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REAL-TIME APPLICATIONS OF THE WRF MODEL AT THE FORECAST SYSTEMS LABORATORY

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1. INTRODUCTION

Scientists at the Forecast Systems Laboratory (FSL) have contributed in myriad ways to the development of the Weather Research and Forecasting (WRF) model system over the past several years. Contributions have included: the Standard Initialization (SI) with a powerful Graphical User Interface (GUI) to set up the model runs; adaptation of a land surface model and the Grell-Devenyi ensemble cumulus parameterization scheme from the Rapid Update Cycle (RUC) modeling system to the WRF; coordination of additions of model physical parameterizations; development of a coupled WRF/Chemistry modeling system for regional air pollution prediction; assistance with the coding of the WRF 3DVAR system; and collaboration with NCAR and NCEP in setting up the Developmental Testbed Center to enable thorough evaluations of the performance of the Eulerian Mass (EM) and Nonhydrostatic Mesoscale Model (NMM) versions of WRF. These activities are being performed in preparation for the Initial Operating Capability slated to be in place at NCEP by October 2004.

FSL was one of the first groups to experiment with real-time WRF forecasting. This paper highlights scientific findings from a wide range of real-time applications of the EM version of the WRF model set up to run by FSL scientists over the last year or two. Five applications are described:

1. Real-time field project modeling support for the International H_20 Project (IHOP_2002)
2. Participation in the NOAA New England High-Resolution Temperature and Air Quality (TAQ) program – including development and testing of the WRF/Chem model
3. Real-time testing of the RUC-initialized WRF against the operational RUC20 model in preparation for the eventual implementation of the WRF "Rapid Refresh" system at NCEP
4. Contribution to an ensemble of models used in the Management Decision Support System (MDSS) for providing guidance to winter road maintenance crews in Iowa
5. The first quasi-operational version of WRF run at very high resolution at a local NWS Forecast Office under the NWS Coastal Storms Initiative

2. IHOP SUPPORT

The overall objective of IHOP is to ascertain whether improved characterization of the four-dimensional distribution of water vapor will result in significant improvements in warm season quantitative precipitation forecasting (QPF) skill using state-of-the-art numerical weather prediction (NWP) models. FSL ran several experimental models in real time in support of the field phase of IHOP, namely the MM5 and WRF models at 4- and 12-km resolution initialized with the LAPS (Local Analysis and Prediction System, Albers et al. 1996) "Hot Start" procedure (McGinley and Smart 2001; Shaw et al. 2001), and the RUC at 10 km resolution (Benjamin et al. 2003 a, b). The Hot Start is a diabatic initialization and dynamical balancing technique previously developed for LAPS. FSL scientists were interested in seeing whether the sizable increase in 1-6 h QPF and cloud prediction skill seen earlier in the cool season from daily Hot Start LAPS/MM5 model forecasts over the Colorado region would translate into significant improvements in warm season QPF skill over the Central U. S. using WRF and the IHOP data sets.

For the LAPS-WRF runs, the Kain-Fritsch cumulus parameterization was employed on only the 12-km grid, whereas the Schultz (1995) microphysics was utilized on both the 12- and 4-km grids. Of particular note is that the LAPS-WRF model runs used full volumetric "wideband" reflectivity and radial velocity data from 11 WSR-88D radars in the LAPS analyses to help define the cloud and precipitation fields in the initial state. In addition, the Ebert and McBride (2000) technique was

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developed to decompose the forecast precipitation errors into displacement, intensity, and shape errors categorized by type of mesoscale convective system.

The IHOP application was the first real experience in running the WRF model for FSL. Unfortunately, none of the WRF runs could be made available for viewing by forecasters in the field. Nevertheless, our experience in IHOP provided LAPS developers with new insights into how to improve the Hot Start procedure. IHOP also provided RUC developers with useful feedback about how best to configure the RUC-initialized WRF runs, completed only two months later, when that model configuration was running with high reliability for the TAQ project.

