UPDATE ON ANALYSIS NUDGING FDDA IN WRF-ARW

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1. INTRODUCTION

Nudging four dimensional data assimilation (FDDA) has been widely used in numerous applications involving mesoscale modeling using MM5, and it is an effective and efficient way to reduce model errors (Stauffer and Seaman 1990). This technique has several major uses. Firstly, it can be used to create four-dimensional dynamically consistent datasets. The model is run with multiscale FDDA over multiple nested grids / scales using gridded analysis nudging and/or observation nudging (Stauffer and Seaman 1994) for long periods to provide a four-dimensional meteorologically self-consistent dataset that also stays on track with the available observations (obs) and gridded analyses (e.g., Zielonka 2006).

In dynamic-analysis or nowcast mode (Schroeder et al. 2006, Stauffer et al. 2007a), the model is used as an intelligent interpolator of obs information between analysis/obs times, to create an FDDA-assisted meteorological (MET) data set that fits the available observations but also produces mesoscale structures missing from the observations and representing local topographic and convective effects. A primary use for such datasets is in air quality and atmospheric transport and dispersion (AT&D) where the model fields may be used to drive off-line chemistry or AT&D models (e.g., Stauffer et al. 2000, Tanrikulu et al. 2000, Deng et al. 2004, Stauffer et al. 2007b). For example, Tanrikulu et al. (2000) showed improved atmospheric chemistry predictions using FDDA-assisted MET when verified against measurements, and Deng et al. (2004) showed improved AT&D predictions when using FDDA-assisted MET inputs to an AT&D model verified against atmospheric tracer data.

Secondly, nudging FDDA can also be used to create better lateral boundary conditions. A nested simulation is run with the outer domain(s) nudged towards analyses and/or observations, and the innermost nest is run without FDDA for a pure scientific investigation of cause-effect relationships (e.g., Reen et al. 2006). This provides better quality MET at the nest boundary than driving it directly from coarser, temporally interpolated analyses, as would be the case if it were the outer domain. This technique can also be used in forecasting, where an outer domain is nudged towards global forecasts / analyses that contain the effects of additional data sources (e.g., satellite radiances).

Finally, nudging FDDA can also be used for dynamic initialization, where the model is relaxed towards observed conditions during a pre-forecast integration period to improve the initial state and the subsequent short-term forecast (e.g., Staufer et al. 2007c, Leidner et al. 2001, Otte et al. 2001). This “running-start” FDDA procedure produces improved spinup of model cloud, precipitation and local circulations at the model initial time (t = 0 h), which then improves the subsequent short-term forecasts (Stauffer et al. 2007c).

The original three-dimensional (3D) analysis nudging and observation nudging FDDA techniques used in MM5 were developed by Stauffer and Seaman (1990, 1994) and the surface analysis nudging by Stauffer et al. (1991). Penn State has developed a prototype version of the 3D analysis nudging FDDA capability that was released in WRF-ARW version 2.2 (Dec. 2006). Penn State has been awarded a new multi-year funding contract from the Defense Threat Reduction Agency (DTRA) to continue the research and development of both the analysis nudging and observation nudging for WRF, with Penn State (Dave Stauffer and Aijun Deng) leading the project and collaborating with NCAR (Josh Hacker, Jimy Dudhia and Yubao Liu) under a subcontract. This work also includes exploration of new hybrid nudging – variational – EnKF techniques (e.g., Lei and Stauffer 2007).

The basic analysis nudging FDDA capability in WRF v2.2 will be described in Section 2. Section 3 presents the experimental design, which tests various options of the new WRF FDDA analysis-nudging capability against those in MM5, with verification against observations during CAPTEX-83 (Deng and Stauffer 2006). Test results, based on both subjective and objective verification, are shown in Section 4, and summary and conclusions appear in Section 5.

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2. METHODOLOGY

In nudging FDDA, the model state is relaxed continuously at each time step toward the observed state by adding to the prognostic equations an artificial tendency term, which is based on the difference between the two states. Stauffer and Seaman (1994) suggest that the assimilation can be accomplished by nudging the model solutions towards gridded analyses based on observations (analysis nudging) or directly toward the individual observations (observation nudging), with an effective multiscale grid-nesting assimilation method using a combination of these two approaches. In analysis nudging, the model fields are nudged at every grid point toward an analysis of the observations on the model grid in a manner such that the nudging term is proportional to the difference between the model and the analysis at each grid point. The nudging term should be smaller in magnitude than any of the other terms in the equation so that the nudging term does not control the tendency. If the nudging is too strong, the model may lose important mesoscale features created by the model, but if it is too weak, the observations will have a minimal effect on the evolution of the model state, allowing phase and amplitude errors to grow. For this reason, the value of the nudging factor should be rather small.

