Implementing and evaluating the Weather Research and Forecast (WRF) Model at NWS WFO Jacksonville, Florida

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1. INTRODUCTION

The NOAA Coastal Storms Initiative (CSI) pilot program was funded by Congress to assist communities in mitigating the impact of coastal storms. The initial implementation site was the St. Johns River basin in Northeast Florida. One of the nine projects approved as part of the CSI was the local implementation of a mesoscale numerical weather prediction (NWP) model with additional local data assimilation at the Weather Forecast Office in Jacksonville, FL (WFO JAX).

A small team of collaborators has put together a mesoscale atmospheric numerical weather prediction (NWP) model and data assimilation system at WFO JAX. Developers of the model system included members of the WFO JAX staff, and selected participants from the NOAA Forecast Systems Laboratory (FSL). The FSL participants has gained substantial expertise from the NASA Range Standardization and Automation (RSA) project (Shaw et al. 2003). 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 (LBCs).

Commercial-Off-The-Shelf (COTS) project hardware and open system software were to be used to the maximum extent possible. In this case, the Linux OS, and a high-performance multiprocessor compiler were coupled to the UCAR Weather Research and Forecast (WRF) model with the FSL-developed Local Analysis and Prediction System (LAPS) diabatic "hot" start.

A commercial Linux computing cluster was purchased and adapted to the specific tasks of [·] running the WRF Numerical Weather Prediction (NWP) model

The COTS Beowulf computer cluster was configured with a master node and eight slave nodes. Each node was powered by dual Athlon 2100 processors and 2 gigabytes of RAM, the latter to minimize disk access to the maximum possible for better performance. Several rebuilds of the Linux kernel were required to optimize it for high computational performance rather than high availability use. A gigabit Ethernet switch was used to handle node communications, with a second 100 megabit Ethernet card for communications with the WFO JAX forecast system.

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.[·] The use of the WRF model provided many potential improvements over the previous models, UCAR MM5 and two versions of the Workstation Eta model which were run locally at 10 km resolution at WFO JAX since January, 2000 and March 2001 respectively.

The use of local data assimilation in the WRF model suite was also an integral part of the experimental design for the project. Diabatic local data assimilation was accomplished by using NOAA FSL's Local Analysis and Prediction System (LAPS) with local radar, satellite, marine and mesonet data. The morning realtime run with full local data assimilation was compared to an immediately subsequent control run without local data assimilation. The purpose here was to evaluate the additional value of local data in the model, and its value for forecast use.

Among items recognized to negatively impact the solution quality of the previous locally run mesoscale models (MM5 and Workstation Eta) predictions were the large grid

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land-sea mask which created strange coastline discontinuities in the model, its very poor resolution of the land use, and lack of permanently wetted areas (lakes, rivers, and swamps) which strongly impact the surface fluxes in Florida. Another item judged to need improvement to enhance Florida forecasts was poor air-sea interaction, but no significant improvement in this area is likely without high resolution SST fields provided on a daily basis. Unfortunately, there seems to be no national program to provide that item. There are also other potential improvements in other areas in the WRF model, including mass-conserving higher order numerics which should produce much better kinematics, and a better surface-boundary layer model suite.

The project merged talents among NOAA entities and cutting edge technology 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 are reported by Shaw et al. (2004). Additional model verification is by Bogenschutz et al. (2004).

2. IMPLEMENTATION

2.1 Linux cluster implementation

A computer cluster is a distributed or parallel processing system, consisting of two or more interconnected components which can function as stand-alone computers, cooperatively and interactively working together as if it is a single, integrated computing resource. The term "cluster" is rather generic, in reality there are a several types of clusters that have evolved in various attempts to solve specific research and commercial computing requirements. The CSI project required a High Performance Cluster similar to the class of clusters (though ours is small by comparison) used by scientific laboratories in both government and commerce. Often called Beowulf clusters after some of the pioneering scientific clusters, they are very flexible and can be configured to perform a variety of high performance jobs including local NWP modeling. They are popular in scientific environments where there is a wide range of IT talent, students, professors and System Administrators (sysadmins) to patch together Linux application packages, compilers, and script processing routines to keep the cluster running smoothly. There is very little that is standard on a Beowulf, and ours was no exception to that rule. The flexibility of these systems comes from the expertise of the users to customize the functionality of the machine, from building custom kernels to configuring efficient storage, network services and distributed processing. A considerable part of the total effort was related to such “sysadmin” work.