The entire 6-week IHOP period has since been rerun with a revised LAPS Hot Start for WRF and the results have been evaluated. One important finding is that the MM5 and WRF Hot Start runs produce substantially improved prediction of QPF, in terms of bias and equitable skill scores, during the first 9 h of the forecasts relative to that of the other operational and experimental models. However, the Hot Start models had trouble maintaining ongoing convection unless it was quite strong in the initial state. This was no less of a problem for model runs made closer to the verification time. All of the models produced useful forecasts of the location of such features as the dryline and frontal systems, but results were mixed when it came to convective outflow boundary forecasts, which naturally limited their usefulness to accurately pinpoint the location and timing of convective initiation. Squall lines and upscale growth of convective systems appeared to be predicted with rather impressive skill by the WRF and MM5, and even isolated supercell storms were sometimes forecast with useful skill. One particularly problematic phenomenon was elevated convection. As the example in Fig. 1 illustrates, the WRF and MM5 both were able to predict the occurrence of non-precipitating convection in subsaturated situations, but often did not forecast the evolution of “virga storms” into precipitating systems.

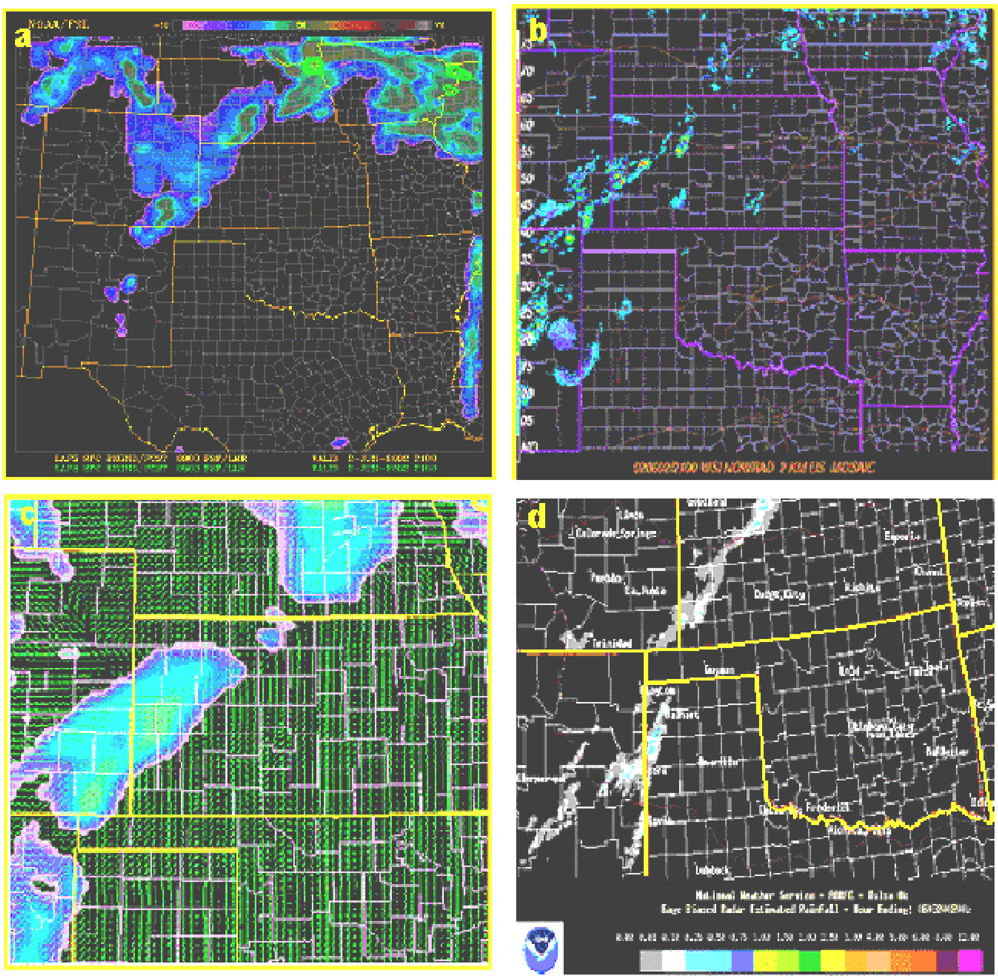

Fig. 1. Example illustrating failure of MM5 and WRF models to correctly forecast the evolution of elevated, non-precipitating convection into rain-producing systems: a) MM5 9-h forecast of reflectivity valid at 2100 UTC 2 June 2002 (image is column composite reflectivity, contours show surface reflectivity fields); b) NOWRAD composite radar analysis at 2100 UTC (dBZ); c) WRF-12 km 6-h forecast of reflectivity valid at 0000 UTC 3 June showing only elevated convection (note absence of any surface reflectivity); and d) radar-derived hourly precipitation totals for 0000 UTC 3 June showing amounts exceeding 0.25 in/h where none was forecast.

