UPDATE ON ANALYSIS NUDGING FDDA IN WRF-ARW

Aijun Deng¹, David R. Stauffer¹, Jimy Dudhia², Tanya Otte³ and Glenn K. Hunter¹

¹Penn State University
²NCAR
³NOAA/EPA

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• Nudging FDDA techniques (both analysis and OBS nudging) was developed at Penn State for MM5 by Stauffer and Seaman in early 1990s.

• Nudging is an efficient way to reduce model errors and it has been successful in MM5 (e.g. DA, DI, better BC for coarse grid)

• Most recent applications include:
  – U.S. Army Profiler (OBS nudging)
  – U.S. Marines NEXGEN (OBS nudging)
  – DTRA in-house MM5 modeling system (OBS and analysis nudging)
• Penn State has implemented a basic 3-D analysis nudging capability in WRF-ARW in WRF2.2 release, supported by EPA and AFWA.

• Basic FDDA functions in WRF-ARW (similar to MM5):
  – User-specified nudging end-time and rampdown period to zero
  – User-specified strength of nudging
  – User-specified nudging within the planetary boundary layer
  – User-specified nudging in lower model layers
Nudging FDDA in WRF

For \( \alpha = \Theta = \mu \cdot \theta \)

\[
\frac{\partial \Theta}{\partial t} = \ldots + \mu \frac{\partial \theta}{\partial t} + \theta \frac{\partial \mu}{\partial t}
\]

\[
\frac{\partial \Theta}{\partial t} = \ldots + \mu \cdot G_\theta \cdot W \cdot (\theta_{ob} - \theta)
\]

\[
+ \theta \cdot G_\mu \cdot W \cdot (\mu_{ob} - \mu)
\]

where \( W = w_{xy} \cdot w_\eta \cdot w_t \)
Currently

- Nudging $u$, $v$, theta, $q$
- $\mu$ is not being nudged
Testing Design

• CAPTEX-83, 48 hours model run, 36-km CONUS domain
  – Starting: 1200 UTC, 18 Sept. 1983

• 3D Analyses from MM5 RAWINS and converted into WRF input format

• All experiments use M.Y.J PBL scheme, KF CPS, WSM 3-class simple ice, Dudhia shortwave and RRTM longwave radiation.
## FDDA Testing Design

<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>ffdda</td>
<td>Full 3-D FDDA</td>
</tr>
<tr>
<td>3</td>
<td>nopbl</td>
<td>FDDA excluded from PBL (by specifying $W_\eta$)</td>
</tr>
<tr>
<td>4</td>
<td>zfac</td>
<td>FDDA excluded from low model layers (by specifying $W_\eta$)</td>
</tr>
<tr>
<td>5</td>
<td>zttfnr6</td>
<td>Same as Exp. 4, except 6-h ramping down ended at 24 h (by specifying $W_t$)</td>
</tr>
<tr>
<td>6</td>
<td>zttfpr6</td>
<td>Same as Exp. 4, except 6-h ramping down started at 24 h (by specifying $W_t$)</td>
</tr>
</tbody>
</table>
Verification Strategies

- WFR output is converted into MM5 format
- Statistic verification using Penn State VEROBS for MM5
- Subjective verification by visually looking at the model-simulated weather patterns
MAE of Surface Layer Wind Speed

MODEL–RELATIVE TIME (HOUR)
(MEAN)

<table>
<thead>
<tr>
<th>Model</th>
<th>Value</th>
<th>Model</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>nofdda</td>
<td>2.1815</td>
<td>fdda</td>
<td>1.6834</td>
</tr>
<tr>
<td>nopbl</td>
<td>1.9876</td>
<td>zfac</td>
<td>2.0150</td>
</tr>
<tr>
<td>ztfnr6</td>
<td>2.0435</td>
<td>ztfpr6</td>
<td>2.0837</td>
</tr>
</tbody>
</table>
48-h Averaged MAE of Wind Speed
MAE of Surface Layer Wind Direction
48-h Averaged MAE of Wind Direction

![Graph showing 48-h averaged mean absolute error of wind direction.](image)
MAE of Surface Layer Temperature

MODEL–RELATIVE TIME (HOUR)
(MEAN)

MEAN ABS ERROR (°C)

1=nofdda  2=fdda  3=nopbl  4=zfac  5=zftfmr6  6=zftfpr6

3.4867  2.4523  3.1417  3.1866  3.2235  3.3194
48-h Averaged MAE of Temperature

- 1=nofdda
- 2=fdda
- 3=nopbl
- 4=zfac
- 5=zftfmr6
- 6=zftfpr6
MAE of Surface Layer Water Vapor Mixing Ratio

![Graph showing MAE of Surface Layer Water Vapor Mixing Ratio](image)

- **Model-Relative Time (Hour)**
  - Mean error values for different models:
    - 1 =nofdda
    - 2 =fdda
    - 3 =nopbl
    - 4 =zfac
    - 5 =ztfmr6
    - 6 =ztfpr6

- **Error Values**:
  - 1.4392
  - 1.1328
  - 1.4010
  - 1.4035
  - 1.4096
  - 1.4684
48-h Averaged MAE of Water Vapor Mixing Ratio
MM5 vs. WRF
MM5

