UCAR

UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

Forecast Sensitivity to Observations & Observation Impact

Tom Auligné

National Center for Atmospheric Research

Acknowledgments: Xin Zhang, Hongli Wang, Anwei Lai, Xiaoyan Zhang, Yansong Bao, Zhiquan Liu, Hui-Chuan Lin, Xiang-Yu Huang, Qingnong Xiao

WRFDA Tutorial – July 23-25 2012

UCAR
UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

Outline

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

Outline

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

Introduction

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

UCAR
UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

Introduction

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

- *A posteriori*, it is possible to evaluate the accuracy of NWP forecasts.
- Using an adjoint technique, we can trace it back to the observations used in the analysis.
- We can determine quantitatively which observations improved 🙂 or degraded 😠 the forecast.
- Forecast Sensitivity to Observations (FSO) is a diagnostic tool that complements traditional denial experiments (OSEs).

UCAR
UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

Introduction

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

- Impact of each observation calculated simultaneously (less tedious than OSEs).
- NWP centers use FSO routinely to monitor their Data Assimilation and Global Observing System
- Can be used to tune Quality Control, Bias Correction, etc.
- Helps assess the impact of specific sensors for data providers.

UCAR
UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

Introduction

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

- Naval Research Laboratory (Monterey, CA)
- NASA/GMAO (Washington, DC)
- ECMWF (Reading, UK)
- Environment Canada (Montreal, Canada)
- Meteo-France (Toulouse, France)
- NCAR/MMM (Boulder, CO)

Introduction

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

- 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)

UCAR

UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

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.

This page is left blank intentionally.

Outline

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

Implementation in WRF

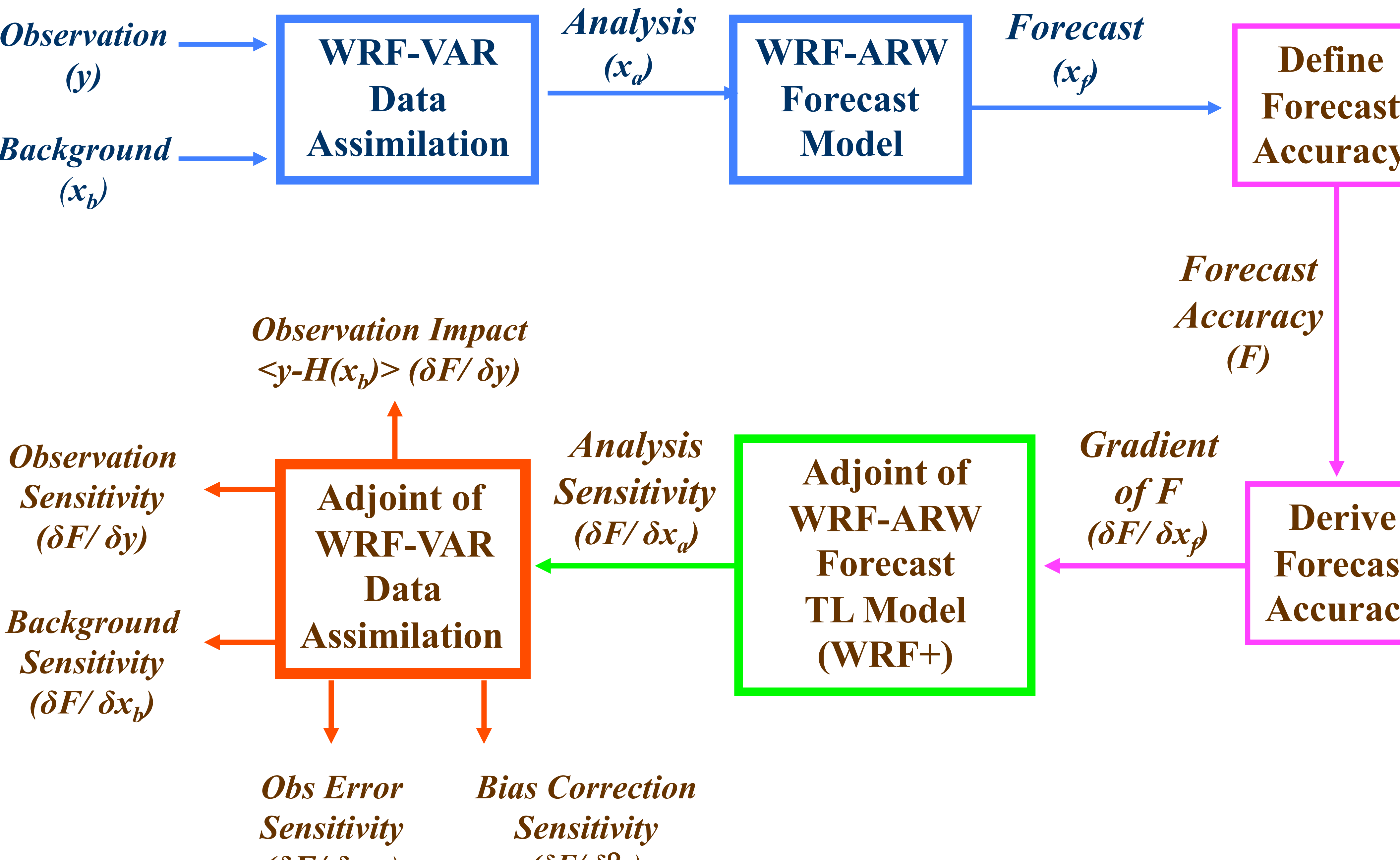
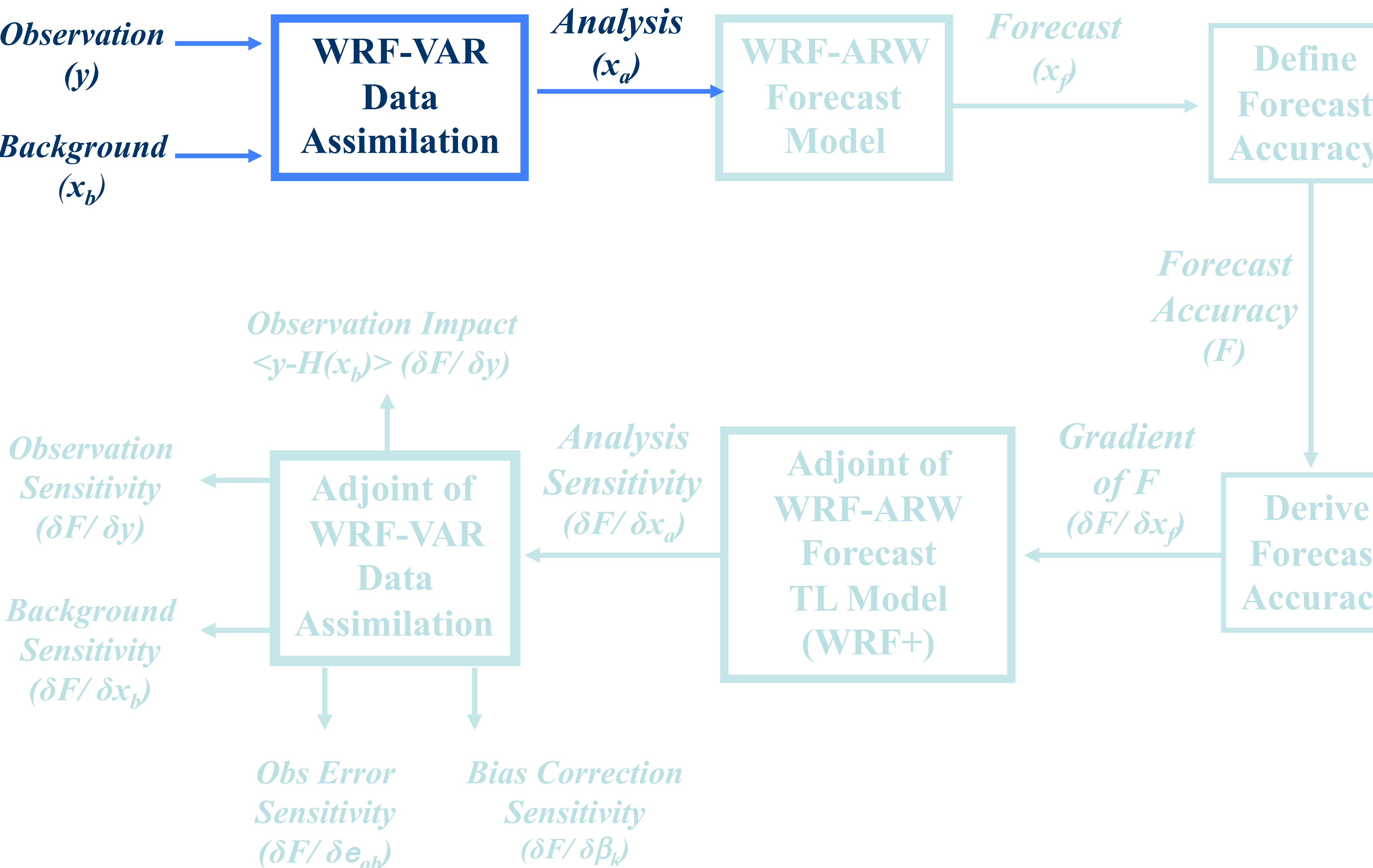
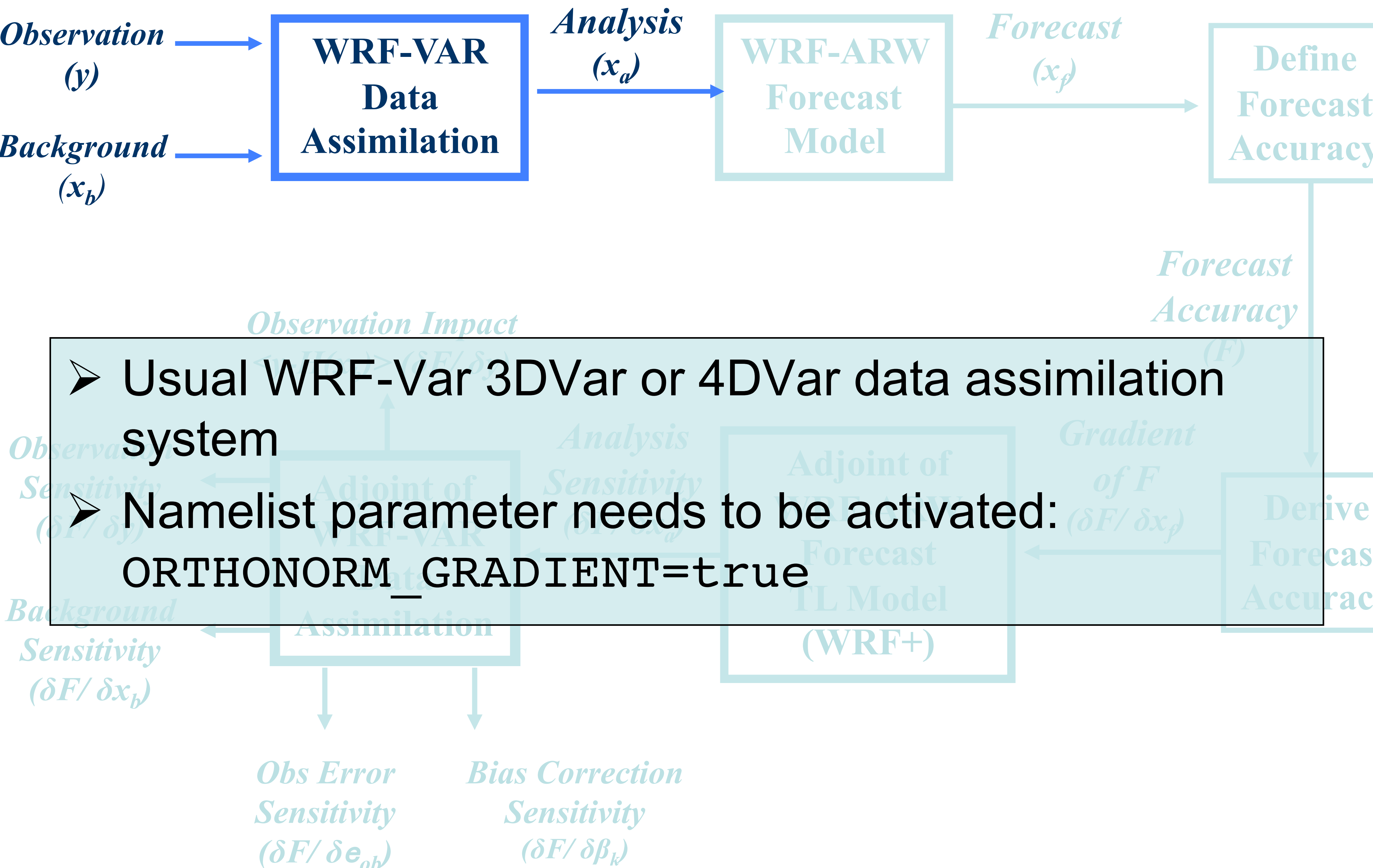


