of Tropical Storm Fay from 0600 UTC 19 August 2008 to 0000 UTC 20 August 2008. The control experiment movement was to the North North-East across the Southwestern peninsula of Florida and it continued on this course until 0000 UTC 20 August 2008; the movement closely resembled the real-time movement until the 0000 UTC 20 August 2008.

Figure 2 depicts sea level pressure on 1500 UTC, 18 UTC and 21 UTC for the control experiment. The modeled sea level pressures were in the high 990's while the real-time NHC readings were in the mid 980's; taking the experiment sea level pressure and subtracting from the real-time sea level pressure; the control experiment sea level pressure was 10 mb greater than the actual pressure reading for Tropical Storm Fay. The control experiment shows an influx of moisture (i.e., latent heat flux) from the high SST into the center of circulation overland for all time periods (Fig. 3). The control experiment suggested the moisture helped Tropical Storm Fay maintain itself, and eventually intensified overland by causing the environment surrounding the center of circulation to remain unstable. The increase of latent heat and upward heat moisture flux at the surface was ingested into the center of circulation, and used in the same way energy from SST is used by tropical cyclones.

The increase of latent heat and upward moisture flux at the surface was ingested into the center of circulation, and processed in the same manner as energy from SST is used by tropical cyclones. The NW – SE cross-section of vertical velocity at 1800 UTC 19 August 2008 shows the strongest vertical velocities were near the storm and around Lake Okeechobee (Fig. 4a). The NW – SE cross-section of equivalent potential temperature and potential vorticity 1800 UTC 19 August 2009 showed strong gradient of both fields near TS Fay and around Lake Okeechobee (Fig. 4b).

The second experiment SST +1°C was similar to the control experiment with the difference being the SST's. All SST's in the model simulation were increased by 1°C to examine the affects the increase would have on the structure, intensity, movement and environment of Tropical Storm Fay. The location and position of SST +1°C experiment of TS Fay was positioned father to the West than the control experiment. Just like the previous experiments SST 26°C was run to examine the affects the decrease in SST would have on the structure, intensity, movement and environment of Tropical Storm Fay. All SST's in the model simulation were lowered to 26°C which is the minimum threshold for tropical cyclone development; the lowering of SST to the minimum threshold to sustain a tropical cyclone would show that TS Fay needed the influx of warm latent and moisture fluxes to eventually sustain itself and intensify over land. The results for the experiment showed cooler latent heat flux, and SST, which resulted in a higher sea level pressure reading as was expected.

b. TC Bogus Experiment

The TC Bogus scheme was used to simulate the correct pressure reading and location of TS Fay; the other simulations for Tropical Storm Fay had sea level pressure readings 10 mb higher than the real-time recorded sea level pressure. When used in previous studies the TC Bogus scheme correctly simulated tropical cyclone movement, structure and intensity correctly.

Figure 5 depicts sea level pressure on 1500 UTC, 18 UTC and 21 UTC for the TC Bogus experiment. The sea level pressure closely followed what was reported by the NHC with readings in the 986 MB range.

Latent heat flux shows an influx of moisture from the high SST into the center of circulation overland (Fig. 6). The moisture helped TS Fay maintain itself, and eventually intensified overland by causing the environment surrounding to TS FAY to remain unstable.

By 1800 UTC 19 August 2008 showed higher equivalent potential temperature, and vertical velocities values underneath TS Fay's center of circulation and near Lake Okeechobee which helped TS Fay become vertically stacked and eventually intensify (Fig. 7a). Subsequently, by 1800 UTC 19 August 2008, the result shows the vertical velocities were greater underneath TS Fay's center of circulation and Lake Okeechobee (Fig. 7b).

c. HWRF Experiment

The HWRF experiment was setup without changing the predetermined setup to see how the HWRF model would handle the initialization, movement and intensity of Tropical Storm Fay. The components of the HWRF that were not used were POMTC Ocean Model, NCEP Coupler, and GFDL vortex tracker, which could cause HWRF to perform poorly. Unlike the other experiments where the times of 15,18 and 21 UTC were analyzed, the HWRF model only outputs data in six hour intervals allowing us to only use 18 UTC 19 August 2008 time for analysis to compare with real-time data.

Figure 8 of sea level pressure for 18 UTC 19 August 2008 for HWRF model was in the high 990's while the real-time NHC reading for the same time was in the mid 980's; taking the experiment sea level pressure and subtracting from the real-time sea level pressure, the HWRF sea level pressure was 10 mb greater than the actual pressure reading for TS Fay. The latent heat flux for the HWRF (Fig. 9) shows low values of flux around TS Fay's center of circulation. TS Fay's latent and moisture flux was not able to tap into the warmer fluxes from SST to its West and over Lake Okeechobee.

