Forecast Sensitivity to Observations & Observation Impact

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WRFDA Tutorial – July 24-26 2013
Outline

- Introduction
- Implementation in WRF
- Applications
- Limitations
- Conclusions
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- Implementation in WRF
- Applications
- Limitations
- Conclusions
Introduction

➢ What?
➢ Why?
➢ Who?
➢ How?
➢ How much?

FSO?
Introduction

- **What?**
  - *A posteriori*, it is possible to evaluate the accuracy of NWP forecasts.

- **Why?**
  - Using an adjoint technique, we can trace it back to the observations used in the analysis.

- **Who?**
  - We can determine quantitatively which observations improved 😊 or degraded 😞 the forecast.

- **How?**
  - Forecast Sensitivity to Observations (FSO) is a diagnostic tool that complements traditional denial experiments (OSEs).
Introduction

- **What?**
  - Impact of each observation calculated simultaneously (less tedious than OSEs).

- **Why?**
  - NWP centers use FSO routinely to monitor their Data Assimilation and Global Observing System.

- **Who?**
  - Can be used to tune Quality Control, Bias Correction, etc.

- **How?**
  - Helps assess the impact of specific sensors for data providers.

- **How much?**
Introduction

- **What?**
  - Naval Research Laboratory (Monterey, CA)
- **Why?**
  - NASA/GMAO (Washington, DC)
  - ECMWF (Reading, UK)
- **Who?**
  - Environment Canada (Montreal, Canada)
- **How?**
  - Meteo-France (Toulouse, France)
- **How much?**
  - NCAR/MMM (Boulder, CO)
Introduction

- **What?**
  - Non-Linear (NL) forecast models can be linearized (with simplifications).
  - The resulting **Tangent-Linear** (TL) represents the linear evolution of small perturbations.

- **Why?**
  - The mathematical transpose of the TL code is called the Adjoint (ADJ) and it transports sensitivities back in time.

- **Who?**
  - The ADJ of the Data Assimilation system is needed to compute the sensitivity to observations.

- **How?**
  - It can be computed with various methods:
    - Ensemble (ETKF, Bishop *et al.* 2001)
    - Dual approach (PSAS, Baker and Daley 2000, Pellerin *et al.* 2007)
    - Exact ADJ calculation (Zhu and Gelaro 2007)
    - Hessian approximation (Cardinali 2006)
    - Lanczos minimization (Fisher 1997, Tremolet 2008)
Introduction

- What?
- Why?
- Who?
- How?
- How much?

- 2 runs of non-linear forecast model
- 2 runs of adjoint model
- 1 run of adjoint of analysis
- The computer cost is estimated to 10-15 times the cost of the forecast model.
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- Implementation in WRF
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- Conclusions
Implementation in WRF

Observation $(y)$

Background $(x_b)$

WRF-VAR Data Assimilation

Analysis $(x_a)$

WRF-ARW Forecast Model

Forecast $(x_f)$

Define Forecast Accuracy

Observation Impact $<y-H(x_b)> (\delta F/\delta y)$

Observation Sensitivity $(\delta F/\delta y)$

Analysis Sensitivity $(\delta F/\delta x_a)$

Adjoint of WRF-VAR Data Assimilation

Adjoint of WRF-ARW Forecast TL Model (WRF+)

Gradient of $F (\delta F/\delta x_f)$

Derive Forecast Accuracy

Obs Error Sensitivity $(\delta F/\delta e_{ob})$

Bias Correction Sensitivity $(\delta F/\delta \beta_k)$

Figure adapted from Liang Xu (NRL)
**Implementation in WRF**

- Observation ($y$)
- Background ($x_b$)

**WRF-VAR Data Assimilation**

- Analysis ($x_a$)

**WRF-ARW Forecast Model**

- Forecast ($x_f$)

**Define Forecast Accuracy**

- Observation Impact $<y-H(x_b)> (\delta F/\delta y)$

**Adjoint of WRF-VAR Data Assimilation**

- Observation Sensitivity ($\delta F/\delta y$)
- Background Sensitivity ($\delta F/\delta x_b$)

- Bias Correction Sensitivity ($\delta F/\delta \beta_x$)