Figure adapted from Liang Xu (NR

Implementation in WRF

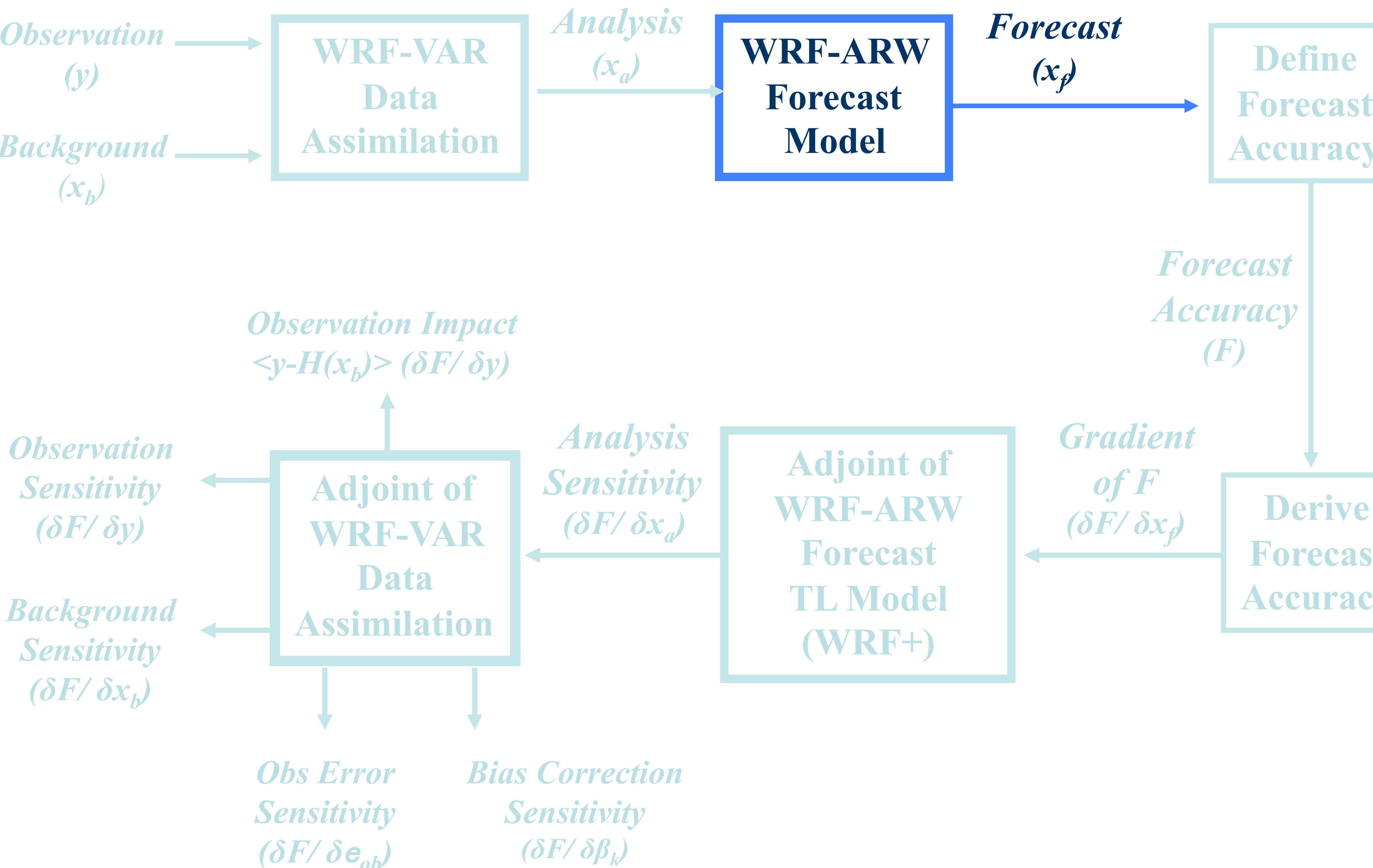


Implementation in WRF

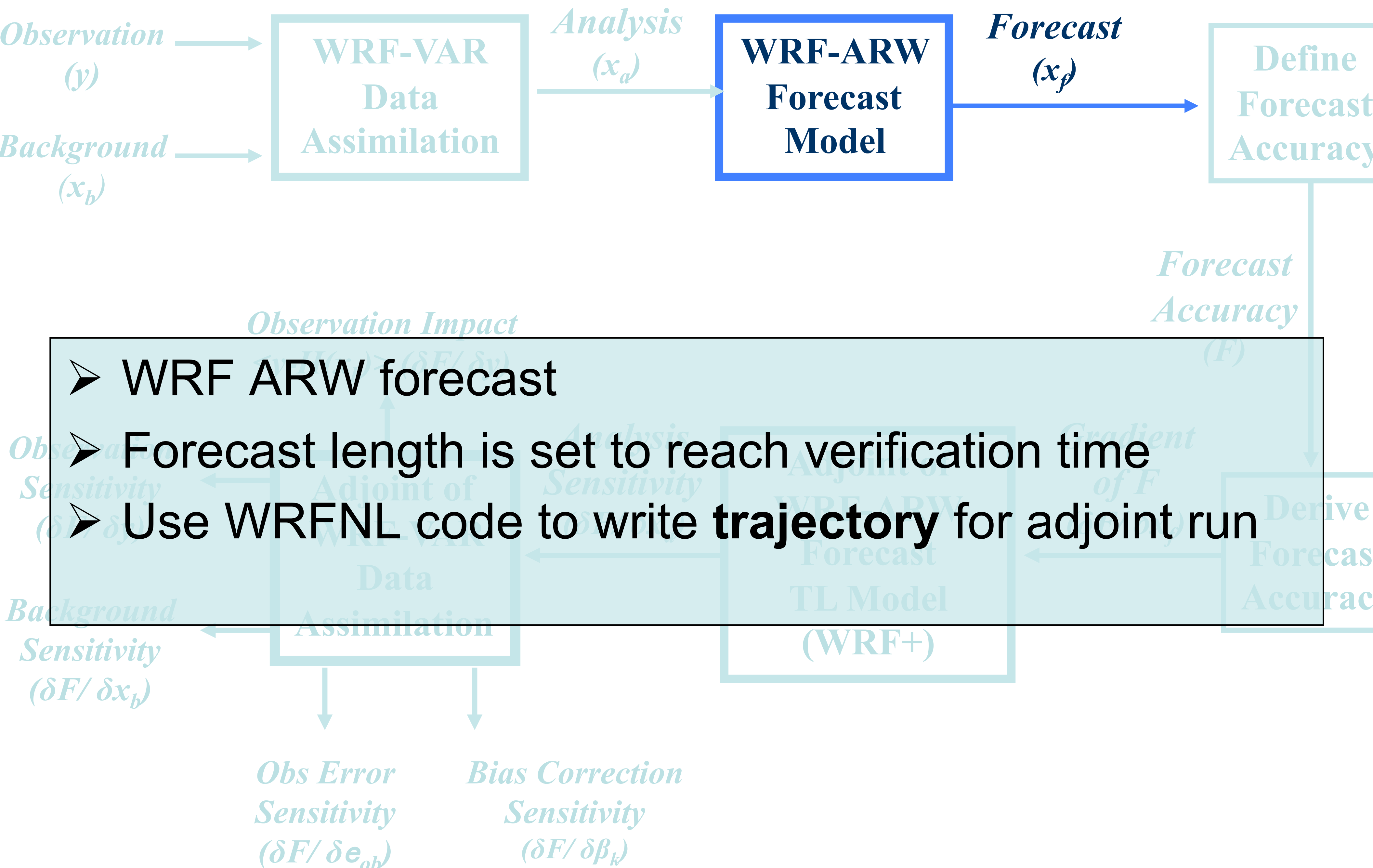


- Usual WRF-Var 3DVar or 4DVar data assimilation system
- Namelist parameter needs to be activated: `ORTHONORM_GRADIENT=true`