4. Discussion

TS Fay was a unique tropical cyclone by reaching its peak intensity over land; Tropical Storm Fay was able to intensify by using the instabilities ahead of the center of circulation created by its outer rain bands, and above normal SST. The assumption is that TS Fay would not have maintained or intensified without the latent heat and moisture flux at the surface being entrained over land into center of circulation which fueled TS Fay's intensification.

The WRF model performed well with the structure and movement of TS FAY. Although the control experiment was not changed, and the SST experiment was increased by +1°C, both were similar in the pressure readings, position and structure for TS Fay (Fig. 10). The decrease in SST to 26°C, the minimum sea surface temperature to sustain tropical cyclones, caused the pressure of TS Fay to increase and the movement to be much slower than the other experiment simulations. The part of the WRF simulation that did an excellent job of capturing the correct movement and intensity of TS Fay was the TC Bogus scheme. Throughout the simulation TC Bogus kept the sea level pressure close to what was reported by the NHC, which was in the mid 980's, while in the other experiments the sea level pressure was over 10 mb higher than what was reported by the NHC (Fig. 10). HWRF experiment had trouble with sea level pressure, which can be attributed to not using all of the components of the HWRF model. The HWRF simulation showed sea level pressure to be 10 mb over the actual pressure reported to the NHC.

Further research on land use and the effects of water covered land needs to be further examined to help understand processes that help maintain or intensify tropical cyclones over land. Using WRF-VAR OR 3D would greatly improve the simulation of Tropical Storm Fay by using real-time variables and data of the atmosphere and environment surroundings of Tropical Storm Fay. The importance of understanding land use and the affect on tropical cyclones can help our understanding of tropical cyclone intensity prediction and help further the skill of model simulation.

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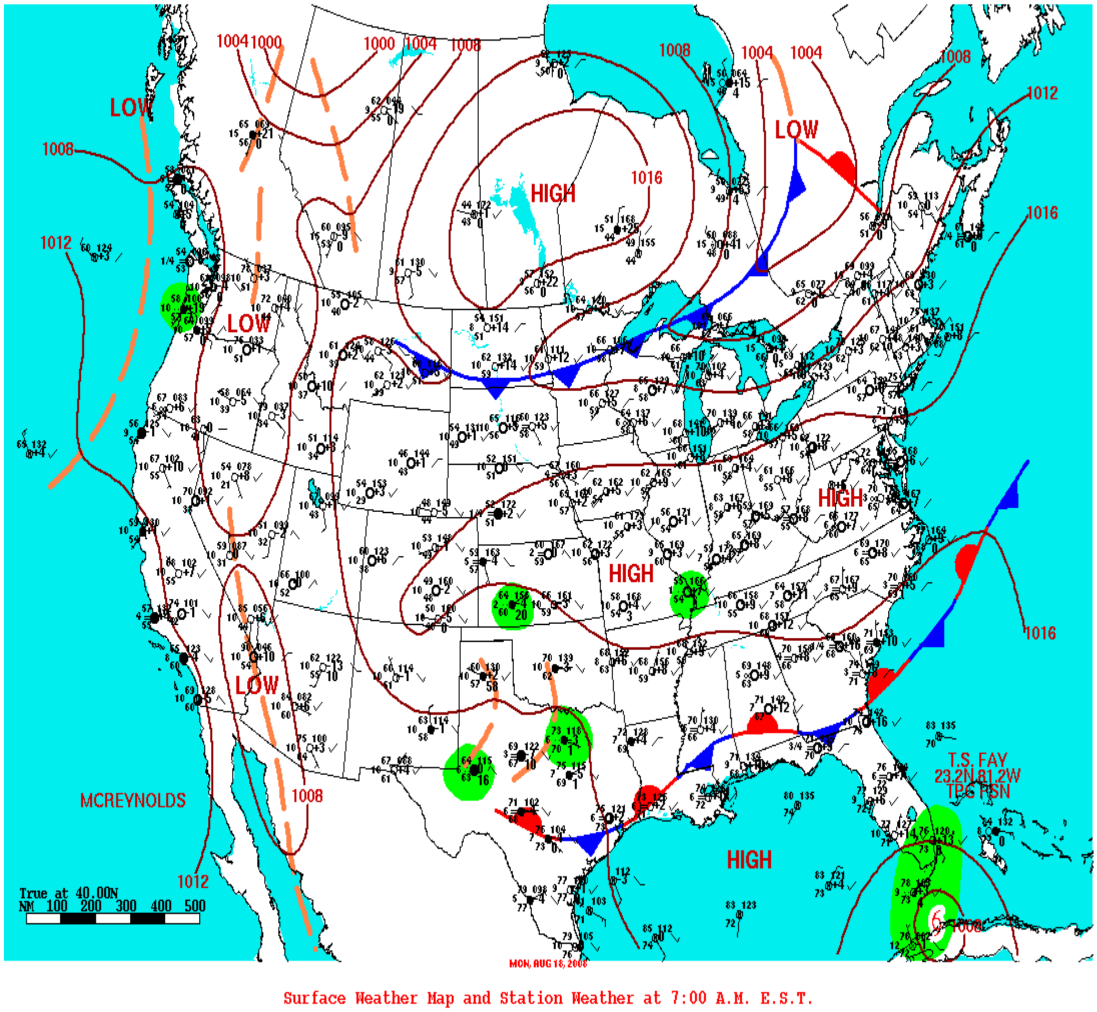

Figure1: Surface weather map valid at 0700 EST 19 August 2008.

