10A.3 NWP WITH THE WEATHER RESEARCH AND FORECAST MODEL AND LOCAL DATA SIIMILATION AS A PRELUDE TO "NEIGHBORHOOD WEATHER"

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1. INTRODUCTION

The NOAA Coastal Storms Initiative (CSI) pilot program was located in the St. Johns River basin in Northeast Florida, and had an overarching goal lessening the impact of storms on the coastal community. One of the nine projects approved as part of the CSI was the implementation of a locally-run mesoscale numerical weather prediction (NWP) model with additional local data assimilation at the Weather Forecast Office (WFO) in Jacksonville (JAX), Florida.

Funded as part of the NOAA CSI, a small team of collaborators has put together a high resolution atmospheric modeling system as an operational adjunct in a National Weather Service Weather Forecast Office (WFO). For the project, commercial-off-the-shelf (COTS) hardware and open system software were to be used to the maximum extent possible. The purpose of the WFO NWP modeling project in particular, was to assess if a WFO could use such a high resolution numerical model to improve forecast services to the public in the pilot program area.·

A commercial Linux Beowulf system was purchased and adapted to the specific tasks of running the Weather Research and Forecast (WRF) Numerical Weather Prediction (NWP) model developed by UCAR. Developers of the project included members of the WFO JAX staff, and selected participants from the NOAA Forecast Systems Laboratory (FSL), NOAA NWS Southern Region Headquarters staff, and Florida State University. NOAA National Ocean Service was the CSI sponsor. The NWS Office of Science and Technology provided project management and coordination. The NWS National Centers for Environmental Prediction (NCEP) Environmental Modeling Center (EMC) provided access to the 12 km tiled version of the Eta Model for use as the lateral boundary conditions.

The use of the WRF model provided many potential improvements over the previous version of the Workstation Eta model run at 10 km resolution locally at WFO JAX since January, 2000. Among those were items recognized to negatively impact the solution quality of the mesoscale Workstation Eta predictions, including the large (18 km) land-sea mask grid which created coastline discontinuities in the model, poor resolution of the land use and lack of permanently wetted areas (lakes, rivers, and swamps) which impact the surface fluxes, and poor air-sea interaction and associated fluxes. There are also other potential improvements in other areas in the WRF model including mass-conserving higher order numerics and a better boundary layer model.

Initialization of the WRF model was from a 6 hour forecast from the Eta model with local data assimilation using the FSL developed Local Analysis and Prediction System (LAPS) (Albers et al., 1996) providing cloud-balanced, diabatic initialization using Doppler radar, satellite and other local datasets (McGinley and Smart 2001).

The project merged diverse talent among NOAA entities, and cutting edge technology together to meet the operational needs of the WFO in a unique accomplishment. The issues involved in the project ranged from the theoretical subtleties of how to best initialize the NWP model to such practical problems as bandwidth limitations, computer security, and automating processes with scripts. This paper seeks to describe the implementation process from the WFO perspective and comment on its value in day to day forecasting. An overview of the WRF system configuration and data assimilation were reported by Shaw et al. (2004). Initial verification results with conventional statistics were reported in a companion paper by Bogenschutz et al. (2004). Implementation issues and results were also concurrently reported by Welsh, et al. (2004)

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2. Information System Design

The system design was highly constrained by available bandwith in the WFO. One of the early identified problems was the Local Display Analysis and Dissemination (LDAD) Server which has inadequate disk memory and I/O resources, and is both a single point of failure for WFO products and insecure. Due to the large files and minimal bandwidth available, system design evolved to accept those limitations, yet accomplish mission critical tasks. Had other resources been available, the final configuration would have clearly been different.

2.1 Design and information flow

Figure 1 indicates the flow of input and output from the Linux cluster to run the Local Analysis and Prediction System data assimilation, and WRF prognostic model.