The project was to highlight the use of open system architecture where possible. In our case this was accomplished by use of Red Hat™ Linux version 7.3 for the operating system software, the open source UCAR WRF model version 1.3 (see: http://www.wrf-model.org) and FSL LAPS version 0-18-10.

For COTS hardware, the cluster was selected based on price and performance. AMD Athlon MP™ processors were selected due to NWS experience gained with Athlon™-based processor results for the workstation ETA model (http://strc.comet.ucar.edu/model/index.htm). Eta benchmarks indicated that the Athlon™ processors were faster for this type of model application, which may be associated with better CPU pre-fetch routines. The nine cluster nodes run dual AMD Athlon MP™ 2100 CPUs on a dual processor motherboard with 2Gb of RAM, a 40Gb IDE hard disk, and Intel Pro/1000 MT™ gigabit network cards.

Installation of the 9 node Linux Beowulf cluster was relatively straightforward in the physical sense, Copious RAM was allocated to allow minimal hard disk access while running the model. In contrast, not one, but several Linux kernel recompilations were necessary to achieve the desired functionality to support the project. FSL personnel installed and compiled the LAPS and WRF software with a COTS high performance multiprocessor compiler from the Portland Group. In all, it was less than 5 months from cluster delivery to the first successful run of the WRF model. Porting the WRF output to AWIPS took an additional two months and was complicated by inaccurate AWIPS system manuals. It should be noted that when the WFO and FSL personnel were able to communicate face-to-face at FSL or the WFO, much greater progress was made in a short period of time. In particular, the role of the WFO Jacksonville Information Technology Officer (ITO) and the SRH Scientific Services

Division were crucial to solving a myriad of emergent technical networking issues as the process evolved. FSL members expertise in the data assimilation and WRF models was equally important and fundamental to the timely success of the project.

2.2 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.

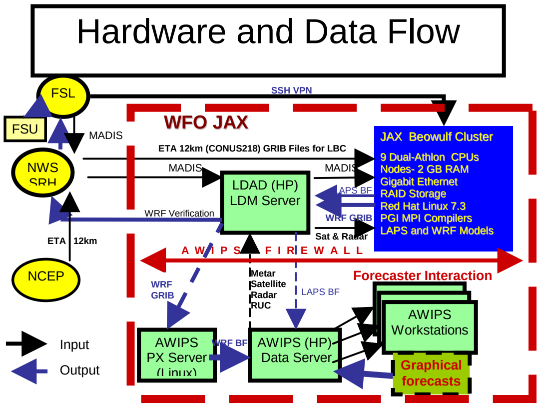

Figure 1. WFO JAX Linux cluster information flow inputs (green) were passed through the Regional network or via LDAD from AWIPS. Output (brown) LAPS NetCDF analysis files and WRF grib prognostic files are passed from the cluster to LDAD to AWIPS for display.

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 00 UTC Eta 12 km tiles, using the 06 UTC 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 15 UTC using the NCEP 12 UTC tiles and LAPS, and at 21 UTC with the 18 UTC tiles and LAPS. Results of the intercomparison of the first two runs and the NCEP 06 UTC ETA (note that the WRF model was initialized from 00 UTC ETA run, +6 hour forecast) 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	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

2.3 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.

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.

Early estimates of computational time were based on the WFO JAX experience with the workstation Eta model which had been running on a 10 km domain since January 2000. The scaling factor to halve the grid spacing on a model domain is nearly a factor of ten since the number of grid points is doubling in the X,Y, and T dimensions, while typically adding more vertical levels, and additional complexity.

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 chosen to be compatible with the existing GFE grid and domain size versus time available. It came as a surprise to the staff of WFO JAX that this seems to make little difference, perhaps due to the improved kinematics of the WRF model.

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.