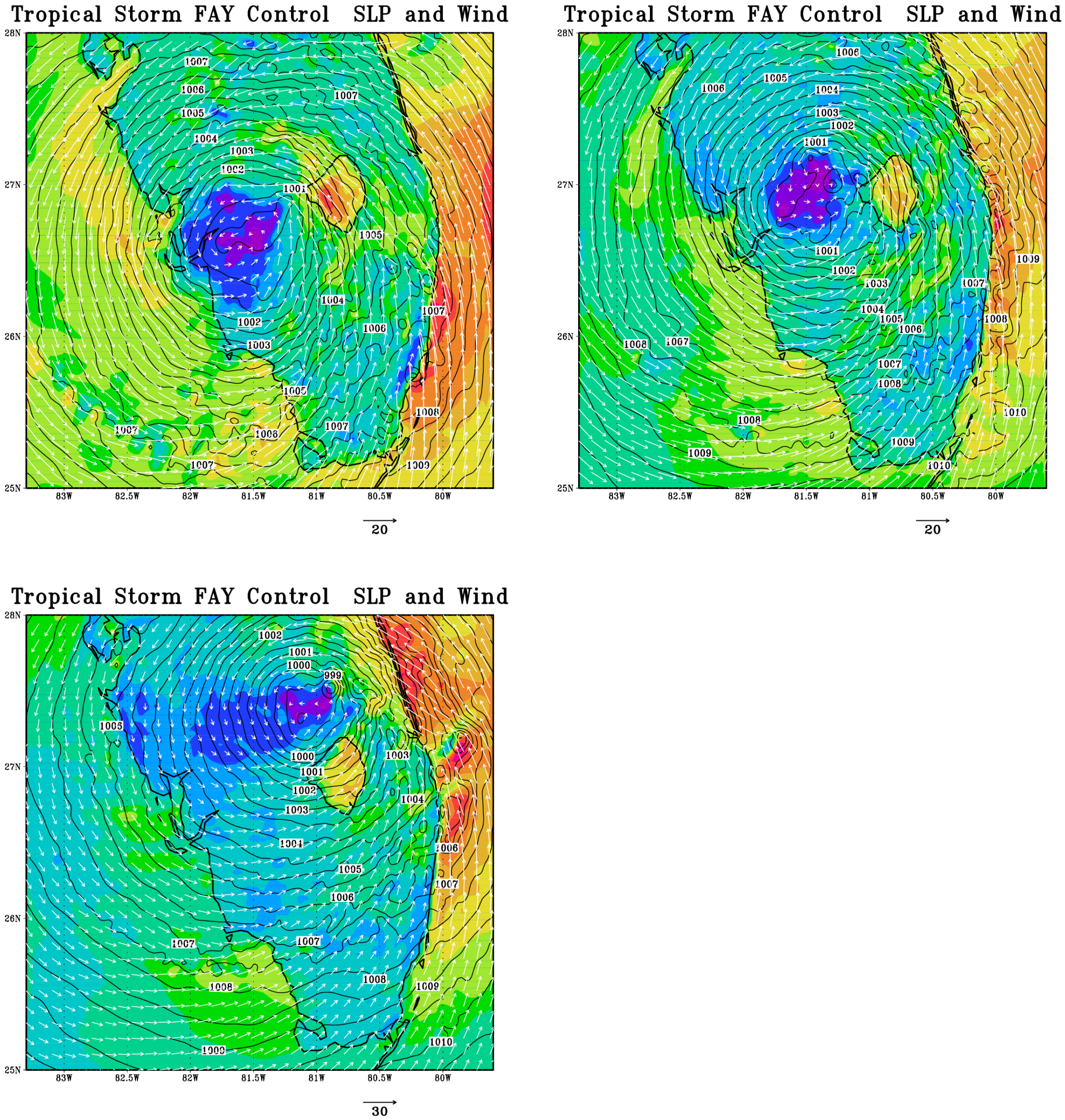

Figure 2 Control Experiment Sea Level Pressure and Wind at (a) 1500 UTC 19. (b) 1800 UTC (c) 21UTC 19 August 2008.

