AFAD / WRF Data Assimilation System

Scientific tunings for an operational implementation

Radi AJJAJI, Ahmad AL KATHERI
and Abdullah DHANHANI
United Arab Emirates Air Force & Air Defense.
1. Brief overview about UAE/WRF
2. Data assimilation as implemented in pre-operational mode.
   - Cycling
   - Observations
   - Background Errors Statistics
3. Tuning of UAE/WRF-VAR: Experimental design.
   - Adaptive tuning
   - Outer loops technique
4. Experiments results.
5. Nested WRF-Var: interaction between nests.
## Brief overview about UAE/WRF

<table>
<thead>
<tr>
<th>WRF 2.2</th>
<th>Domain ‘d01’</th>
<th>Domain ‘d02’</th>
<th>Domain ‘d03’</th>
<th>Domain ‘d01’</th>
<th>Domain ‘d02’</th>
<th>Domain ‘d03’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid dimensions</td>
<td>40 km 156 x 126 x 38</td>
<td>13.33 km 256 x 226 x 38</td>
<td>4.44 km 172 x 136 x 38</td>
<td>Radiation</td>
<td>RRTM/Dudhia scheme</td>
<td>RRTM/Dudhia scheme</td>
</tr>
<tr>
<td>Time step</td>
<td>225 s</td>
<td>75 s</td>
<td>25 s</td>
<td>PBL</td>
<td>YSU scheme</td>
<td>YSU scheme</td>
</tr>
<tr>
<td>Micro-physics</td>
<td>Ferrier*</td>
<td>Ferrier*</td>
<td>Ferrier*</td>
<td>Surface physics</td>
<td>Noah LSM</td>
<td>Noah LSM</td>
</tr>
<tr>
<td>Cumulus scheme</td>
<td>Kain-Fritsch scheme</td>
<td>Kain-Fritsch scheme</td>
<td>Explicit.</td>
<td>Initial and Boundary Conditions.</td>
<td>NCEP GFS/GSI analyses</td>
<td>Two-way nest</td>
</tr>
</tbody>
</table>

- **d01**: Middle-East
- **d02**: Arabian Peninsula
- **d03**: United Arab Emirates
- **WPS** is used for LBC interpolation.
- WRF-VAR is still in parallel suite (for d01, d02 and d03)
- UAE/WRF outputs on the net: [http://www.afmet.ae/main.html](http://www.afmet.ae/main.html)
Adopted 3D-VAR FGAT Cycling type

Forecast +9 hours
Start: 12:45 UTC

Forecast +9 hours
Start: 18:45 UTC

Forecast +9 hours
Start: 00:45 UTC

Free Forecast +120 hours
Starting at: 04:30 UTC

GSI/FOR +00
00:34 UTC

GSI/FOR +3
00:36 UTC

GSI/FOR +6
00:38 UTC

GSI/FOR +9
00:40 UTC

3h30mn short cut-off
7 time slots

GTS, GPS, RADAR

3D-VAR FGAT

6 hourly GFS
0.5x0.5 Forecasts
Observational coverage over Middle-East region

Numbers are given per FGAT analysis
Assimilation of Radar Data

- 6 Doppler Radars (Abu Dhabi, Dubai, Al Ain, Liwa, Delma)
- 1 km horizontal resolution, 11 different elevation angles and 15 minutes frequency.
- Normal/Anomalous Propagation ground clutter corrected by Radar software (Radar Echo Classifier software)
- Mosaic radial velocities, reflectivities, precipitation rates in BUFR format.
- BUFR to GRIB/ASCII (super-obbing)
- Raw observations are thinned (1 super obs. / 3 km), then a rejection threshold of 20 dBZ is applied.
- Three dimensional coherence control
- Time distribution coherent with FGAT.
- Multi-radar redundancy check.
- Observations errors depend on the distance to the Radar center.

Actual composite Radar reflectivity

Monday, 02 April 2007, 15:00 UTC

DWSR-88C, 240 km horizontal range
Information content of each individual observation type in AFAD/WRF assimilation system as represented by the DFS estimation.

DFS = \text{Tr} (HK) : sensitivity of the analysis to the different observation types.
CV5 computed using 1 month WRF outputs for d01, d02 and d03.
CV3 tuned in such way that single observations experiments increments look like those generated by CV5.
CV5 variances decreased 10 % to reflect model error variances at 9 hours range.
We should inflate background variances by a factor of 1.75

Attention should be paid to GEAMV error factors: their error is spatially correlated and this correspond to a limitation of the used tuning technique (Chapnik et al.)
Description of the experiments