Implementation in WRF

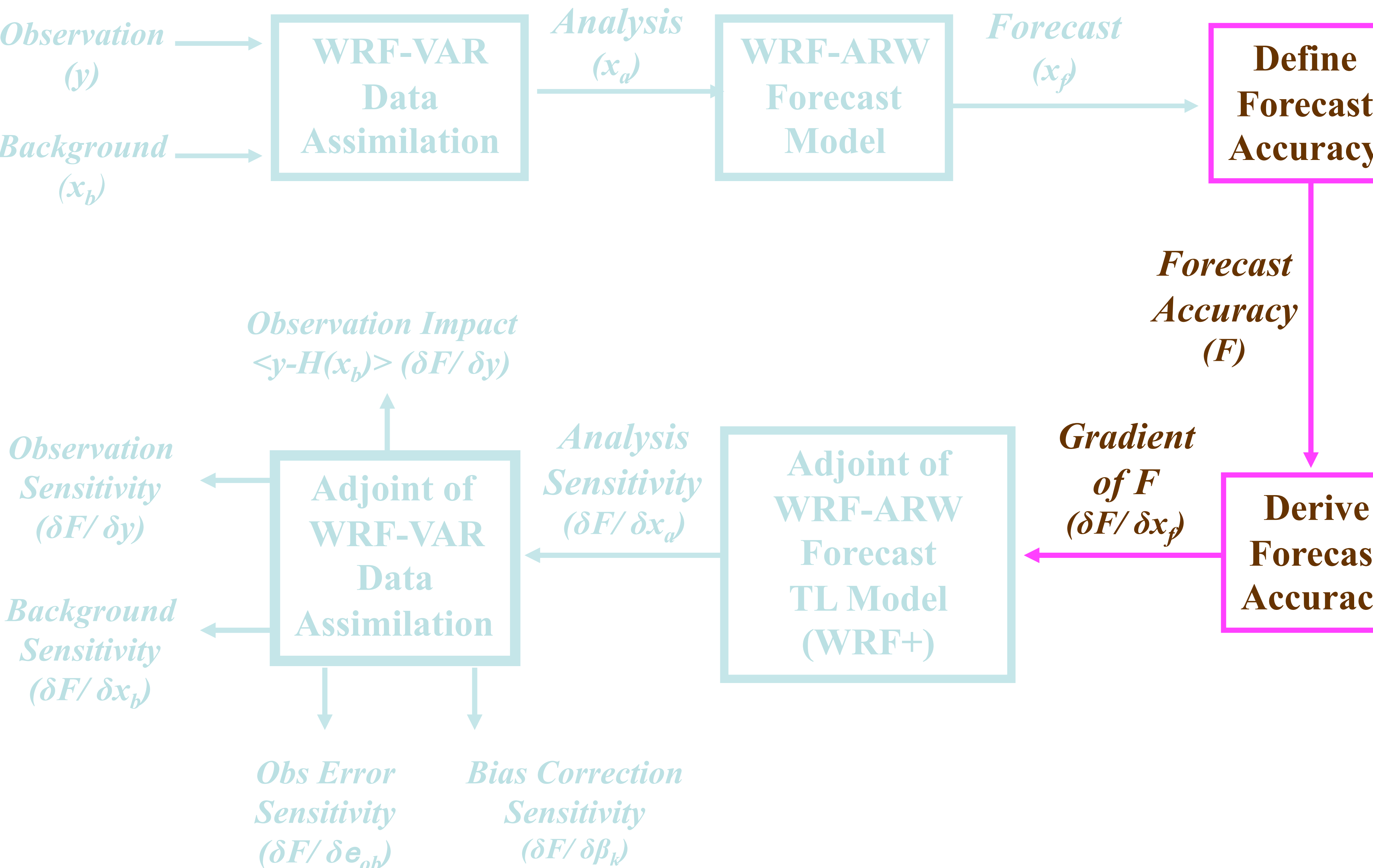


Implementation in WRF



- WRF ARW forecast
- Forecast length is set to reach verification time
- Use WRFNL code to write **trajectory** for adjoint run

Implementation in WRF



UCAR
UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

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

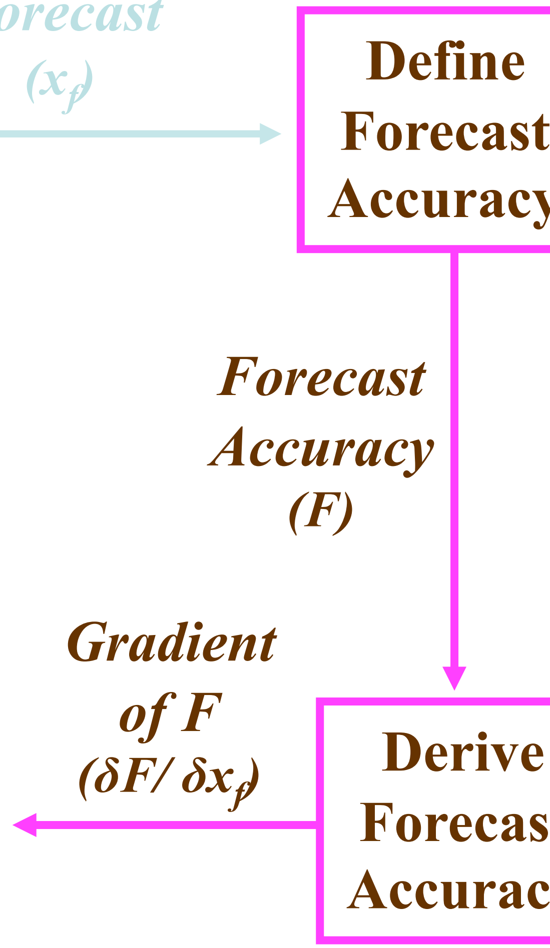
- **Forecast Aspect:** depends on reference state
  - 1 and 2: Total Dry Energy

$$<\mathbf{x},\mathbf{x}> = \frac{1}{2}\iiint_{\Sigma}[u'^2 + v'^2 + \left(\frac{g}{\bar{N}\bar{\theta}}\right)^2 \theta'^2 + \left(\frac{1}{\bar{\rho}c_s}\right)^2 p'^2]d\Sigma$$

  - 3: WRFVar Observation Cost Function: J_o

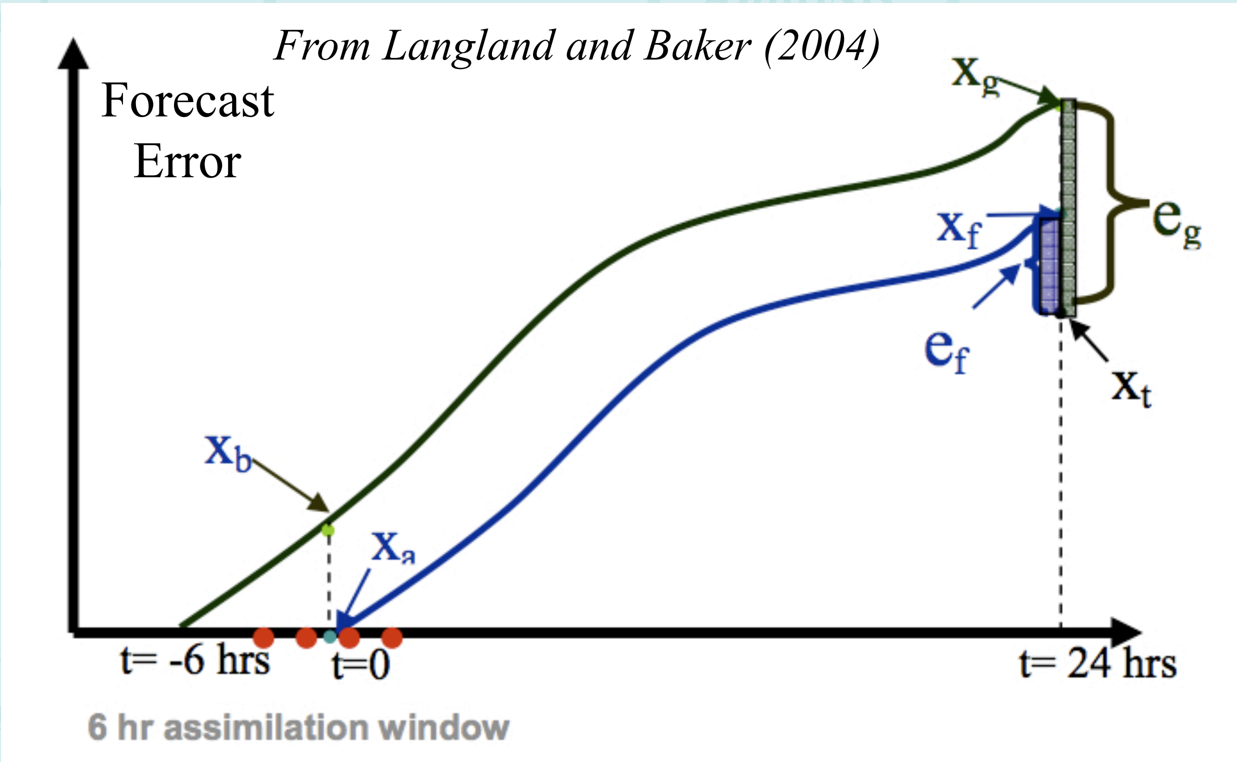
- **Geo. projection:** Script option for box (default = whole domain)
  ADJ_ISTART, ADJ_IEND, ADJ_JSTART, ADJ_END, ADJ_KSTART, ADJ_KEND

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



UCAR
UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

Implementation in WRF



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: $F = De^{f,g} = e^f - e^g$