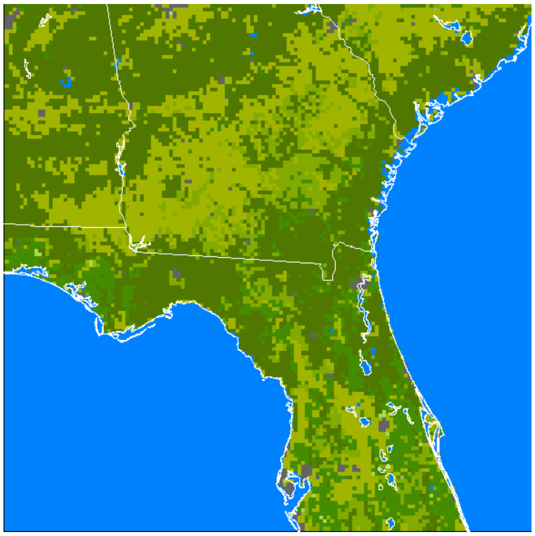

Figure 2. WRF Model domain as USGS gridded 5 km land use. Note the inclusion of lakes and the St Johns River as well as the urban, wetland and xeric upland terrain.

2.4 WRF model improvements

The authors believe the most important WRF contributions are in the high resolution land use (Figure 2.) and the Noah Land-Surface Model physics. Earlier local NWP model deficiencies in this area were noted in Welsh et al. (1999). In addition, the WRF numerical and computational improvements noted in Shaw et al. (2004) are a clear advantage.

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 is 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 routinely seen this physical forcing in WRF model prognostic fields.

3. Results

3.1 First time successes

This project incurred considerable risk, but was accomplished by a dedicated team on budget and delivered early, with strong justification for the effort in the verification results below. Along the way to achieving the project strategic milestones, were some specific accomplishments of note in their own right.

First, this project was the first time NOAA and the NWS had fully funded a local modeling study by a WFO-led team. Secondly, it was also the first use of the WRF model in the operational WFO environment, and may in fact be the first such operational use anywhere (March, 2003). 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 output has been configured for, and displayed in a WFO AWIPS.

None of these were trivial accomplishments on their own since they were firsts, and suffered from the typical lack of documentation as first attempts always do. While these were significant events, the real goal here was and still is, operational use of the mesoscale WRF model to improve the forecast process. The model first was displayed in AWIPS near the time of installation of the Operational Build #1 (OB1) in early May 2003, and was judged to be ready for verification as of 1 June 2003.

The WRF model itself has proven much more robust than the scripts and downloads of the LBCs and data 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 to files and configuration in AWIPS which was disrupted by overwritten files in an AWIPS update or a broken connectivity item such as a Frame Relay network router change.

3.2 Winds and state parameters

One of the most important mesoscale fields for the WFO in an asynoptic environment such as the Florida peninsula in summer, is the mesoscale wind. Fortunately this was one of the WRF strengths. 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) in Mahoney et al. (2002). Only rarely were the Eta model winds superior to the WRF winds. Results in RTVS since 01 June 2003 are available online at:
http://www-ad.fsl.noaa.gov/fvb/rtvs/csi

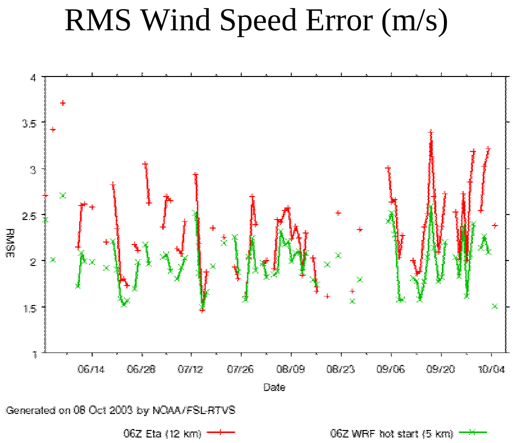

Figure 3. Comparison of 5 km WRF "hot" start and NCEP Eta derived wind speed RMS error.

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 LAPS temperature bias (thus increased stability and more stratiform vice cumulus cloud formation) from the PBL top to at least mid-levels of the atmosphere. Correction of the assimilation system error produced much greater correspondence between the WRF with assimilation and the control (no assimilation) run errors. While that was corrected at the end of the summer, but it is still unclear whether all of these noted effects will improve, or that still more needs to be done (Figure 4). The authors believe that most of the remaining temperature bias is a direct result of the existing PBL parameterization which allows full-depth PBL mixing, which though true of the mechanical mixed layer, is not true for the deeper convective PBL. Minimum temperatures were comparable to the Eta and are not shown.