<table>
<thead>
<tr>
<th>WRF V2.2</th>
<th>BES</th>
<th>FGAT</th>
<th>OBS. ERR. FACTORS</th>
<th>OUTER LOOPS</th>
<th>GEOAMV</th>
<th>RADAR**</th>
</tr>
</thead>
<tbody>
<tr>
<td>TUNEDCV3</td>
<td>NCEP CV3</td>
<td>YES</td>
<td>NO</td>
<td>1</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>RAWCV5</td>
<td>NMC CV5</td>
<td>YES</td>
<td>NO</td>
<td>1</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>ERFCV5</td>
<td>NMC CV5</td>
<td>YES</td>
<td>YES</td>
<td>1</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>ITS3CV5</td>
<td>NMC CV5*</td>
<td>YES</td>
<td>YES</td>
<td>3*</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>NOGMV</td>
<td>NMC CV5*</td>
<td>YES</td>
<td>YES</td>
<td>3*</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>RADARCV5</td>
<td>NMC CV5*</td>
<td>YES</td>
<td>YES</td>
<td>3*</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>NCEPGSI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Reference = *No assimilation*, cold start using GSI analyses

* Variances and length scales are modified during outer loops (feature added in the WRF-VAR source code)

** WRF-VAR code has been modified to output Radar observations contribution to the cost function (in both parallel and serial execution modes). Adaptive tuning procedure (tune.f90) is made working for Radar.
## Tuning Background covariances

<table>
<thead>
<tr>
<th>Variance</th>
<th>Outer loop 1</th>
<th>Outer loop 2</th>
<th>Outer loop 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSI</td>
<td>1.75</td>
<td>1.00</td>
<td>0.50</td>
</tr>
<tr>
<td>CHI_u</td>
<td>1.75</td>
<td>1.00</td>
<td>0.50</td>
</tr>
<tr>
<td>T_u</td>
<td>1.75</td>
<td>1.00</td>
<td>0.50</td>
</tr>
<tr>
<td>q/qsg</td>
<td>1.00</td>
<td>1.00</td>
<td>0.50</td>
</tr>
<tr>
<td>psfc</td>
<td>1.75</td>
<td>1.00</td>
<td>0.50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Length scale</th>
<th>Outer loop 1</th>
<th>Outer loop 2</th>
<th>Outer loop 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSI</td>
<td>1.00</td>
<td>0.50</td>
<td>0.25</td>
</tr>
<tr>
<td>CHI_u</td>
<td>1.00</td>
<td>0.50</td>
<td>0.25</td>
</tr>
<tr>
<td>T_u</td>
<td>1.00</td>
<td>0.50</td>
<td>0.25</td>
</tr>
<tr>
<td>q/qsg</td>
<td>1.00</td>
<td>0.50</td>
<td>0.25</td>
</tr>
<tr>
<td>psfc</td>
<td>1.00</td>
<td>0.50</td>
<td>0.25</td>
</tr>
</tbody>
</table>

- Variances are increased (1.75) in the first outer loop in order to fit more the observations. Length scales are maintained (1.00) to spread the information at a maximum radius.
- In the second and third outer loops, more confidence in the guess (Var. factor = 1.00), and only small scales are analyzed (L.S. factor = 0.50, 0.25)
CV5, Adaptive tunings, 3 outer loops with different BES scaling performs quite well.

General bad performance at the beginning of the forecast.
Radar reflectivities impact

NCEPGSI

RADARCV5

ITS3CV5

ACTUAL
Geostationary Atmospheric Motion Vectors impact

- **METEOSAT 8** data (5 times denser than METEOSAT 7)
- IR winds: with QI > 85
- Vis winds: below 700 hPa and QI > 70
- WV cloudy: above 400 hPa and QI > 85
- **Thinning**: 1 observation per grid box
- The **reduction in RMS** is denoting high quality METEOSAT 8 AMVs.
Interaction between nests in WRF VAR.

- Introduce, in a coherent manner, large and longer scales in the small scale analysis.
- Deal with the LBC issue in 3D-Var and provide information from observations outside the nest domain.
- Avoid costly multiple outer loops per nest.
- Introduce progressively high resolution observations.
Nested WRF 3D-Var: 1st Scenario

\[ J_k(\delta x) = \frac{1}{2}(\delta x)^T B_k^{-1}(\delta x) + \frac{1}{2}(H_k \delta x - d)^T R_k^{-1}(H_k \delta x - d) \]

\[ \begin{align*}
d &= y - H_k \left( x_{a_{k-1}}^{L \rightarrow H} \right) \\
\delta x &= x - x_{b_k} 
\end{align*} \]

- \( J_k(\delta x) \): Incremental cost function for nest k
- \( x_{b_k} \): First Guess for nest k
- \( B_k \): Background errors for nest k
- \( H_k \): Observation operator inside nested domain k
- \( H_k \): The non linear observation operator
- \( y_k \): Observation vector inside nested domain k
- \( R_k \): error covariances of observations inside nest k
- \( x_{a_{k-1}}^{L \rightarrow H} \): Analysis in nest k – 1 interpolated to nest k grid.
Nested WRF 3D-Var: 1st Scenario

- 3D-Var analysis over d01.
- Compute innovations in domain d02 using d01 analysis.
- 3D-Var analysis over d02 based on d02 first guess
- 3D-Var analysis over d03 with the same technique
- Large scale information is introduced inside the small scale analysis through the innovations.
- Necessitate minor changes in the code.

