4D-REKF: A next-generation Relaxation FDDA for WRF-ARW

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Outlines

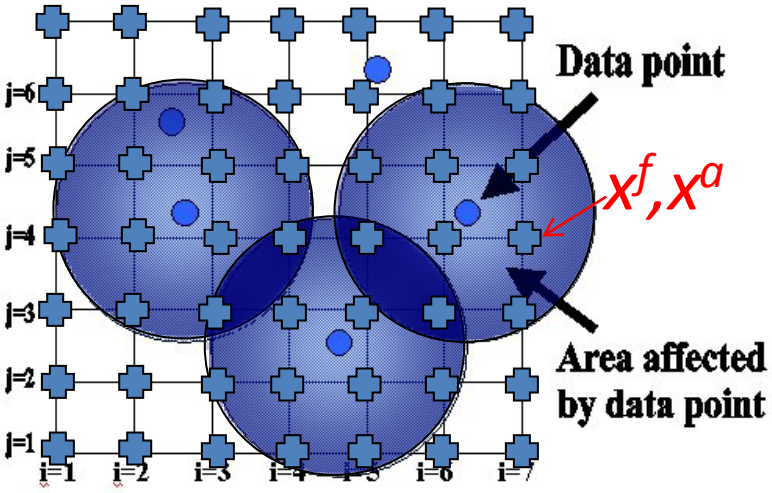
1. A Brief Review: What is 4D-REKF?
2. Formulation of 4D-REKF and Two "Flavors"
3. Implementation Challenges
4. Validation and Preliminary Results
5. Summary

Review: What is 4D-REKF (1)

analysis | 1st guess | obs | Pseudo-obs

3DDA

$$x_i^a = x_i^f + K\left((y_i^{obs} - \mathrm{H}(x_i^f)\right),\ i = 1, 2, \ldots, N$$



OA: K- simple distance functions; Isotropic weight with ad-hoc adjustments

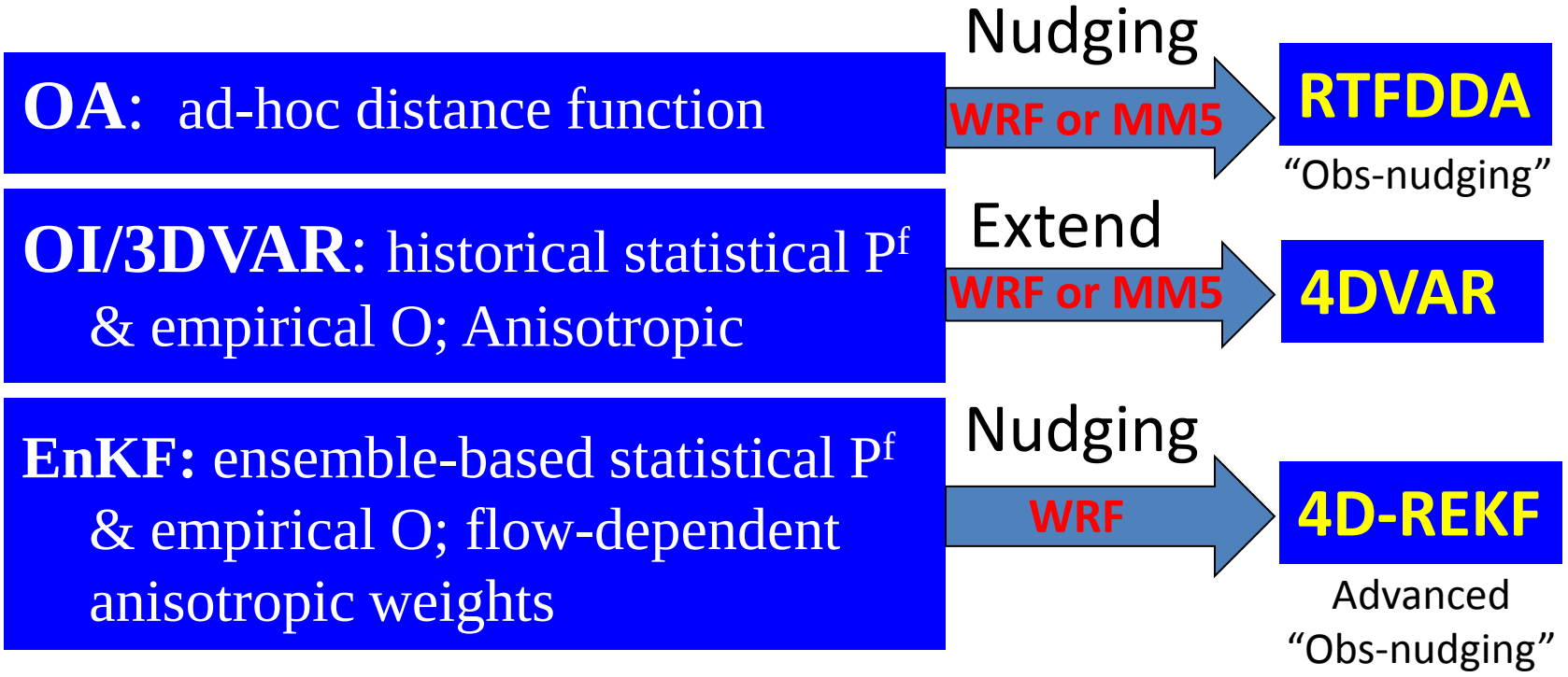
EnKF: K_e-ensemble statistical P^f and empirical O; Anisotropic weight

$$K = K_e = P^f H^T (H P^f H^T + O)^{-1}$$

(~200 papers in the last 10 years)

Review: What is 4D-REKF (2)

From 3DDA to 4DDA



4D-REKF: 4-Dimensional Relaxation Ensemble Kalman Filter

Review: What is 4D-REKF (3)

4D-REKF: Next-Generation "obs-nudging FDDA"
It is a paradigm of seamless EPS and EDA

1. Replaces the "obs-nudging" FDDA empirical, Cressman-type, data weight functions with an advanced "flow-dependent" weight functions computed from ensemble forecasts ("Kalman gains").
2. Combines the advantage of both "obs-nudging" and EnKF technologies.
3. When completed, all data, direct (i.e. U, V, T, and Qv) and indirect (e.g. radar radial winds and reflectivity, satellite radiance ...) can be assimilated.