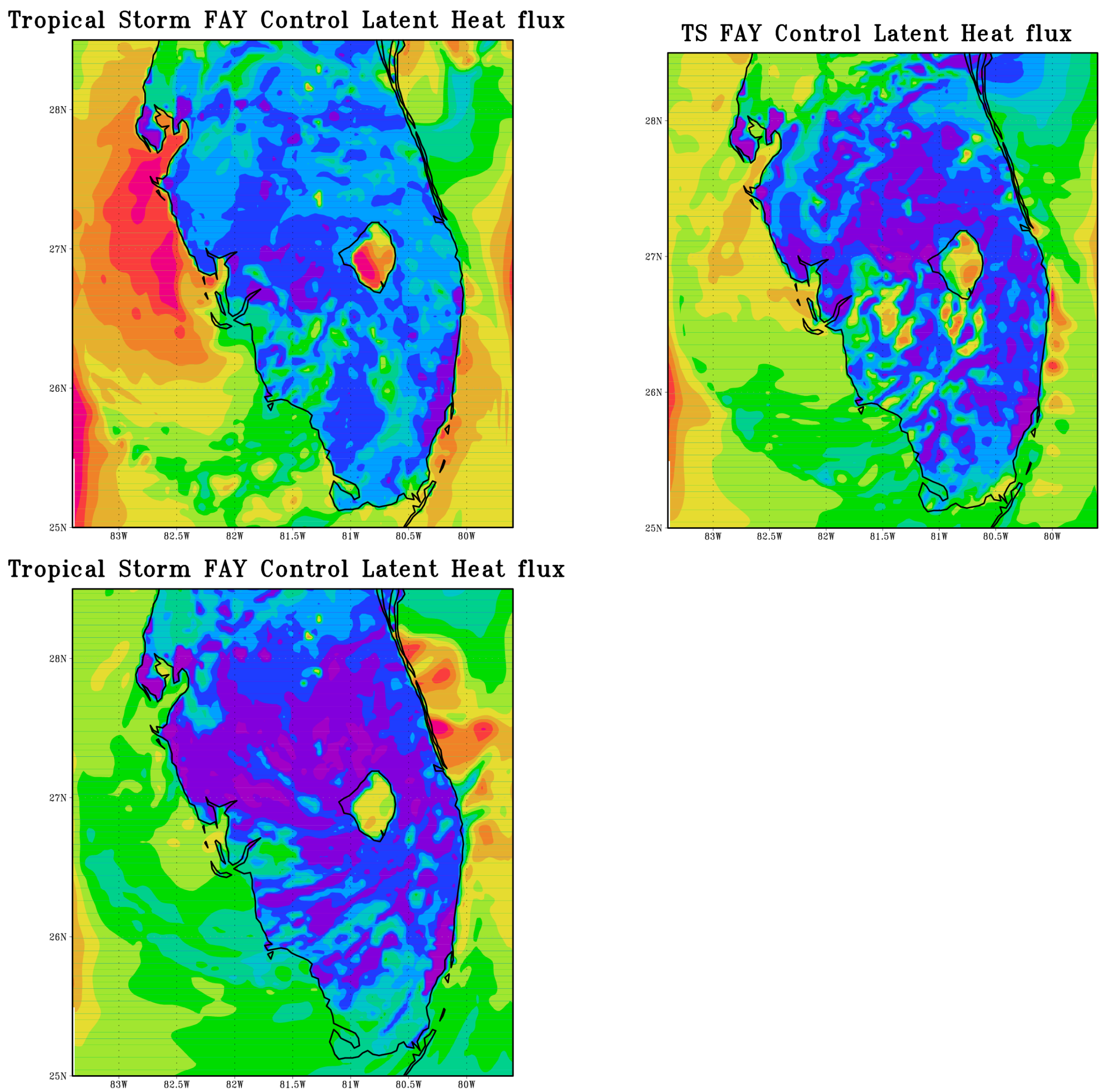

Figure 3 Control Experiment Latent Heat Flux at Surface (a) 1500 UTC 19, (b) 1800 UTC, and (c) 2100 UTC 19 August 2008.