- Obs Error Sensitivity ($\delta F/\delta e_{ob}$)

**Adjoint of WRF-ARW Forecast TL Model (WRF+)**

- Gradient of $F (\delta F/\delta x_f)$

- Derive Forecast Accuracy ($F$)
Implementation in WRF

WRF-VAR Data Assimilation

Observation \((y)\)
Background \((x_b)\)

Analysis \((x_a)\)

WRF-ARW Forecast Model

Forecast \((x_f)\)

Define Forecast Accuracy

- Usual WRF-Var 3DVar or 4DVar data assimilation system
- Namelist parameter needs to be activated: `ORTHONORM_GRADIENT=true`

Observation Impact

Obs Error Sensitivity \((\delta F/ \delta e_{ob})\)
Bias Correction Sensitivity \((\delta F/ \delta \beta_x)\)
Implementation in WRF

Observation
(y)

WRF-VAR
Data Assimilation

Analysis
(xa)

WRF-ARW Forecast Model

Forecast
(xf)

Define Forecast Accuracy

Observation Impact
<y-H(xb)> (δF/δy)

Adjoint of WRF-VAR Data Assimilation

Analysis Sensitivity
(δF/δxa)

Adjoint of WRF-ARW Forecast TL Model (WRF+)

Gradient of F
(δF/δxf)

Derive Forecast Accuracy

Observation Sensitivity
(δF/δy)

Background Sensitivity
(δF/δxb)

Obs Error Sensitivity
(δF/δeob)

Bias Correction Sensitivity
(δF/δβk)
Implementation in WRF

- WRF ARW forecast
- Observation $(y)$
- Background $(x_b)$
- Analysis $(x_a)$
- Forecast $(x_f)$
- Define Forecast Accuracy

- Observation Sensitivity $(\delta F / \delta y)$
- Background Sensitivity $(\delta F / \delta x_b)$
- Obs Error Sensitivity $(\delta F / \delta e_{ob})$
- Bias Correction Sensitivity $(\delta F / \delta \beta_k)$
- Adjoint of WRF-VAR Data Assimilation
- Adjoint of WRF-ARW Forecast Model
- Adjoint of TL Model (WRF+)

- Forecast length is set to reach verification time
- Use WRFNL code to write trajectory for adjoint run
Implementation in WRF

Observation
(y)

Background
(x_b)

WRF-VAR
Data Assimilation

Analysis
(x_a)

WRF-ARW
Forecast Model

Forecast
(x_f)

Define Forecast Accuracy

Observation Impact
<y-H(x_b)> (δF/δy)

Observation Sensitivity
(δF/δy)

Background Sensitivity
(δF/δx_b)

Adjoint of
WRF-VAR
Data Assimilation

Analysis Sensitivity
(δF/δx_a)

Adjoint of
WRF-ARW
Forecast TL Model
(WRF+)

Gradient of F
(δF/δx_f)

Derive Forecast Accuracy

Obs Error Sensitivity
(δF/δe_{ob})

Bias Correction Sensitivity
(δF/δβ_k)
Implementation in WRF

- **Reference state**: Namelist `ADJ_REF` is defined as
  - 1: \( X^t = \text{Own (WRFVar) analysis} \)
  - 2: \( X^t = \text{NCEP (global GSI) analysis} \)
  - 3: \( X^t = \text{Observations} \)

- **Forecast Aspect**: depends on reference state
  - 1 and 2: Total Dry Energy
    \[
    \langle x, x \rangle = \frac{1}{2} \iint \iint \left[ u'^2 + v'^2 + \left( \frac{g}{N \theta} \right)^2 \theta'^2 + \left( \frac{1}{\bar{\rho} c_s} \right)^2 p'^2 \right] d \Sigma
    \]
  - 3: WRFVar Observation Cost Function: \( J_o \)

- **Geo. projection**: Script option for box (default = whole domain)
  - `ADJ_ISTART, ADJ_IEND, ADJ_JSTART, ADJ_END, ADJ_KSTART, ADJ_KEND`

- **Forecast Accuracy Norm**: \( e = (x^f - x^t)^T C (x^f - x^t) \)
Implementation in WRF