4D-REKF Formulation

RTFDDA

$$\frac{\partial X}{\partial t} = F(X,x,y,\sigma,t) + G_\alpha \frac{\sum_{i=1}^{N} W_{xy,i}^2 W_{\sigma,i}^2 W_{t,i}^2 \cdot W_{qc,i}^2 \cdot (y_i^{obs} - HX)}{\sum_{i=1}^{N} W_{xy,i} W_{\sigma,i} W_{t,i} W_{qc,i}}$$

Cressman Weight

$$W_{xy} = \frac{R^2 - d^2}{R^2 + d^2}$$

Nudging coefficient

E-RTFDDA Ensemble Kalman Gain

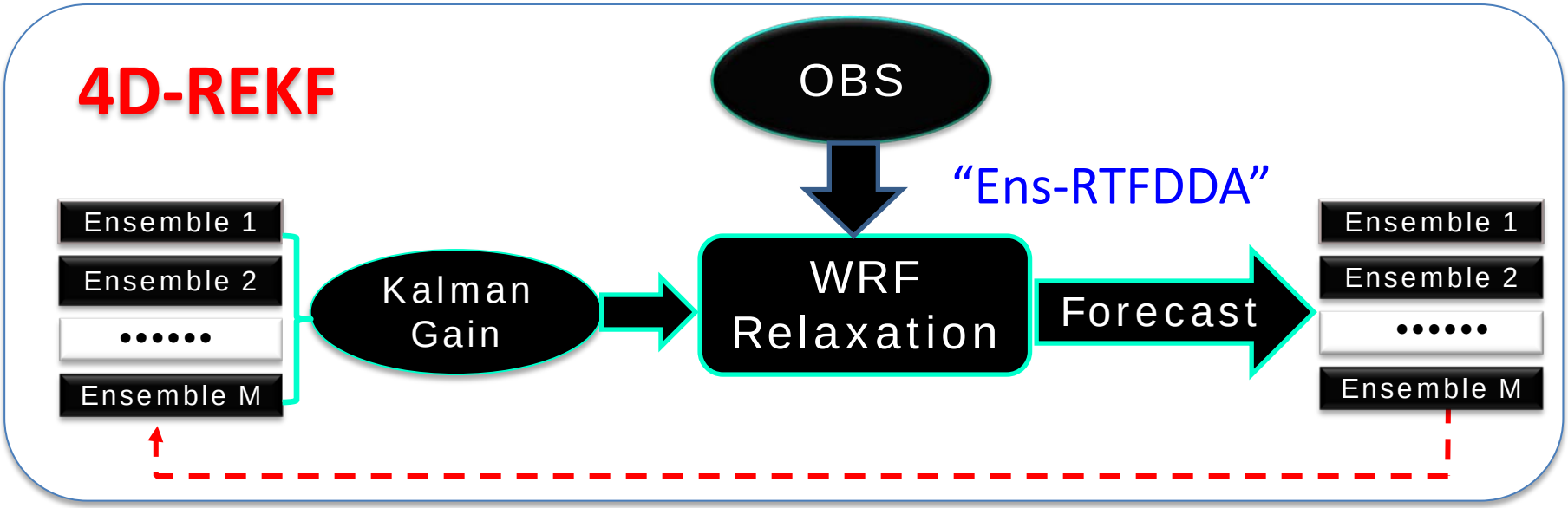
$$W_{xy,j} = K_e = P^f H^T (H P^f H^T + O)^{-1}$$

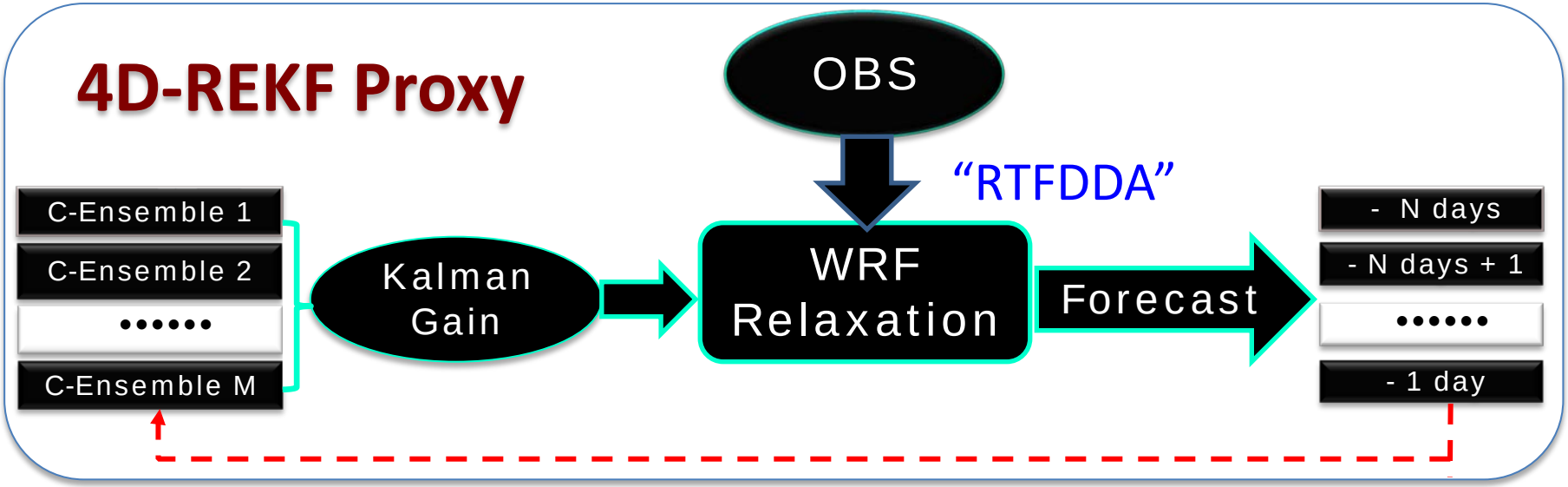
4D-REKF

$$\frac{\partial X}{\partial t} = F(X,x,y,\sigma,t) + G_\alpha \frac{\sum_{i=1}^{N} W_{xy,i} W_{\sigma,i}^2 W_{t,i}^2 W_{qc,i}^2 \cdot (y_i^{obs} - HX)}{\sum_{i=1}^{N} W_{\sigma,i} W_{t,i} W_{qc,i}}$$

Related Research	Lei, Stauffer et al. (2010): 3th EDA workshop; (2011) IOAS-AOLS Liu et al. (2009) WRF users workshop; 19th NWP; (2011) IOAS-AOLS Pan et al., (2010), 3rd EDA workshop; WRF 11th users workshop; (2011) IOAS-AOLS

4D-REKF Data Flow and "Two Flavors"





Implementation Challenges

- **Code changes into the WRF architecture**

Unlike the traditional EnKF which acts on model output, 4D-REKF acts on WRF. 4D-REKF needs modify the WRF code.