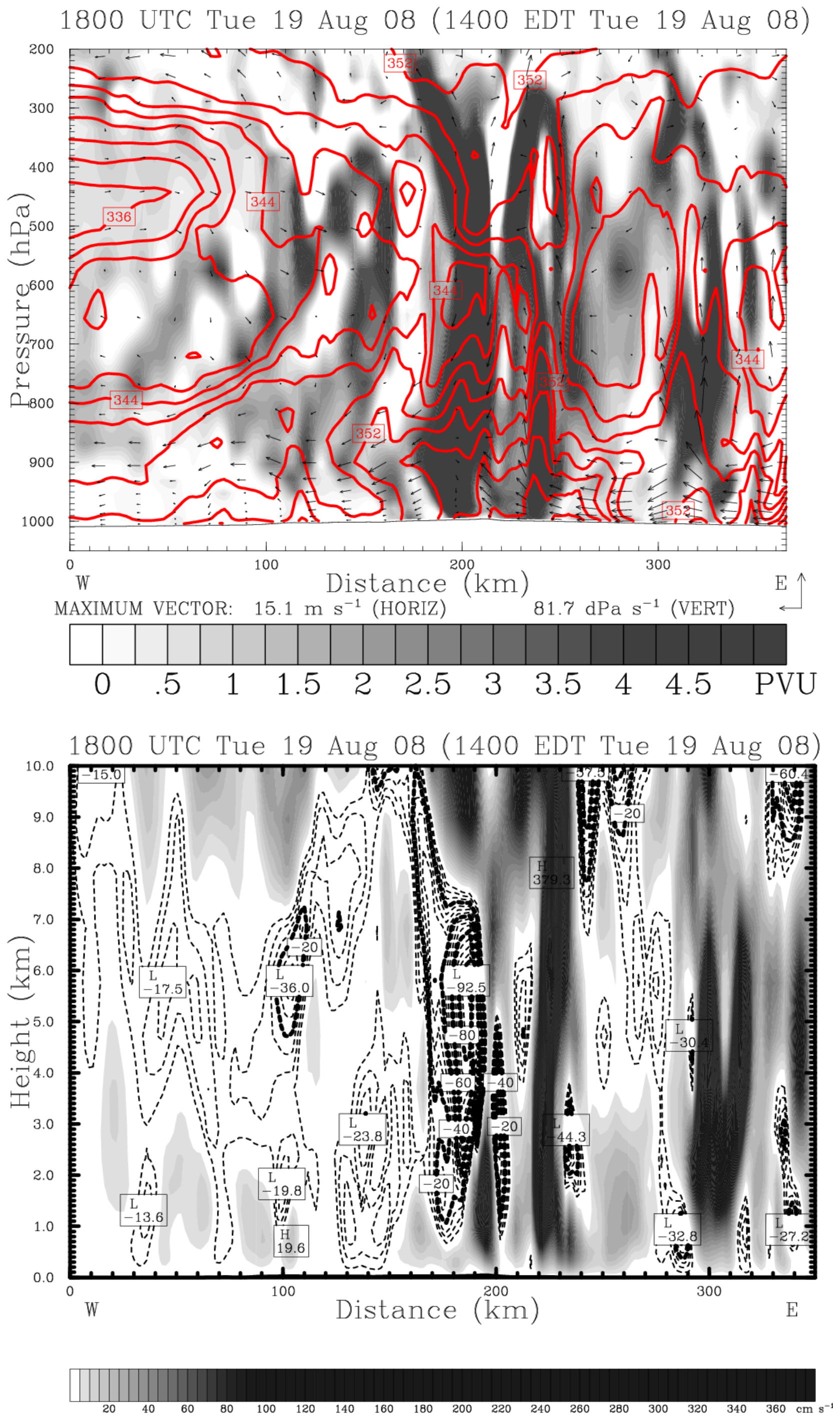

Figure 4: NW-SE cross-section of (a) equivalent potential temperature (θe) and potential vorticity, and (b) vertical velocity (positive: shaded; negative: dash line) at 1800 UTC 19 August 2008 from the CTRL experiment.