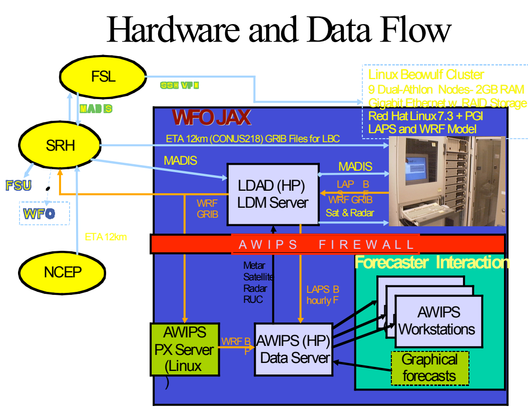

Figure 1. WFO JAX Linux cluster information flow inputs (green) were passed through the Regional network or via LDAD from AWIPS. Output (brown) LAPS NetCDF analysis files and WRF grib prognostic files are passed from the cluster to LDAD to AWIPS for display.

In order to validate the WRF model, as well as local data assimilation, four WRF model runs were conducted daily. The first run was initialized from the NCEP 00Z Eta 12 km tiles, using the 06Z forecast hour as the initial state with data assimilation from the FSL Local Analysis and Prediction System (LAPS) used as a diabatic "hot" start. This run was considered the operational run for forecast use. The second run of the day was initiated on completion of the first run, and was the same except the data assimilation and LAPS steps were omitted. This allowed an evaluation of the value of the local data assimilation to the WRF project, since these two early runs were otherwise identical. Two additional runs were initiated like the first run, at 15Z using the NCEP 12Z tiles and LAPS, and at 21Z with the 18Z tiles and LAPS. Results of the intercomparison of the first two runs and the NCEP 06Z Eta (note that the WRF model was initialized from 00Z Eta) are contained in Shaw et al. (2004).

While this design was not optimal from the forecast perspective it served well enough, while attempting to answer the questions of whether this local modeling paradigm was suitable for WFO implementation, whether the added local data assimilation actually added value over simple nesting within the NCEP model grids, and most importantly, would it actually improve forecasting.

Table 1. Model output available for CSI Local Modeling Project evaluation

Model	Initialized	Reso-lution	Run times
NCEP Eta	No local data, EDAS,cold start	12km	0600 UTC
WRF	No local data , Eta COLD start	5 km	~11 UTC 00Z + 6 hr initialized
WRF	Initialized with LAPS hot start, uses local data	5 km	0600, 1500, and 2100 UTC

2.2 Limiting issues

One of several design constraints on the implementation was that the Linux cluster be established outside the WFO Advanced Weather Information System (AWIPS) firewall. This constraint was to prevent any miscues (of which there were few) from also impacting the WFO forecast system, but also separated the modeling system from the many necessary data sets that were available directly within AWIPS. This required extensive scripting and handling routines for several data sets with highly constrained timing. These same data sets would be available with an NFS mounted directory inside the firewall. At the same time this configuration was critical for the project to succeed by allowing direct Internet access.

On the positive side, for our developmental effort, having the Linux cluster outside the AWIPS firewall with Internet access allowed for frequent updates to software packages, access to search engines to find the excellent web based documentation in the open source community, and use of external terminals with connection to the cluster. In our opinion, this development effort could not have been accomplished otherwise. The cost of this cluster positioning with respect to the AWIPS firewall was increased latency of the data, and poorer reliability due to the dependence on scripts to transfer data sets that would otherwise be available by an NFS mounted directory on the AWIPS Data Server.

Perhaps the most serious constraint was the limitation of WFO bandwidth, a constraint that was recognized early in the planning process, but even with funds and early addition of bandwidth to the WFO and the Regional SRH network, bandwidth – both internal and external to the WFO, remains a controlling issue. Due to bandwidth, the entire modeling system suffers from high latency, the time required for NCEP to produce the initial Eta model grids and download them to the WFO via the Regional network exceeded the time required for LAPS data assimilation and WRF model prognostic grid production, and was a frequent source of run failure. Satellite Broadcast Network (SBN) transmission of the NCEP grids with the proposed improvements in SBN bandwidth would bring major decreases in system latency and improve the overall system reliability.

Internal throughput and disk storage space was also a serious limitation, for example, the large size of the NetCDF file from the WRF model (about two gigabytes) could have easily been generated on the Linux cluster, but the Local Display Analysis and Dissemination (LDAD) server internal bandwidth and disk space made passing the WRF NetCDF file untenable, so the hourly WRF forecasts were each passed separately in grib format and converted to NetCDF format in the AWIPS PX Linux server.

Any future WFO operational local modeling should include careful consideration of bandwidth with particular concern for the limitations of the LDAD server. LDAD is now a single point of failure for not only our local modeling effort, but also for processes which update our websites and the National Digital Forecast Database (NDFD).