- **Spatial and temporal interpolation of gain matrices**

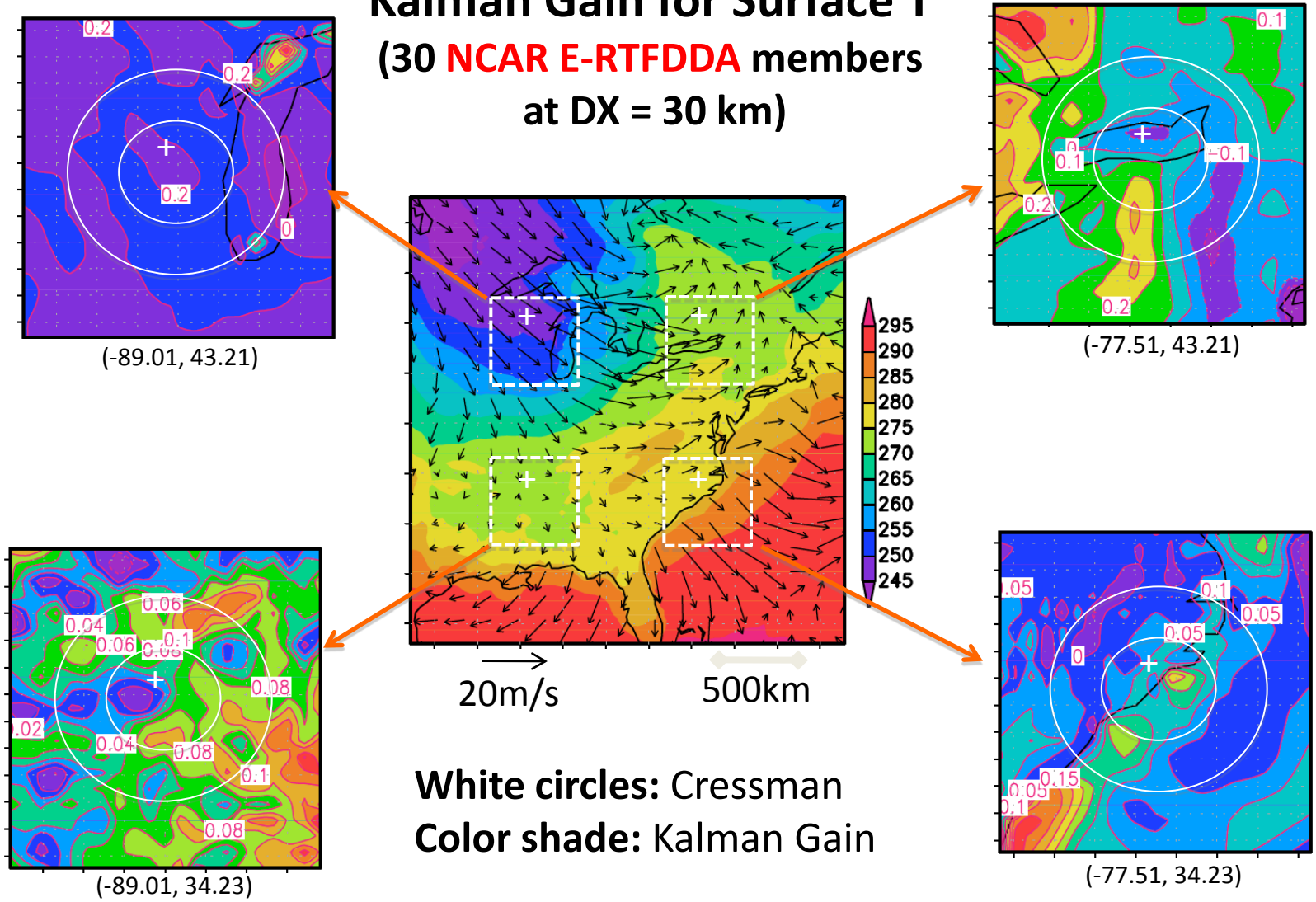
Like RTFDDA, 4D-REKF assimilates each observation with spatiotemporal weight functions centered at the measuring time and location. Spatial and temporal interpolation of the gain matrices is required to make the problem tractable.

- **Many issues and algorithms in Ensemble DA family apply**

Model errors (e.g. bias); covariance localization; observation errors and error covariance specification, …

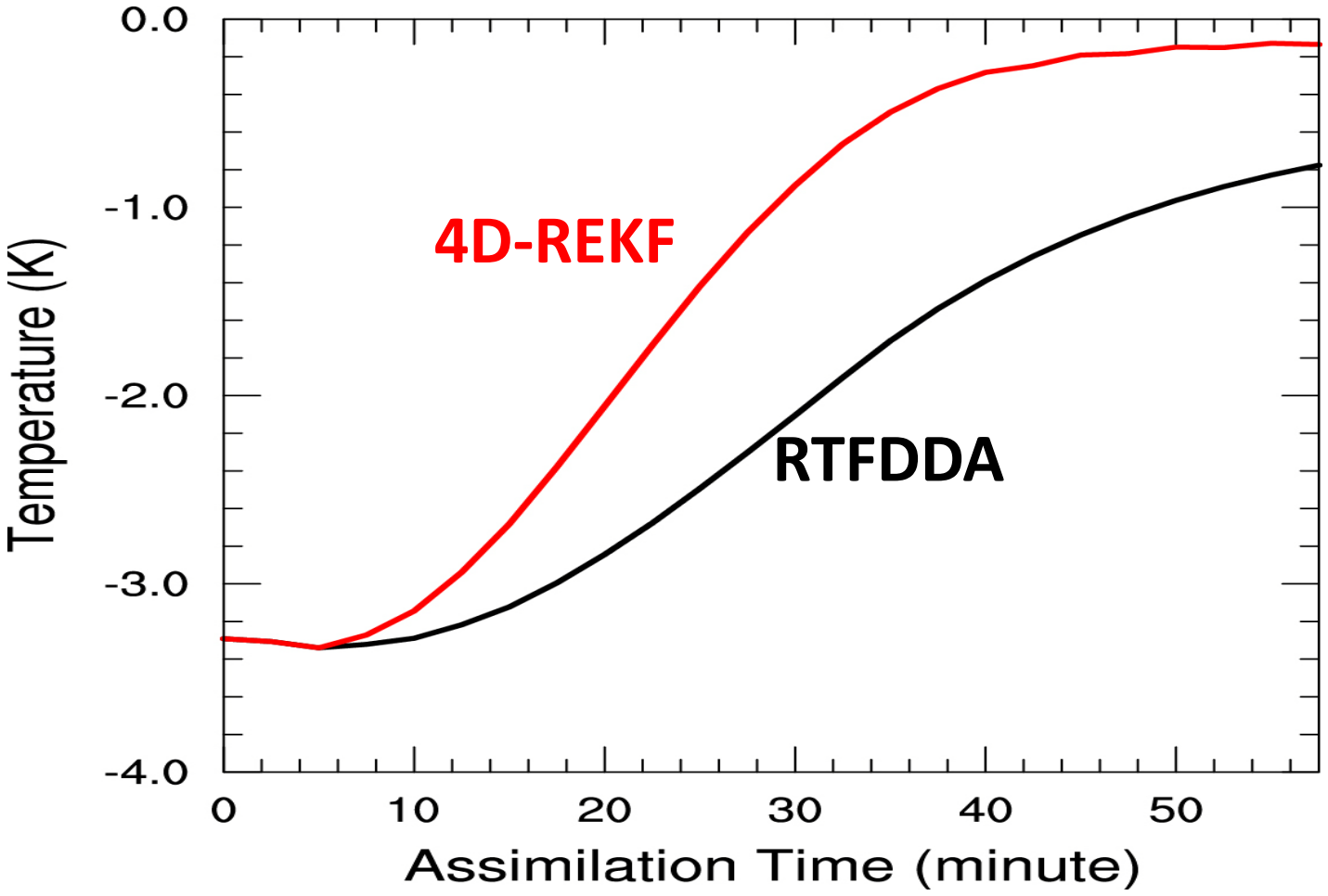
Validation Experiments (1)