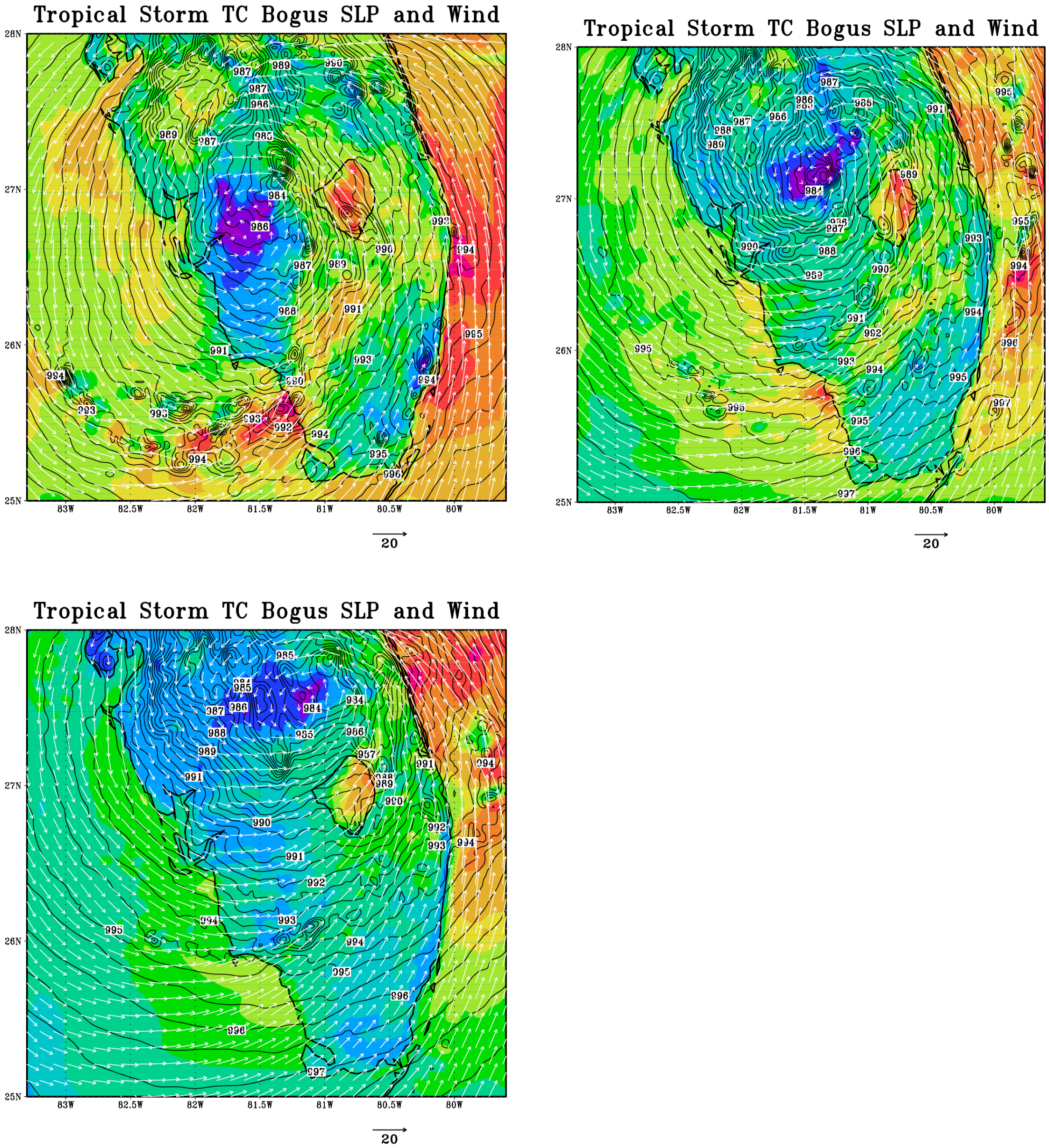

Figure 5 TC Bogus Sea Level Pressure and Wind (a) 1500 UTC, (b) 1800 UTC, and (c) 2100 UTC 19 August 2008.

