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A COMPLETELY INTEGRATED, COST-EFFECTIVE, LOCAL DATA ASSIMILATION AND FORECASTING SYSTEM TO SUPPORT SPACE LAUNCH RANGE OPERATIONS

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1. INTRODUCTION

Weather plays a critical role in the planning and execution of spacecraft launch operations at both the Eastern Range (ER), located in Florida, and the Western Range (WR), located in California. Each launch vehicle has specific tolerances for wind shear. Cloud cover, temperature, and lightning constraints are common for all launch vehicles. The presence of convective activity in the vicinity of the range can be significant due to the potential for lightning strikes and electrostatic discharge. In the event of a launch mishap, toxic clouds have the potential to endanger ground personnel, thereby requiring high-resolution wind and stability information for input into atmospheric dispersion models used for risk-mitigation prior to launch and as an emergency response tool.

An Air Force program to modernize and standardize the command and control infrastructure of both ranges, known as the Range Standardization and Automation (RSA) program, has been underway for several years. Included in this upgrade is a task to improve the systems used by the weather squadrons for monitoring and forecasting weather conditions in support of launch and emergency response activities.

The Forecast Systems Laboratory (FSL) has been involved in this effort since 1996, when Observation Simulation and Sensitivity Experiments (OSSEs) were performed to determine optimum placement of the various observing systems being acquired. Additionally, FSL was funded to develop a data assimilation and forecast system using the Local Analysis and Prediction System (LAPS, Albers et al. 1996). The LAPS analysis was coupled with the

Colorado State University Regional Atmospheric Modeling System (RAMS) as a prototype for this data assimilation system. The planned configuration consisted of a coarse nest with a grid spacing of 16 km and a fine nest with a grid spacing of 4 km. To meet the operational timelines, which require that a 24-h forecast be produced within 6 h of wall time, the domains were very limited in size, using 40 x 40 horizontal points. Since that decision was made, the cost of computational power has dramatically decreased, and it is now feasible, within the budget of the program, to expand the size of the domain and add a third nest to approach the objective requirement of 1 km grid spacing.

Additionally, a decision was recently made by the Air Force and the primary RSA contractor, Lockheed Martin Mission Systems, to leverage other work being done by FSL on behalf of the National Weather Service (NWS). The program has selected the Advanced Weather Interactive Processing System (AWIPS) as the mechanism for ingesting and interacting with all of the standard and range-unique meteorological data. To maximize performance while minimizing cost, the version of AWIPS being tailored for the RSA project will use relatively inexpensive PCs running the Linux operating system. Details of the RSA AWIPS implementation are discussed in Wilfong et al. (2002).

This paper discusses the details of the data assimilation and forecasting system, including the recent improvements made to the LAPS analysis, the selection and configuration of the forecast model, the revised domain configuration, and how the data assimilation and forecast system is integrated within AWIPS. The paper concludes by covering issues related to running forecast models within the AWIPS environment and future plans for the RSA assimilation system.

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2. SYSTEM OVERVIEW

2.1 *The LAPS Analysis*

LAPS has a rich history of operational application. It is available on all operational NWS AWIPS systems within the continental U.S., and has been used by other national centers, both foreign (e.g., the Taiwan Central Weather Bureau) and domestic (e.g., the US Air Force Weather Agency). Initially, LAPS was designed to provide a computationally efficient method of combining all available sources of meteorological information into a single, coherent, three-dimensional depiction of the state of the atmosphere, with an emphasis on nowcasting. In recent years, LAPS has been increasingly used as a means to initialize numerical weather prediction (NWP) models because of its robust data ingest, quality control, and fusion capabilities.

Recently, LAPS has been modified to allow diabatic initialization of NWP models, referred to as the "hot start" technique (Shaw et al. 2001a). This initialization method virtually eliminates the problem of model "spin up" by including cloud and precipitation fields in the initial condition in conjunction with a dynamic balance constraint. The specific enhancements making this technique possible include an improved cloud analysis (Schultz and Albers 2001) and a dynamic balance package (McGinley and Smart 2001). Additionally, the moisture analysis has been improved to take better advantage of the satellite, GPS, and ground-based moisture observations via the use of a variational technique (Birkenheuer 2001).

The cloud analysis utilizes a wide variety of observational data, including GOES satellite imagery, pilot reports (PIREPs), METARs, and WSR-88D radar reflectivity data. It diagnoses the mixing ratios of each hydrometeor species, performs cloud typing based on stability and temperature information, and assigns appropriate vertical motion profiles to each cloud based on a "steady state" assumption.