- Low resolution analysis
- Observations
Nested WRF 3D-Var: 2nd Scenario

\[ J_k(\delta x) = \frac{1}{2} (\delta x)^T B_k^{-1}(\delta x) + \frac{1}{2} (H_k \delta x - d)^T R_k^{-1}(H_k \delta x - d) \]

\[ d = y - H(x_{b_k}) \]

\[ \delta x = x - x^{L\rightarrow H}_{a_{k-1}} \]

- **\( J_k(\delta x) \): Incremental cost function for nest k**
- **\( x_{b_k} \): First Guess for nest k**
- **\( B_k \): Background errors for nest k**
- **\( H_k \): Observation operator inside nested domain k**
- **\( y_k \): Observation vector inside nested domain k**
- **\( R_k \): error covariances of observations inside nest k**
- **\( x^{L\rightarrow H}_{a_{k-1}} \): Analysis in nest \( k-1 \) interpolated to nest \( k \) grid.**
Nested WRF 3D-Var: 2nd scenario

- 3D-Var analysis over d01.
- d02 analysis is based on d01 analysis as background
- d02 innovations are computed using d02 First Guess.
- 3D-Var analysis over d03 with the same technique
- Large scale information is introduced inside the small scale analysis through the background term.
- Adaptive tuning for $B_k$ to be coherent with the used background (low resolution analysis).
- Necessitate minor changes in the code.

- Low resolution analysis
- Observations
Nested WRF 3D-Var: 3rd scenario

d01 (Res1)

- Low resolution analysis
- Observations

d02 (Res2)

d03 (Res3)

FG d01 Res1

3D-Var

AN d01 Res1

FG d02 Res2

AN d01 – FG d01 Res1

FG d02 + (AN d01 – FG d01)Res2

3D-Var

AN d02
Conclusion about the different scenarios

- Larger and longer scales information are introduced in the nest
- Only small scales are kept from the guess.
- Provide implicitly information from observations outside the nest as well as data near the boundary inside the domain.
- No need for more than 1 outer loop per domain since, for example the, 3D-Var analysis on domain d03 is an implicit third outer loop.
- Less expensive when compared to the use of multiple outer loops per domain.
- Corresponding experiments are ongoing.
Summary & Conclusion

- WRF-VAR is successfully implemented in the UAE/WRF operational suite taking advantage of:
  - Multiple nests
  - Local BES
  - FGAT
  - Outer loops technique
  - Adaptive tuning technique
  - Radar data assimilation

- Certain weaknesses were noticed and planned to be processed in the near future:
  - Initialization (digital filters)
  - Surface analysis.

- Experiments dealing with the interaction between nests in assimilation mode are being performed.
Extra slides
Nested WRF 3D-Var: 4th scenario

\[
J_k(x) = \frac{1}{2} (x - x_{b_k})^T B_k^{-1} (x - x_{b_k}) + \frac{1}{2} (H_k(x) - y_k)^T R_k^{-1} (H_k(x) - y_k) + \frac{1}{2} (x - x_{a_{k-1}}^{L\rightarrow H})^T A_{k-1}^{-1} (x - x_{a_{k-1}}^{L\rightarrow H})
\]

(1) 

\[J_k(x): \text{Cost function for nest } k\]

\[x_{b_k}: \text{First Guess for nest } k\]

\[B_k: \text{Background errors for nest } k\]

\[H_k: \text{Observation operator inside nested domain } k\]

\[y_k: \text{Observation vector inside nested domain } k\]

\[R_k: \text{error covariances of observations inside nest } k\]

\[x_{a_{k-1}}^{L\rightarrow H}: \text{Analysis in nest } k-1 \text{ interpolated to nest } k \text{ grid.}\]

\[A_{k-1}^{-1} = B_{k-1}^{-1} + H_k^T R_k^{-1} H_k^T\]

\[B_{k-1}: \text{Background errors covariances for nest } k-1 (\text{parent}) \text{ interpolated to nest } k \text{ grid.}\]
Nested WRF 3D-Var: 4\textsuperscript{th} scenario

- Large scales taken from the parent nest
- Small scales taken from the WRF forecast (First guess).
- Use progressively high resolution observations (Adapted thinning, Radar, ...etc)
- Nest $k-1$ information could be introduced into nest $k$ during the minimization process at the level of inner loops in the following manner:

Let's suppose that we have 3 nested domains $d01$, $d02$ and $d03$

Intuitively convergence is guaranteed because the increments tend to stabilize with the number of inner loops.