In the prototype version of the 3D analysis nudging in WRF-ARW, the following equation represents a nudging term for potential temperature or any general predictive variable in WRF coupled with the dry hydrostatic pressure $\mu$, where

$$\Theta = \mu \cdot \theta$$  \hspace{1cm} (1)

and the prognostic equation including the nudging terms becomes

$$\frac{\partial \Theta}{\partial t} = \cdots + \mu \frac{\partial \Theta}{\partial t} + \theta \frac{\partial \mu}{\partial t}$$

$$= \cdots + \mu \cdot G \cdot W \cdot (\Theta_{obs} - \Theta) + \theta \cdot G \cdot W \cdot (\mu_{obs} - \mu)$$  \hspace{1cm} (2)

where the four-dimensional weighting function is given by $W = w_{xy} \cdot w_{y} \cdot w_{t}$, the nudging coefficient is $G$, and $1/G$ is the e-folding time, which is a representative time scale for the artificial nudging term and this time scale should be longer than the time scale of the slowest physical process in the model. WRF-ARW uses $\mu$ in its terrain following vertical coordinate $\eta$, similar to the way total pressure was used in the hydrostatic MM4/MM5 vertical $\sigma$ coordinate. However, the WRF-ARW vertical coordinate surfaces ($\eta$) are not located at fixed heights independent of time as is the case in the nonhydrostatic MM5.

Currently in WRF-ARW, nudging can be applied to $u$ (west-east wind component), $v$ (north-south wind component), $\theta$ (potential temperature), and $q_v$ (water vapor mixing ratio). Currently, nudging is not applied to $\mu$. 3D gridded fields are ingested at user-defined time intervals and temporally interpolated between the 3D analysis times. The user can specify the analysis nudging strength for each variable, and analysis nudging can be restricted (by variable) within the atmospheric boundary layer where nudging toward large-scale analyses may prevent reasonable mesoscale structures from being developed and have detrimental effects, especially for fine-scale simulations. In addition, users can eliminate analysis nudging below a user-specified model level for a given variable on a specific grid. This capability may be useful to limit the assimilation of coarse resolution analyses that may not capture and may inhibit the simulation of important features, e.g., a low-level jet (LLJ) above the atmospheric boundary layer at nighttime. In some FDDA applications such as dynamic initialization, the nudging should be used during a pre-forecast period but then gradually ramped down at the start of the free forecast period. This FDDA capability allows the user to specify the time period over which the nudging is gradually (linearly) ramped down to zero. This user-defined temporal weighting is applied to all grids at the same time.

3. EXPERIMENT DESIGN

The basic analysis nudging FDDA capabilities are tested using the CAPTEX-83 case study, which is described in Deng and Stauffer (2006). WRF-ARW is set up over the continental United States and run for 48 hours, from 1200 UTC 18 September to 1200 UTC 20 September 1983. Various sensitivity experiments associated with each of the FDDA options described above are performed. Similar MM5 experiments were also conducted using the exact same domain configurations and same initial and lateral boundary conditions. Figure 1 shows the locations of the 108-km, 36-km, 12-km and 4-km nested domains for the MM5 and WRF experiments.

Initially the focus is on the 36-km domain. The gridded analyses are created using the MM5 RAWINS program, where gridded background analyses from NCEP are enhanced with observations at the surface and on pressure levels. These surface and pressure-level analyses, interpolated to the MM5 B-grid and its sigma levels for the MM5 analysis-nudging experiments, are interpolated to the WRF C-
grid and its eta levels for the WRF analysis-nudging experiments. An example of this gridded analysis for the surface temperature and sea-level pressure fields is shown in Fig. 2.

Subjective and objective approaches are used to evaluate this study. Evaluation of simulated meteorological features is accomplished by subjectively comparing the model-simulated weather patterns including wind, temperature, water vapor mixing ratio and sea-level pressure to the observed patterns in the analyses. Objective evaluation is performed by comparing the statistical scores of these model-simulated fields to the WMO surface and sonde observations with focus here placed on mean absolute error (MAE).

Statistical scores are calculated based on Penn State’s VEROBS software package which was designed for MM5 verification. To use VEROBS to verify the WRF results, WRF netcdf output and grid geometry were converted to MM5’s binary format and grid geometry.