Kalman Gain for Surface T
(30 NCAR E-RTFDDA members at DX = 30 km)



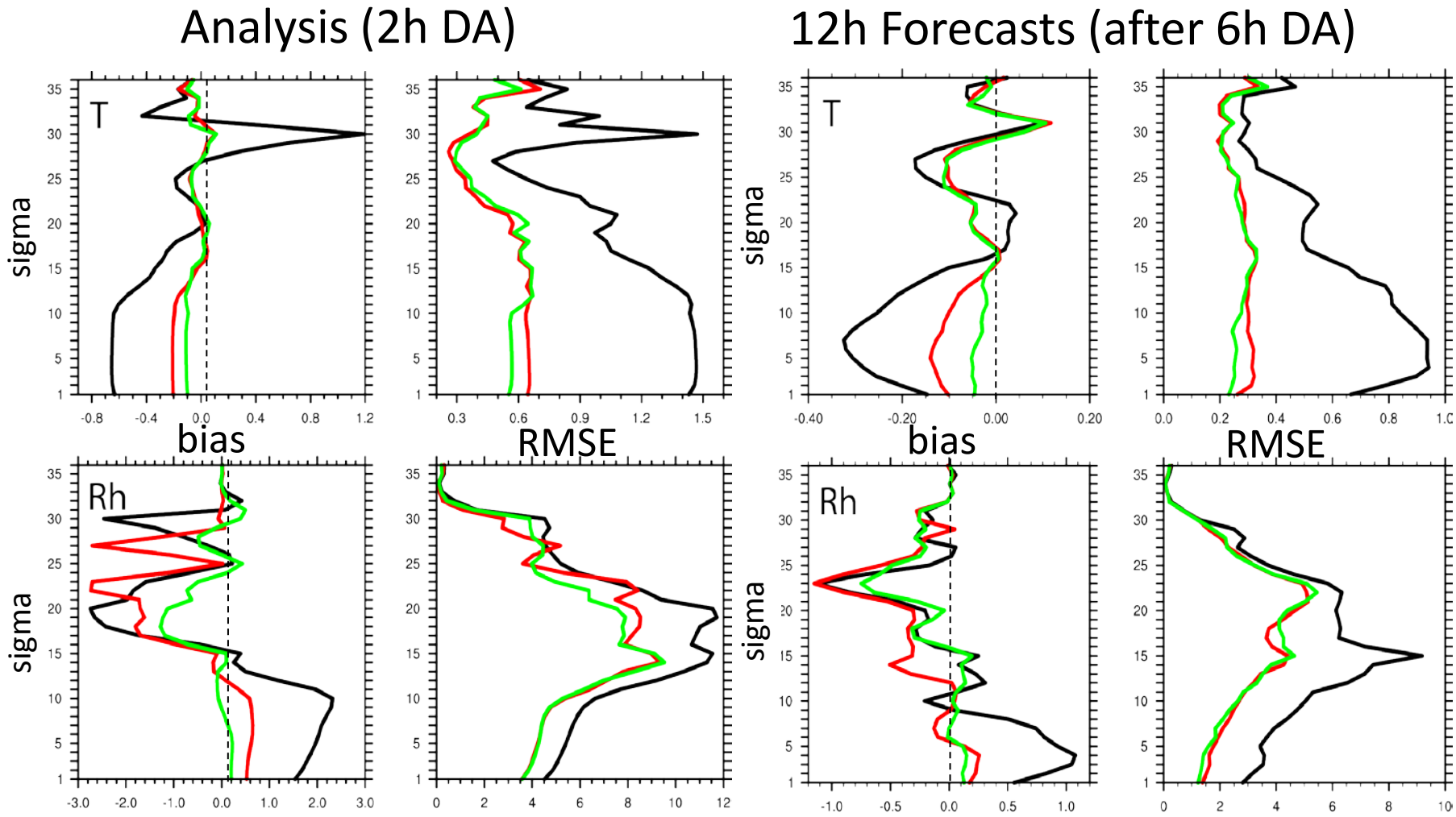
White circles: Cressman
Color shade: Kalman Gain

Validation Experiments (2)



OSSE - CAD

Validation Experiments (3)