Reliability was impacted as the AWIPS data streams were subject to failure of the multiple processes and script timing necessary to pass the required data and boundary condition files for successful model runs outside the firewall. It should be noted here that the Linux cluster was configured with an internal firewall and more current security features than exist in AWIPS and the LDAD server. In the author's opinion, the cluster could replace the functions of the LDAD server for about the same cost, with nearly an order-of-magnitude increase in security computational power, and storage over LDAD.

Planned upgrades to AWIPS, networks, and security measures frequently interrupted the flow of input or output from the model by changing or overwriting customized WFO configurations, data set handling scripts, and chronological execution files. This may not reoccur with the recent frequency, since some of the interruptions were to install the new AWIPS PX servers, and that is now complete. A positive aspect of these same changes was that they allowed the processing power and disk space to handle the WRF NetCDF files which might have been an unacceptable additional load to the Data (DS) or Application Servers (AS) in AWIPS. In spite of such interruptions the Linux cluster and the WRF model were remarkably robust; they often continued to run with whatever data sets were available, even when the model output was not available in AWIPS, it was often found stored on the Linux cluster.

2.4 Domain selection

Domain selection is a critical process for setting up a local model in the WFO. The domain must be large enough that the WFO forecast domain and the local topographic features are included, but it must also be computationally feasible within the time constraints that allow for forecast use. Domain selection balanced several competing requirements, the most constraining of which was that the output was to be available to the forecast staff of the WFO by the shift change so that a morning convective update could be made using the WRF prognostics. This required estimating the the total computations required for the new domain and the speed improvement expected from the cluster. As an example, for WFO JAX the domain needed to be large enough to include the Florida Big Bend area (Apalachee Bay) to the west, the Gulf Stream to the east, the Georgia coastal plain to the north, and the Interstate 4 corridor to the south. Whether this domain could be run with the proposed hardware in under the three hour timeframe that was available between the receipt of the NCEP grids and the time the morning forecaster needed to produce the forecast update.

Estimating the run time was necessary to make sure the desired domain, forecast timing, and cluster cost all converged on a feasible solution. Even though the 5 km grid size is undesirable for explicit convection, it was a compromise with existing GFE grid and domain size versus time available to complete the run.

For the foreseeable future, computational resources will continue to expand, and the limitations discussed here will be less of a burden, but the demand for higher resolution will continue to tax available resources.

What we envision for the near future, and the authors believe is implementable now, is a resolution from 2-3 km at the scale that the public considers "my neighborhood". With this scale in place and given that we can actually achieve reliable forecasts (no small feat, but in the authors opinion possible with WRF ARW), the economic impact of weather forecasts increase dramatically, not by the value of a single decision, but by the magnifier of millions of good decisions made by the public and private entities across the country.

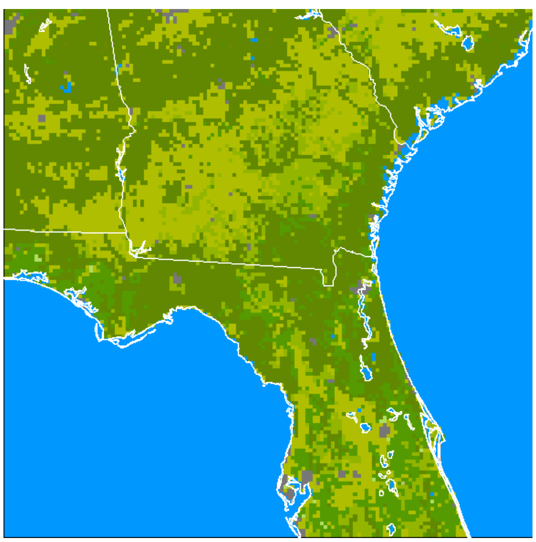

Figure 2. WRF Model domain as USGS gridded 5 km land use. Note the inclusion of lakes and the St Johns River as well as the urban, wetland and xeric upland terrain.

2.4 WRF model improvements

In addition to the numerical and computational improvements noted in Shaw et al. (2004), the authors believe the most important WRF contributions are in the high resolution land use (Figure 2.) and the NOAH land surface model coupled with the Yonsei University PBL model. Earlier local NWP model deficiencies in this area were noted in Welsh et al. (1999). In Florida, the role of the large lakes and swamps adjacent to xeric areas along the limestone ridge produce moisture gradients capable of creating the energetic equivalent of the sea breeze.

