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Developing Hurricane Related Inland Flooding Forecasts at EMC

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1. Motivation

Tropical cyclones can produce extremely powerful winds and torrential rain, and are also able to produce high waves and damaging storm surge as well as spawning tornadoes. Heavy rainfall brought by tropical cyclones can produce significant flooding inland, and their effects on human populations can be devastating. In the 1970s, '80s, and '90s, more than half of the deaths associated with tropical cyclones in the United States were caused by inland flooding (NHC). Therefore, developing a forecast technique for hurricane-related inland flooding is very important.

2. Methodology

A hurricane-related inland flooding forecast technique is under development at Environmental Modeling Center (EMC) by enhancing the HWRF (Weather Research and Forecast system for hurricane prediction) forecast capability with a comprehensive and advanced land surface model (LSM), and linking the HWRF model with the EMC streamflow routing scheme.

2.1 The HWRF model

The HWRF is a new computer model for hurricane forecasting developed at EMC. This model was designed to take into account the strengths of the WRF software system, the use of the well-tested NMM dynamic core, and the physics packages of the highly successful GFDL hurricane forecast system. The model is a nested grid system with an outermost domain and a nested grid with resolutions of 27 and 9 km respectively and 42 vertical levels. The HWRF uses a modified 6-hour forecast as the first guess and regional GSI 3DVAR data assimilation for the hurricane vortex initialization. The HWRF is coupled to a high-resolution version of the Princeton Ocean Model for the Atlantic Basin. The ocean initialization system uses observed altimeter observations to provide a more realistic Loop Current and Gulf Stream conditions. The HWRF is running operationally at EMC to produce hurricane forecasts every six hours for up to four tropical storms at a time.

2.2 The Noah LSM

One of the goals of EMC is to use HWRF model output as input to hydrology and inundation models to forecast hurricane-related inland flooding through its land surface component. However, the operational version of HWRF uses the GFDL (Geophysical Fluid Dynamics Laboratory) Slab LSM to model land-atmosphere interactions. In the Slab LSM, only one layer soil temperature is predicted while the initial soil moisture remains fixed in time during the HWRF forecast. Additionally, the Slab LSM does not predict the runoff response to HWRF precipitation forecasts. Hence the Slab LSM is unable to serve the hydrology goals cited above. Therefore, the Noah LSM, a more comprehensive and advanced LSM, was added as an option to HWRF. The Noah LSM uses: 1) multiple soil layers with a one-layer vegetation canopy, 2) spatially-varying root depth and seasonal cycle of vegetation cover, 3) frozen soil physics for cold regions, and 4) improved soil and snowpack thermal conductivity. The Noah LSM predicts soil moisture, soil temperature, latent heat and sensible heat flux, and total runoff which accounts for sub-grid variability in precipitation and soil moisture. The runoff prediction can then be used as forcing input to the EMC Streamflow Routing Scheme (Lohmann et al., 2004). Additionally, the HWRF-Noah forecasts of soil moisture and runoff are good spatial indicators of soil moisture saturation (water logging) and flooding.

2.3 The EMC River Routing Scheme

In the streamflow routing scheme, the concentration time for runoff reaching the outlet of a grid box and the transport of water in the channel system is computed, with water leaving the grid cell through (at least) one of eight directions, the runoff transport process is linear and time invariant, and the causality and the impulse response functions are nonnegative (Lohmann et al., 2004). With use of the Noah LSM, the HWRF prediction of runoff can be used to drive the EMC streamflow routing scheme to produce HWRF forecasts of streamflow and river flow.

3. Experiments

The replacement of the Slab LSM with the Noah LSM can enhance the HWRF forecast capability. Tests and evaluations were conducted to ensure that the replacement of the LSM will not degrade forecasts of hurricane track and intensity. Eight tropical cyclones (Figure 1) were selected based on their tracks in this study. KATRINA, DENNIS, RITA, IKE, and GUSTAV made their way to the southern US via the Gulf of Mexico, HANNA moved along the east coast of Atlantic Ocean, DEAN made its way to Mexico while FAY stopped over several islands before making landfall over Florida. Two different runs for each case were conducted with the Slab LSM and Noah LSM, respectively. These experiments are summarized in Table 1.

Table 1. Summary of experiments to look at the LSM effects on hurricane track and intensity forecasts

Runs	**Physics Options Over Land**		
	LSM	Surface Layer Scheme	PBL Scheme
Control Run (N883)	Slab	GFDL	GFS
Test Run (N893)	Noah	GFDL	GFS

Among the selected hurricanes, the HWRF model did the best job for Katrina in terms of track, intensity and rainfall forecast. As such, Katrina was selected to test the river routing scheme. The current operations of the HWRF forecast use GFS outputs as initial fields, including soil moisture. GFS soil moisture is driven by GDAS predicted precipitation, plus nudging towards a monthly soil moisture climatology. The soil moisture for NLDAS and NAM are driven by observed precipitation. Therefore, NAM soil moisture is more realistic than GFS soil moisture, for example, the GFS soil moisture is much wetter than the NAM soil moisture over the southeastern US on 28 August, 2005 (Figure 2). Two runs were conducted to look at the effects of the initial soil moisture.