Black: NoDA Red: RTFDDA Green: 4D-REKF

OSSE - CAD

EXPs with Real-Case-Real-Data

Surface Verification

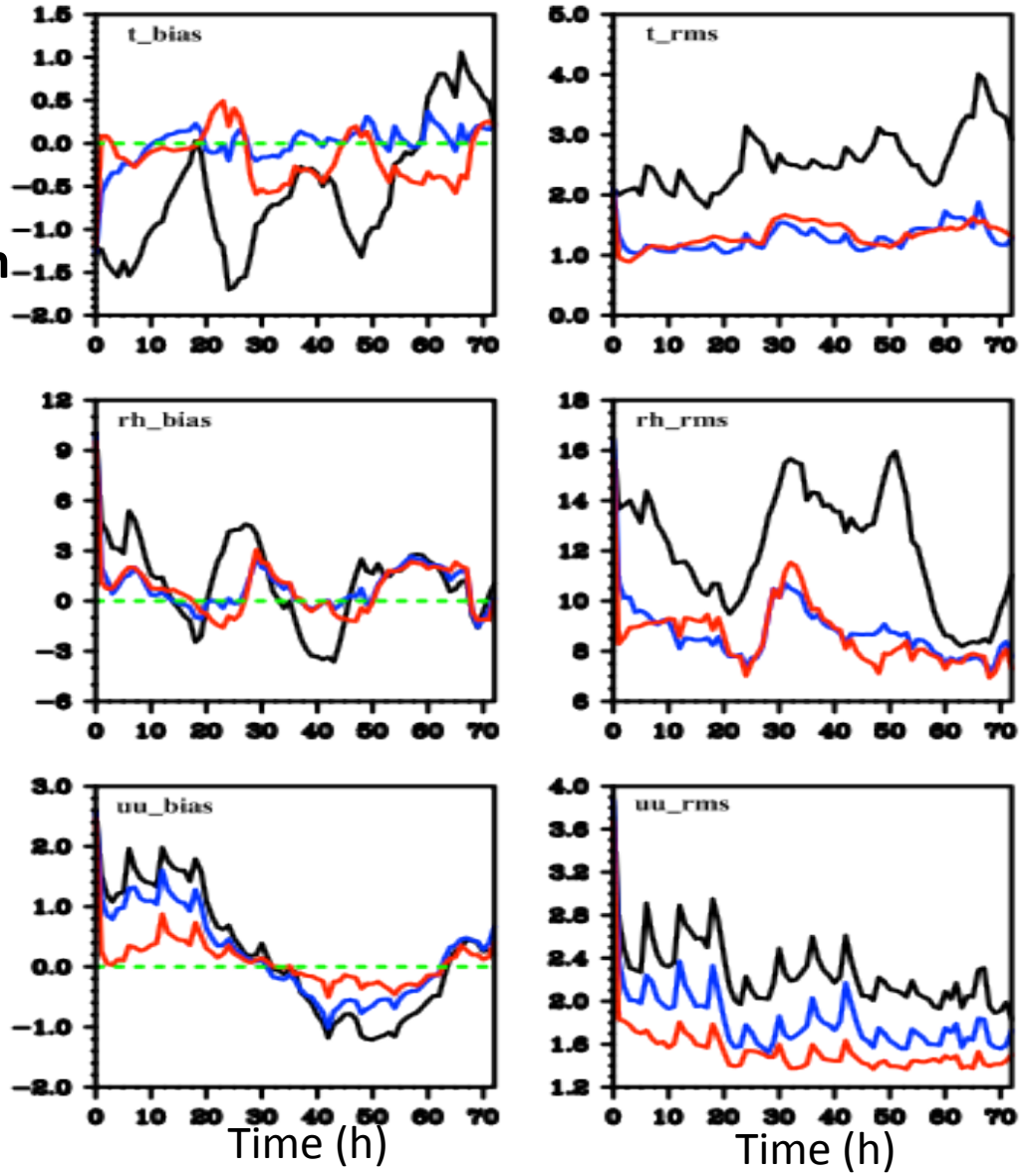
NoDa : no data assimilation

RTFDDA: old nudging scheme

4D-REKF: new nudging scheme

Key Parameters:
Rinxy=200km
Coef_u=2.5E-3

Period : 18Z Feb 10 — 18Z Feb 13, 2008



EXPs with Real-Case-Real-Data

NCAR

Upper-air Verification

NoDa : no data assimilation

RTFDDA: old nudging scheme

4D-REKF: new nudging scheme

Key Parameters:
Rinxy=200km
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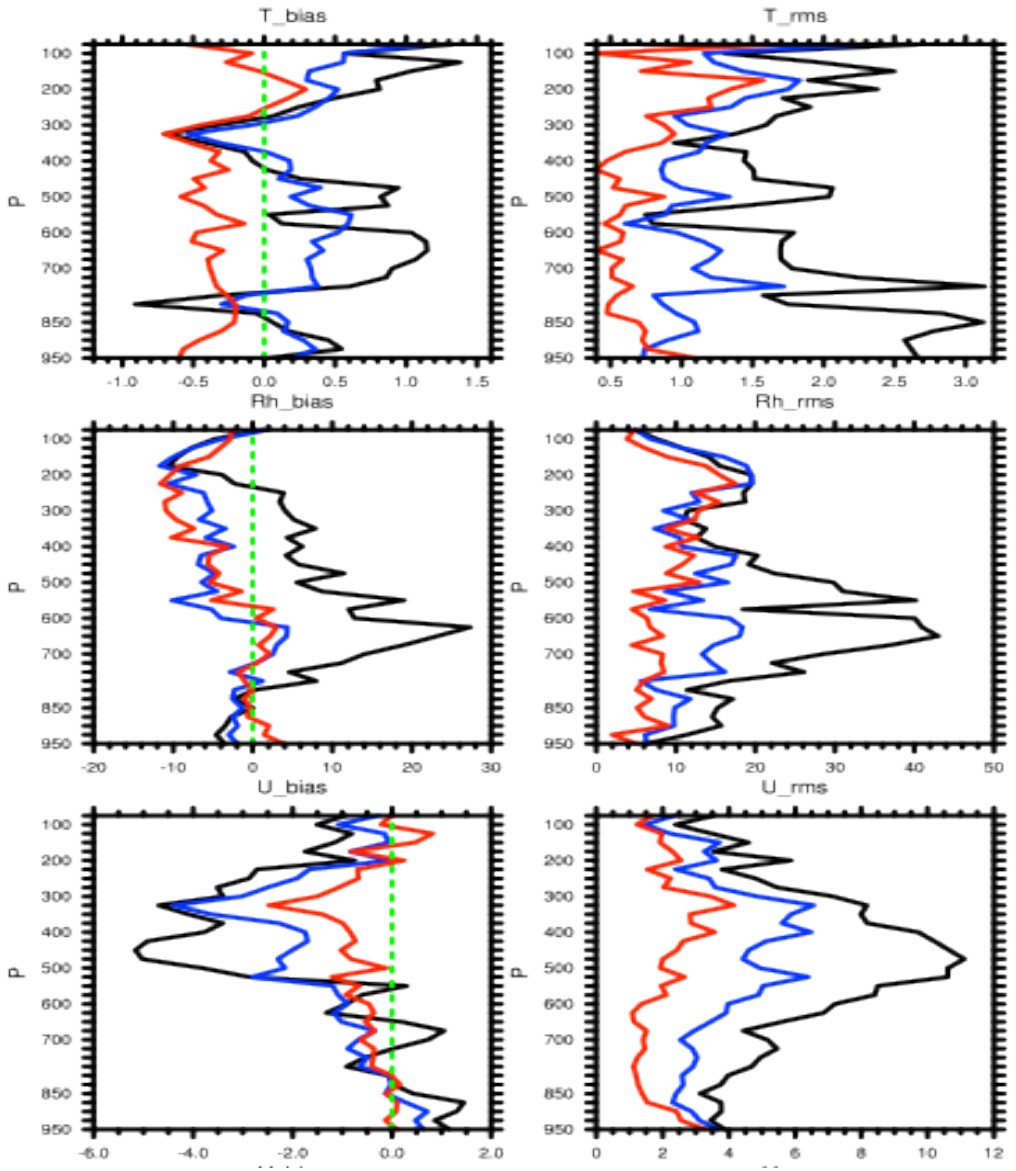
Period : 18Z Feb 10 — 18Z Feb 13, 2008