Products: $\delta F/\delta x_a{}^f = C(x_a{}^f - x^t)$

$\delta F/\delta x_b{}^f = C(x_b{}^f - x^t)$

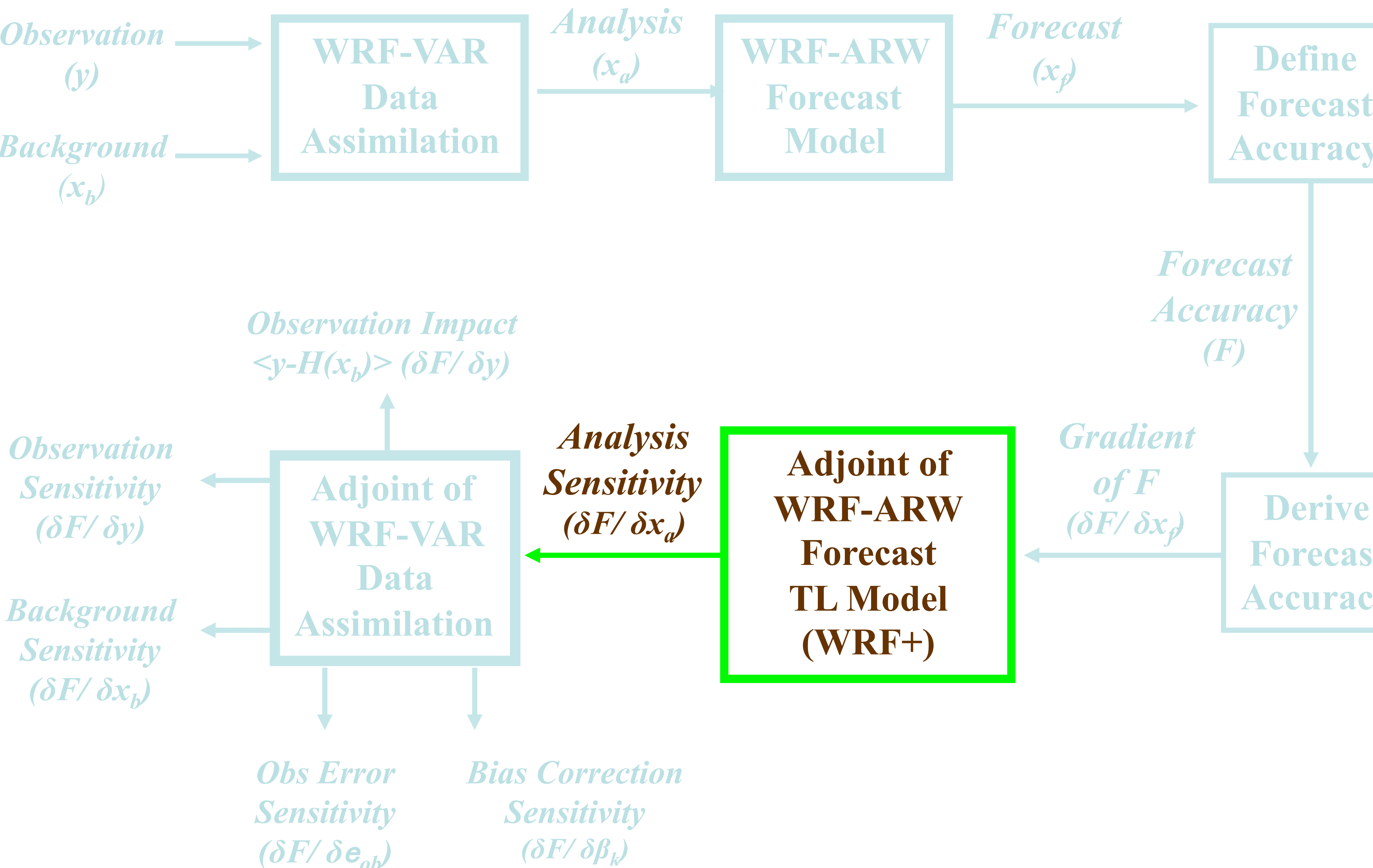
Define Forecast Accuracy

Forecast Accuracy (F)

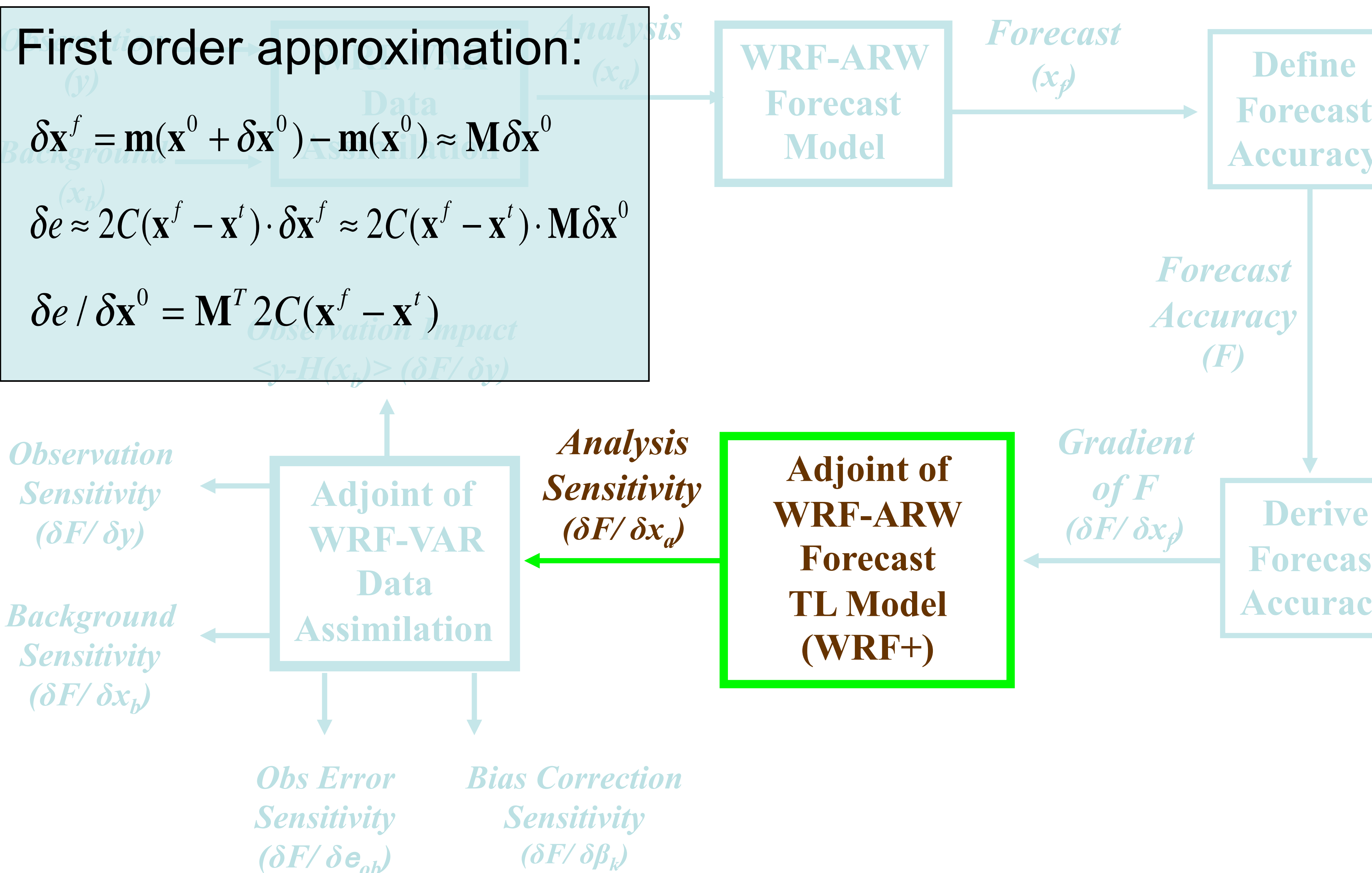
Derive Forecast Accuracy

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

Implementation in WRF



Implementation in WRF



First order approximation:

$$\delta \mathbf{x}^f = \mathbf{m}(\mathbf{x}^0 + \delta \mathbf{x}^0) - \mathbf{m}(\mathbf{x}^0) \approx \mathbf{M}\delta \mathbf{x}^0$$

$$\delta e \approx 2C(\mathbf{x}^f - \mathbf{x}^t) \cdot \delta \mathbf{x}^f \approx 2C(\mathbf{x}^f - \mathbf{x}^t) \cdot \mathbf{M}\delta \mathbf{x}^0$$

$$\delta e / \delta \mathbf{x}^0 = \mathbf{M}^T 2C(\mathbf{x}^f - \mathbf{x}^t)$$

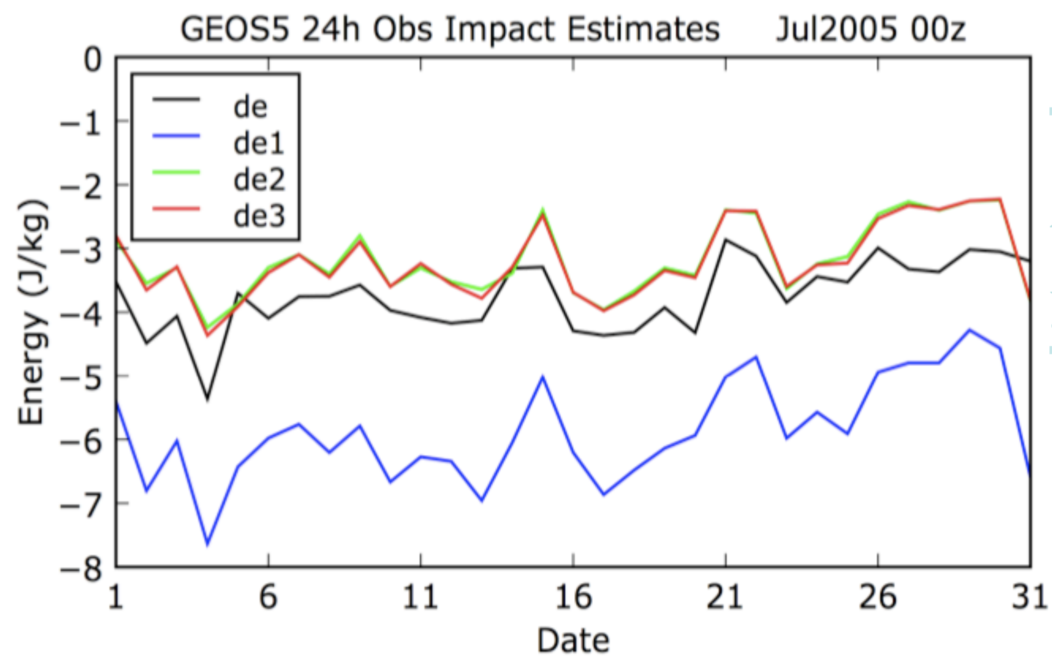
Implementation in WRF

First order approximation:

$$\delta \mathbf{x}^f = \mathbf{m}(\mathbf{x}^0 + \delta \mathbf{x}^0) - \mathbf{m}(\mathbf{x}^0) \approx \mathbf{M}\delta \mathbf{x}^0$$

$$\delta e \approx 2C(\mathbf{x}^f - \mathbf{x}^t)\cdot \delta \mathbf{x}^f \approx 2C(\mathbf{x}^f - \mathbf{x}^t)\cdot \mathbf{M}\delta \mathbf{x}^0$$

$$\delta e / \delta \mathbf{x}^0 = \mathbf{M}^T 2C(\mathbf{x}^f - \mathbf{x}^t)$$