Table 1 shows all six WRF FDDA experiments performed in this study. All six experiments use

<table>
<thead>
<tr>
<th>Exp No.</th>
<th>Exp Name</th>
<th>FDDA Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>nofdda</td>
<td>No FDDA</td>
</tr>
<tr>
<td>2</td>
<td>fdda</td>
<td>Full FDDA</td>
</tr>
<tr>
<td>3</td>
<td>nopbl</td>
<td>FDDA excluded from PBL</td>
</tr>
<tr>
<td>4</td>
<td>zfac</td>
<td>FDDA excluded from low levels</td>
</tr>
<tr>
<td>5</td>
<td>zffnr6</td>
<td>Same as Exp. 4, except negative 6-h ramping from 24 h</td>
</tr>
<tr>
<td>6</td>
<td>zffpr6</td>
<td>Same as Exp. 4, except positive 6-h ramping from 24 h</td>
</tr>
</tbody>
</table>

Mellor-Yamada-Janjic TKE PBL scheme for PBL physics, WMS3 simple ice microphysics and Kain-Fritsch for cumulus parameterization. For atmospheric radiation the Dudhia scheme is used for shortwave and the RRTM is used for longwave. These experiments are designed to show the effects of the various analysis nudging FDDA options. The nudging coefficient, G, is set to 0.0003 s⁻¹ for wind, temperature and moisture for all FDDA experiments. The 6-h ramping period chosen for Exps. 5 and 6 is mainly for the purpose of testing the FDDA switches; a more typical value of 1-3 hours is often used for mesoscale applications.

4. PRELIMINARY RESULTS

4.1 MM5 versus WRF

Since MM5 already has the analysis nudging FDDA and its many options, it is important to first compare the effects of the comparable FDDA switches in WRF to those in MM5. Figures 3 and 4 compare the MAE time series of MM5- and WRF-simulated surface layer vector wind difference (VWD) for experiments similar to 1 – 5 in Table 1 except a 2-h positive ramp is used in Exp. 5 starting at 24 h. Although there are some differences in the 48-h averaged MAE error (ms⁻¹) between the two models (e.g. 3.5170 in MM5 vs. 3.7078 in WRF for no FDDA Exp. 1, 2.7082 vs. 2.7752 for full FDDA Exp. 2, 3.0878 vs. 3.3342 for the NO-PBL FDDA Exp. 3, 3.2311 vs. 3.4213 for the ZFAC Exp. 4, and 3.3098 vs. 3.4584 for the 2-h Ramping Exp. 5), the general patterns for these MAE curves are quite similar between MM5 and WRF. Exp. 2 (Full FDDA) errors oscillate in time and have the lowest average value over the 48-h period and Exp. 1 (No FDDA) errors generally increase in time through the period and have the largest average error. Experiments 3, 4 and 5 have similar patterns in both models and relative to each other, with average values falling between Exps. 1 and 2. Comparison of model-simulated surface VWD for all experiments...
appears to show that MM5 errors are 0.1 – 0.25 ms⁻¹ smaller than those in WRF.

Figures 5 and 6 compare the 48-h averaged MAE vertical profiles of MM5 and WRF simulated VWD at all model layers. Again the general patterns for these MAE curves are quite similar between MM5 and WRF. The vertically-averaged MAE values (ms⁻¹) are somewhat different between MM5 and WRF, with 4.4916 in MM5 vs. 4.1738 in WRF for no-FDDA Exp. 1, 1.6601 vs. 1.6985 for full-FDDA Exp. 2 experiments, 1.8497 vs. 2.2537 for the no-PBL FDDA Exp. 3, 2.4900 vs. 2.3139 for the ZFAC Exp. 4, and 3.5339 vs. 3.1720 for the 2-h Ramping Exp. 5. The vertical profiles of 48-h average wind errors do not suggest that either model is superior. The largest difference of MAE score between the two models was for the no-PBL FDDA Exp. 3, which implies that the PBL physics/depth in the two models may be somewhat different.

4.2 Testing of WRF FDDA Options

A 48-h WRF forecast of surface layer temperature and sea-level pressure for CAPTEX-83 without FDDA (Exp 1, see Table 1) is shown in Fig. 7, and the same using analysis nudging FDDA (Exp. 2, see Table 1) through the 48-h period is shown in Fig. 8. Comparison of Fig. 7 and Fig. 8 with the analysis in Fig. 2 indicates that WRF with full analysis nudging FDDA has produced improved simulations of the surface layer temperature and sea-level pressure fields over the large-scale domain.
Fig. 7. WRF-simulated surface-layer temperature and sea-level pressure fields at t = 48 h, 1200 UTC 20 September, from Exp. 1 without FDDA.