Sensitivity to Tunable Parameters

4D-REKF

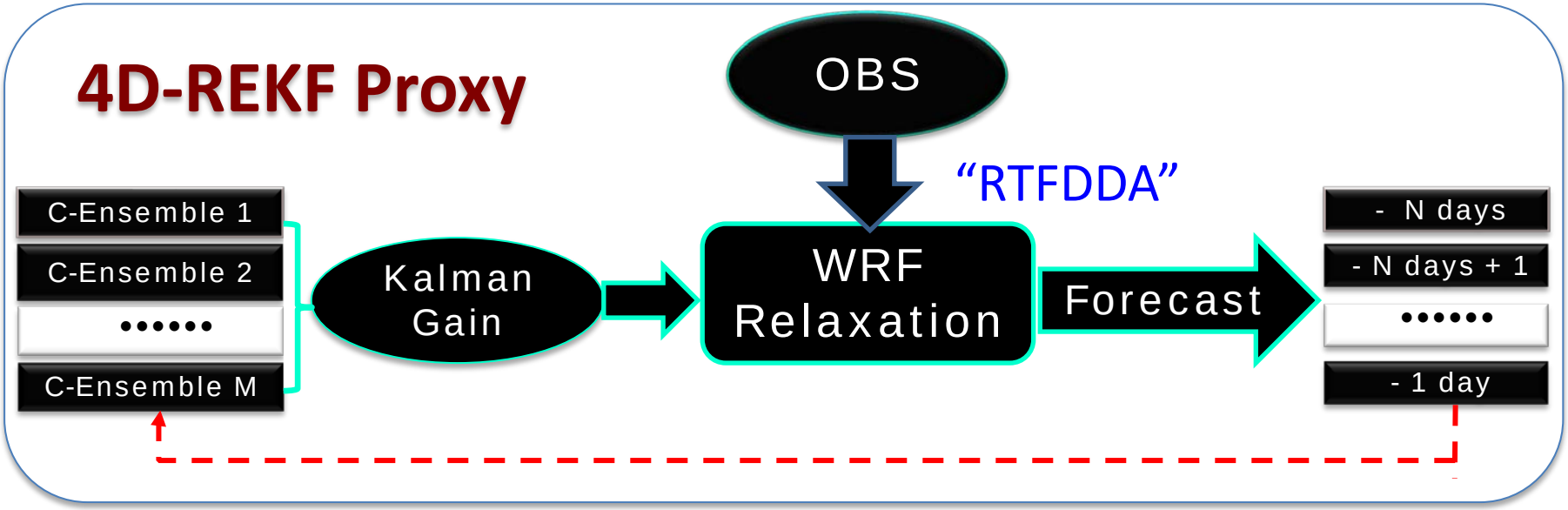
$$\frac{\partial^* X}{\partial t} = F(X,x,y,\sigma,t) + G_x \cdot P^* \frac{\sum_{i=1}^{N} W_{xy,i} W_{\sigma,i}^2 W_{t,i}^2 \cdot W_{qc,i} \cdot (Y_i^{obs} - H_i(X))}{\sum_{i=1}^{N} W_\sigma W_t}$$

$$W_{xy,i} = K = \tilde{X}^f (\tilde{Y}^f)^T [\tilde{Y}^f (\tilde{Y}^f)^T + O]^{-1}$$

- K: spatiotemporal interpolations
- G_x: relaxation strength (nudging coefficients)
- Influence radii ("K localization")

Exps results: Wu et al. Poster 63

4D-REKF Proxy: Test for DPG, UT



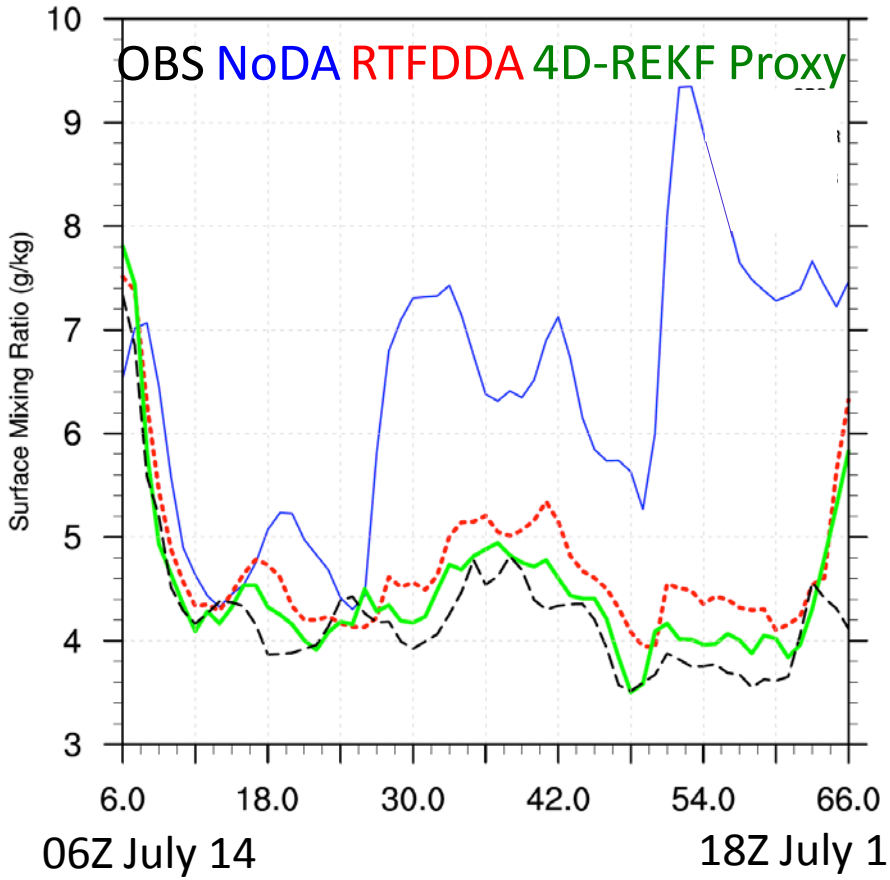
- Use "climo-" ensembles as a proxy to E-4DWX;
- Take advantage of 4D-REKF without running ensemble;