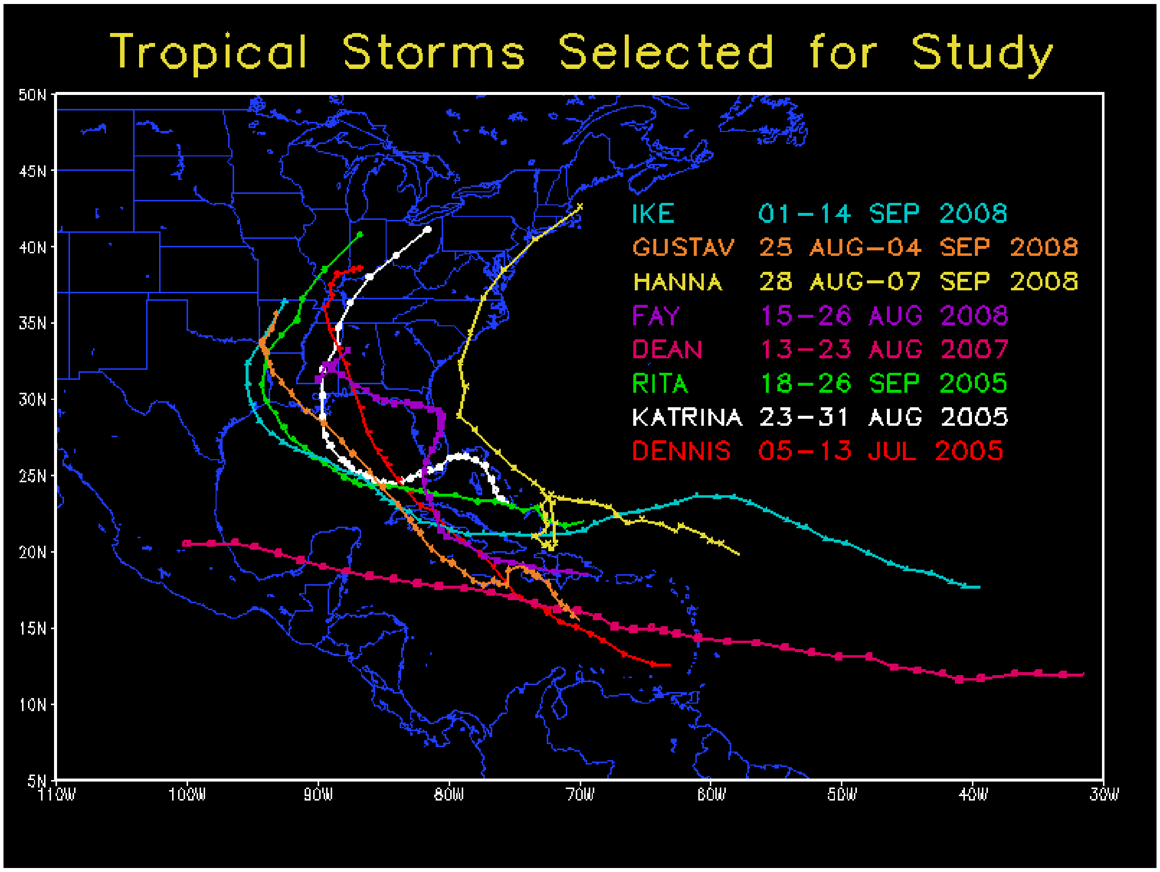

Figure 1. Tracks and Dates of the selected tropical cyclones in 2005, 2007 and 2008.

Corresponding the HWRF WET run and HWRF DRY run for Katrina, the streamflow routing was also run twice using the runoff from the WET run and DRY run, respectively. In both runs, NLDAS streamflow analysis is used as the initial condition as well as for verification. Daily average streamflow measurements from USGS station are also used for verification.

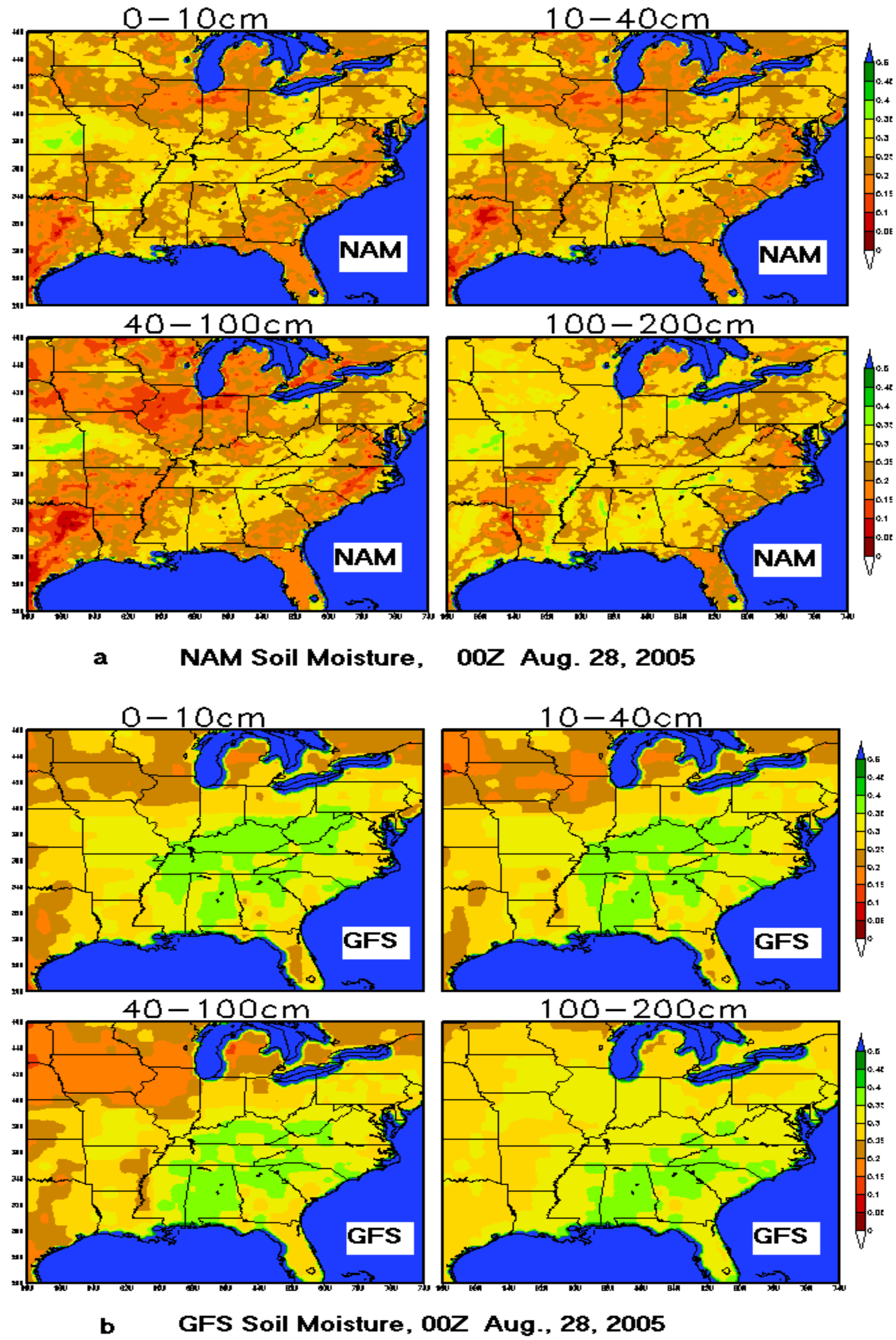

Figure 2. GFS and NAM soil moisture at 4 layers at 00Z on 28 August 2005 over the southeastern US. a). NAM soil moisture; b). GFS soil moisture

4. Results and Summary

Analysis on the track and intensity forecasts for the eight hurricanes shown in Figure 1 is given in subsection 4.1. Analysis on the forecasts of rainfall, soil moisture and runoff for hurricane Katrina is given in subsection 4.2. The results of streamflow forecast for hurricane Katrina is given in subsection 4.3. A brief summary is given in subsection 4.4

4.1 Track and Intensity Comparison for the Eight Hurricanes

To look at the effects of the replacement of the LSM on hurricane track and intensity forecasts, 28 runs were conducted for the eight hurricanes. The HWRF model is initialized with GFS forecasting in all runs. As shown in Figure 3, the effects of the replacement of the LSM in the HWRF on hurricane track and intensity forecasts are very small for the eight cases shown in Figure 1. This suggests that the SLAB LSM can be replaced by Noah LSM in the HWRF.

