3.7 AN "OBSERVATION-NUDGING"-BASED FDDA SCHEME FOR WRF-ARW FOR MESOSCALE DATA ASSIMILATION AND FORECASTING

Yubao Liu[1], Alfred Bourgeois, Tom Warner and Scott Swerdlin
(National Center for Atmospheric Research, Boulder, Colorado)

1. INTRODUCTION

An implementation of the WRF "observation-nudging"-based continuous four-dimensional data assimilation (FDDA) scheme, developed jointly by the NCAR Research Application Laboratory (RAL) and the Army Test and Evaluation Command (ATEC), was described. The FDDA scheme is adapted from the "observation-nudging" module in the standard Penn State and NCAR MM5, which was significantly refined by NCAR/RAL over the last five years while supporting the ATEC test range operations *(http://www.rap.ucar.edu/projects/armyrange/references/publications.html)*. This "observation nudging" package has been included as a standard FDDA component in the latest release (November 2006) of WRF-ARW model for community use.

In this paper, the main features/capabilities of the "observation-nudging" WRF-FDDA scheme in the latest WRF-ARW release (Nov. 2006) are summarized. The data assimilation procedure are validated using perfect model/data experiment based on an Observing System Simulation Experiments (OSSE) technique. The WRF-FDDA performance for real data NWP is evaluated based on real-time operational mesoscale data analyses and forecasting at the ATEC test ranges and on case studies with significant weather events. Finally, the rationale for employing "observation-nudging" in mesoscale NWP is argued along with the other popular data assimilation approaches. Plans for future developments are given in the last section.

It should be pointed out that WRF-ARW model is a mesoscale weather model. The FDDA system described in this paper is developed for mesoscale weather data analysis and NWP. It is our hope that the philosophy and experience with the WRF FDDA scheme can be useful for building data assimilation system for space weather analyses and forecasts.

2. A BRIEF HISTORY OF NCAR/ATEC RTFDDA SYSTEMS

The NCAR/ATEC RTFDDA (Real-Time FDDA and forecasting) system was originally built around the Penn State/NCAR Mesoscale Model version 5 (MM5) for support of ATEC test operations at the test ranges. By effectively incorporating detailed terrain, coastline masks, and land-use information, and using synoptic-scale model analyses from NWS and real-time mesoscale observations, the system has proven capable of forecasting many realistic local circulations (Liu et al. 2002), making it a great tool for supporting weather-sensitive applications, including various military tests at the test ranges, homeland security, emergency decision support, and many others. Besides running operationally at five US Army test ranges and a few other sites related to homeland security, as of May 2006, the RTFDDA systems have also been implemented at 20+ other sites/regions globally, supporting various Department of Defense missions and industrial and public applications and field experiments.

From late 2004, NCAR/RAL started transitioning the analysis and forecasting core of the NCAR/ATEC RTFDDA system from MM5 to

---

[1] *Corresponding author address*: Yubao Liu, NCAR/RAL, P.O. Box 3000, Boulder, CO 80307-3000; email: yliu@ucar.edu

WRF. Two major porting tasks were involved – to migrate the ATEC “observation-nudging” module from MM5 to WRF, and to plug the WRF into the RTFDDA framework to replace the MM5. The basic code porting was completed in April 2005 (Liu et al. 2005). Since then, the WRF-FDDA system has been tested with real-time cycling and used in case studies of several weather processes of special interest.

3. FEATURES OF WRF “OBSERVATION-NUDING”

Implementation of “observation-nudging”-based FDDA into the WRF-ARW core and the details of the “observation-nudging” scheme can be found in Liu et al. (2005). In this presentation, we will discuss the main features of the nudging scheme. Verifications with the OSSE approach and tested for various case studies including forecasting hurricanes Rita-2005 and Katrina-2005 are demonstrated. The main features included in the latest WRF-ARW release can be summarized as the following.

- Assimilate synoptic and asynoptic data resources, including diverse surface data (METAR, SYNOP, SPECI, ship, buoy, QuikScat seawinds, mesonets and others) and various upper-air observations (TEMP, PILOT, wind profilers, aircrafts, satellite cloud-drifting winds, dropsondes, radiometer profilers, Doppler radar VAD winds and others).

- An observation-nudging FDDA control parameters can be adjusted in the namelist block added to the standard WRF/ARW namelist.