4D-REKF Proxy results: Pan et al. Poster 66

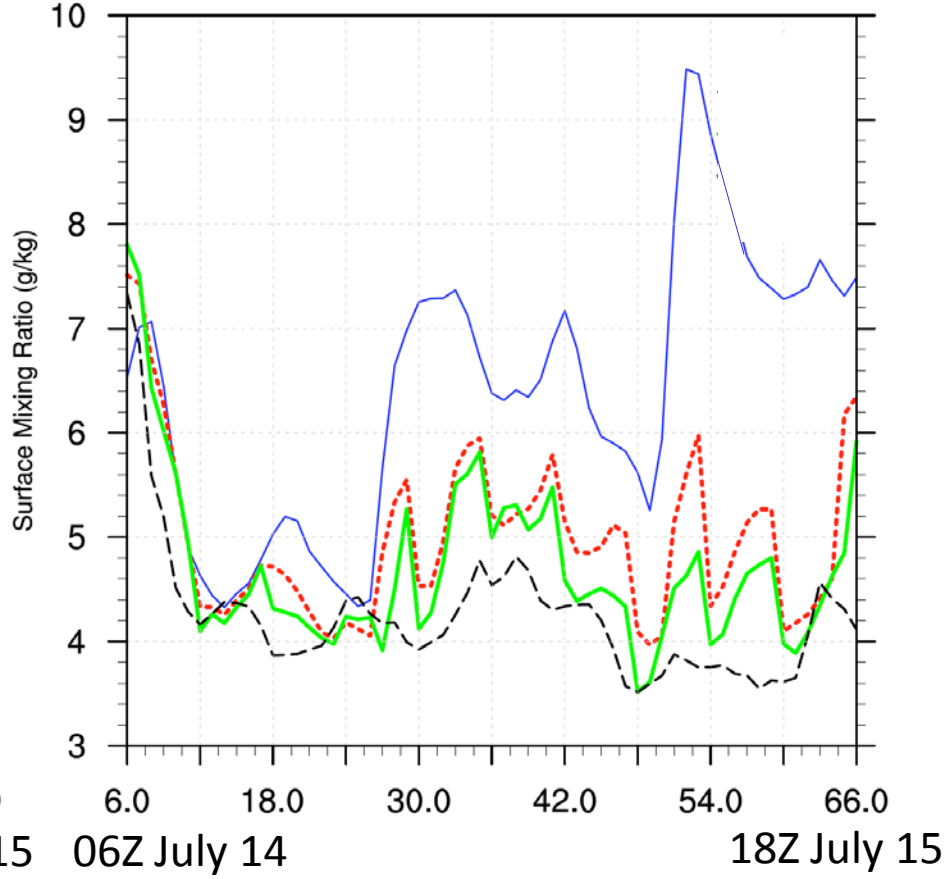
4D-REKF Proxy: DPG Real Case

DX=3.3km; 00Z July 14 to 18Z July 15, 2010. Cycles: 6 hourly
Weak forcing, local circulations

Final Analysis



0 – 6 h forecasts



Strengths of 4D-REKF

- **Inherits all advantages of "obs-nudging" (E-)RTFDDA**
  - Allows continuous 4D-DA and forecasting cycles and thus provides "spun-up" analyses (ICs) and forecasts
  - Follows the model-obs state synchronization paradigm
  - Works with E-RTFDDA → forms a seamless EDA + EPS (cf. Liu et al. 2010)
- **Realizes EnKF in true 4D space**
  - The analysis increments are nudged into model in 4D
  - 4D-REKF is insensitive to "variance inflation"
  - Can readily incorporate new ideas and advances in EnDA/EnKF (e.g. adaptive covariance localization).
- **A DA scheme letting model "talk" to observation directly**

Summary

- "4D-REKF": an advanced FDDA technology that combines and leverages the ensemble Kalman Filter data assimilation technology into WRF "observation-nudging" FDDA (RTFDDA).
- A "baseline" 4D-REKF has been developed with WRF-ARW. Two flavors of the 4D-REKF scheme have been formulated and tested (and proven to be superior to RTFDDA).
- Work in progress:
  - Test and evaluate with real-time analysis and forecast cycles
  - Continue to understand and optimize the tunable parameters
  - Develop the advanced aspects of 4D-REKF including radar DA, and cross-variable DA
- The ultimate goal: a seamless WRF ensemble DA and EPS system