While this is locally well known, it is poorly studied. That the WRF model land surface physics appears able to include the creation of such moisture gradients is a major step in the right direction. Since the WRF has been displayed in AWIPS, forecasters have for the first time, actually seen this powerful forcing in action.

3. Results

3.1 First time successes

This project incurred considerable risk, but was accomplished by a dedicated team. Along the way several strategic milestones were accomplishments in their own right. First, this project was the first time NOAA and the NWS had funded a local modeling study by a WFO-led team. Secondly, it is also the first WFO quasi-operational use of the WRF model, and may in fact be the first such use anywhere. Third, this is the first time the WRF model has been initialized with operational radar and satellite data from AWIPS. Fourth it is the first time the WRF model has been configured for and displayed in AWIPS.

None of these are trivial accomplishments on their own, but the real goal here was operational use of the model. The model first ran in March 2003 and was available in AWIPS shortly after the installation of the Operational Build #1 (OB1) in early June 2003.

The model itself has proven much more robust than the scripts and downloads of the LBCs and NCEP data download to initialize the model. Occasionally. a single run for the day would fail, and usually the next run would complete. Longer gaps were due to changes in AWIPS or broken connectivity.

3.2 Winds and state parameters

Wind forecasts of the WRF model have a reduced root mean square error (RMSE), Figure 3, over the Eta model for all forecast hours for the summer season (1 June to 8 October) from the FSL Real Time Verification System (RTVS) as described Mahoney et al. (1997, 2002).

It is the poor ETA model wind performance in the Southeast US that initially led the Florida forecasters and researchers to attempt MM5 and other local modeling efforts.

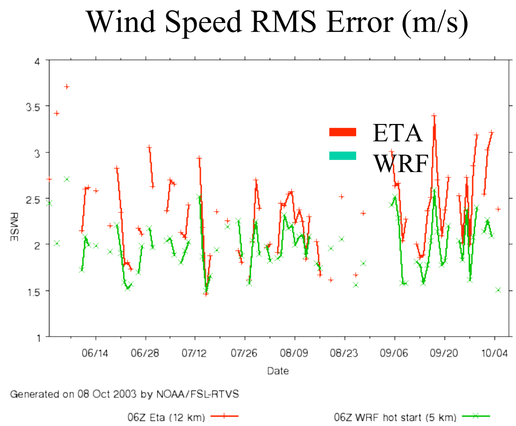

Figure 3. Comparison of 5 km WRF "hot" start and NCEP Eta derived wind speed RMS error.

Additional wind bias, diurnal temperature bias and RMSE, and Quantitative Precipitation are reported in Shaw, et al. (2004). One of the early discoveries was a large and persistent low bias in the diurnal maximum temperature by the WRF model. This was quickly noted by the JAX forecasters in the first weeks once the WRF was ingested into AWIPS. This bias was linked to the loss of short wave energy reaching the ground due to an excessive amount of stratiform cloud cover generated by the model. The FSL team traced that problem to a warm temperature bias (increased stability) from the PBL top to a least mid-levels of the atmosphere.

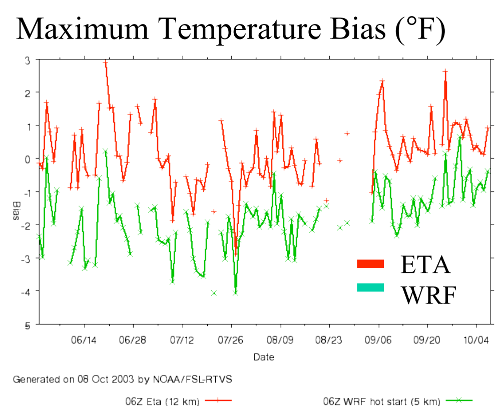

Figure 4. Diurnal Maximum Temperature Bias. WRF version 1.3 had a consistent low bias for maximum temperatures, corrected in version 2.0.