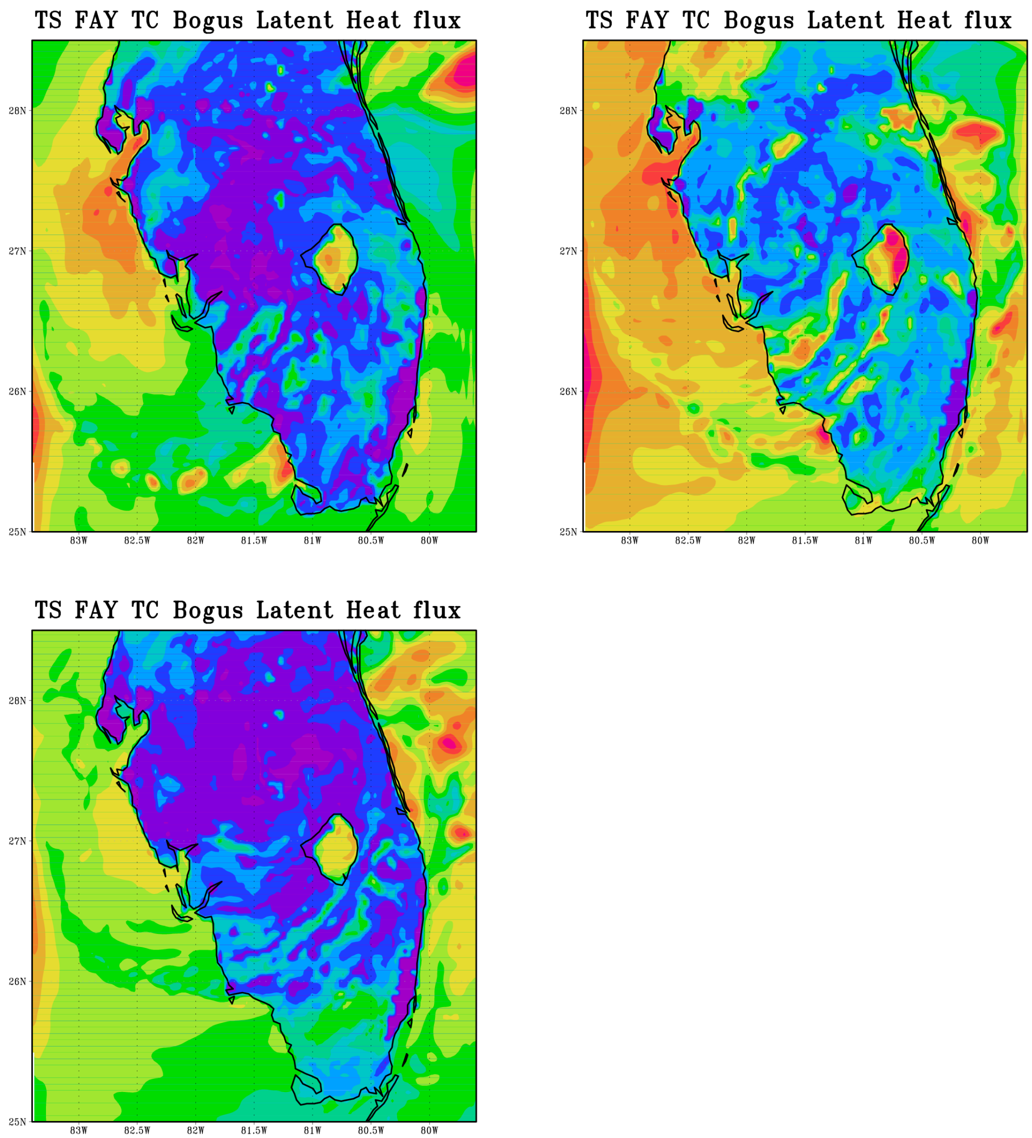

Figure 6 TC Bogus Latent Heat Flux at Surface (a) 15 UTC, (b) 18 UTC, and (c) 2100 UTC 19 August 2008.

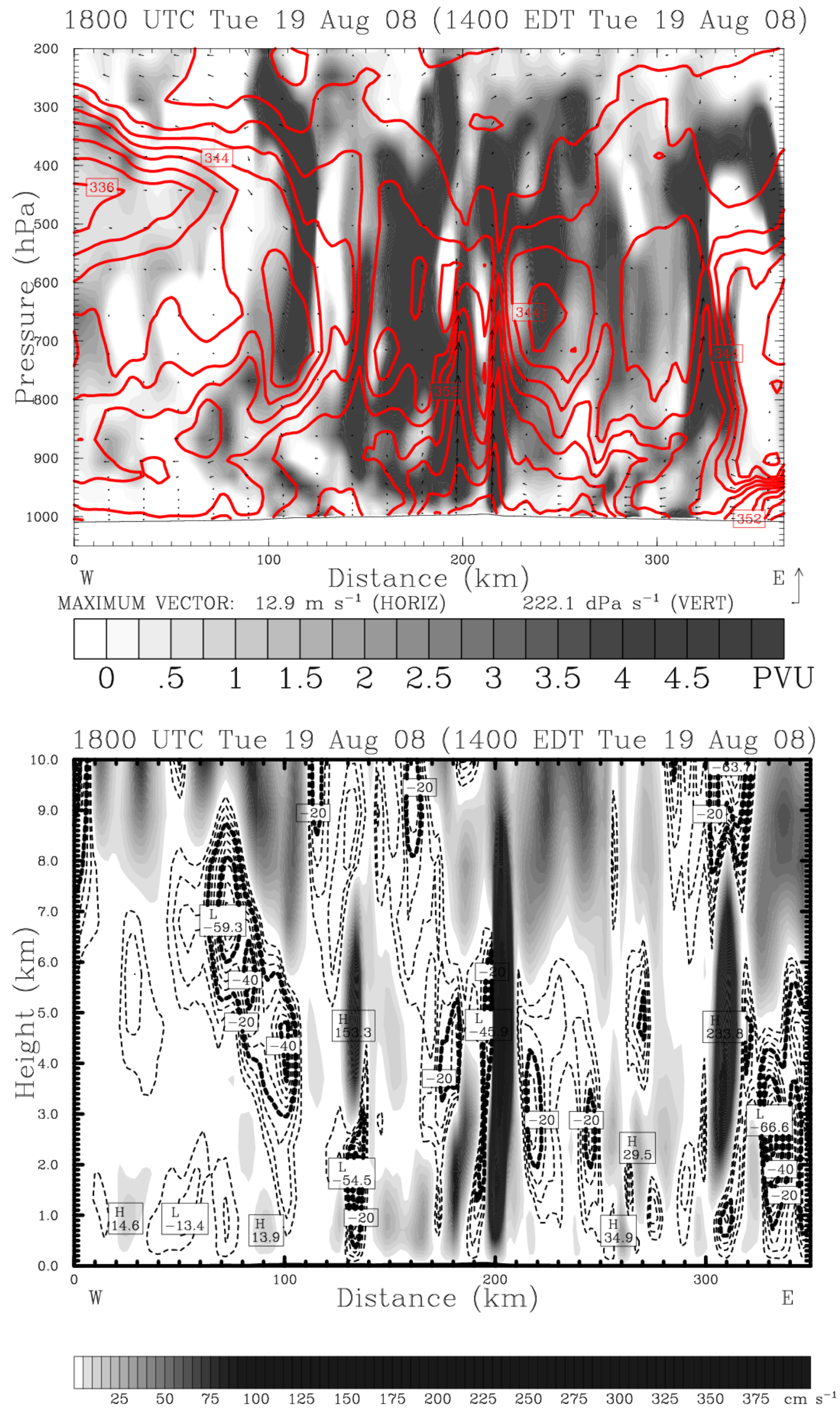

Figure 7: NW-SE cross-section of (a) equivalent potential temperature (θe) and potential vorticity, and (b) vertical velocity (positive: shaded; negative: dash line) at 1800 UTC 19 August 2008 from the TC Bogus experiment.