The modified balance package utilizes a three-dimensional variational (3DVAR) formulation to combine the background "first-guess" fields with the initial univariate analyses of the mass and momentum fields while considering the cloud-derived vertical motions. A strong constraint of continuity is applied such that horizontal winds are slightly adjusted to produce divergence fields consistent with the cloud-induced vertical motions. In addition, to prevent the introduction of excessive gravity wave noise during the initial model integration periods, the balance package minimizes the time tendencies of the horizontal wind components as one of the constraints. The last step of the balance adjustment consists of raising the specific humidity in grid boxes containing any cloud water to the saturation level. This step prevents the cloud water from being immediately evaporated, which would result in net cooling and a subsequent downdraft generation, thus immediately destroying the initial cloud field.

This initialization technique has been tested in real-time at FSL for nearly a year, with ongoing

improvements being made. Statistical verification during the winter of 2000–2001 showed significant improvement (Shaw et al. 2001a) in the 0–6 h forecast period compared to other more traditional initialization methods. For example, the 1–h forecast of cloud cover exceeding 50% scored a 0.71 equitable threat score (ETS) using this method. In comparison, runs performed using a 3–h pre-forecast analysis "nudging" period (where the model is nudged toward subsequent LAPS-analyzed state variables for a 3–h period prior to the desired initial time) only scored a 0.56. Simulations for the same period initialized only with the 6–h forecast from the Eta model (state variables only) produce a much lower score of 0.29. In addition to the objective verification, the real-time runs have been provided to the Denver/Boulder NWS Forecast Office for operational evaluation, and feedback from the forecasters has been very positive (Shaw et al. 2001b). This initialization method is being used as the operational RSA solution.

The LAPS data ingest capability is being significantly enhanced to support the RSA project. In addition to the various data sources already supported (METARs, ACARS, PIREPS, WSR-88D, GOES imager and sounder, GOES layer precipitable water, GPS, NOAA wind profiler network, etc., some of which are not yet available on AWIPS), the capability to ingest the range-unique data is being added. These data include 915-MHz and 50-MHz wind profilers, miniSODARs, RASS, and RTAMPS atmospheric profiles. The addition of these high-resolution data sources should improve the atmospheric analyses and subsequent forecasts of boundary layer winds and stability, both of which are critical for dispersion modeling.

Other software improvements to LAPS directly related to the RSA project include the capability to specify pressure levels explicitly rather than using a fixed increment, allowing higher vertical resolution in areas of higher interest (e.g., the boundary layer). Additionally, a new LAPS postprocessor that supports MM5, RAMS, and the new Weather Research and Forecasting (WRF) model has been developed to provide additional flexibility in the choice of forecast models coupled to LAPS. This postprocessor could be easily extended to support additional models (e.g., ARPS or the workstation Eta) as the need arises.

2.2 *The MM5 Forecast Model*

In principle, LAPS can be coupled with any mesoscale NWP model. The NCAR/PSU fifth-generation mesoscale model (MM5, Grell et al. 1995) has been selected for use as the forecast component for the RSA project. FSL's close working relationship with NCAR and extensive experience with the MM5 model, combined with its public domain nature, make it a logical choice. Additionally, the selection of MM5 as the forecast component places the RSA program on a direct track for upgrading to the emerging Weather Research and Forecast (WRF) model in the future.

MM5 Version 3, Release 4 (MM5v3-4) is the version

implemented within the RSA program. MM5 is a nonhydrostatic model utilizing a terrain-following pressure coordinate and offers a wide variety of boundary layer schemes, cumulus parameterizations, microphysical schemes, and longwave radiation formulations. Minor modifications have been made to accommodate the diabatic initialization technique. Additionally, the model and its pre- and postprocessing programs have been placed into a directory structure more analogous to LAPS, and various Perl scripts to configure and run the model in real time have been developed. Scripts to ensure that LAPS and MM5 are "plug compatible" have been developed and a new MM5 postprocessor to facilitate a full four-dimensional data assimilation (4DDA) cycle was introduced. In addition to the LAPS-format netCDF output files, the postprocessor can also produce Vis5D output and tabular point forecast files for a list of specified locations. Furthermore, this postprocessor is able to take advantage of the buffered output option supported in Version 3 of MM5, so the range forecasters will be able to view the model output as it is incrementally available, rather than waiting until the entire forecast run is complete. Like LAPS, this FSL MM5 package is maintained using revision control tools and modifications undergo extensive, multiplatform testing before being included in future releases.