This has been corrected with the dual changes of the LAPS correction and the implementation of the WRF version 2.02 in July 2004. Results from Bogenschutz 2004 have shown that large cold bias has been reduced to the order of one degree, comparable to the NCEP ETA model. The average WRF ARW version 2.0 surface maximum temperature bias for 2004 warm season (less the hurricane period) is -0.8 K, compared to the WRF version 1.3 bias of -2.5 K for the 2003 warm season. While the WRF-LAPS version 2.0 still suffers from a cool temperature bias, it is now comparable to most mesoscale models. For the 2004 summer period, the WRF-LAPS ARW model forecasts temperatures slightly better than both the Eta model and WRF-Eta (Bogenschutz, et al 2005).

3.3 Convective performance

The WRF ARW version 1.3 and 2.0 surface convective performance was evaluated by Bogenshhutz (2004b) for the 2003 and 2004 warm seasons respectively. The statistical performance was good, but suffers from the well known statistical bias against higher resolution numerical models which pay a double penalty for temporal or spatial errors compared to coarser resolution models. For this evaluation, the technique of Ebert and McBride (2000) was used for the concurrent WRF ARW and Eta models compared to the NCEP Stage IV precipitation. This technique also allows identification of the model systematic error types, whether from propagation, under-forecasting or overforecasting. Results for Florida convection for 2003 are in Figure 5.

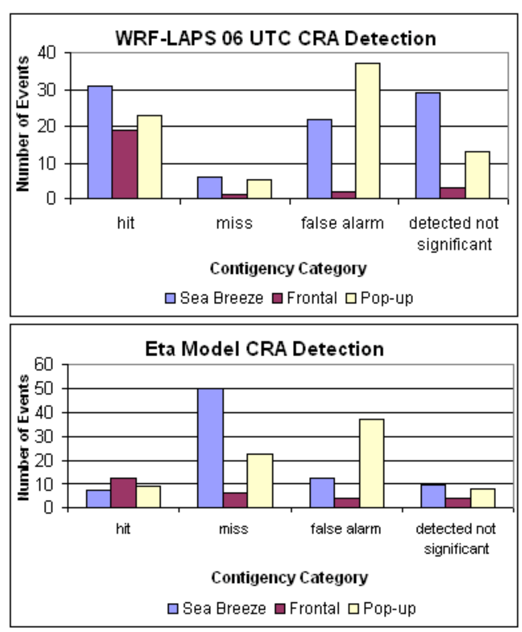

Figure 5. Convective Rain Performance of the WRF ARW and NCEP ETA Models for Summer 2003. Events were categorized as sea breeze, linear or airmass (pop-up) convection.

The Ebert-McBride method clearly indicates:
1) That the WRF ARW did dramatically better at detecting sea breeze convection and random convection than the ETA, but also generated a large number of false alarms for these classifications. Nonetheless the hit to miss ratios are vastly improved for these storm types.
2) That for linear convective systems the WRF ARW was more successful without the false alarms with more than double the hit to miss ratio.
3) It is clear that the WRF ARW is too sensitive to weak convection and overdevelops these systems. Further investigation by Bogenschutz indicated that the cold inland temperature bias was creating excessive convergence close to the coast and preventing full inland propagation of the sea breeze, but over-forecasting the number of sea breeze storms.

3.4 Sea breeze performance

The WRF-ARW sea breeze performance was evaluated by Bogenschutz et al. (2005) using the Contour Error Map method in five subdomains within the WRF ARW domain. There were 92 sea breeze occurrences (of which 66 were convective) during the summer of 2003 during a 58 day period. During this period the ETA model detected 34 percent of the sea breezes, with the WRF ARW detecting 84 percent.

During the hurricane-abbreviated 2004 season the WRF ARW detected 93 percent of the sea breeze transitions. Sea breeze transition timing errors during the short 2004 season after the thermal error correction also were dramatically reduced from 1.24 hours to 0.55 hours with a bias of only 0.20 hours.

3.5 Tropical Cyclone performance

The WRF-ARW tropical cyclone performance showed surprising skill during the 2003 season as has been previously reported in Welsh 2005.

Detailed comparison of the 2004 season Tropical Cyclone performance is in preparation for future publication, but Figures 6 and 7 below indicate that the local WRF ARW model was capable of not only forecasting the Hurricane tracks, but also the cumulative precipitation and structure better than the concurrent ETA model. In particular, the banding structure of the hurricanes is quite evident in the WRF results. Where the precipitation did not fall (Figure 7.) is equally important to forecasters.

