Forecast Sensitivity to Observations & Observation Impact

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Outline

- Introduction
- Implementation in WRF
- Applications
- Limitations
- Conclusions
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- Introduction
- 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)
Non-Linear (NL) forecast models can be linearized (with simplifications).

The resulting **Tangent-Linear** (TL) represents the linear evolution of small **perturbations**.

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

The ADJ of the Data Assimilation system is needed to compute the sensitivity to observations. 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.
Outline

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

Task: “Develop adjoint of WRF-Var’s minimization algorithm, additional I/O, and couple with 4D-Var’s adjoint of the ARW forecast model, to create a diagnostic tool for evaluating observation/analysis impact on forecast accuracy”
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

Forecast Accuracy $(F)$

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

Adjoint of WRF-VAR Data Assimilation

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

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

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

Derive Forecaest Accuracy

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

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

Figure adapted from Liang Xu (NRL)
Implementation in WRF

**Observation** (\(y\)) \rightarrow \text{WRF-VAR Data Assimilation} \rightarrow \text{WRF-ARW Forecast Model} \rightarrow \text{Define Forecast Accuracy}

**Background** (\(x_b\)) \rightarrow \text{WRF-VAR Data Assimilation} \rightarrow \text{Adjoint of WRF-ARW Forecast TL Model (WRF+)} \rightarrow \text{Derive Forecast Accuracy}

**Analysis** (\(x_a\)) \rightarrow \text{WRF-ARW Forecast Model} \rightarrow \text{Gradient of } F (\frac{\partial F}{\partial x_f})

**Observation Impact** \(<y-H(x_b)> (\frac{\partial F}{\partial y})\)

**Observation Sensitivity** (\(\frac{\partial F}{\partial y}\)) \rightarrow \text{Adjoint of WRF-VAR Data Assimilation}

**Background Sensitivity** (\(\frac{\partial F}{\partial x_b}\)) \rightarrow \text{Adjoint of WRF-VAR Data Assimilation}

**Analysis Sensitivity** (\(\frac{\partial F}{\partial x_a}\)) \rightarrow \text{Adjoint of WRF-ARW Forecast TL Model (WRF+)}

**Obs Error Sensitivity** (\(\frac{\partial F}{\partial \epsilon_{ob}}\)) \rightarrow \text{Adjoint of WRF-VAR Data Assimilation}

**Bias Correction Sensitivity** (\(\frac{\partial F}{\partial \beta_k}\)) \rightarrow \text{Adjoint of WRF-VAR Data Assimilation}
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

- Usual WRF-Var 3DVar or 4DVar data assimilation system
- Namelist parameter needs to be activated: \texttt{ORTHONORM\_GRADIENT=true}

Observation Impact

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

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

Adjoint of TL Model (WRF+)

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

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

Obs Error Sensitivity $(\partial F/\partial \epsilon_{ob})$
Implementation in WRF

Observation \( (y) \) \rightarrow WRF-VAR Data Assimilation \rightarrow Analysis \( (x_a) \) \rightarrow WRF-ARW Forecast Model \rightarrow Forecast \( (x_f) \) \rightarrow Define Forecast Accuracy

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

Observation Sensitivity \( (\partial F/\partial y) \) \rightarrow Adjoint of WRF-VAR Data Assimilation

Background Sensitivity \( (\partial F/\partial x_b) \) \rightarrow Adjoint of WRF-ARW Forecast TL Model (WRF+)

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

Gradient of \( F \) \( (\partial F/\partial x_f) \) \rightarrow Derive Forecast Accuracy

Obs Error Sensitivity \( (\partial F/\partial \varepsilon_{ob}) \)

Bias Correction Sensitivity \( (\partial F/\partial \beta_k) \)
Implementation in WRF

- WRF ARW forecast
- Forecast length is set to reach verification time
- Use WRFNL code to write \textit{trajectory} for adjoint run
Implementation in WRF

Observation \((y)\)

WRF-VAR Data Assimilation

Analysis \((x_a)\)

WRF-ARW Forecast Model

Forecast \((x_f)\)