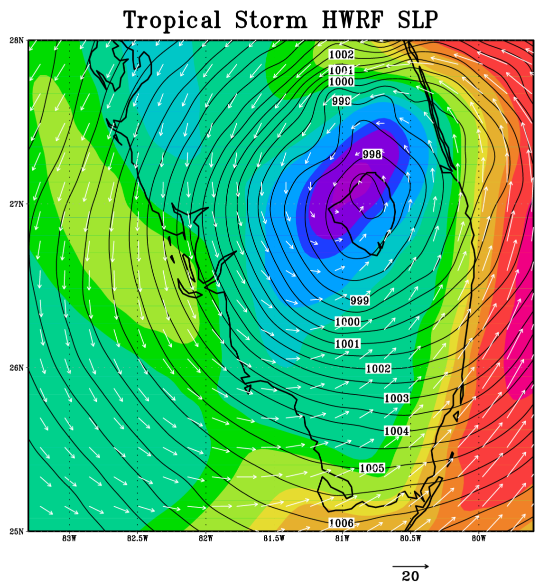

Figure 8 HWRF Sea Level Pressure and Wind 18 UTC 19 August 2008

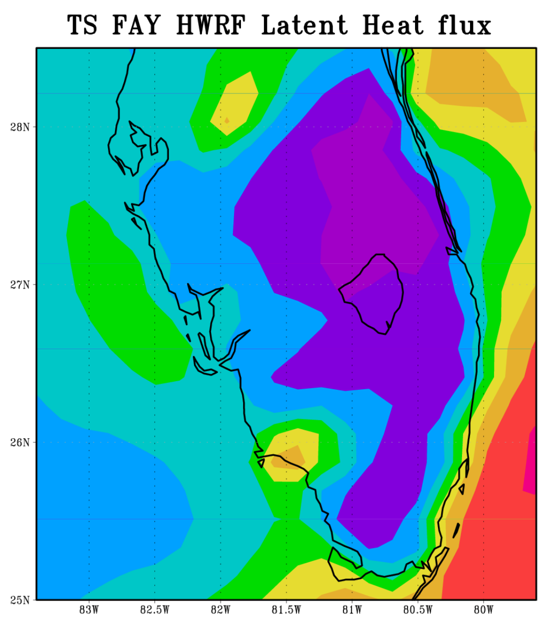

Figure 9 TC Bogus Latent Heat Flux at Surface 18 UTC 19 August 2008.

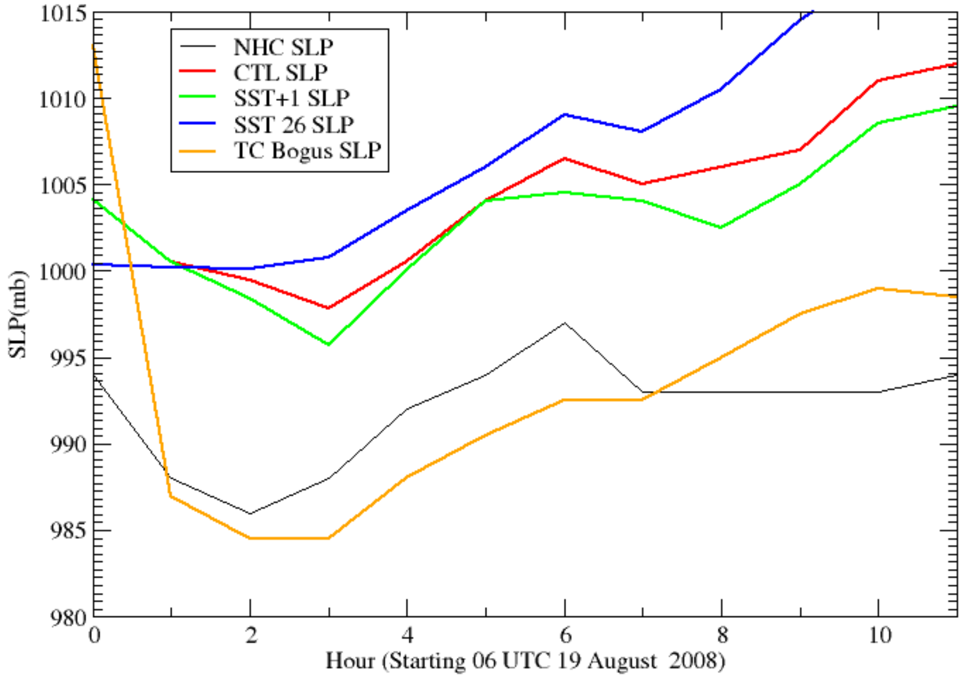

Figure 10: Time evolution of simulated sea level pressure vs. NHC obs