Gelaro et al. (2007)

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

$$\delta e_1 = 2(\mathbf{x}_a - \mathbf{x}_b)^T \mathbf{M}_b^T C(\mathbf{x}_a^f - \mathbf{x}^t)$$ -----------------------> 62.25%

$$\delta e_2 = (\mathbf{x}_a - \mathbf{x}_b)^T [\mathbf{M}_b^T C(\mathbf{x}_a^f - \mathbf{x}^t) + \mathbf{M}_a^T C(\mathbf{x}_b^f - \mathbf{x}^t)]$$ ---------> 19.68%

$$\delta e_3 = (\mathbf{x}_a - \mathbf{x}_b)^T [\mathbf{M}_b^T C(\mathbf{x}_b^f - \mathbf{x}^t) + \mathbf{M}_a^T C(\mathbf{x}_a^f - \mathbf{x}^t)]$$ -----------> 11.45%

Results are consistent with Gelaro et al. (2007)

UCAR
UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

Implementation in WRF

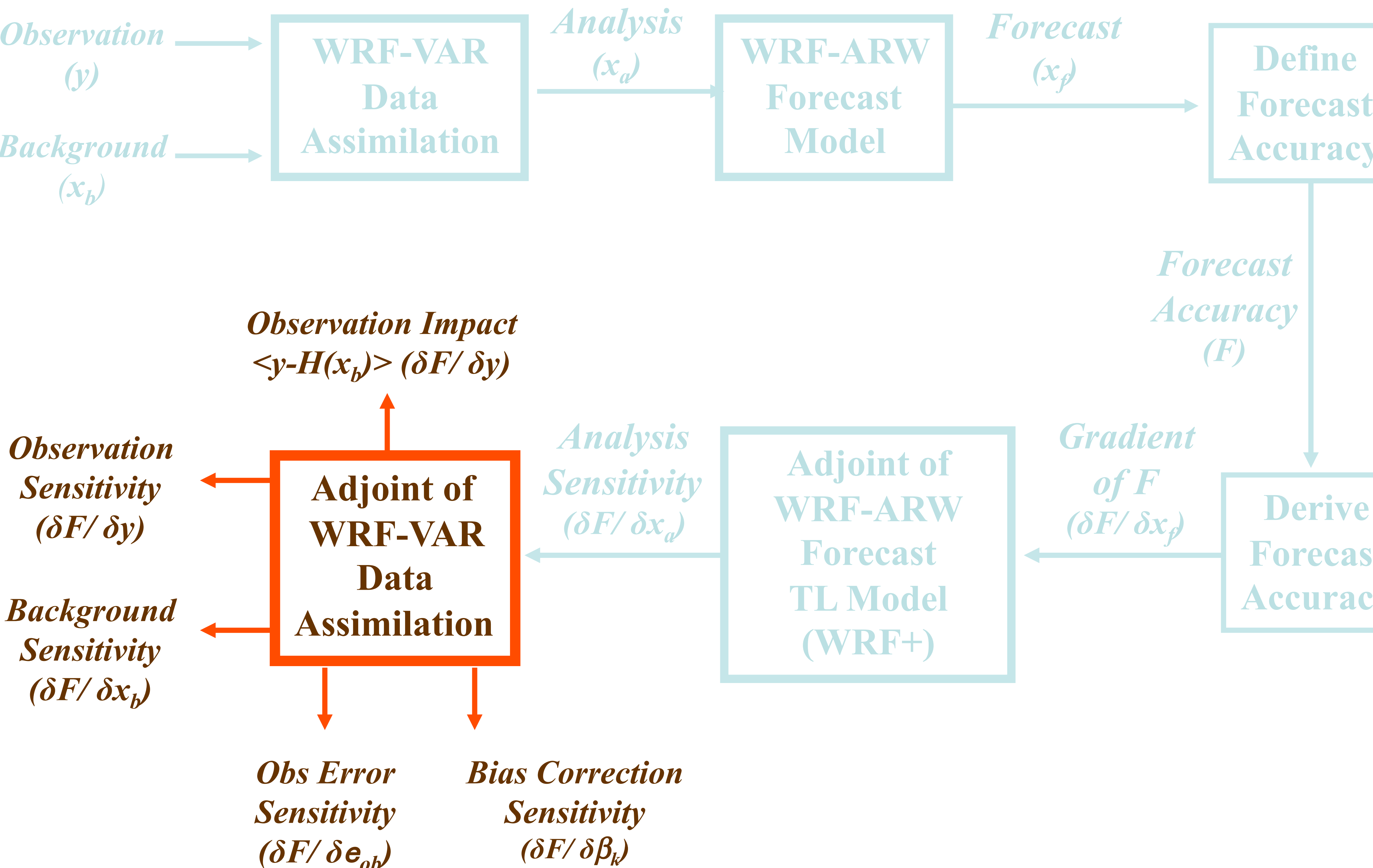
- Script variable `ADJ_MEASURE` defined as:
  - 1: first order
  - 2: second order
  - 3: third order
  - 4: variant of third order

- 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

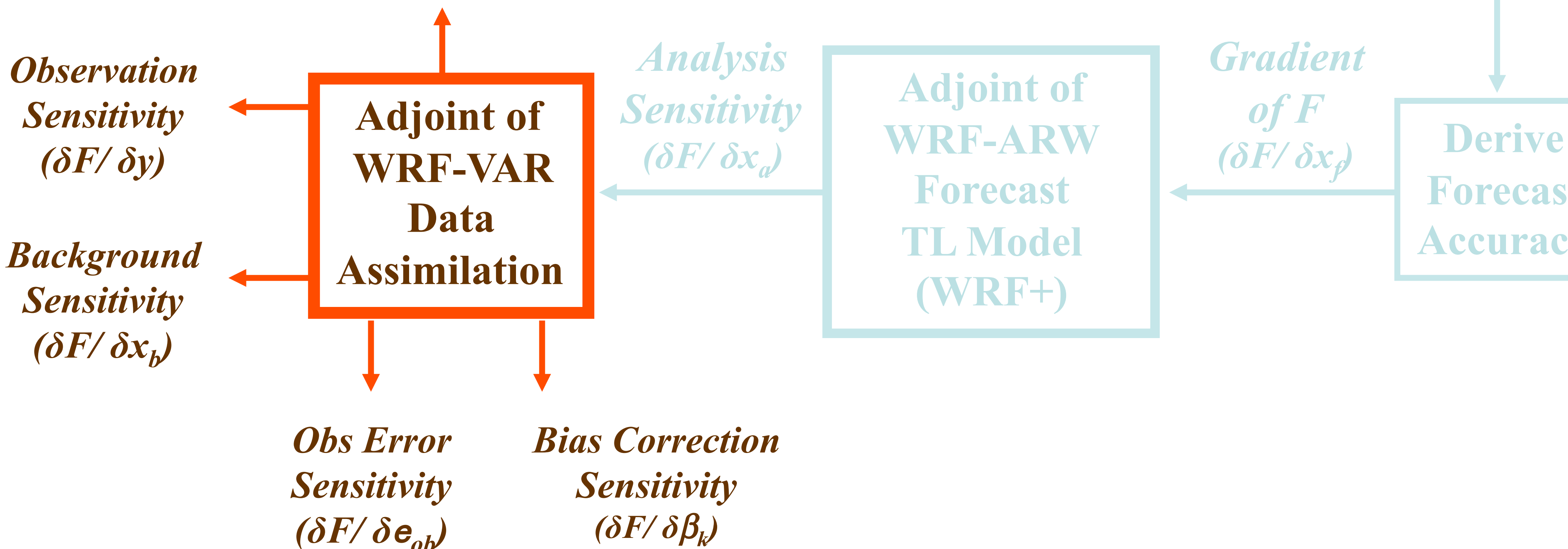
- Finally, both sensitivities are added together