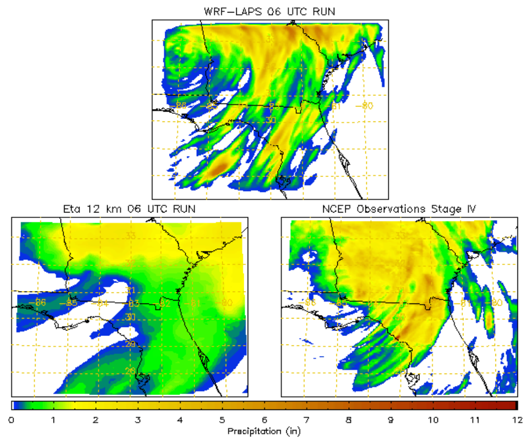

Figure 6. Hurricane Frances Precipitation comparing WRF with LAPS assimilation of local data (top) , NCEP ETA (left) and NCEP Stage IV accumulated 24 hour precipitation.

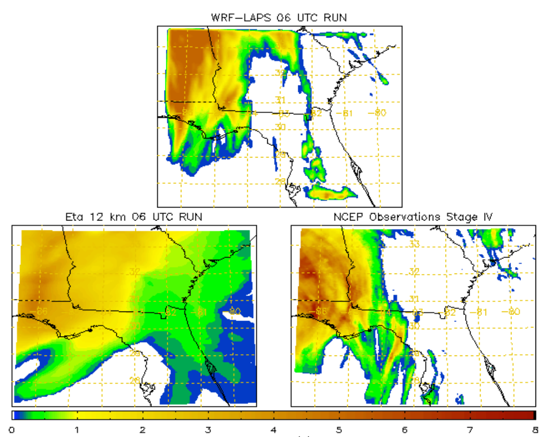

Figure 7. Hurricane Ivan precipitation performance. (Layout as in Figure 6.)

4. Summary and Recommendations

In summary the NOAA CSI local modeling project was an unqualified success. Not only did the project team lead the country in getting the WRF model into the forecast process, the team of WFO forecasters, NOAA FSL and Florida State University participants also have shown conclusively the value of local diabatic data assimilation to the forecast process. The success of this project in improving the quality of prognostic products available to the forecaster in the sea breeze environment is unparalleled for a small scale effort. It is clear that the WRF ARW model with LAPS diabatic data assimilation is the only product currently shown to be capable of the high spatial and temporal forecast requirements of the National Digital Forecast Database (NDFD) for Florida. That this same model has shown surprising skill with both convective rain and tropical cyclone rainfall argues strongly for a renewed and funded effort to produce these same results for the entire Southeast CONUS.

4.1 Local Modeling Project Summary

The WRF modeling project implementation under CSI has been highly successful on several levels:

1) The NOAA-led team assembled and configured a Linux-cluster-based version of the WRF model with LAPS local data assimilation and had it running in five months, under budget and early. The LAPS "hot start"data assimilation scheme used to initialize the WRF model included local AWIPS satellite, mesonet and radar data leads to superior results for both sea breeze detection and convective rainfall as indicated by extensive verification of the model with FSL RTVS, and at Florida State University.

2) The LAPS initialized WRF ARW model is demonstrably superior to WFO available version of the Eta model "out-of-the-box" and has continued to show improvement. Verification to date indicates that WRF ARW is substantially improved in operations when compared to the NCEP ETA, particularly in winds, visibility, sea breeze structure and timing, convection and tropical cyclone precipitation applications.

4.2 Recommendations

Recommendations derived from the experiences of this project are:

To continue funding local model WRF ARW prototype development, with the Florida NWS offices taking the lead, and FSL and local Universities providing support. It should be noted such a testbed was proposed as far back as December 2003 at the USWRP Mesoscale Modeling meeting (Dabberdt et al 2005 in press).

To continue to expand local data assimilation to include multiple radar site Doppler radial winds and reflectivity, Global Positioning System derived atmospheric moisture, and additional mesonet sites as WFO bandwidth permits.

To further develop a Hurricane forecast version of WRF (HWRF) as an outgrowth of ARW version shown here from the NOAA CSI model. It is clear that the model carries hurricane structure as well as track and rainfall information.

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