4.2 Rainfall, Soil Moisture and Runoff for Katrina

Two runs were conducted for Katrina using GFS and NAM soil moisture as initials, respectively to look at the initial soil moisture effects on the forecasted rainfall, runoff and streamflow. The run using GFS soil moisture as the initial is referred as HWRF WET run while the run using NAM soil moisture as the initial is referred as HWRF DRY run later in the text for convenience. 12-hour accumulated rainfall for both of the observations and simulations are shown in Figure 4. At 00Z on 29 August 2005, there were some widely spread light rainfall over the eastern CONUS. Both WET and DRY run captured most of the coastal rainfall, but missed the rainfall inland. At 00z on 30 August 2005, the center of simulated rainfall at the coast of Louisiana matches well with the observations. However, the model missed the rainfall over the Ohio valley. At 00z on 31 August 2005, the simulated rainfall center is located to the southwest of the observed, and the model missed most of the rainfall over the northeast of US. There is little difference between the wet run and dry run, indicating that the initial soil moisture had a very small effect on rainfall prediction.

However, the effect of initial soil moisture on soil moisture prediction is significant as shown in Figure 5 and 6. At 00Z on 29, 30 and 31 August 2005, soil moisture in layer 1 and 2 in the DRY run is very close to the NLDAS soil moisture while the soil moisture in the WET run was much more wet, leading much more subsurface runoff (Figure 8).

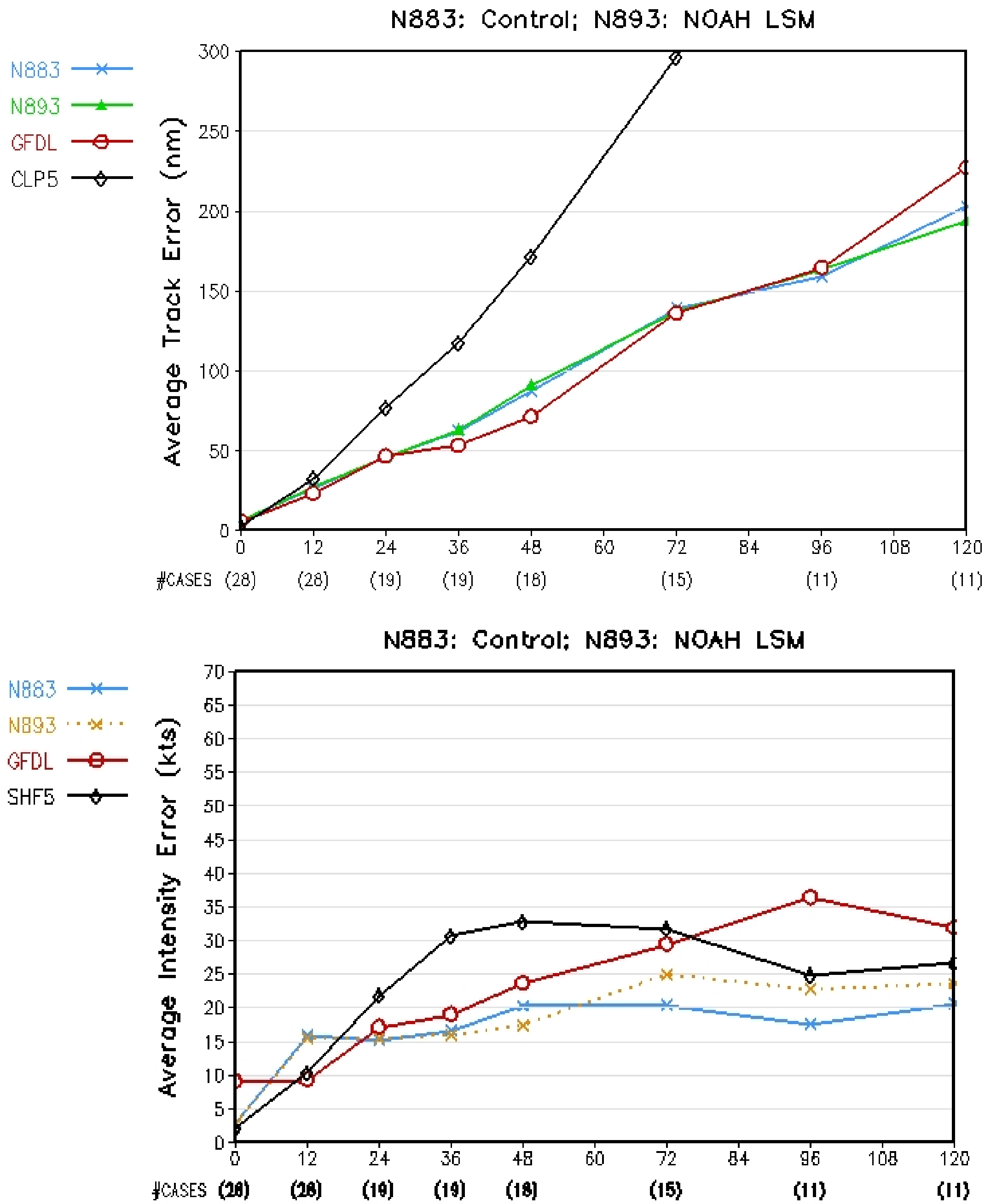

Figure 3. Track error and intensity error comparisons. a) Top panel, track error comparison; b). Bottom panel, intensity error comparison.