Implementation in WRF



Implementation in WRF

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



Implementation in WRF

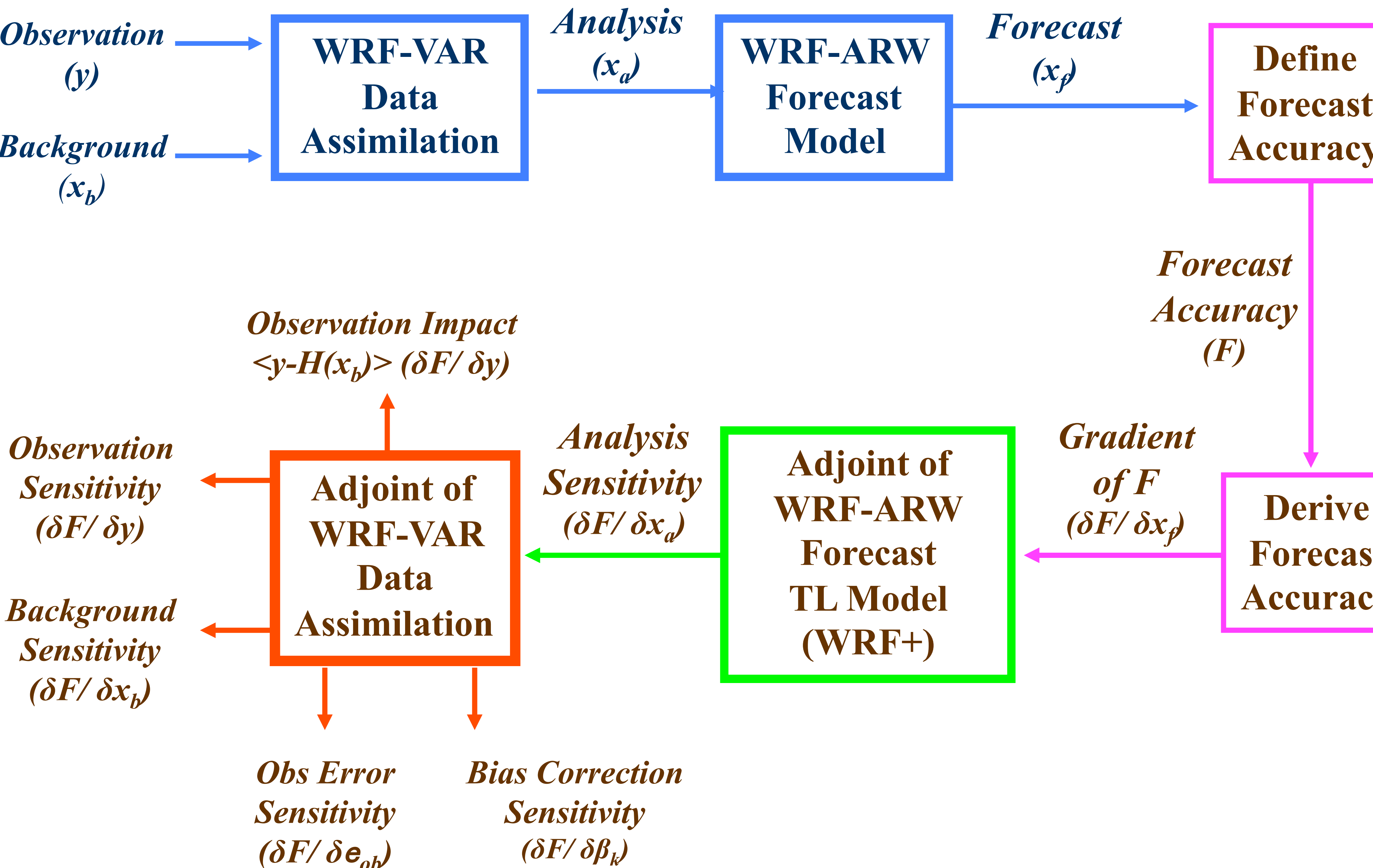
- Analysis increments: $\delta x = x_a - x_b = \mathbf{K}\,[y-H(x_b)] = \mathbf{K}\,d$
- Sensitivity of analysis to observations: $\delta x_a / \delta y = \mathbf{K}^T$
- Adjoint of the variational analysis: $\delta F/\delta y = \mathbf{K}^T\,\delta F/\delta x_a$
- New minimization package activated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

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

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

UCAR
UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

Implementation in WRF



UCAR
UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

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

UCAR
UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

Outline

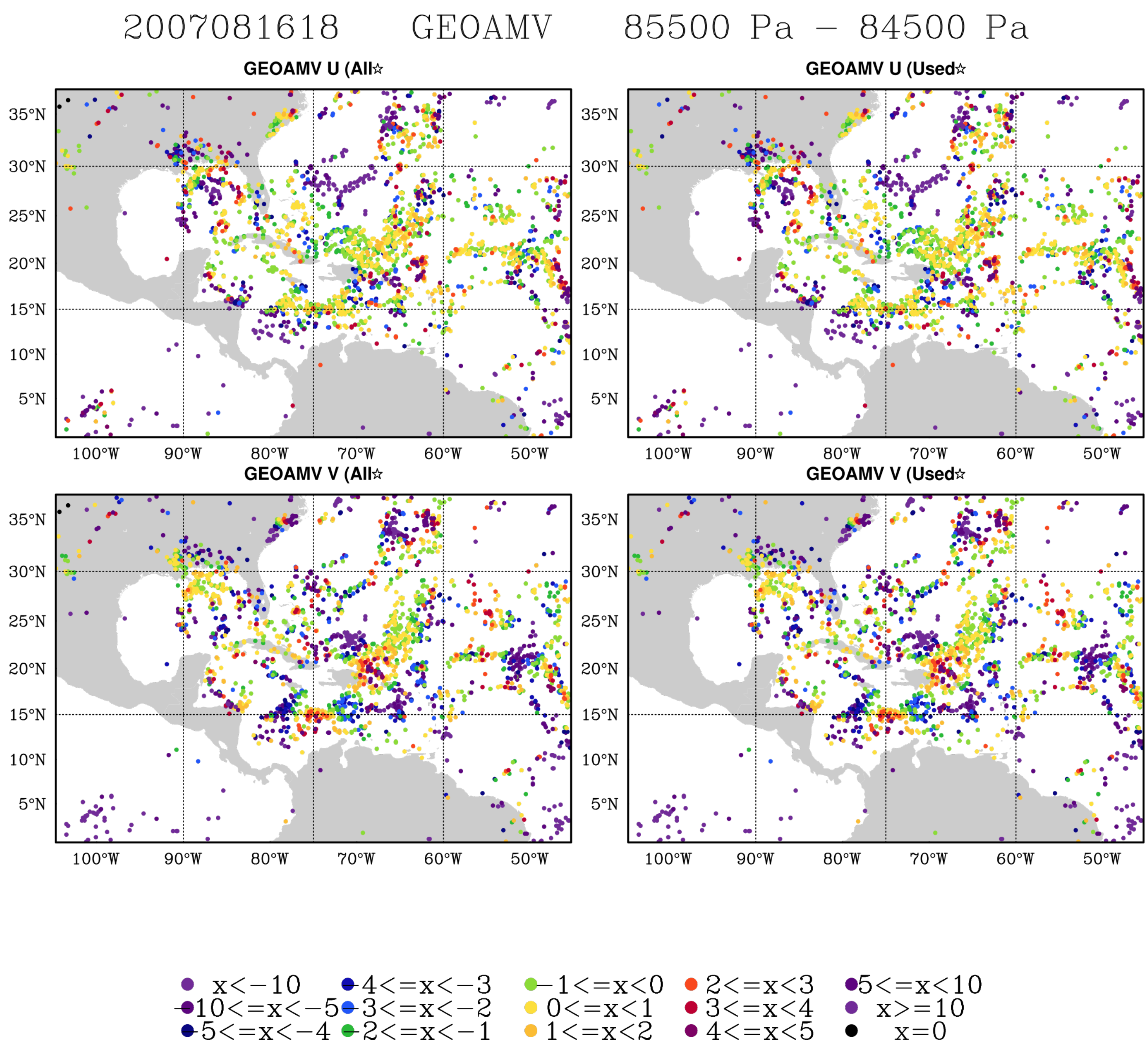
- Introduction
- Implementation in WRF
- Applications
- Limitations
- Conclusions

Applications

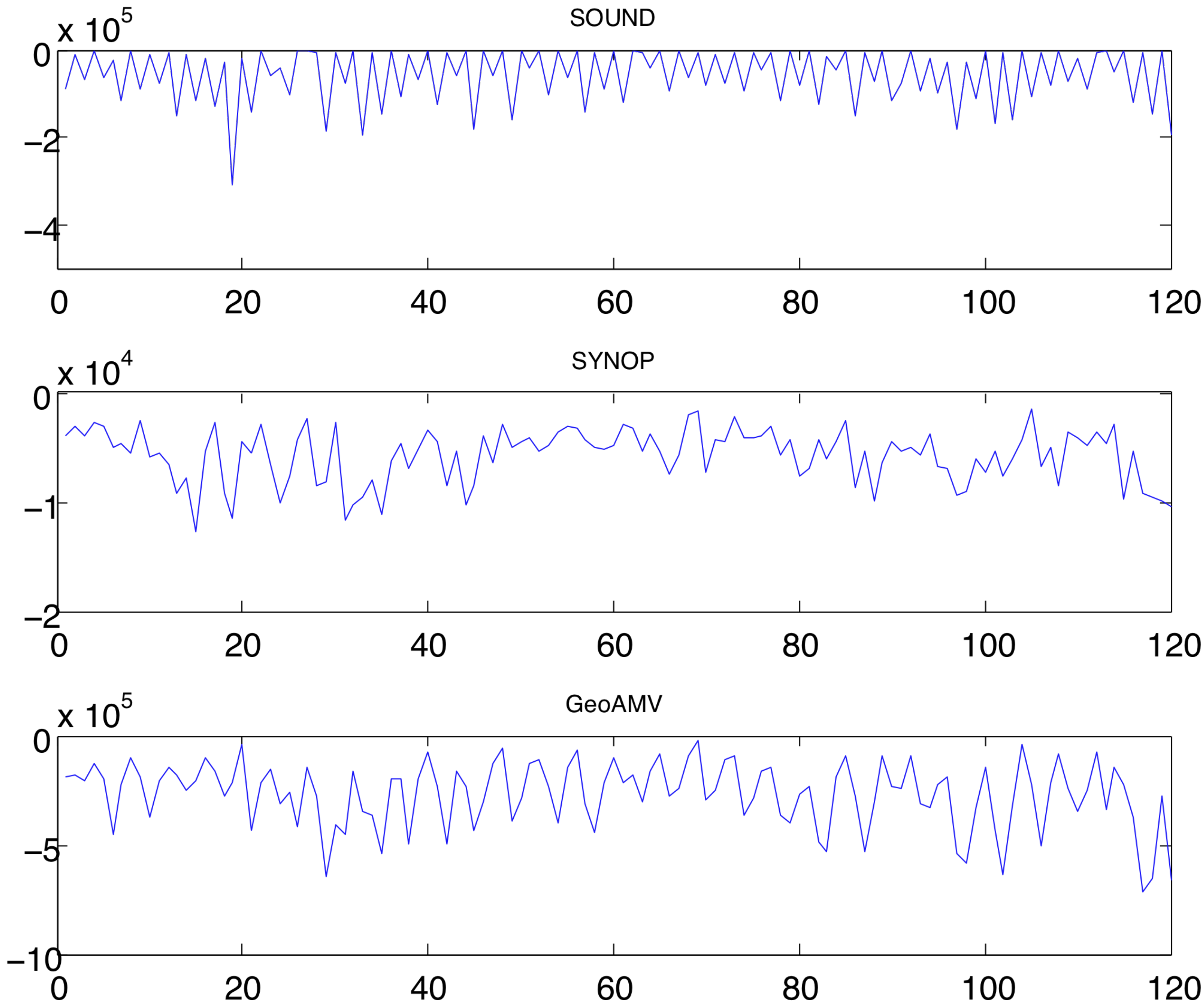
One-month 6-hr cycling experiment (20070815 – 2070915)

