AN UPDATE ON "OBSERVATION-NUDGING"-BASED FDDA FOR WRF-ARW: VERIFICATION USING OSSES AND PERFORMANCE OF REAL-TIME FORECASTS

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1. INTRODUCTION

At the 2005 WRF-MM5 workshop, 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 presented by Liu et al. (2005). The FDDA scheme is adapted from the "observation-nudging" module in the standard 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). During the past year, the WRF observation-nudging FDDA scheme has been further tested and improved. In early April 2006, NCAR WRF-ARW modelers and RAL started to work jointly to adapt the "observation-nudging" scheme to the WRF-ARW community for release in July 2006.

In this paper, the main features/capabilities of the "observation-nudging" WRF-FDDA scheme in the next release are summarized. The nudging codes and performance are validated using perfect model experiment based on 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. The WRF results are compared with those of the companion operational MM5 system using statistical and subjective verification. Next, the rationale for employing "observation-nudging" in mesoscale NWP is argued along with the other popular data assimilation approaches. Brief guidance for users to set up and use the observation-nudging scheme is included. Plans for future developments and community contributions are given in the last section.

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 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.

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3. FEATURES OF WRF "OBSERVATION-NUDING"

Implementation of "observation-nudging"-based FDDA into the WRF-ARW core and details of the RTFDDA "observation-nudging" scheme and basic technical coding approach can be found in Liu et al. (2005). In the past year, the WRF FDDA scheme has been continuously tested and evaluated for real-time experimental operations over the central Rockies and the eastern states. It is also verified with the OSSE approach and tested for various case studies including forecasting hurricanes Rita-2005 and Katrina-2005. From April 2006, NCAR the MMM/WRF group and RAL/RTFDDA group started to integrate the ATEC "observation-nudging" scheme into the standard WRF/ARW community model, scheduled for release in July 2006.

The ATEC RTFDDA "observation-nudging" scheme (Cram et al. 2001; Liu et al. 2002, 2005) is a refined version of the "observation-nudging" module in the standard MM5 which was introduced by Stauffer and Seaman (1994). The main features of the nudging scheme included in the coming WRF-ARW release can be summarized as follows:

- 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).
- At present, the input data are in formatted ASCII for the convenience of debugging. There are two data formats: one is designed for upper-air observations while the other is designed for surface observations. The upper-air data can be multi-level, sounding-like profiles or single-point measurements, such as aircraft reports. Utility programs such as those for fetching the NCAR ADP data, time sorting and data reformatting will be provided. Nevertheless, it is the user's responsibility to collect the data of interest, conduct data-quality control, and write the selected data into the required formats.
- An observation-nudging FDDA namelist block is added to the standard WRF/ARW namelist. The WRF observation-nudging FDDA namelist block allows one to conveniently experiment with important nudging-control parameters, such as nudging coefficients (how fast one wants push the model toward observations) and influence radii for each nested grid, data influence window, and nudging window. Parameters for optimizing model execution are also provided. Note that there are a few other control parameters which can be adjusted in the code by experienced modelers. Also note that, as described in Liu et al. (2005), some further "in-situ" adjustments were done in the code for some namelist parameters. For instance, the influence radii given in the namelist is valid for surface height only. For upper air observations, the radii is set to linearly increase to a double length from surface to 500 hPa and keep the length above.
- 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 PBL top.
- 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-search scheme 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 benefit of 3DVAR assimilation 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. OSSE-BASED PERECT MODEL EXPERIMENT

In the last several months, NCAR and AirDat LLc. Have been jointly developing an OSSE bed 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 dramatically 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 upper-air data available now. 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.

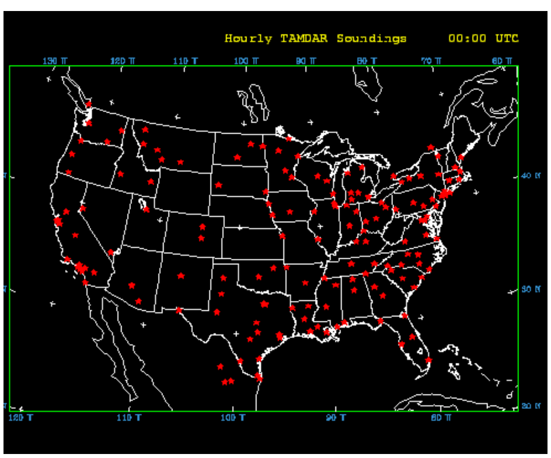

Fig. 1 TAMDAR Sounding locations (red stars) between 23:00 UTC and 00:00 UTC according to the current flight schedules of commercial regional and special airlines.

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 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, discussed below, is ideal. We are in process of using OSSE experiments that take account of TAMDAR observation errors to quantify the more realistic impact of TAMDAR.