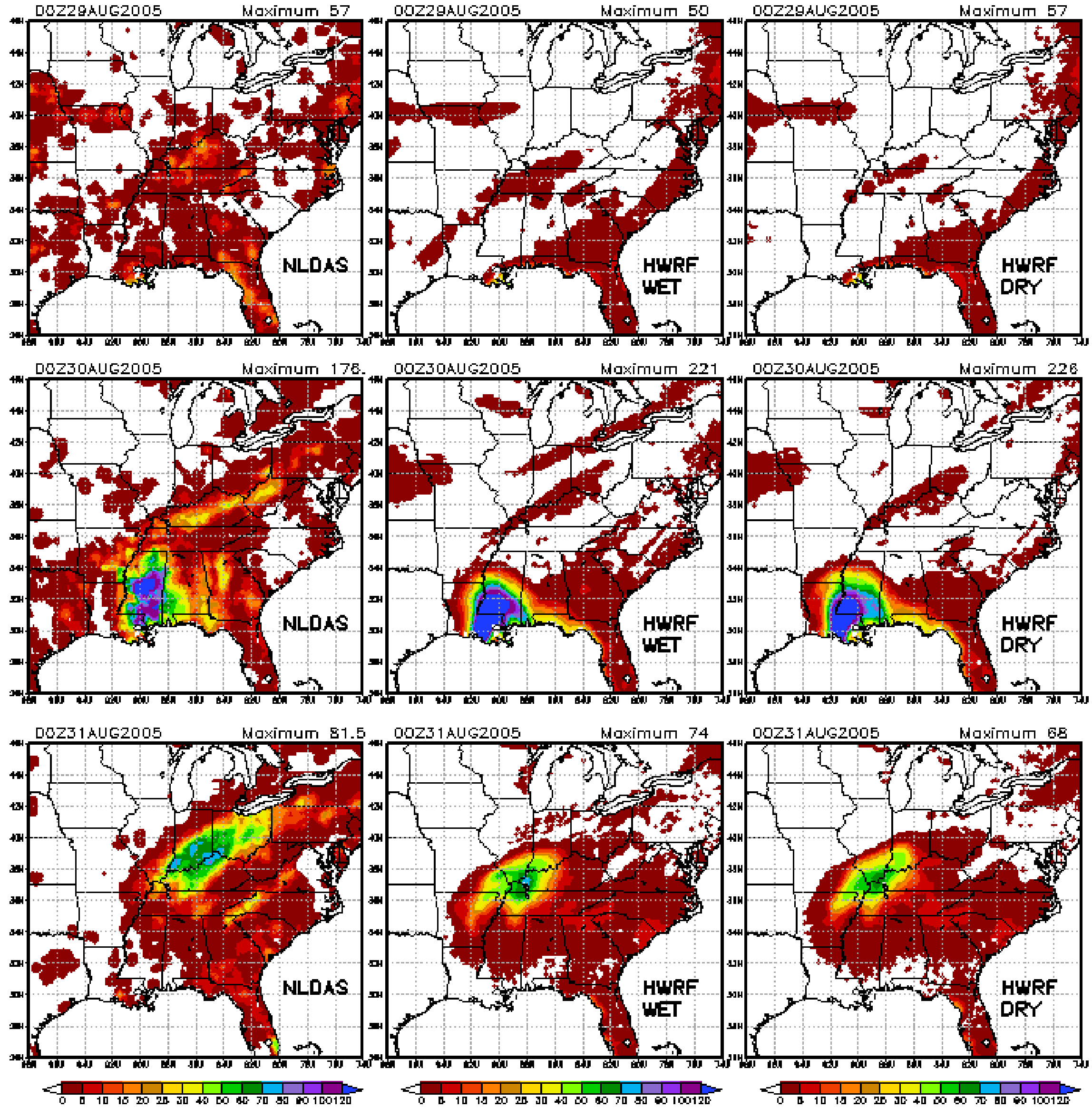

Figure 4. 12-hour accumulated rainfall at 00Z on 29, 30 and 31 August 2005.

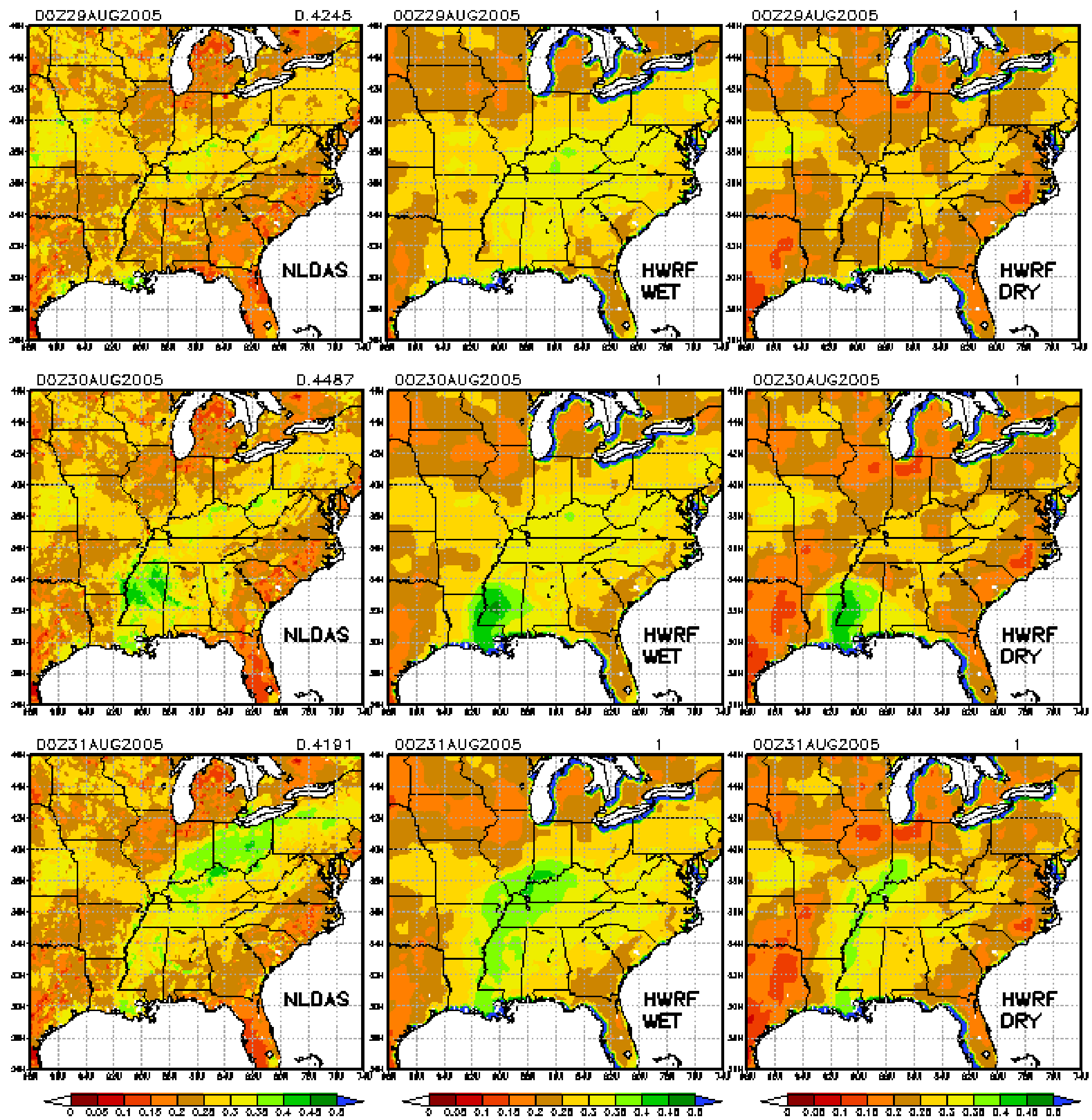

Figure 5. HWRF soil moisture for layer 1 at 00Z on 29, 30 and 31 August 2005.