WRF
Subjective Verification
Surface Temperature and Sea Level Pressure

MM5 ANALYSIS

WRF NO FDDA

WRF FDDA
850 hPa Temperature and Geopotential Height

Dataset: 36 km RAP: mm5 interp 36 km
Forecast: 48.00 h Valid: 1200 UTC Tue 20 Sep 23
Temperature at pressure = 850 hPa
Geopotential height at pressure = 850 hPa

MM5 ANALYSIS

WRF NO FDDA

WRF FDDA
500 hPa Temperature and Geopotential Height

Dataset: 36km RIF: mm5 interp 36km
Fcast: 48.00 h

Temperature
at pressure = 500 hPa

Geopotential height
at pressure = 500 hPa

MM5 ANALYSIS

WRF NO FDDA

WRF FDDA
200 hPa Temperature and Geopotential Height

Dataset: 36km  RP: mm5 interp 36km  Init: 1200 UTC Sun 18 Sep 83
Forecast: 48.00 h  Valid: 1200 UTC Tue 20 Sep 83 (0000 LDT Tue 20 Sep 83)
Temperature at pressure = 200 hPa
Geopotential height at pressure = 200 hPa

MM5 ANALYSIS

WRF NO FDDA

WRF FDDA
Surface Winds and Sea Level Pressure

Dataset: 36km REF: mm5 interp 36km
Forecast: 48.00 h Valid: 1200 UTC Tue 20 Sep 83 (0000 LDT Tue 20 Sep 83)
Horizontal wind speed at k-index = 32
Horizontal wind vectors at k-index = 34
Sea level pressure
Sea level pressure
Sea level pressure

MM5 ANALYSIS

WRF NO FDDA

WRF FDDA
850 hPa Winds and Geopotential Height

MM5 ANALYSIS

WRF NO FDDA

WRF FDDA
500 hPa Winds and Geopotential Height

Dataset: 36km R: mm5 interp 36km
Forecast: 48.00 h
Init: 1200 UTC Sun 18 Sep 83
Valid: 1200 UTC Tue 20 Sep 83 (1800 LDT Tue 20 Sep 83)

Horizontal wind speed: 600 hPa
Geopotential height: 500 hPa
Horizontal wind vectors: 500 hPa

MM5 ANALYSIS

WRF NO FDDA

WRF FDDA
200 hPa Winds and Geopotential Height

Dataset: ncedda36  RF: 32_end mm5 36km v2.1.2  Init: 1200 UTC Sun 18 Sep 83
Valid: 1200 UTC Tue 20 Sep 83 (0800 LDT Tue 20 Sep 83)
Forecast: 48.00 h
Horizontal wind speed at pressure = 200 hPa
Geopotential height at pressure = 200 hPa
Horizontal wind vectors at pressure = 200 hPa

MM5 ANALYSIS

WRF NO FDDA

WRF FDDA
850 hPa Mixing Ratio and Geopotential Height

Dataset: 36km  RF: mm5 interp 36km  Init: 1200 UTC Sun 18 Sep 83
Est: 48.00 h  Valid: 1200 UTC Tue 20 Sep 83 (0000 LDT Tue 20 Sep 83)
Water vapor mixing ratio at pressure = 850 hPa
Geopotential height at pressure = 850 hPa

MM5 ANALYSIS

WRF NO FDDA

WRF FDDA
Summary and Conclusions

- Penn State has implemented a basic 3-D analysis nudging FDDA capability
  - User-specified nudging end-time and rampdown period to zero
  - User-specified strength of nudging
  - User-specified nudging within the planetary boundary layer
  - User-specified nudging in lower levels

- Testing and statistical verification on CAPTEX-83 case show that all FDDA switches work properly as designed.

- WRF simulations of weather patterns are improved by applying analysis nudging FDDA.

- Effects of analysis nudging FDDA in WRF-ARW are similar to MM5
Future Work

Penn State (with NCAR as subcontractor) has received new three-year funding from DTRA to continue the research and development of both analysis and OBS nudging for WRF.

- More general analysis nudging (e.g. including surface analysis nudging through PBL)

- The analysis and observation nudging will also be designed to better use statistical information from variational and ensemble Kalman filter methods

- Exploration of new hybrid nudging-variational-EnKF techniques, etc.

- .....................
Nudging FDDA

\[
\frac{\partial \alpha}{\partial t} = G \bullet (\alpha_{ob} - \alpha) + \ldots
\]

\[
\int_0^t (\ ) \, dt \Rightarrow \alpha(t) = (\alpha_0 - \alpha_{ob}) \bullet e^{-Gt} + \alpha_{ob}
\]

\[\alpha(t) = (\alpha_o - \alpha_{ob}) \bullet e^{-Gt} + \alpha_{ob}\]

\[
\frac{1}{G} \equiv e^{-folding \, time} \quad O(1h)
\]
WRF Mass-Coordinate Model Integration Procedure

Begin time step

Runge-Kutta loop (steps 1, 2, and 3)
(i) advection, p-grad, buoyancy using \( \phi^t, \phi^*, \phi^{**} \)
(ii) physics if step 1, save for steps 2 and 3
(iii) mixing, other non-RK dynamics, save...
(iv) assemble dynamics tendencies

Acoustic step loop
(i) advance U, V, then \( \mu, \Theta \), then w, \( \phi \)
(ii) time-average U, V, \( \Omega \)

End acoustic loop
Advance scalars using time-averaged U, V, \( \Omega \)

End Runge-Kutta loop
Adjustment physics (currently microphysics)

End time step
Domains: 108, 36, 12 and 4 km