Fig. 8. WRF-simulated surface-layer temperature and sea-level pressure fields at t = 48 h, 1200 UTC 20 September, from Exp. 2 with FDDA.

(e.g., better trough location through southeast Oklahoma with colder air and 1020 hPa contour extending into northwest Oklahoma, and better thermal pattern over the western Atlantic Ocean), which more closely match those in the analysis in Fig. 2.

Figure 9 shows the MM5 RAWINS analysis of 850-hPa wind and geopotential height fields valid at 1200 UTC 20 September 1983. Figure 10 (Figure 11) shows the WRF simulation of the same fields at the same time without (with) FDDA. The WRF with FDDA improved the simulations of the low level wind and height fields over the large-scale domain and the patterns (e.g., the stronger winds on the western side of the trough, its position over central Oklahoma, and stronger wind speeds over the Texas coast region), more closely match those in the analysis.

Fig. 9. MM5 Rawins analysis of 850-hPa wind and geopotential height fields valid at 1200 UTC 20 September 1983.

Fig. 10. WRF-simulated 850-hPa wind and geopotential height fields valid at t = 48 h, 1200 UTC 20 September, from Exp. 1 without FDDA.

Fig. 11. WRF-simulated 850-hPa wind and geopotential height fields valid at t = 48 h, 1200 UTC 20 September, from Exp. 2 with FDDA.
Figure 12 shows the MAE time series of WRF-simulated surface-layer wind speed (m/s) for all experiments listed in Table 1. Exp. 1 (without FDDA) has the largest 48-h average MAE error (2.1815 m/s) and Exp. 2 (with FDDA) has the smallest average MAE error (1.8834 m/s). Experiments 3 and 4 which exclude FDDA from the PBL and lowest 10 layers, respectively, show larger surface MAE for wind speed as expected compared to Exp. 2 in which FDDA has full strength. Exp. 5 and Exp. 6 shows moderate MAE error because FDDA has ramped down to zero since t = 18 h in Exp. 5 and t = 24 h in Exp. 6. Comparison among all six curves again suggests that WRF FDDA has been implemented as designed.

Figure 13 shows 48-h averaged MAE vertical profile of WRF-simulated wind speed for the experiments listed in Table 1. It is shown again that Exp. 1 has the largest model error (2.6433 m/s) for the entire column and Exp. 2 has the smallest MAE error (1.0980 m/s). Exp. 3 and 4 show increased MAE error in the lower atmosphere, compared to the Exp. 2 in which FDDA has full strength. Exp. 5 and Exp. 6 shows moderate MAE error because FDDA has ramped down to zero since t = 18 h in Exp. 5 and t = 24 h in Exp. 6. Comparison among all six curves again suggests that WRF FDDA has been implemented as designed.

Figure 14 shows the MAE time series of WRF-simulated surface-layer wind direction (deg) for all experiments listed in Table 1. Exp. 1 (No-FDDA) has large wind direction error (38.1383 deg) and Exp. 2 (FDDA) shows the best MAE score (33.9961 deg).
Fig. 16. MAE time series of WRF-simulated surface-layer temperature (°C) for all experiments listed in Table 1.

The rest of the experiments show some degree of degradation as expected. In Fig. 15, the 48-h averaged MAE vertical profile of WRF-simulated wind direction, Exp. 1 is the worst and Exp. 2 is the best in MAE scores. Experiments 3 - 6 show similar degradations as before in the lower model layers, and Exps 5 and 6 with 6-h ramping also show some degradation in upper levels as expected. Experiments 5 and 6 generally have better MAE scores than Exp. 1 and worse MAE scores than Exp. 2.

Figure 16 shows MAE time series of WRF-simulated surface-layer temperature. Using full FDDA reduces MAE error from 3.4867 °C in Exp. 1 to 2.4583 °C in Exp. 2. The statistics for rest of the experiments are bounded by Exp. 1 and Exp. 2. In Fig. 17, 48-h averaged MAE vertical profile of WRF-simulated temperature, Exp. 1 has the worst MAE score (1.8892 °C) and Exp. 2 has the best MAE score (0.9677 °C). Degradations in lower model layers are seen as before in Exps. 3 and 4, with further degradation with 6-h ramping in Exps. 5 and 6.

Figure 18 shows MAE time series of WRF-simulated surface-layer water vapor mixing ratio (g kg⁻¹) for all experiments listed in Table 1.

Fig. 17. 48-h averaged MAE vertical profile of WRF-simulated temperature (°C) for experiments listed in Table 1.