2.3 Analysis and Forecast Configuration

At the time of writing, the new Linux cluster hardware acquired for the RSA program was not yet available for testing. However, based on extrapolation of test runs on other similar systems, the initial configuration that should meet the timeliness and spatial resolution requirements consists of a triple-nested domain, with each grid having 97 x 97 horizontal gridpoints. The grid spacing for the nests are 10 km for the outer nest, 3.33 km for the middle nest, and 1.11 km for the inner nest. The nests are centered over each launch range. Figure 1 depicts the nest configuration for the Kennedy Space Center. During model integration, two-way nesting (i.e., the solution from the inner nest is propagated upscale to its parent) is employed to ensure forecast consistency between the nests.

In the vertical, LAPS has been configured to use 51 pressure levels ranging from 1100–50 mb, with the highest concentration in the boundary layer. The initial test configuration of the MM5 model utilizes 34 levels, with the highest concentration in the boundary layer. The number of levels selected for the forecast model is a trade-off between resolution and operational efficiency. Doubling the number of vertical levels has the net effect of quadrupling the number of computations required to complete a forecast; twice as many time steps are needed for model stability, and these time steps have to be computed on twice as many grid points. Once the RSA computing platform is available for extended test periods, the number of vertical levels, as well as other parameters, will be adjusted to obtain the best possible balance between

run-time efficiency and forecast performance.

The initial physics options used in MM5 have been selected for optimum performance. The MRF Planetary Boundary Layer (PBL) scheme, Schultz (1995) microphysics, and the Rapid Radiative Transfer Model (RRTM) longwave radiation options are employed. A 30-s time step is used for model integration on the coarse grid. This configuration should allow a full 24-h forecast to complete in less than the required 6-h timeline. However, the system is extremely flexible and the various options can be adjusted as needed to accommodate changes in requirements.

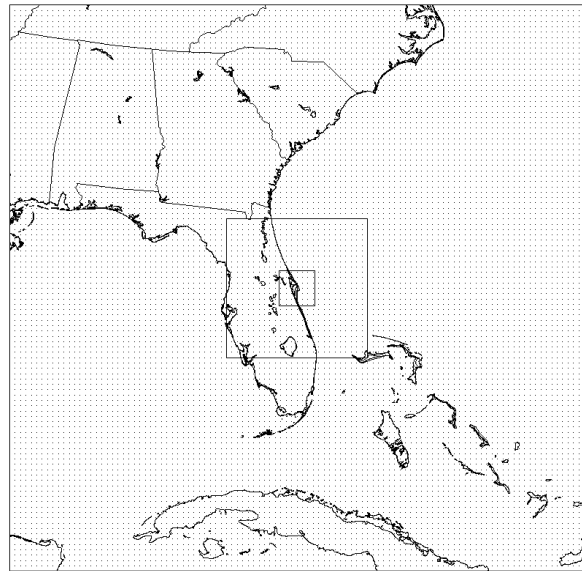


Figure 1. Triple-nested domain for the Eastern Range.

The system has been designed to run the analyses and forecasts using a 4DDA scheme with a 1-h update cycle. That is, every hour the LAPS analysis from each of the three nests is used to initialize MM5. The MM5 then produces a 1-h forecast which is subsequently used as the first guess for the next analysis. Preliminary verification of running a 4DDA cycle for a domain over Colorado, however, has shown no significant improvement compared to the real-time runs using a "static" diabatic initialization. Potential reasons for this are discussed in section 3. Therefore, until it can be shown that improvements will be gained utilizing a 4DDA cycle, the initial operational system may not fully exercise this option.

2.4 Hardware Configuration and AWIPS Integration

LAPS and MM5 share a Linux cluster "application server" which is fully integrated within the local AWIPS network. The cluster consists of nine, dual-processor nodes containing Intel Pentium-III processors with clock speeds of 1 GHz. One node serves as a "front end" node where LAPS and the model preprocessors run. The remaining 8 nodes (16 processors) are

utilized by the MM5 model, which runs in parallel mode using the Message Passing Interface (MPI) protocol.

While the concept of running local mesoscale models to support operations is not new (e.g., McGinley 1995) what makes this system unique is the level of integration within AWIPS. Having a separate application server on the AWIPS network provides a level of modularity that allows easier upgrades to LAPS and the forecast model without impacting the rest of AWIPS. The connection to the local AWIPS network allows improved data sharing. In many offices, running a local model requires transfer of data between various systems. For the RSA project, the application server is able to import the various directories containing the observational and background model data (e.g., the NCEP Eta grids used for lateral boundary conditions) and export its own data directories, providing a seamless environment between the local data assimilation system and the human-machine interface. This provides the additional advantage of being able to use the model output in other AWIPS applications, such as the Interactive Forecast Preparation System (IFPS) being tested in several NWS offices (Mathewson et al. 2000).