Define Forecast Accuracy

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

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

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

Adjoint of WRF-VAR Data Assimilation

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

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

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

Derive Forecast Accuracy

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

Bias Correction Sensitivity \((\partial F/ \partial \beta_k)\)
Implementation in WRF

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

- **Forecast Aspect:** depends on reference state
  - 1 and 2: Total Dry Energy
  - 3: WRFVar Observation Cost Function: \( J_0 \)

- **Geo. projection:** Script option for box (default = whole domain)
  \( ADJ\_ISTART, ADJ\_IEND, ADJ\_JSTART, ADJ\_JEND, ADJ\_KSTART, ADJ\_KEND \)

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

**Define Forecast Accuracy**

**Forecast Accuracy (F)**

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

**Derive Forecast Accuracy**
**Implementation in WRF**

From Langland and Baker (2004)

**Observation** ($y$)
**WRF-V AR**
**Data Assimilation**
**WRF-ARW**
**Forecast** ($x_f$)

**Define Forecast Accuracy**

**Forecast Accuracy** ($F$)

**Derive Forecast Accuracy**

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

$x^t$ is the true state, estimated by the analysis at the time of the forecast.
$x^f$ is the forecast from analysis $x^a$
$x^g$ is the forecast from first-guess at the time of the analysis $x^a$

**Impact of analysis**: $F = \Delta e^{f,g} = e^f - e^g$

**Products**: $\delta F/\delta x^a_f = C(x^a_f - x^t)$
$\delta F/\delta x^b_f = C(x^b_f - x^t)$

**Observation Impact**: $<y-H(x^b)>$ ($\partial F/\partial y$)

**Adjoint of WRF-V AR Data Assimilation**

**Obs Error Sensitivity** ($\partial F/\partial \epsilon_{ob}$)

**Background Sensitivity** ($\partial F/\partial x^b$)

**Background Sensitivity** ($\partial F/\partial x^a$)

6 hr assimilation window

$t=-6$ hrs  $t=0$  $t=24$ hrs
Implementation in WRF

Observation \((y)\)

WRF-VAR Data Assimilation

Analysis \((x_a)\)

WRF-ARW Forecast Model

Forecast \((x_f)\)

Define Forecast Accuracy

Forecast Accuracy \((F)\)

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

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

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

Derive Forecast Accuracy

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

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

Obs Error Sensitivity \((\partial F/ \partial \varepsilon_{ob})\)

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

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

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

\[ \delta e / \delta x^0 = M^T 2C(x^f - x^0) \]
Implementation in WRF

First order approximation:

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

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

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

Relative error in WRF (linear vs. non-linear propagation of perturbation)

\[
\delta e_1 = 2(x_a - x_b)^T M^T_b C(x_a^f - x^t)
\]

\[
\delta e_2 = (x_a - x_b)^T [M^T_b C(x_a^f - x^t) + M^T_a C(x_b^f - x^t)]
\]

\[
\delta e_3 = (x_a - x_b)^T [M^T_b C(x_a^f - x^t) + M^T_a C(x_a^f - x^t)]
\]

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

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 \((\delta F/\delta y)\)

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

Adjoint of WRF-VAR Data Assimilation

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

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

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

Derive Forecast Accuracy

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

Bias Correction Sensitivity \((\delta F/\delta \beta_k)\)
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
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: $K^T$

$$< \delta x, \delta x > = < \delta x, K d> \text{ compared to } <K^T \delta x, d> \longrightarrow 10^{-13} \text{ relative error}$$
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**

**Forecast Accuracy** ($F$)

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

**Derive 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** ($\delta F / \delta x_b$)

- **Adjoint of WRF-ARW Forecast TL Model (WRF+)**
- **Analysis Sensitivity** ($\delta F / \delta x_a$)

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

- **Obs Error Sensitivity** ($\delta F / \delta \epsilon_{ob}$)
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
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Impact of METAR data on forecast error
Applications

Conventional Observations

Satellite Radiances

Total

per obs
Applications

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

from Gelaro et al. 2009
Applications

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 and represent.
  - 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 will be available in next WRF public release.
- A small User’s Guide will be provided.
- Due to lack of funding, no support to be expected ;-((
- Have fun!