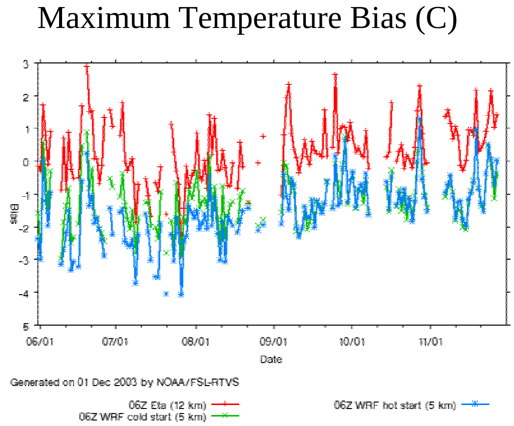

Figure 4. Diurnal Maximum Temperature Bias. WRF had a consistent low bias for maximum temperatures. One clue to the source of this problem was that the WRF with LAPS was worse then the control (null) run, indicating an assimilation error. After the correction, in October the two runs became much closer, though a bias still exists.

A valuable WRF output is the ability to display pseudoreflectivity a simulated radar return from the storms generated in the model. While it has not proven very skillful in producing convective storms in the right place at the right time, it has enabled the forecasters to quickly get an assessment of the nature and intensity of the diurnal convection. In contrast to diurnal convection, dynamically forced convection is often well forecast, with realistic structure in the pseudo-reflectivity fields (see below).

Of particular note, the WRF forecasts of visibility have often been very successful in both timing and intensity. This was noticed almost immediately by the forecasters, and was the first WRF (locally called Warf) field noted in a WFO JAX Area Forecast Discussion, and changed the fog forecast from patchy to dense fog with visibility below a quarter mile that night based on a WRF prognostic visibility parameter.

3.3 Tropical Cyclone performance

In the two tropical cyclone cases which entered the WFO JAX domain during the summer of 2003, the WRF forecasts of tropical cyclone winds and rainfall patterns were judged to be excellent. Though this is an extremely limited sample, it is quite encouraging. For Tropical Storm Henri, the WRF precipitation amounts were on the order of two to three inches in Florida. These prognostics fields of rainfall were not considered credible at the time, but proved to be excellent. An example of a four hour WRF forecast of developing Tropical Depression #7 which formed off Jacksonville, is shown as a good example of the strength of the LAPS initialization and the WRF kinematics. This combination generates very realistic tropical cyclone banding where other models were not as realistic in both timing and intensity of the rainfall.

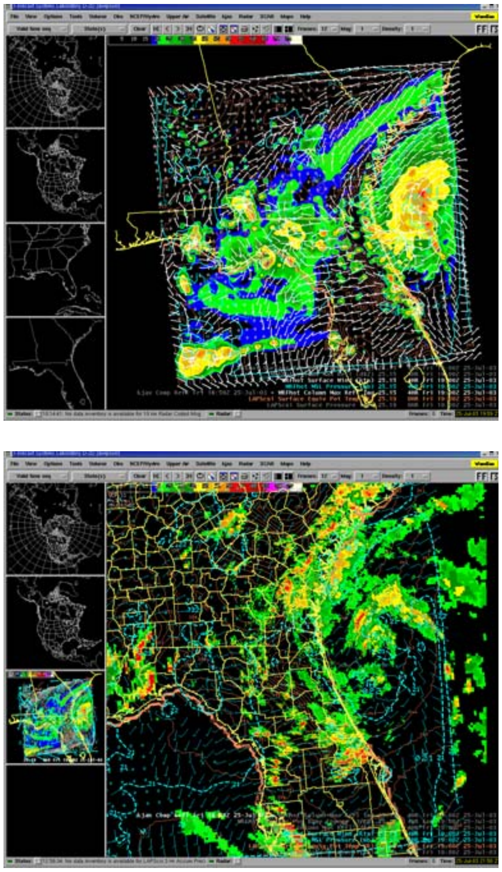

Figure 5. Comparison of 5 km WRF with LAPS "hot" start four hour forecast (top) of TD #7 pseudo-reflectivity and winds from the 15 UTC model run (valid 19 UTC on 25 July 2003) and the KJAX WSR-88D radar data at that time. Note that the model produces pseudo-reflectivity that is below the radar horizon particularly offshore, but captures well the intense precipitation areas along the Georgia coast, Cape Canaveral, near Tallahassee, and in the southerly offshore feeder band. No other model available to the forecasters at that time represented TD #7 winds and convection structure as well.