- Unlike the original observation-nudging scheme in MM5, multi-level upper-air observations, such as radiosondes and wind profilers, are assimilated by taking advantage of vertical coherency, instead of using them as a series of point observations.

- Surface observations are first adjusted to the first model level according to the Similarity Theory. The adjusted temperature, wind and water vapor innovations at the lowest model level are then used to correct the model through the mixing layer, with weights gradually reduced toward the top of PBL.

- Terrain-dependent nudging weight correction is designed to reduce horizontal weight according to the pressure differences between a model grid-point and an observation station. Also a ray-searching scheme was developed to eliminate the influence of an observation to a model grid-point if the two sites are physically separated by a significant mountain ridge or a deep valley.

- RTFDDA “observation-nudging” is built for multi-scale mesoscale data assimilation. The multi-scale features are taken into account by setting different influence radii for different grids and making use of a “double-scan” approach. On the other hand, grid-based analysis nudging can be used jointly to take advantages of the 3DVAR analyses that assimilating non-direct remote sensing observations such as satellite brightness temperature and GPS occultation. “Analysis-nudging” is not recommended for meso-beta and gamma scale.

4. PERFECT MODEL EXPERIMENT

In the last several months, NCAR and AirDat LLc. have been jointly developing an OSSE testbed for evaluating and optimizing the potential impact of the future CONUS-scale TAMDAR (Tropospheric Airborne Meteorological Data Reporting) system. The full-fleets of TAMDAR aircrafts provide a significantly higher resolution coverage of temperature, winds and moisture observation in the lower troposphere among the regional and international airports in day-time comparing to other existing upper-air measurement platforms. The number of TAMDAR flight soundings (one flight is divided into two soundings – ascending and descending) varies greatly from 500+ in daytime to only a few soundings in nighttime, according to the current flight schedule. Fig. 1 gives an example of the TAMDAR sounding locations within a 1-hour period from 23:00 UTC to 00:00 UTC.

Using the framework for the TAMDAR OSSE bed, the WRF FDDA scheme was tested to study its robustness and effectiveness by assimilating hypothetic TAMDAR fleet observations. A cold-air outbreak case of 17-20 Jan. 2005 was selected for the study. A three-day natural run was conducted with a 4-km-grid

CONUS domain. TAMDAR soundings are derived from the natural run. Then, two forecasting experiments with 12-km grid mesh were conducted, one started with an 18-hour pre-forecast data assimilation period with "observation-nudging" of the TAMDAR data and the other without. Note that for the purpose of FDDA scheme validation in this paper, the retrieved TAMDAR data are assumed to contain no errors ("perfect" data, which differ from the real TAMDAR observations that contain errors). Therefore, the error reduction by FDDA shown below is ideal and does not represent the magnitude of the true values of TAMDAR.

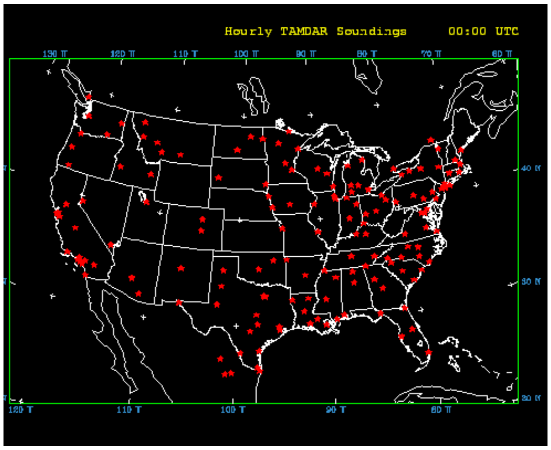

Fig. 1 TAMDAR Sounding locations (red stars) between 23:00 UTC and 00:00 UTC according to the current flight schedules of commercial regional and special airlines.

The perfect model experiment results exhibit a good performance of the "nudging"-based WRF-RTFDDA system. Figs. 2 and 3 compare the 2-m and 850 hPa temperature errors of the 30-h forecasts with TAMDAR (TAMDAR) and without (CTRL). By using the default nudging parameters that were specified in the current operational MM5-RTFDDA systems, assimilating the hypothetic TAMDAR profiles obtained at the regional airports and at the typical daily flight schedule times, WRF-RTFDDA is able to reduce the model forecast errors by 40-60% for 0 - 36 hour forecasts. As expected, the observation nudging scheme can effectively correct analysis and forecast errors in the region close to the observations and the effect of the corrections propagates toward the downwind side. In the regions with less TAMDAR flights, such as over the Rocky Mountains, the forecast errors are relatively larger.