3. TAQ AND WRF/CHEM

The NOAA Temperature and Air Quality project was conducted over New England during the summer months of 2002 and 2003 in real time as a joint effort of several NOAA Research Laboratories (FSL, ETL, AL, NSSL) and the National Weather Service. The immediate purpose of TAQ was to evaluate the benefits to the energy industry of improved skill at predicting surface temperature resulting from the assimilation into high-resolution models of special observations obtained from meteorological platforms set up by ETL for the project. The ultimate purpose was to lay the foundation for potential air quality and high-resolution temperature forecasting capabilities that might someday become part of the NOAA product line. In addition, an ensemble of models was run and evaluated by NSSL during the TAQ_2002 phase to determine the extent to which an ensemble of models, including special configurations of the WRF, RUC, and Eta models, was superior to deterministic forecasts produced by any single model.

In order to initialize the WRF model with RUC initial and boundary conditions during TAQ, it was necessary to adapt the WRF SI to use RUC20 native isentropic-sigma coordinate data, including cloud hydrometeor and land-surface fields from the RUC20. This "WRF-RUC" model with 35 sigma-p levels and 10-km resolution was used to make 48-h forecasts every 12 h from 15 July – 31 August 2002 over the domain shown in Fig. 2.

In addition, three different resolution MM5/Chem models were run (at 27, 9, and 3 km) and evaluated during TAQ_2002. This "online" coupled modeling system allows for feedback between the meteorological fields and the chemical species. Thus, the chemistry and meteorology use the same coordinate systems and physical parameterizations for sub-grid scale transport. The chemical mechanism is derived from the Regional Acid Deposition Model (RADM2) system, and includes dry deposition, biogenic emissions, and photolysis. The WRF model transports all the species at the grid scale, and parameterized turbulence and convection transports species at the sub-grid scales. A number of changes to the WRF system were required to attain this capability. The WRF Registry was modified to describe and manage the new data flow and I/O. An anthropogenic emissions database had to be added as an input file. The REAL.exe program was modified to initialize some 40 chemical species needing to be transported; also, 60 aerosol species were added for the WRF/Chem development. The boundary condition routines were also changed to accommodate the chemical fields.

The MM5/Chem system formed the foundation for a real-time WRF/Chem modeling system that followed in the summer of 2003. The primary purpose of this effort was quality control (ensuring a robust model with debugging of all new routines, and development of an optimum model configuration for the fastest runtime). This is being done to prepare for the New England Air Quality Studies 2004 (NEAQS2004) project, when a 12-km version of the WRF/Chem will be run in the summer of 2004 over the central and eastern U.S. to allow for direct comparison with the "offline" Eta-CMAQ (Community Model for Air Quality) air chemistry modeling system and other real-time models. Results so far suggest that the online WRF/Chem system is more computationally efficient than the offline system. Subjective analysis indicates that high ozone and particulate matter episodes, as well as unpolluted air masses, can be accurately predicted by the WRF/Chem system (Grell et al. 2004).

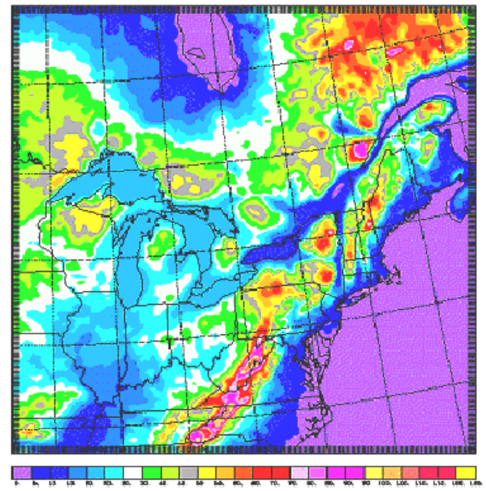

Fig.2. WRF-RUC domain and terrain contours (dm) used for the TAQ demonstration.