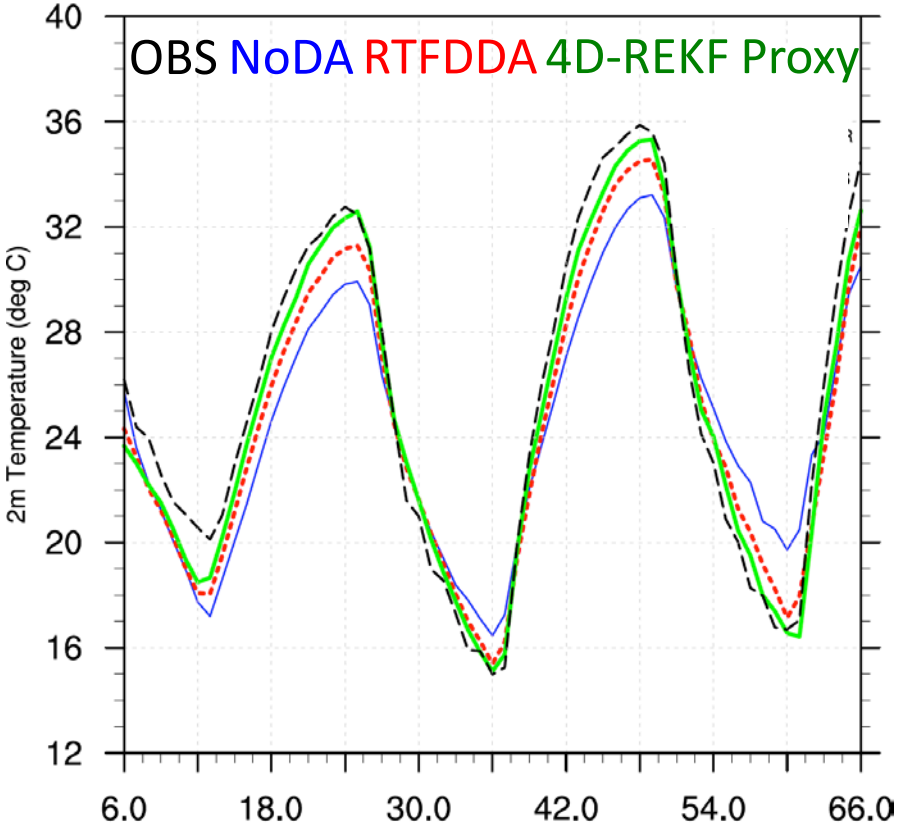
NCAR

Thank you! Questions?

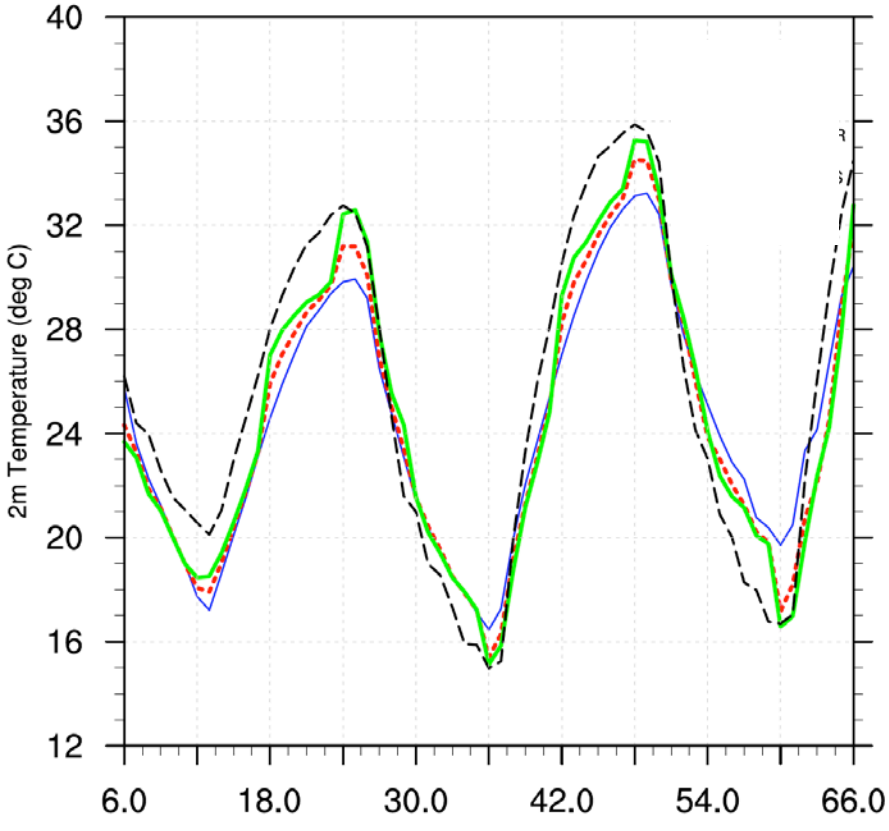
4D-REKF Proxy: DPG Real Case

00Z July 14 to 18Z July 15, 2010. Cycles: 6 hourly
Weak forcing, local circulations

Final Analysis



0 – 6 h forecast



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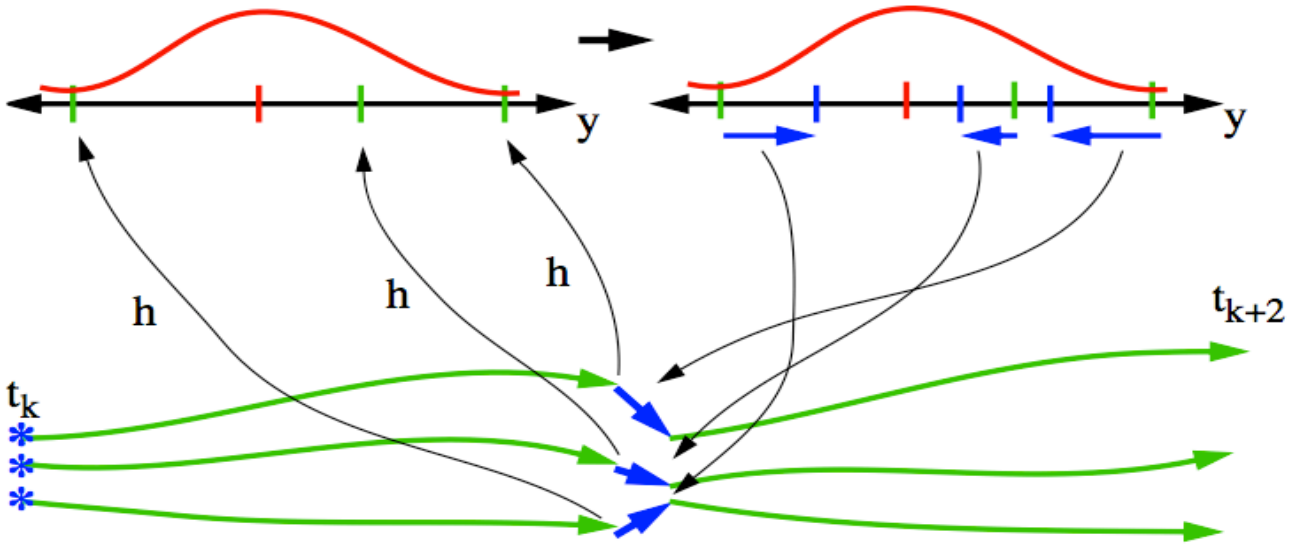
Ensemble Kalman Filter: A Monte Carlo realization of Kalman filter



Anderson: Ensemble Tutorial 14 9/8/06

$$x_i^a = x_i^f + K(y^{obs} - HX) \qquad i = 1, 2, \ldots, N$$

$$K_e = P^f H^T (HP^f H^T + O)^{-1}$$ Kalman gain