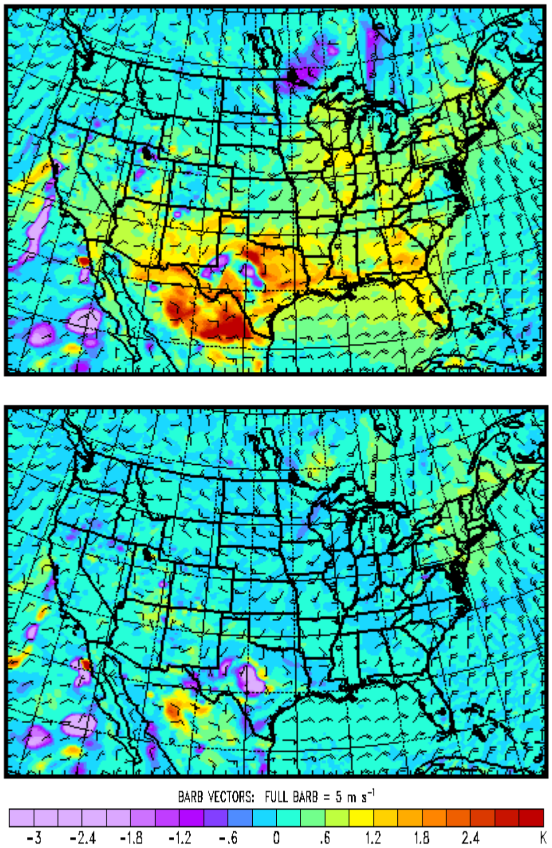

Fig. 2 Errors (differences between forecasts and the natural run) of 2-m temperature of 36-h forecasts, valid at 00UTC 19 January 2005, initiated with no observation (upper-panel) and with FDDA using hypothetic TAMDAR observations (lower panel).

5. EVALUATION OF WRF-RTFDDA SYSTEM

After a few months of in-house testing, two WRF, "observation-nudging"-based RTFDDA systems were set up and began running semi-operationally at the ATEC Dugway Proving Ground (DPG, UT) and Aberdeen Test Center (ATC, MD) in October 2005. Since then, NCAR ATEC modelers and test range forecasters have been actively evaluating the WRF-RTFDDA performance for daily operations and comparing the WRF-RTFDDA outputs with the operational MM5-RTFDDA system. Starting in May 2006, more WRF-RTFDDA systems were implemented in the other ATEC test ranges.

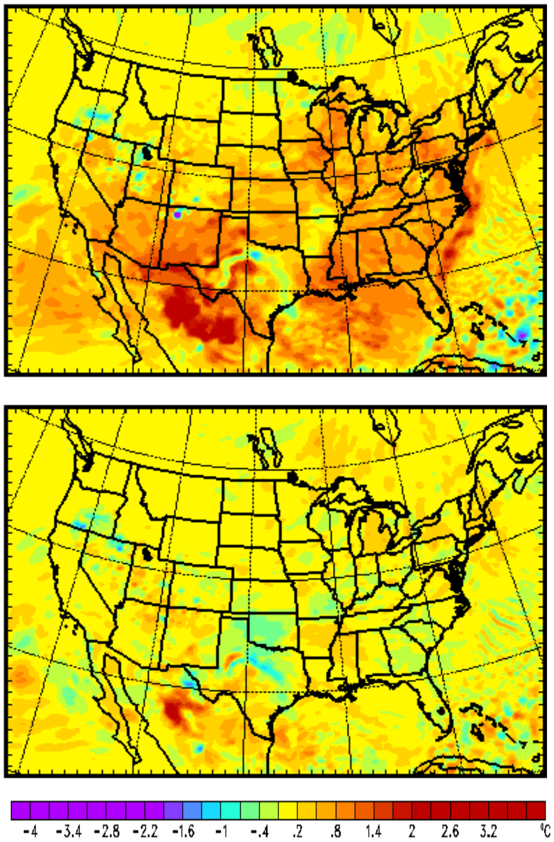

Fig. 3 Same as Fig.3, but for temperature at 850 hPa.