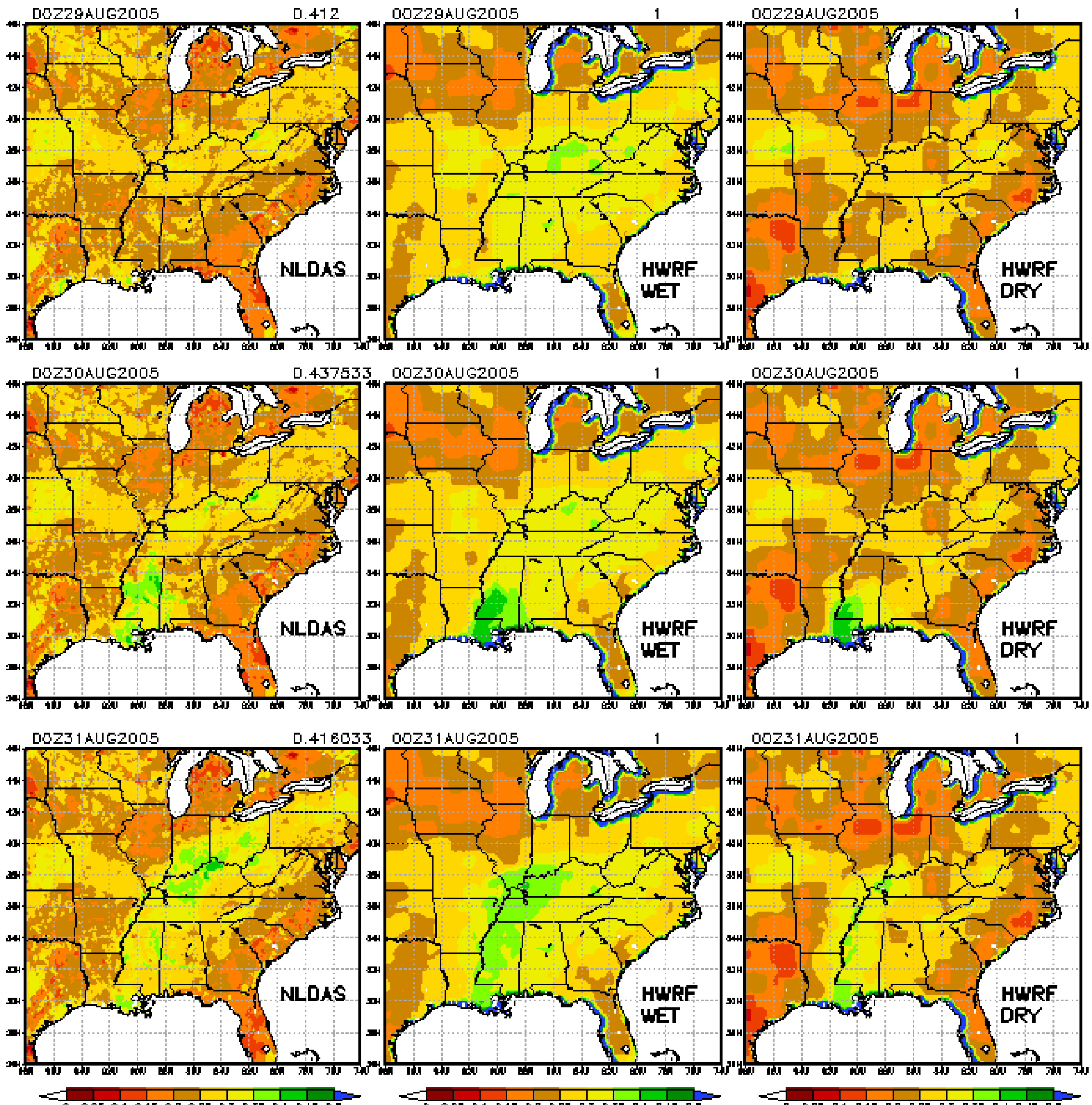

Figure 6. HWRF soil moisture for Layer 2 at 00Z on 29, 30 and 31 August 2005.

The simulated surface runoff， subsurface runoff and total runoff (the sum of the surface runoff subsurface runoff) from NLDAS, the HWRF WET run and the HWRF DRY run are shown in Figure 7, Figure 8 and Figure 9, respectively. The surface runoff simulated in both the WET and DRY run are comparable, and match well with the that simulated by the NLDAS. However, the subsurface runoff and the total runoff simulated in the WET run is much higher and spreads in a much wider area than in the DRY run and NLDAS over the southeast US.