4. PRE-RAPID REFRESH TESTING

A "Rapid Refresh" (RR) configuration of the WRF model is scheduled to replace the operational RUC model run at NCEP by 2006. The RUC model is updated hourly with the latest observations, and the WRF RR model is likely to have even higher update frequency, notably because of plans to use broadband radar data. The assimilation and modeling techniques developed for RUC will be retained where applicable. As a first step in reaching this goal, FSL has set up real-time tests of the WRF EM model initialized with RUC20 initial and boundary conditions. This initialization is identical to what was developed for IHOP and TAQ, namely the use of the full-resolution RUC data on its native isentropic/sigma coordinate system, including hydrometeor and land surface fields. The WRF-RUC model is being tested and evaluated relative to the operational RUC20 model over CONUS in real time using various configurations of physics packages (cumulus parameterization, microphysics, and land surface, in particular), in order to arrive at the optimum configuration for the WRF RR. In addition, the 10-km version of WRF-RUC continues to run over New England (Fig. 2).

5. MDSS ENSEMBLE MODELING

WRF has played yet another unique role in real-time applications at FSL. The Federal Highways Administration has sponsored the development and implementation of a Management Decision Support

System (MDSS) as an experiment aimed at providing real-time guidance to road maintenance crews. This cooperative project between FSL, NCAR, CRREL (DOD/Army Cold Region Research and Engineering Laboratory), and MIT/Lincoln Labs has produced a decision support system and tested it in the winter of 2002-2003 in a region centered over Iowa. The WRF was used along with the MM5 and RAMS (Regional Atmospheric Modeling System) models, plus 2 sets of boundary conditions (from the AVN and Eta models) to produce an ensemble composed of 6 members. The MM5, WRF, and RAMS models all utilized the LAPS Hot Start initialization procedure discussed earlier. An example of four such forecasts of precipitation valid at the same time is displayed in Fig. 3. Equitable Skill Score and Bias statistics for precipitation amount forecasts from the three models (Fig. 4) show very similar performance for the WRF and MM5 models, with the RAMS configuration falling behind in the scores. The MM5 model displayed a near perfect Bias = 1.0 for all thresholds, whereas WRF exhibited a 40-50% overprediction bias in precipitation forecasts. Additional details can be found in Schultz (2004).

During the winter of 2002-2003, point-specific weather and road condition probabilistic forecasts were updated on a 12-km grid every 6 hours from models that issued 27-hour forecasts. A new configuration has recently been established for the winter of 2003-2004 to increase the 6-hourly to a 1-hourly update, 15-h forecast system. This new system also uses “time-lagged ensembles” as a replacement for the use of differing lateral boundary conditions. The time-lagged ensemble system consists of a number of model forecasts initialized at different times that verify at the same time. The reason for this latter change is that the experience from the winter of 2003-2003 failed to show significant dispersion among the member forecasts resulting from varying lateral boundary conditions.

6. WRF FORECASTING AT A WFO

FSL has also set up the WRF model to run in real-time at a NWS Weather Forecast Office (Jacksonville, FL) for the first time ever. For this application, which is being conducted under the NWS Coastal Storms Initiative (CSI), a 5-km version of the Hot Start WRF was set up on an Athlon Linux cluster with 8 dual-processors in July 2003 and has been running reliably ever since, producing four forecasts daily for use by the NWS forecasters. The primary interest in this experiment is high-resolution surface wind accuracy and convection forecasts (the winds drive water flow models). The FSL Real-Time Verification System (RTVS) is being used to objectively evaluate the model forecasts, and subjective evaluations are also being performed at the WFO.

Equitable Skill Score and Bias statistics are shown in Fig. 5 for precipitation forecasts made by three models: 1) the WRF-LAPS Hot Start, 2) a Cold Start WRF-Eta, and 3) the operational Eta-12 km model. The Cold Start WRF-Eta run is simply a WRF model initialized with Eta model fields interpolated to the WRF 5-km grid for initial and boundary conditions. The WRF-LAPS Hot Start uses Eta lateral boundary conditions and LAPS analyses from real data for initial conditions along with the Hot Start balanced vertical motions and cloud analysis scheme. The results show a slow spin-up of precipitation in the first few hours of the Eta model forecasts, and that the Hot Start system produces forecasts superior to both of the other model setups for 3h forecasts (and out to 9h, not shown). However, by 12h, the boundary conditions for this rather limited model domain exert an overriding effect on the solutions, thereby limiting the usefulness of the Hot Start procedure. Another contributing factor is that the 5-km run often will produce more detailed structures than the 12-km Eta. After a period of time, thunderstorm outflows wrongly interact with new cells resulting in location and timing errors of new convection – hence, the ESS statistics penalize the 5-km WRF more heavily than the smoother forecast from the 12-km Eta model. On the other hand, the WRF surface wind forecasts outperform the other models even beyond 12 h, perhaps because of the better numerics and lesser diffusion in the WRF model relative to the Eta model. Additional details appear in Shaw et al. (2004).