3. ISSUES AND FUTURE WORK

During the development and testing of this system, several issues requiring further work have been identified. One of the larger issues involves the use of the NOAA Satellite Broadcast Network (SBN) as the source of nationally available observation and model data. Another previously mentioned issue is the use of a 4DDA cycle.

The SBN data feed was not designed to support local modeling efforts. Regardless of forecast model used, a source of lateral boundary conditions for these limited area models is required. Typically, the national NCEP models (e.g., the RUC, Eta, and AVN) are used. Within FSL, the Eta grids are available every six hours with three-hourly output on a 40-km CONUS grid. On the SBN, only the grid labeled as the "MesoEta" is available on this grid. The operational Eta actually runs on a national 22-km grid, so the MesoEta fields are actually from the same model run as those labeled as "Eta." However, on this higher-resolution grid, not all of the vertical levels are available for all state variables. The Eta dataset containing the required state variables for all of the atmospheric levels is only available on the coarse 80-km grid, and are only available every 12 h with 6-hourly output. Similar issues are found with the AVN and RUC models. Additionally, there is no source of sea surface temperature or land skin temperature available in any of the SBN model datasets for use as lower boundary conditions. FSL is in the process of requesting that additional fields be transmitted from NCEP. However, bandwidth is limited and these requirements must be weighed against other operational requirements. Until solutions for these issues can be found, there will be some degradation in forecast quality, compared to the test runs done at FSL

due to poorer specification of the lateral boundaries.

As mentioned previously, preliminary results have shown no added benefit to using a rapidly updating 4DDA cycle. One issue may be related to the specification of the background errors in the dynamic balance package. While the balance package specifies three-dimensional arrays for both background and observation error, these error values are currently being estimated rather than explicitly computed, and the estimated values currently only vary by vertical level. Furthermore, the same estimates of background error are used regardless of which model (e.g., MM5, Eta, etc.) provides the first guess. Thus, when using MM5 as the first guess, it is assumed to have errors equivalent to the national Eta or RUC grid. Since MM5 runs at a higher resolution, resolves mesoscale features, and uses a very short-range forecast (1 h), it should be given precedence over the national model guidance. Second, the primary purpose of using a 4DDA cycle is to reduce model spinup by generating clouds and precipitation that are (from the model's perspective) in complete dynamic balance with the mass and momentum fields. The LAPS diabatic initialization technique already accounts for a large portion of the appropriate balance, thus we hypothesize that issues such as the background error specification become increasingly important if we are to realize advantages in using a rapid 4DDA update cycle.

Throughout the next year, these issues, as well as other improvements, will be addressed by FSL under an ongoing collaborative effort with the RSA program. Tasks include the development of an online verification system which can be used by the forecaster to assess model performance as well as provide background and analysis error estimates for the balance package. Improvements in the use of GOES satellite data in the cloud analysis, specifically the use of the visible and 3.9 micron channel, will be pursued. Although LAPS can use the Level II (wideband) WSR-88D data that will be provided at the ranges, additional work is needed to improve the blending of multiple radar sites. Within the balance package, work on integrating a thermodynamic constraint will continue. This will be especially important for elegantly removing "anomalous" convection in a dynamically consistent manner from the background first-guess field when running 4DDA. As the range-unique data sources become integrated within LAPS, FSL will engage in "tuning" the system to ensure that these data are appropriately weighted and that they are having a positive impact on forecast quality. In the longer term, it is anticipated that the ranges will migrate from the MM5 model to the new WRF model, and FSL will be prepared to support this activity as well. FSL also will be providing training on the use of the system to the onsite meteorologists and to the primary contractor.

This project marks the first known "operational" (in the most strict interpretation) implementation of a locally run data assimilation and forecast system using relatively inexpensive Linux clusters within a US government facility. While done on behalf of the Air

Force, the synergistic nature of the program implies that benefits from this project can be reaped within other components of the national meteorological infrastructure, including NWS forecast offices. The use of a local, diabatically initialized mesoscale model does not replace the necessity for high quality national products. Rather, it has the potential to complement those products by filling the niche between nowcasting techniques, which work well for the 0–2 h period, and the national NWP guidance, which performs well for the "day 1" and beyond forecast. Furthermore, a locally run data assimilation system takes advantage of high spatial and temporal resolution observational data not available to the national models and provides users with flexibility to tailor the operational run–time environment to specific needs. This project may well be a "pathfinder" for the local forecast office of the future.

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