As described in Liu et al. 2005, for comparison purposes, the WRF-RTFDDA systems were set to run with the same nested-grid configurations as those used in the MM5-based RTFDDA systems operated at the ranges. The models have three nested grids with grid sizes of 30, 10 and 3.333 km, respectively. Both systems run with 36 vertical levels and assimilate the same observations. The NAM AWIP 212 forecasts are used to provide initial conditions at cold-starts and boundary conditions during continuous data assimilation and forecasts for both models. Readers can refer to Liu et al. 2005 for more details about the system and cycle settings.

Both statistical verification and subjective verification of daily operations show that the WRF-RTFDDA systems perform very similar to the MM5 counterparts. The nudging-processes are able to track the model states toward the observed states and the correction amount in the WRF is close to those in the MM5. The differences of the two modeling systems appear to be associated more with the model dynamical algorithms and physics implementation than the nudging part. For example, the WRF-RTFDDA system tends to produce a large warm bias in the nighttime and the MM5-RTFDDA cold bias in the afternoon. Our general feeling is that there is no clear advantage in either system over the other. WRF tends to produce slightly better larger-scale cloud cover while MM5 appears to forecast surface precipitation and fine scale winds over the mountain regions slightly better.

Aside from OSSE experiments and verification statistics of the long-term model operations, various case studies are also conducted, focusing on some special weather processes. These studies include contrast forecasting simulations with WRF- and MM5-RTFDDA systems over month-long model runs for the warm-season orographically-forcing convection in New Mexico and Arizona in August 2005, high-impact weather events in Israel (see our companion papers on this workshop, Yu et al. 2006, Rostkier-Edelstein et al. 2006), and hurricanes Rita-2005 and Katrina-2005. For the hurricane studies, we found that the FDDA scheme is capable of tracking hurricane vortices locations and "spinning-up" their intensities very competently to the other vortex-bogus methods and is able to generate short-term hurricane track and intensity forecasts superior to the national operational models, running at a similar resolution, in terms of track, intensity and internal wind and precipitation structures.

6. "NUDGING" AND KALMAN FILTER

"Observation-nudging" is a station-oriented filter scheme in which individual observations are taken sequentially and independently. At a particular time step, the way observations are taken is similar to that in the ensemble square root Kalman Filter (enSRF) (Whitaker and Hamill, 2002). The "nudging" scheme differs from SQRKF in two aspects: first, observations have an influence time window with a time weight equal to one and gradually reduced from the observation time. Second, the spatial weighting in the nudging scheme is prescribed with a structure function defined by a few parameters that are specified based on experiences and sensitivity studies. Essentially, at a particular time step, if we shrink the time influence window to a very small value and replace the weighting-structure function with the Kalman Gain, estimated using background and observation error co-variances, the “observation-nudging” scheme will become a full Kalman Filter. Furthermore, if one repeats this filtering process for every time step, the “observation-nudging” becomes a full-4D Kalman Filter.

Meso- beta and gamma scale weather systems tend to change dramatically from day-to-day and hour-to-hour, which makes it very difficult to build universal, accurate background error co-variances for the individual mesoscale process. Since an optimal Kalman Filter rely on an accurate estimate of background co-variances, the background errors computed using currently available statistical methods, such as the “NCEP method”, can render an optimal scheme (i.e., 3DVAR) far from the “optimum” for a mesoscale weather process. The mesoscale ensemble Kalman Filter approach is a computationally practical way to solve this problem. Nevertheless, until one could build a mesoscale ensemble that can properly mimic the real world PDF, it will suffer from the same problem as the ones using the statistical errors. In contrast to the “optimal” data assimilation schemes, the nudging with experience-based observation weighting function suffers less from the errors of the background error estimation. The nudging process is

On the other hand, due to the nature of rapid changes of most mesoscale processes, small timing and/or phase errors can lead to large innovations. At present, substantial phase and timing errors often exist in mesoscale weather predictions. Thus, it can be problematic to properly digest these large increments (shocks) to produce accurate, balanced analyses with a 3-D analysis method. This issue can be addressed with a continuous FDDA. The “nudging” approach, which allows a time for a model to gradually adjust toward observations, seems to be a feasible way to mitigate this kind of shock.