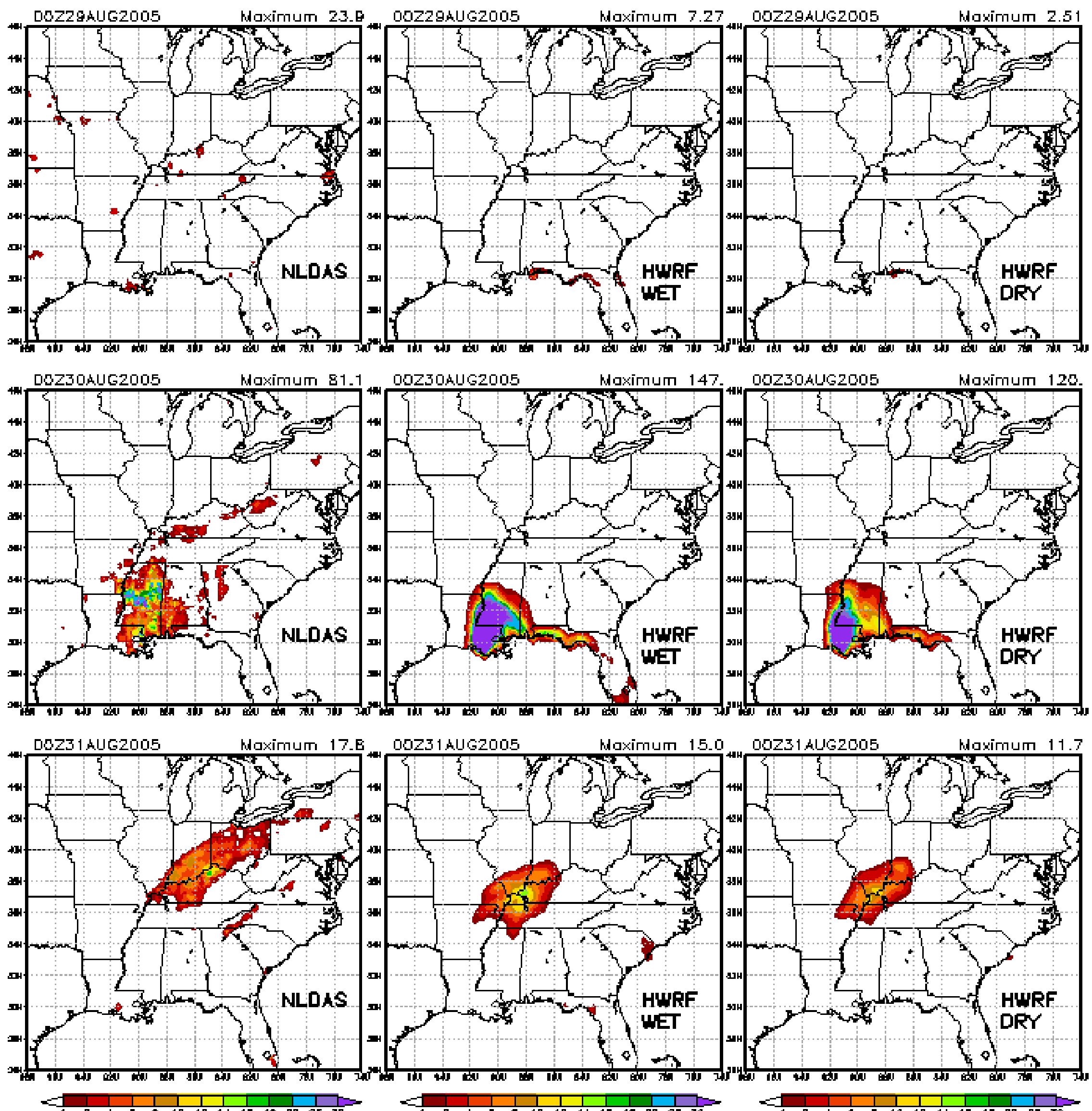

Figure 7. 12-hour accumulated surface runoff at 00Z on 29, 30 and 31 August 2005.

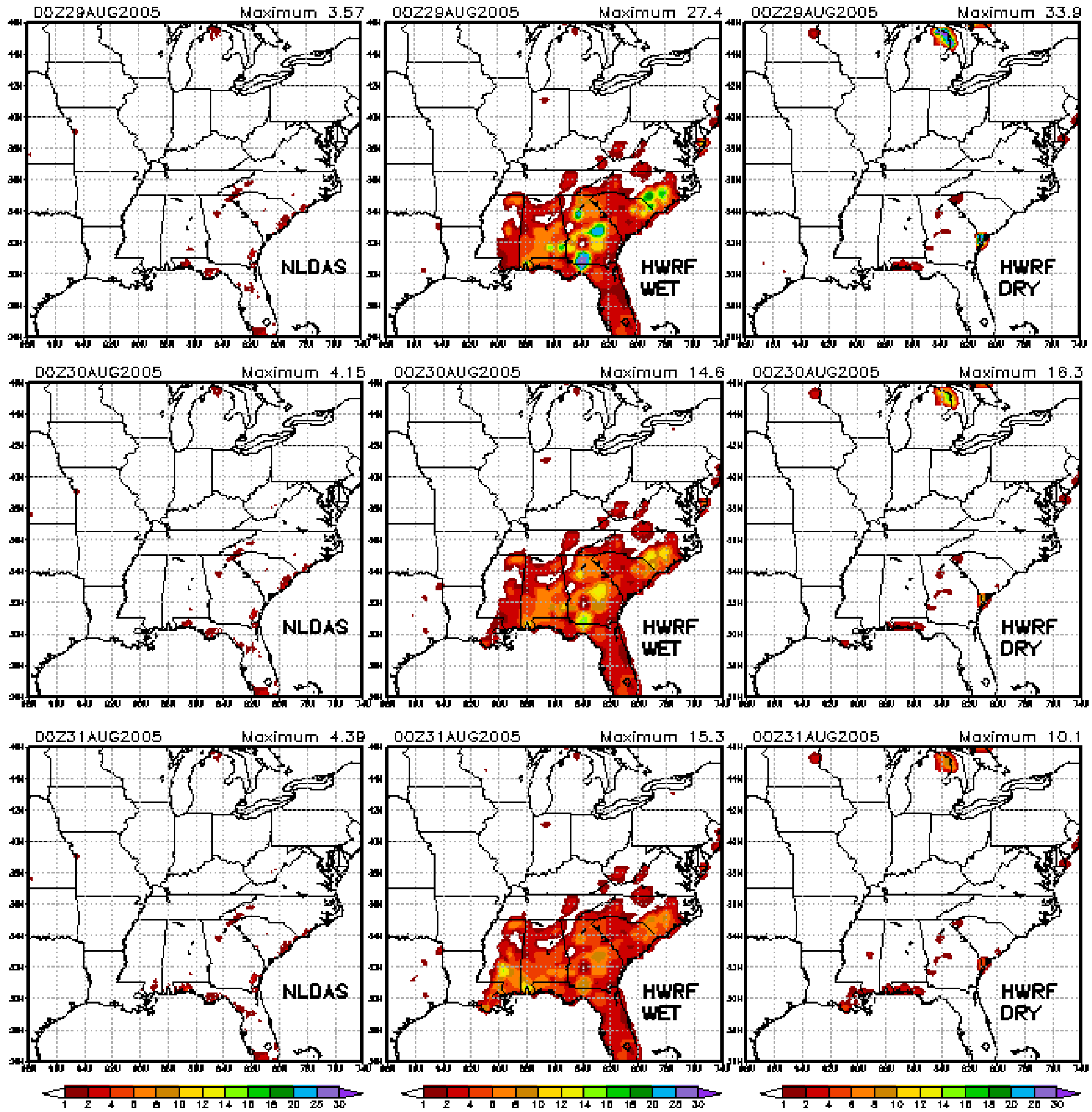

Figure 8. 12-hour accumulated subsurface runoff (base flow) at 00Z on 29, 30 and 31 August 2005.