7. SUMMARY AND OUTLOOK

A wide range of applications has been found for the WRF model run at FSL in just the last year or two. The applications run the gamut from the testing of future operational configurations of WRF, to demonstration of experimental local modeling systems, to the coupled chemistry modeling for air pollution forecasting. WRF is quickly becoming the primary model being used at FSL for the LAPS applications, and the results from multiple applications (MDSS, CSI, IHOP) all testify to the superior results produced by the Hot Start LAPS procedure for 1 – 9 h forecasts. In the future, the LAPS Hot Start will transition into a full 3DVAR application for the WRF model. The WRF Rapid Refresh model will be running at NCEP within a couple of years, having gained from knowledge accrued from continuing real-time runs of the WRF-RUC. Assessments of both this system and the WRF/Chem model will continue. Mesoscale model ensemble work at FSL will likely expand in a quest to obtain the desired degree of ensemble diversity, and be used in an increasingly broad array of applications.

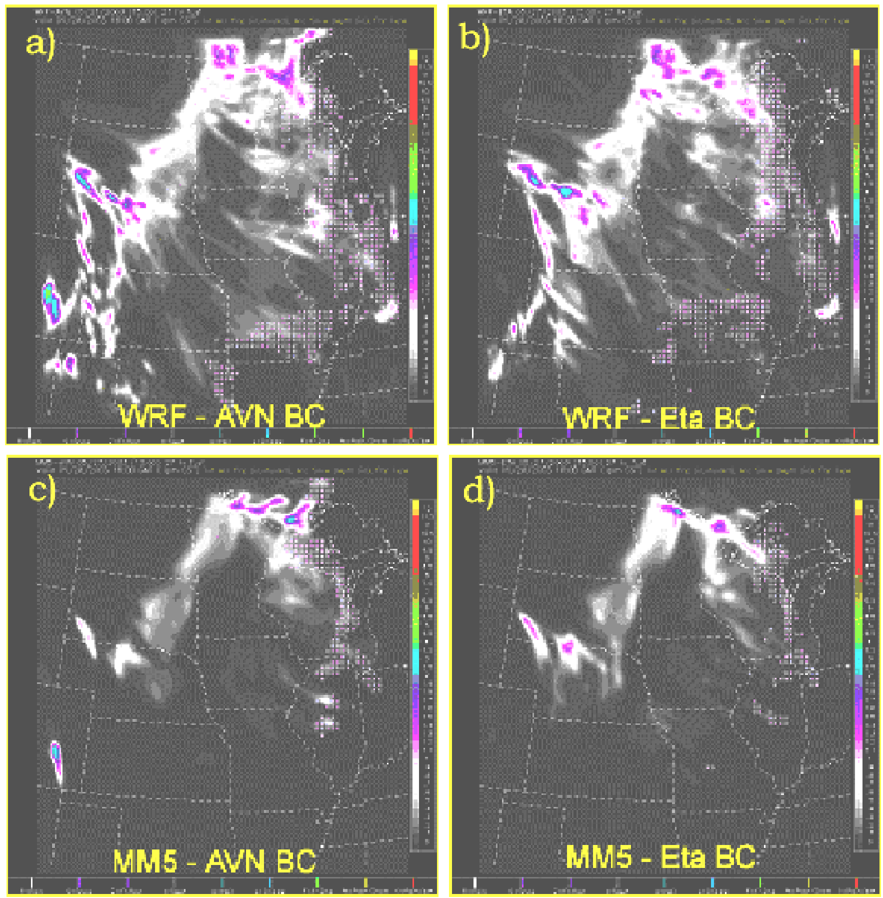

Fig.3. Four model forecasts of accumulated precipitation (inches) valid at the same time from MDSS: a) WRF model using AVN boundary conditions, b) WRF model using Eta boundary conditions, c) MM5 model using AVN boundary conditions, and d) MM5 model using Eta boundary conditions. Largest amounts (in purple) are 2.5 in.