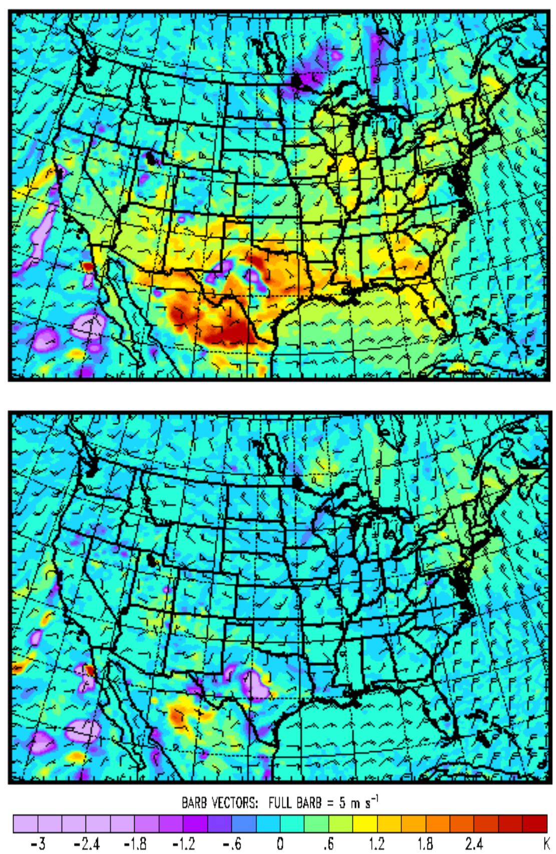

Fig. 2 Errors (differences between forecasts and the natural run) of 2-m temperature of 36-h forecasts, valid at 00UTC 19 January 2005, initiated with no observation (upper-panel) and with FDDA using hypothetic TAMDAR observations (lower panel).

The perfect model experiments indicate an encouraging performance of the "nudging"-based WRF-RTFDDA system. Figs. 2 and 3 compare the 2-m and 805 hPa temperature errors of the 36-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, with the observation nudging scheme forecast errors are corrected most in the region close to the observations and the effect of the corrections are propagating downwind side. In regions with thin TAMDAR flights, such as over the Rocky Mountains, the forecast errors are relatively larger.

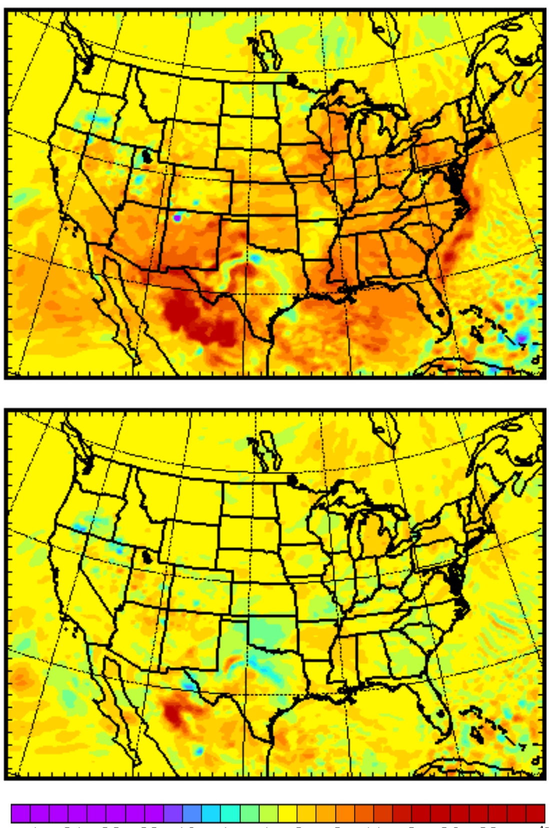

Fig. 3 Same as Fig.3, but for temperature at 850 hPa.

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.

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 of 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 slightly better surface precipitation and fine scale winds over the mountain regions.

Besides conducting OSSE experiments and

verification statistics of the long-term model operations, various case studies are also conducted, focusing on weather processes of special interest. These studies include contrast forecasting simulations with WRF- and MM5-RTFDDA systems over month-long runs for the summer orographically-forcing convections 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 WRF-RTFDDA system, like the MM5-RTFDDA, is capable of tracking and "spinning-up" the hurricane vortices locations and intensities very competently to the state-of-the art vortex-bogus methods and generate short-term hurricane track and intensity forecast superior to the national operational models, running at a similar resolution, in terms of track, intensity and internal wind and precipitation structures.

6. RATIONALE FOR "OBSERVATION NUDGING"

"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 the 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 influence time window to a very small value and replace the weighting-structure function with the Kalman Gain, defined by 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" will become a full-4D Kalman Filter.

The RTFDDA system, according to our multi-year operational experiences and comparison studies, performs very competitively for mesoscale weather analyses and forecasts, although it is conceptually simple and computationally inexpensive when compared to other data assimilation approaches. A couple of points are argued for the applicability of the "observation-nudging scheme" for mesoscales:

1) On meso- beta and gamma scales, weather systems can change dramatically from day-to-day and hour-to-hour. This makes it very difficult to build universal, accurate background error co-variances for the individual mesoscale process. Since an optimal Kalman Filter will always 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) way off 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 experience-based observation weighting function will suffer less from the errors of the background error estimation.

2) As most mesoscale processes evolve very rapidly, 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 should 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, 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 and observation error. 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 the 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 either applying ensemble-based error co-variance in nudging or 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.