Fig. 18. MAE time series of WRF-simulated surface-layer water vapor mixing ratio (g kg⁻¹) for all experiments listed in Table 1.

Fig. 19. 48-h averaged MAE vertical profile of WRF-simulated water vapor mixing ratio (g kg⁻¹) for experiments listed in Table 1.

simulated temperature, Exp. 1 has the worst MAE score (1.8892 °C) and Exp. 2 has the best MAE score (0.9677 °C). Degradations in lower model layers are seen as before in Exps. 3 and 4, with further degradation with 6-h ramping in Exps. 5 and 6.

Figure 18 shows MAE time series of WRF-simulated surface-layer water vapor mixing ratio. Using full FDDA over all layers reduces water vapor mixing ratio MAE error from 1.4392 g kg⁻¹ in Exp. 1 to 1.1328 g kg⁻¹ in Exp. 2. The curves for the rest of experiments are generally located between Exp. 1 and Exp. 2. In Fig. 19, the 48-h averaged MAE vertical profile of WRF-simulated water vapor mixing ratio, Exp. 1 has the worst MAE score (1.1332 g kg⁻¹) and Exp. 2 has the best MAE score (0.2964 g kg⁻¹). Degradations in lower model layers are seen in Exps. 3 and 4. In the lowest 10 model layers the MAE
scores in Exps. 4, 5 and 6 are worse than Exp. 1 which does not have FDDA applied. Although one possible explanation includes alteration of model convection due to use of analysis nudging of moisture with its nudging strength the same as the other variables, and thus the moisture nudging being too strong producing inaccurate low-level moisture convergence with coarse, sonde-scale moisture analyses (Stauffer et al. 1991), further investigation is still needed.

Similar conclusions regarding the WRF FDDA options and switches can be drawn from Fig. 20, the MAE time series of WRF-simulated sea-level pressure. Although the sea-level pressure field is not directly assimilated toward an analysis, applying analysis nudging FDDA towards thermal and wind analyses has shown noticeable improvement in the WRF-simulated sea-level pressure field through the 48-h period, with Exps. 5 and 6 showing larger errors than the other FDDA experiments following their ramp down periods.

5. SUMMARY AND CONCLUSIONS

A prototype version of the 3D analysis nudging FDDA capability is implemented in WRF-ARW. Currently, nudging can be applied to the two horizontal wind components (u and v), the potential temperature, and the water vapor mixing ratio. The current release version of the analysis nudging FDDA codes also has the following capabilities:

a) User-specified nudging end-time and rampdown period to zero. Nudging can be discontinued during the simulation, as for a running-start dynamical initialization. Since turning nudging off suddenly can lead to model noise, there is a capability for ramping the nudging down over a period, typically 1-3 hours, to reduce the shock.

b) User-specified strength of nudging by variable. The timescale (1/G) for nudging can be controlled individually for winds, temperature and moisture. Typically the namelist value of G = 0.0003 s\(^{-1}\) is used for all variables, corresponding to a timescale of about 1 hour, but this may be reduced for moisture where there may be less confidence in the analysis if based on coarse rawinsonde data above the surface.

c) User-specified restrictions on nudging within the planetary boundary layer by variable. If the analyses do not resolve the diurnal cycle, it is better not to nudge in the boundary layer to let the model PBL evolve properly, particularly the temperature and moisture fields. Each variable can therefore be selectively not nudged in the model boundary layer, the depth of which is given by the PBL physics.

d) User-specified elimination of nudging in lower levels by variable. Alternatively the nudging can be deactivated for any of the variables below a certain vertical layer throughout the simulation. For example, the lowest ten layers can be specified to be free of the nudging term to better simulate a low level jet that is not resolved by the wind analyses based on the rawinsonde network.

These basic analysis nudging FDDA capabilities have been tested using the CAPTEX-83 case study and model configuration (Deng and Stauffer 2006). Tests have shown that the various FDDA options have been implemented properly. Penn State has received a new three-year funding support to continue the research and development of both the analysis nudging and observation nudging for WRF. In the newly funded effort, the analysis nudging capabilities will be made more general and also include the surface analysis nudging through the PBL (Stauffer et al. 1991). This method also accounts for data-analysis confidence by using the number and locations of observations that were used to produce the surface analyses in the nudging weighting functions. The analysis and observation nudging will also be designed to better use statistical information from variational and ensemble Kalman filter methods. This work includes exploration of new hybrid nudging – variational – EnKF techniques (e.g., Lei and Stauffer 2007).

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7. REFERENCES


8. DISCLAIMER

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