*From Langland and Baker (2004)*

- **Forecast Error**
- **6 hr assimilation window**
- **xt** is the true state, estimated by the analysis at the time of the forecast
- **xf** is the forecast from analysis xa
- **xg** is the forecast from first-guess at the time of the analysis xa

**Impact of analysis:**

\[ F = \Delta e_{f,g} = e_f - e_g \]

**Products:**

\[ \frac{\delta F}{\delta x_f} = C(x_f - x^t) \]

\[ \frac{\delta F}{\delta x_a} = C(x_a - x^t) \]
Implementation in WRF

Observation \((y)\)

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Forecast \((x_f)\)

Define Forecast Accuracy

Forecast Accuracy \((F)\)

Observation Impact \(<y-H(x_b)> (\delta F/\delta y)\)

Adjoint of WRF-VAR Data Assimilation

Analysis Sensitivity \((\delta F/\delta x_a)\)

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Gradient of \(F (\delta F/\delta x_f)\)

Derive Forecast Accuracy

Observation Sensitivity \((\delta F/\delta y)\)

Background Sensitivity \((\delta F/\delta x_b)\)

Obs Error Sensitivity \((\delta F/\delta e_{ob})\)

Bias Correction Sensitivity \((\delta F/\delta \beta_k)\)
First order approximation:

\[ \delta x^f = m(x^0 + \delta x^0) - m(x^0) \approx M \delta x^0 \]

\[ \delta e \approx 2C(x^f - x^t) \cdot \delta x^f \approx 2C(x^f - x^t) \cdot M \delta x^0 \]

\[ \frac{\delta e}{\delta x^0} = M^T 2C(x^f - x^t) \]

\[ \frac{\delta F}{\delta y} \]

\[ \frac{\delta F}{\delta x^a} \]

\[ \frac{\delta F}{\delta x_b} \]

\[ \frac{\delta F}{\delta e_{ob}} \]

\[ \frac{\delta F}{\delta \beta_k} \]
First order approximation:
\[
\delta x^f = m(x^0 + \delta x^0) - m(x^0) \approx M \delta x^0
\]
\[
\delta e \approx 2C(x^f - x^t) \cdot \delta x^f \approx 2C(x^f - x^t) \cdot M \delta x^0
\]
\[
\delta e / \delta x^0 = M^T 2C(x^f - x^t)
\]

Relative error in WRF (linear vs. non-linear propagation of perturbation)
\[
\delta e_1 = 2(x_a - x_b)^T M_b^T C(x_a - x_b)
\]
\[
\delta e_2 = (x_a - x_b)^T [M_b^T C(x_a - x_b) + M_a^T C(x_b - x^t)]
\]
\[
\delta e_3 = (x_a - x_b)^T [M_b^T C(x_a - x_b) + M_a^T C(x_a - x^t)]
\]

Results are consistent with Gelaro et al. (2007)
Implementation in WRF

- Script variable `ADJ_MEASURE` defined as:
  1: first order
  2: second order
  3: third order
  4: variant of third order

- Use WRF+ code to compute WRF-ARW adjoint with Namelist `ADJ_SENS=true`:
  - Activate pressure in the adjoint
  - Switch off intermediate forcing

- WRF+ is run for both trajectories from $x_a$ and $x_b$

- Finally, both sensitivities are added together
Implementation in WRF
Implementation in WRF

- Analysis increments: $\delta x = x_a - x_b = K [y-H(x_b)] = K \delta y$
- Sensitivity of analysis to observations: $\delta x_a / \delta y = K^T$
- Adjoint of the variational analysis: $\delta F / \delta y = K^T \delta F / \delta x_a$
- New minimization package, activated with Namelist `USE_LANCZOS=true`

**Diagram:**

- **Observation Sensitivity** ($\delta F / \delta y$)
- **Background Sensitivity** ($\delta F / \delta x_b$)
- **Adjoint of WRF-VAR Data Assimilation**
- **Adjoint of WRF-ARW Forecast TL Model (WRF+)**
- **Gradient of $F$** ($\delta F / \delta x_f$)
- **Derive Forecast Accuracy**
- **Define Forecast Accuracy ($F$)**
- **Forecast Model**
- **Analysis** ($x_a$)
- **Forecast** ($x_f$)
- **Analysis increments:** $\delta x = x_a - x_b = K [y-H(x_b)] = K \delta y$
- **Sensitivity of analysis to observations:** $\delta x_a / \delta y = K^T$
- **Adjoint of the variational analysis:** $\delta F / \delta y = K^T \delta F / \delta x_a$
- **New minimization package, activated with Namelist USE_LANCZOS=true**
Implementation in WRF