Impact evaluated for 6hr forecast in d02 domain

Applications

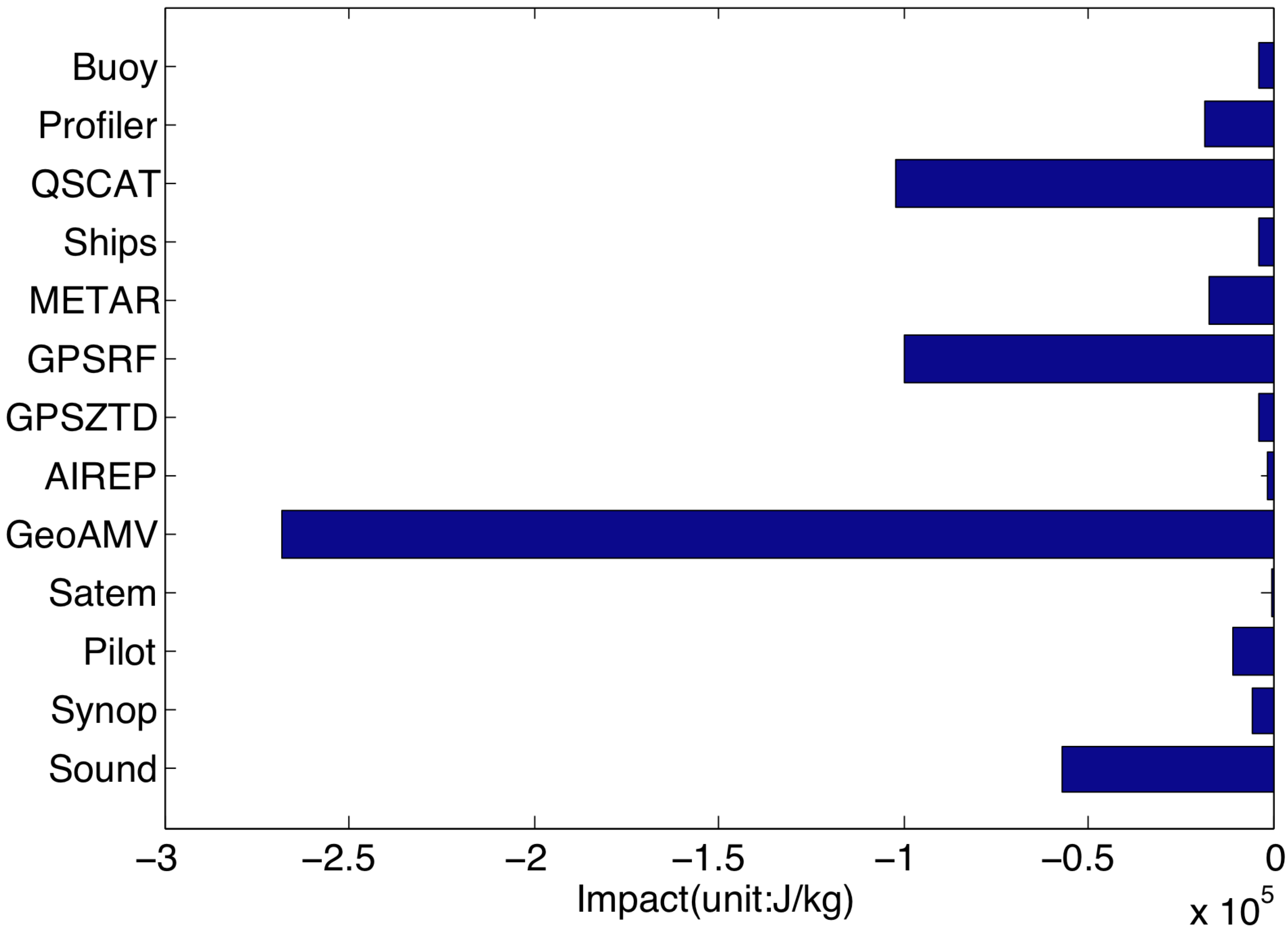


Applications

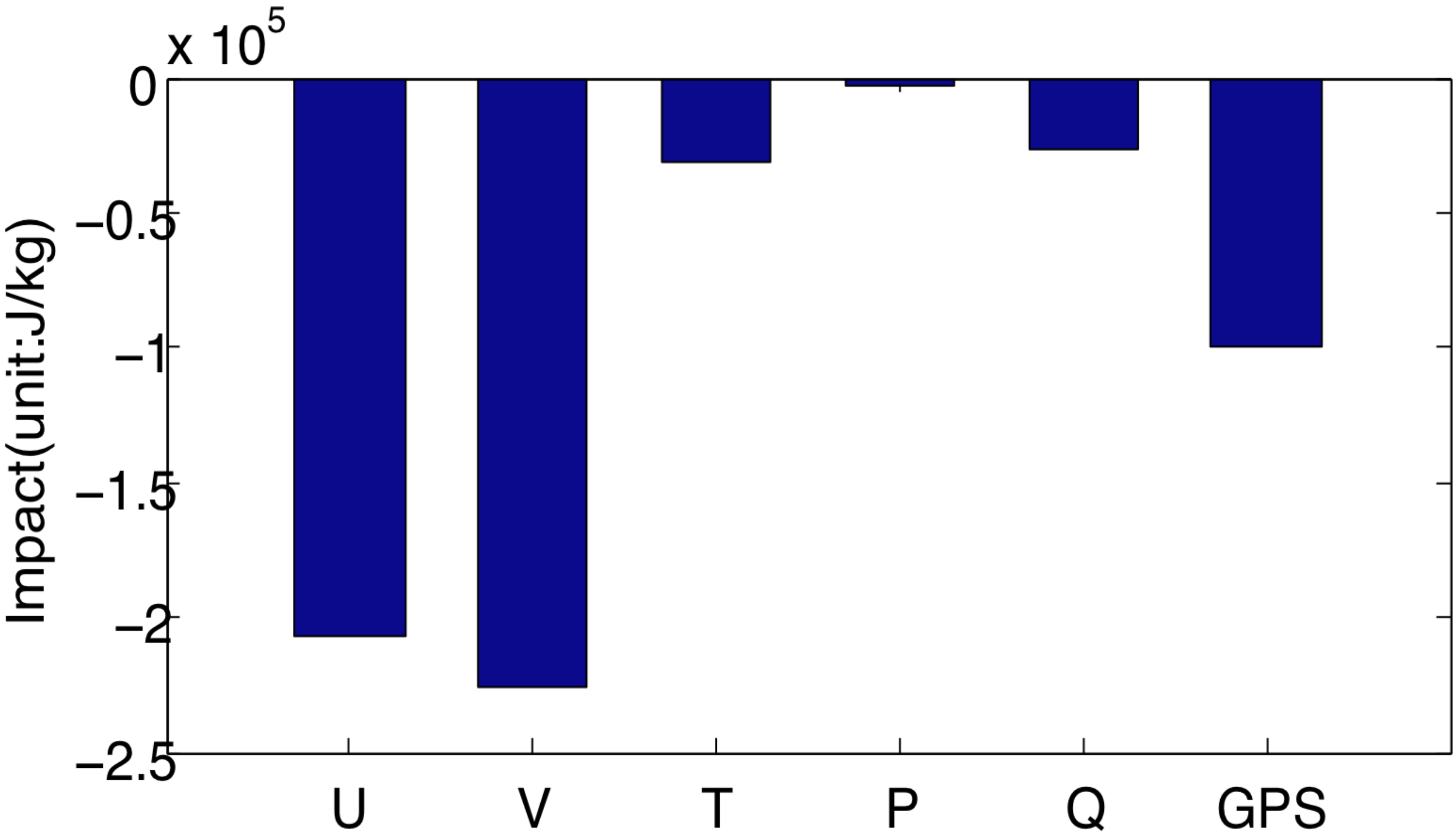


UCAR
UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

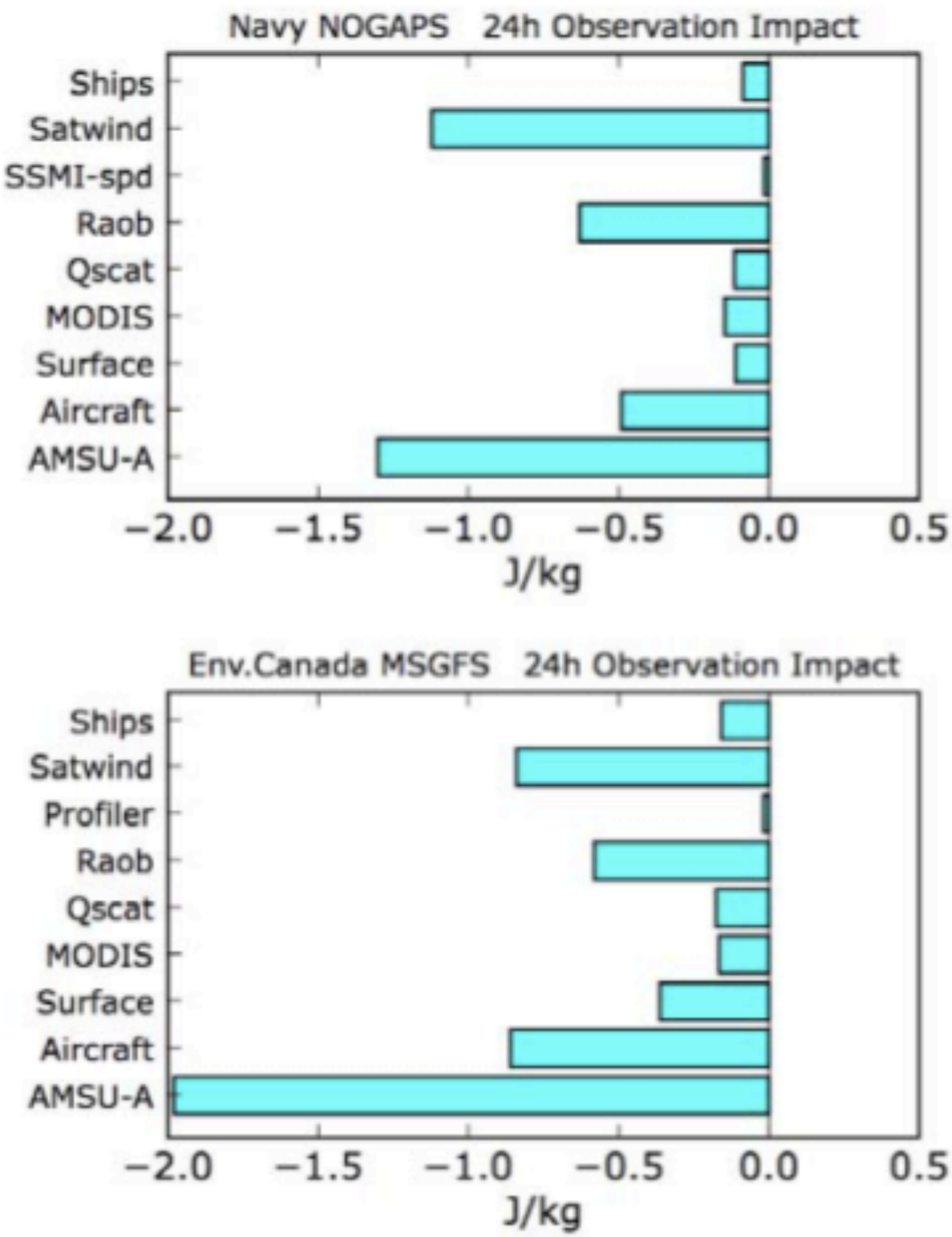
Applications



Applications



Applications

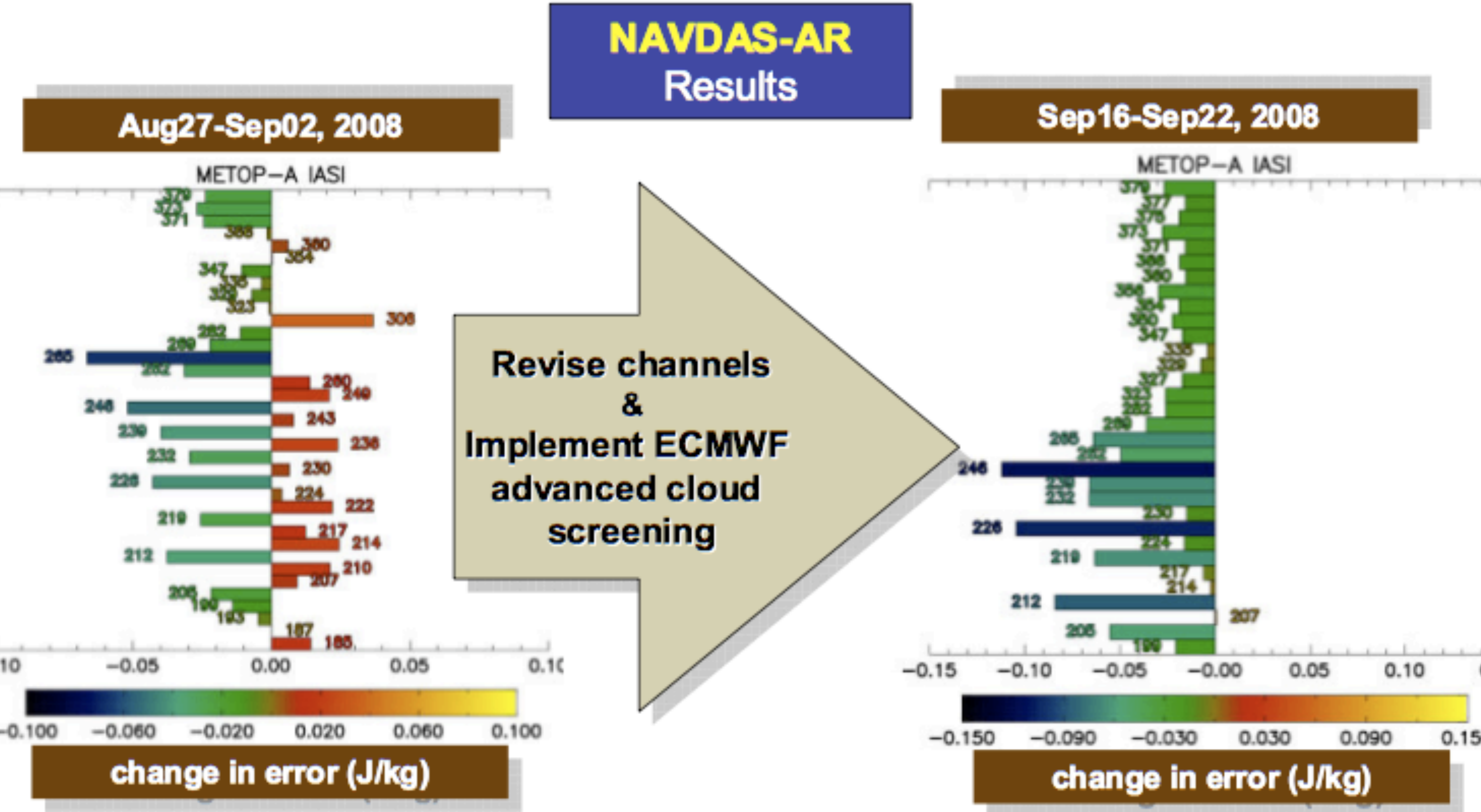


AMSU-A Observations Have the Greatest Benefit at all Three Centers.

from Gelaro et al. 2009

UCAR
UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

Applications



from Langland 2009

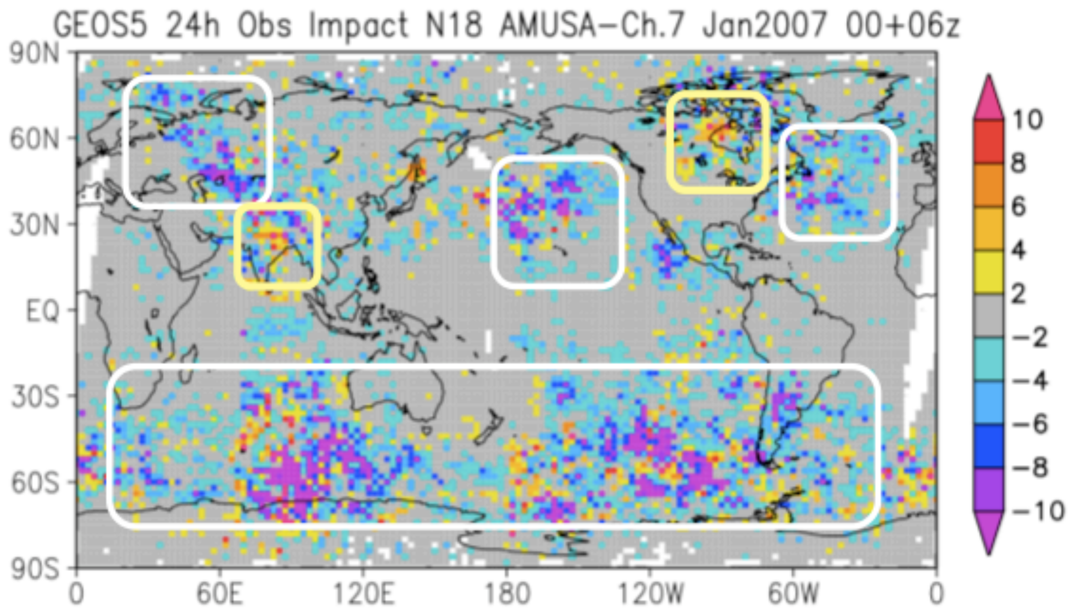
Applications

UCAR
UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

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

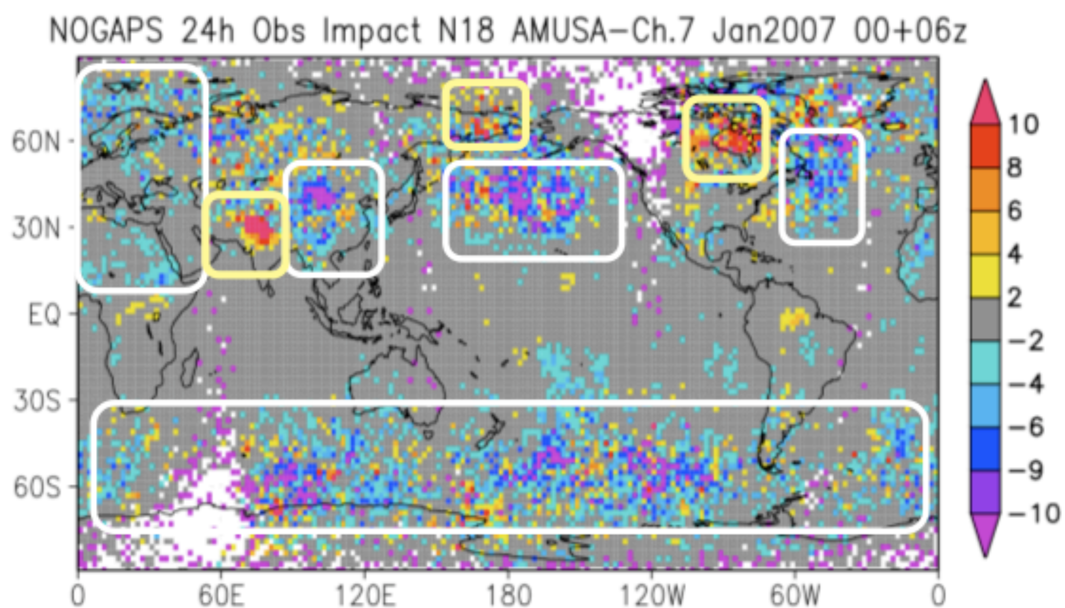
Observations that produce large forecast error reductions

Observations that produce forecast error increases in **both models**



NASA GEOS-5

Land or ice surface contamination of radiance data?



Navy NOGAPS

Baseline Intercomparison
Jan 2007 00+06 UTC

from Gelaro 2009

UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

Outline

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

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.

UCAR
UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

Outline

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

Conclusions

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

- Testing package &User's Guide available on demand

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

- Have fun!