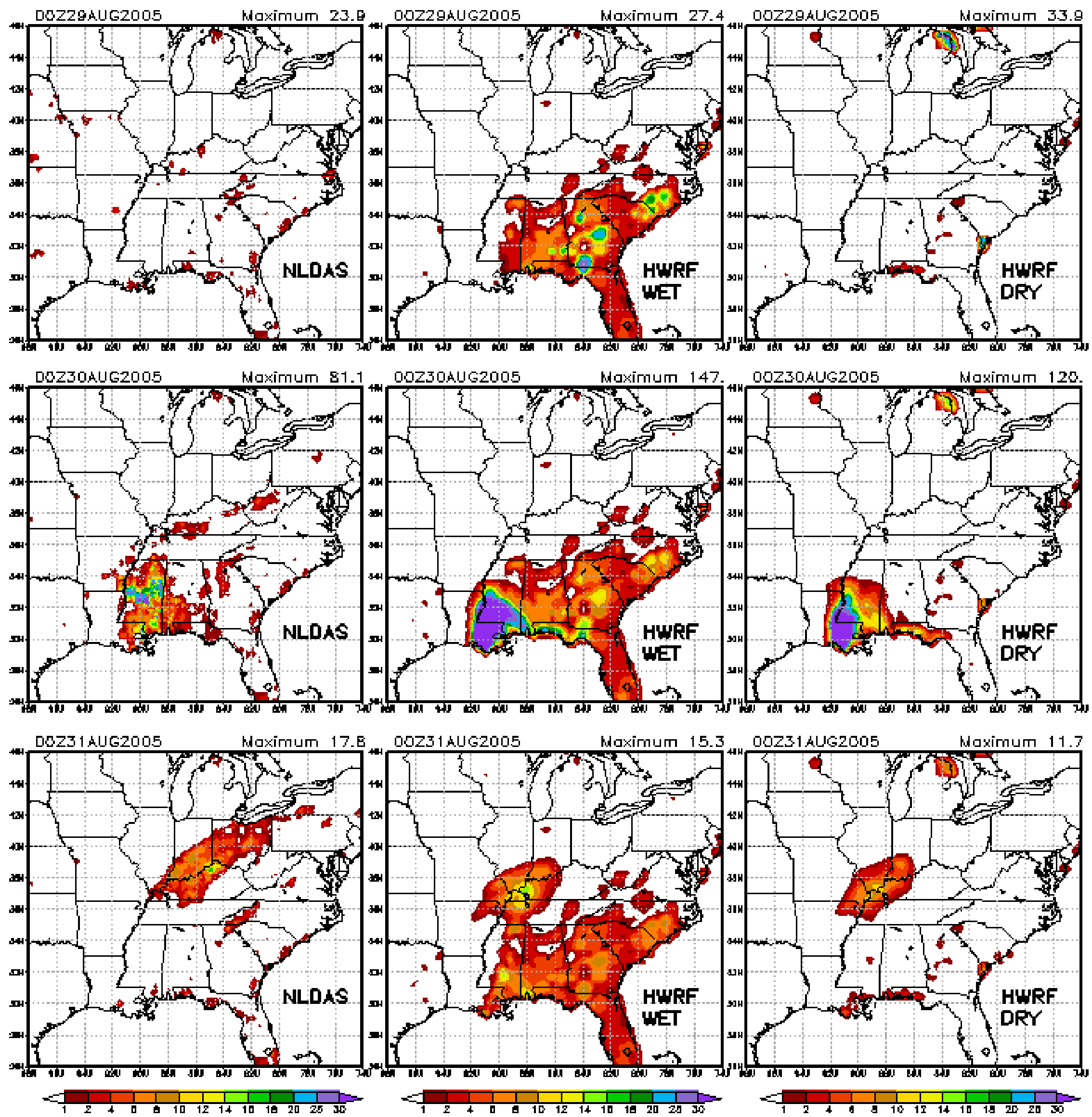

Figure 9. 12-hour accumulated total runoff (the sum of the surface runoff and base flow) at 00Z on 29, 30 and 31 August 2005.

4.3. Streamflow for Hurricane Katrina

The preliminary results in the HWRF N893 experiment for Hurricane KATRINA are shown in Figure 10. Before KATRINA landfall (at 00Z on 29 August 2005), only river flows are shown in the figure for NLDAS and the HWRF DRY run while water logging condition may occur over the southeastern US in the HWRF WET run. Around the Katrina landfall, small flooding area on LA coastal region was simulated in NLDAS and the HWRF DRY run while a large flooding area was simulated in the HWRF WET run. After KATRINA landfall, (at 00Z Aug. 31, 2005), a big flooded area is shown along the KATRINA path in NLDAS and HWRF runs. The streamflow in the WET run is much higher, and flooding area in the run is much larger than those in the DRY run and NLDAS. The time series of streamflow at 32N and 89W (Figure 11) shows that the flooding at the point lasted about 3 days. The streamflow rate in the WET run is overforecasted due to the overforecast of rainfall and high initial soil moisture. The streamflow rate in the DRY run and NLDAS is more comparable to the observations.