- Analysis increments: \( \delta x = x_a - x_b = K [y-H(x_b)] = K d \)
- Sensitivity of analysis to observations: \( \delta x_a / \delta y = K^T \)
- Adjoint of the variational analysis: \( \delta F / \delta y = K^T \delta F / \delta x_a \)
- New minimization package activated with Namelist USE_LANCZOS=true

Cost Function and Gradient are IDENTICAL to Conjugate Gradient
- Lanczos estimates the Hessian = Inverse of Analysis error \( A^{-1} \)
- \( K^T = R^{-1} H A^{-1} \)
- We calculate the EXACT adjoint of analysis gain: \( K^T \)

\( < \delta x, \delta x > = < \delta x, K d> \) compared to \( <K^T \delta x, d> \) \( \longrightarrow 10^{-13} \) relative error
Implementation in WRF

Observation (y)

WRF-VAR Data Assimilation

Analysis (x_a)

WRF-ARW Forecast Model

Forecast (x_f)

Define Forecast Accuracy

Background (x_b)

Observation Impact <y - H(x_b)> (∂F/∂y)

Adjoint of WRF-VAR Data Assimilation

Analysis Sensitivity (∂F/∂x_a)

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Gradient of F (∂F/∂x_f)

Derive Forecast Accuracy

Observation Sensitivity (∂F/∂y)

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Obs Error Sensitivity (∂F/∂e_{ob})

Bias Correction Sensitivity (∂F/∂β_k)
Implementation in WRF

**Scripts:**

- **Analysis Experiment**
  - WRF-Var with Namelist ORTHONORM_GRADIENT=true

- **Trajectories**
  - WRFNL from $X_a$ and from $X_b$

- **Forecast Accuracy**
  - ADJ_REF to choose reference for forecast accuracy
  - ADJ_ISTART, ADJ_IEND, etc. to define a box

- **Adjoint of Model**
  - ADJ_MEASURE to select order of Taylor expansion
  - WRF+ (Adjoint mode) with Namelist ADJ_SENS=true

- **Adjoint of Analysis**
  - RUN_OBS_IMPACT=true launches WRF-Var with Lanczos
Applications

One-month 6-hr cycling experiment (20070815 – 20070915)

Impact evaluated for 6hr forecast in d02 domain
Applications
Applications
Applications
Applications

AMSU-A Observations Have the Greatest Benefit at all Three Centers.

from Gelaro et al. 2009
Applications

**NAVDAS-AR Results**

**Aug27-Sep02, 2008**

**Sep16-Sep22, 2008**

Revise channels & Implement ECMWF advanced cloud screening

change in error (J/kg)

from Langland 2009
Applications

Observation Impacts for NOAA-18 AMSU-A Ch. 7

Observations that produce large forecast error reductions

Observations that produce forecast error increases in both models

Land or ice surface contamination of radiance data?

Baseline Intercomparison Jan 2007 00+06 UTC

from Gelaro 2009
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Limitations

- Uncertainties are difficult to estimate
  - The reference for the calculation of forecast accuracy is NOT perfect and often correlated with the initial analysis.

- The adjoint model is not an accurate representation of the NL model behavior (linearization, simplification, dry physics). Langland (2009) proposes a method to mitigate these errors.

- For higher than first-order approximation of de, nonlinear dependence on dy, which complicates the separation of observation impact (Errico 2007). These errors are small for the calculation of average impact (Gelaro et al. 2007).
Limitations

- Results are strongly dependent on the norm chosen to define forecast accuracy.

- The interpretation of information and application is not always straightforward.
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Conclusions

- All code and scripts for FSO are available in current WRF public release

- Testing package & User’s Guide available on demand

**DISCLAIMER**

Due to lack of funding, no support is to be expected ;-(

- Have fun!