7. FUTURE WORK

As discussed above, observation nudging-based FDDA technology, like OI, 3DVAR, and EnKF, stands on the Kalman Filter theory. Essentially, the differences between the prevailing optimal schemes, such as statistical interpolation, 3DAVR, 4DVAR, and EnKF, and the simple observation-nudging, are at the estimations of the Kalman Gain, which is dependent on an estimation of background error covariance and observation error covariance. Apart from this, all schemes face common issues and challenges. The temporal relaxation in the observation-nudging gives the extra benefit that the model state can be tracked along the true states through continuous synchronization of observed and model states at each time step. Research to combine the advantages of the other technologies into the “observation-nudging” time relaxation can be very beneficial. The following areas of the WRF “observation nudging” scheme will be studied in the next few years:

1) Develop capabilities for incorporating statistical background error covariance based on local-scale flow climatolography, and ensemble-based real flow-dependent background error covariance. Essentially, the current fixed spatial weighting functions in the nudging scheme will be adjusted to reflect background error covariance structures.

2) Develop an ability to take and weigh upper-air observations of either pressure or height-based. At present, the nudging scheme only takes pressure-based upper-air observations. The height-based observations such as wind profilers are needed to estimate the pressure for each height level for nudging. The pressure estimation error may affect the assimilation accuracy.

3) Develop a comprehensive data quality control scheme to discriminate bad and unrepresentative measurements. Estimating representativeness errors of observations and incorporating the errors in the data assimilation are very important. Representativeness errors are mainly affected by three factors: the size of the sampling volume, model grid resolutions, and the turbulent characteristics of the atmosphere. The sampling volume and model resolution are constant for given sensors and given model configurations, whereas the atmospheric turbulent characteristics can vary greatly in space and time.

4) Compare “observation-nudging” FDDA with cycling WRF-VAR and WRF-EnKF (NCAR/DART) approaches with the same cases/periods and use the same data. Investigate a hybrid approach and method to assimilate non-conventional indirect remote sensing observations. Continue case studies and nudging refinements with high-impact weather and weather of different regimes.

It should be pointed out that both applying ensemble-based error co-variance in nudging and comparing the nudging FDDA with EnKF requires one to run the ensemble model. To develop and run a proper mesoscale ensemble system is challenging and it is one of the research foci of the on-going ATEC modeling R&D areas.

8. REFERENCES

Cram, J. M., Y. Liu, S. Low-Nam, R-S. Sheu, L. Carson, C.A. Davis, T. Warner, J.F. Bowers, 2001: An operational mesoscale RTFDDA analysis and forecasting system. *Preprints 18th WAF and 14th Conf. on Numerical Weather Prediction*., AMS, Ft. Lauderdale, FL.

Liu, Y., and co-authors, 2002: Performance and enhancement of the NCAR/ATEC mesoscale FDDA and forecast system. *15th Conf. on Numerical Weather Prediction*, 12-16 August 2002, San Antonio, Taxes, 399-402.

Liu, Y., and co-authors, 2005: Implementation of observation-nudging based FDDA into WRF for supporting ATEC test operations. 2005 *WRF Users Workshop*, Boulder, Colorado, June, 2005.

Rostkier-Edelstein, D., Y. Liu, M. Ge, T. Warner, S. Swerdlin A. Pietrkowski and Y. Segev, 2006: Simulation of a high impact weather event over Israel with the WRF-RTFDDA system – a case study. *2006 WRF Workshop*, Boulder, CO. June 2006. P8.9.

Stauffer, D.R., and N.L. Seaman, 1994: Multi-scale four-dimensional data assimilation. *J. Appl. Meteor*., 33, 416-434.

Whitaker, J and T. M. Hamill, 2002: Ensemble data assimilation without perturbed observations. *Mon. Wea. Rev.*, **130**, 1913-1924

Yu, W., Y. Liu, T. Warner, R. Bullock, B. Brown and M. Ge, 2006: A comparison of very-short-term QPF for summer convection over complex terrain areas with the NCAR/ATEC WRF and MM5-based RTFDDA system. *2006 WRF Workshop*, Boulder, CO. June 2006.