3.4 Assessing the value of LAPS local data assimilation in the mesoscale WRF model.

In Florida, for much of the year the weather is asynoptic and governed by mesoscale processes and mesoscale forcing. Some of this forcing is sudgridscale even to the 12 km version of the NCEP ETA model. Other than the diurnal temperature maximum problem shown above, the WRF with local LAPS assimilation, equalled or out performed the NCEP 12 km ETA model in all state variables in the first 12 hours. WRF kinematics and rainfall were substantially better through all hours.

Rainfall Skill Comparison (ETA and WRF)

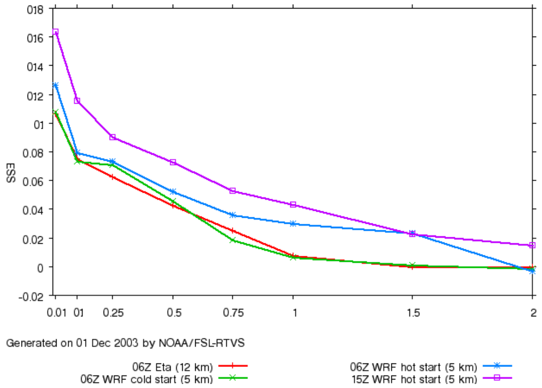

Figure 6. Comparison of 5 km WRF "hot" start and NCEP Eta derived precipitation with local LAPS data assimilation. Note that the Eta model (red) and WRF control run (green) are virtually indistinguishable, while the WRF with LAPS (hot start) runs, 06UTC (cyan), and 15UTC (magenta) are both improved substantially. Data is for all dates from 01 June to 01 December 2003. Note: the 15 UTC WRF hot start run is much better for lower precipitation amounts, we speculate that this may be due to visible imagery and morning wind reports being available for the LAPS ingest and assimilation, improving initial conditions.

4. Summary and Recommendations

4.1 Local Modeling Project Accomplishments

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

1. A high performance Linux cluster was built by a COTS vendor and was operated and

configured to run the WRF by a WFO staff with help from FSL. 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 just five months after hardware delivery.

2. The local data assimilation scheme used to initialize the WRF model included local AWIPS satellite, mesonet and radar data, and results clearly showed its value. The LAPS analysis and WRF model output were ported to display on AWIPS, and used in the GFE.

3. Extensive verification of the model was accomplished in real time (with FSL RTVS).

4. As a direct result of forecaster input, at least one improvement in the WRF model has already been implemented due to the CSI WRF model project.

5. The LAPS initialized WRF model is competitive with the Eta model "out-of-the-box" and should continue to show improvements with additional funded development work. Ingest of WSR-88D level 2 data and GPS-IPWV as well as additional mesonet data from the new Florida Road Weather Information System (RWIS) are planned for this year.

4.2 Recommendations

Recommendations derived from the experiences of this project are:

1. Continue funding local model prototype development. There is clearly a lot more work to do, but the WRF is ready for "prime time". We believe "one model fits all" is not optimal at the mesoscale, given the different weather regimes across the Conus. Mesoscale model prognostic output requires more than a gigabyte of WFO throughput per hour at the convective scale; bandwidth that will not be available in the near term. Local modeling is the interim answer.

2. Send Eta and GFS tiled LBCs via the SBN when bandwidth upgrades permit, to reduce the large latency of the NCEP Eta LBC arrival at the WFOs, which varies from two to four hours.

3. Fund additional bandwidth for the NWS Regional Networks to permit adjacent WFOs access to local modeling products. It should be noted that Florida has three mesoscale modeling systems with additional data assimilation currently in place at WFOs JAX, MLB and MIA, but do not share products due to limited bandwidth, even though coverage overlaps.

4. Continue to fund WRF assessment via RTVS and additional development of WRF assimilation studies.

5. Continue to expand local data assimilation to include multiple radar site Doppler radial winds and reflectivity, Global Positioning System(GPS) derived atmospheric moisture, additional mesonet sites, and particularly to include local mesoscale SST analysis (see www.seacoos.org).

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