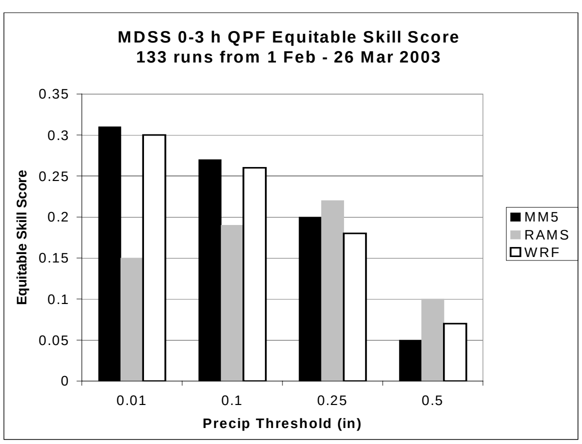

Fig. 4a. 3h precipitation Equitable Skill Score (ESS) statistics for the MM5 (black), RAMS (gray), and WRF (white) models used in the MDSS effort.

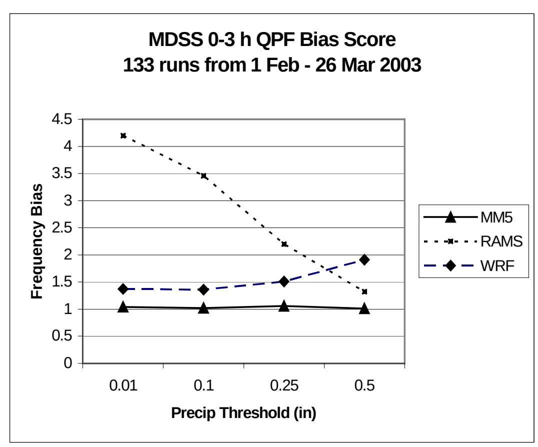

Fig. 4b. 3h bias statistics for the MM5 (black), RAMS (gray), and WRF (white) models used in the MDSS effort, for thresholds varying from 0.01 to 0.50 inches of precipitation.

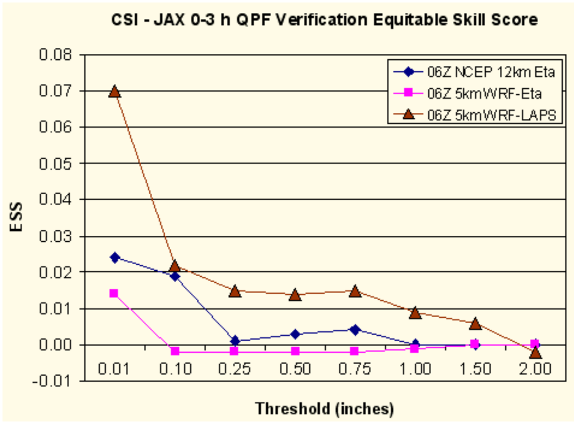

Fig. 5a. 3h precipitation Equitable Skill Score (ESS) statistics for 1 July – 30 September 2003 for the Eta-12 km, WRF-LAPS Hot Start, and WRF-Eta Cold Start model configurations used in the CSI demonstration at Jacksonville.

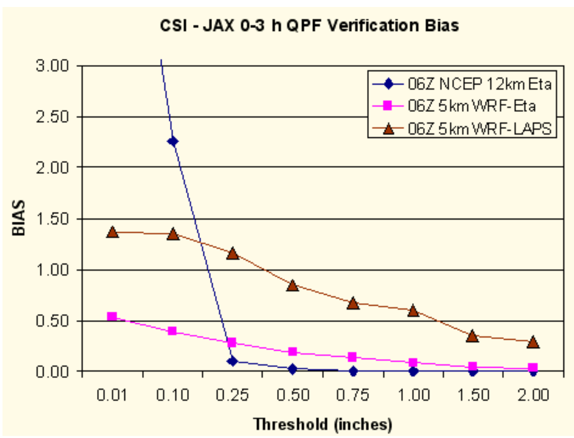

Fig. 5b. As in Fig. 5a, except for Bias statistics.

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