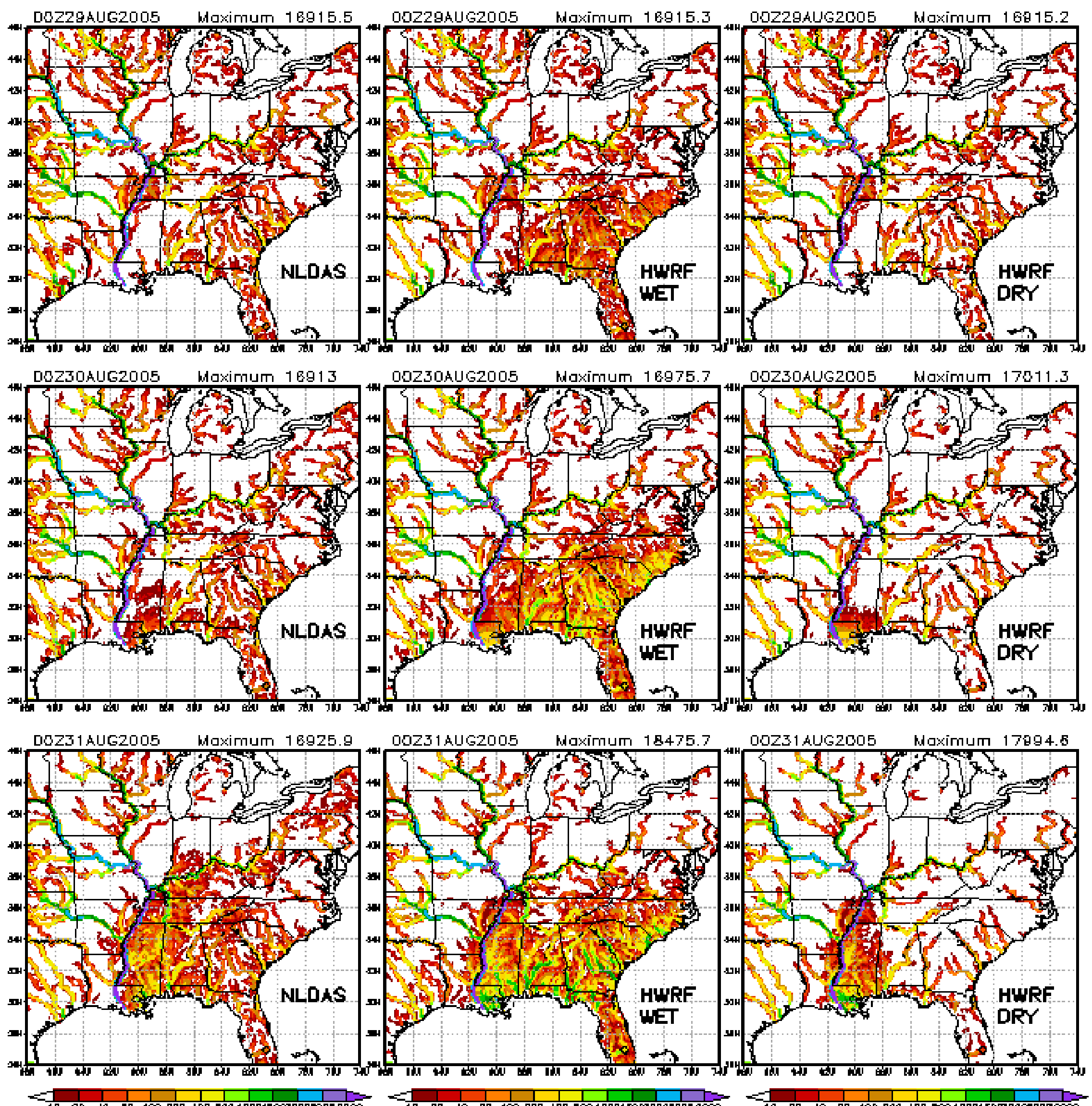

Figure 10. Simulated streamflow at 00Z on 29, 30 and 31 August 2005.

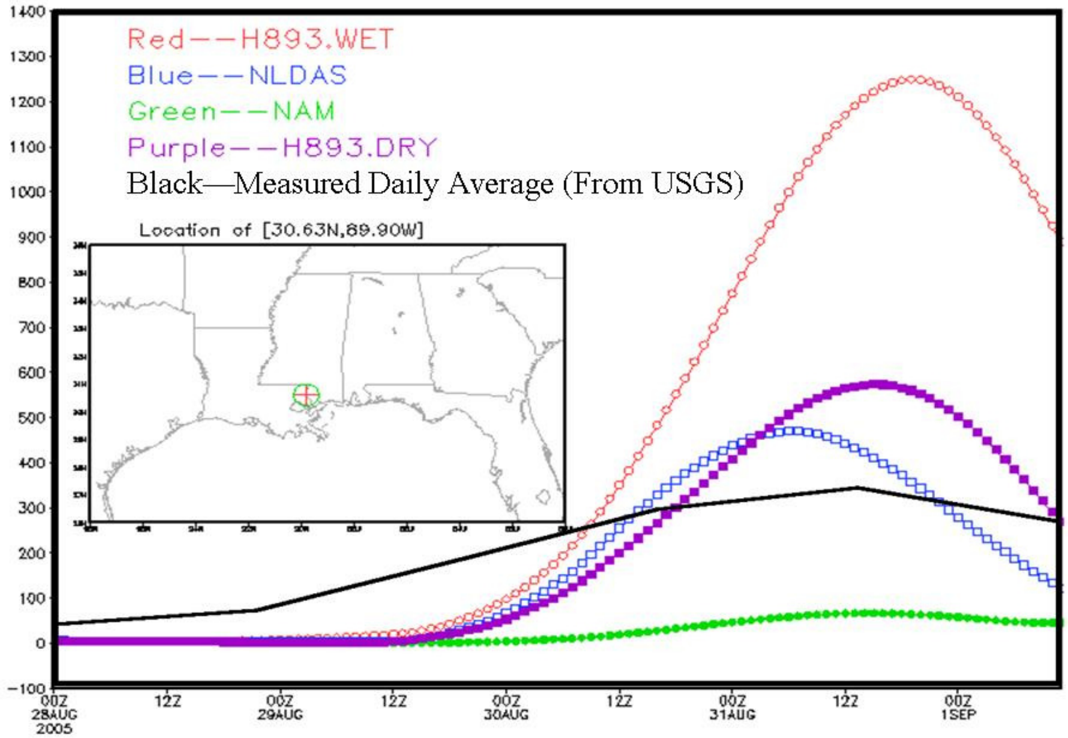

Figure 11. Time series of observed and simulated streamflow at the point of 30.63 N and 89.90 W.

4.4 Summary

A hurricane-related inland flooding forecast technique has been developed based on the existing models and techniques at EMC. The inland flooding caused by Katrina in 2005 was successfully simulated by the system. The replacement of the SLAB LSM in the HWRF system by the Noah LSM can enhance the forecasting capability of the HWRF. HWRF-Noah forecasted runoff as well as the forecasted streamflow is sensitive to the initial soil moisture. Streamflow forecasted from the HWRF-Noah predicted runoff is more realistic when NAM soil moisture is used as the initial field.

REFERENCES

Ek, M. B., K. E. Mitchell, Y. Lin, E. Rogers, P. Grunmann, V. Koren, G. Gayno, and J. D. Tarpley (2003), Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model, *J. Geophys. Res.,* **108**, D22, 8851, 2178 doi:10.1029/2002JD003296.

Lohmann, D., K. E. Mitchell, P. R. Houser, E. F. Wood, J. C. Schaake, A. Robock, B. A. Cosgrove, J. Sheffield, Q. Duan, L. Luo, R. W. Higgins, R. T. Pinker, J. D. Tarpley, 2004, Streamflow and water balance intercomparison of four land-surface models in the North American Land Data Assimilation System (NLDAS), *J. Geophys. Res.,* **109**, D07S91, doi:10.1029/2003JD003517.

NHC: http://www.nhc.noaa.gov/HAW2/english/inland_flood.shtml

USGS: http://waterdata.usgs.gov