

What is an Ensemble Kalman Filter (EnKF)? _____

Given forecast ensemble, valid at some t

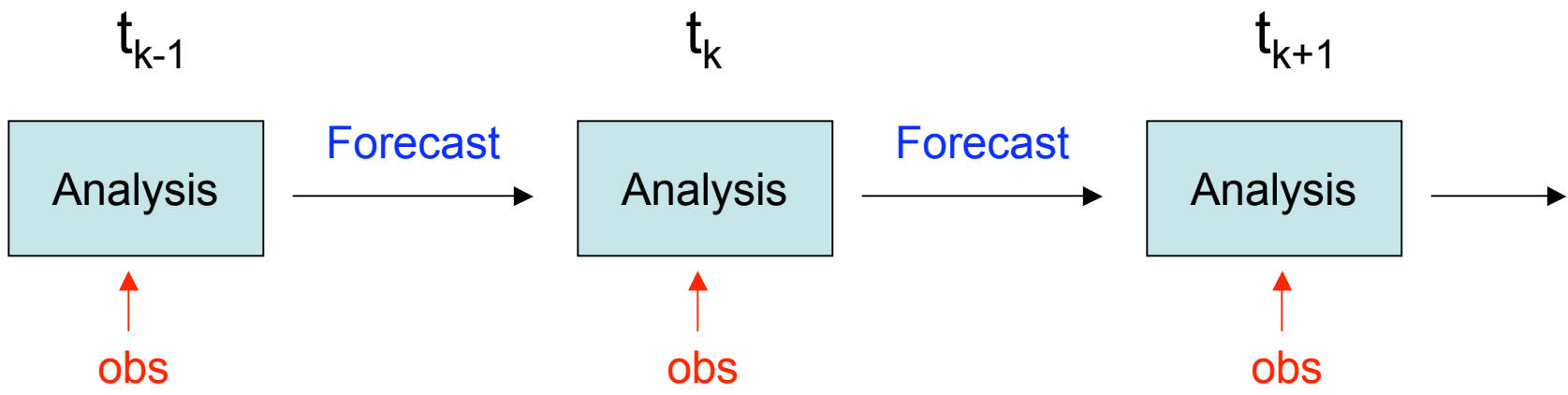
- ▷ estimate forecast-error covariances needed for DA using sample covariance of ensemble
- ▷ perform analysis for each member based on obs available at t
⇒ analysis ensemble
- ▷ integrate forecasts from analysis ensemble to the time of next observations

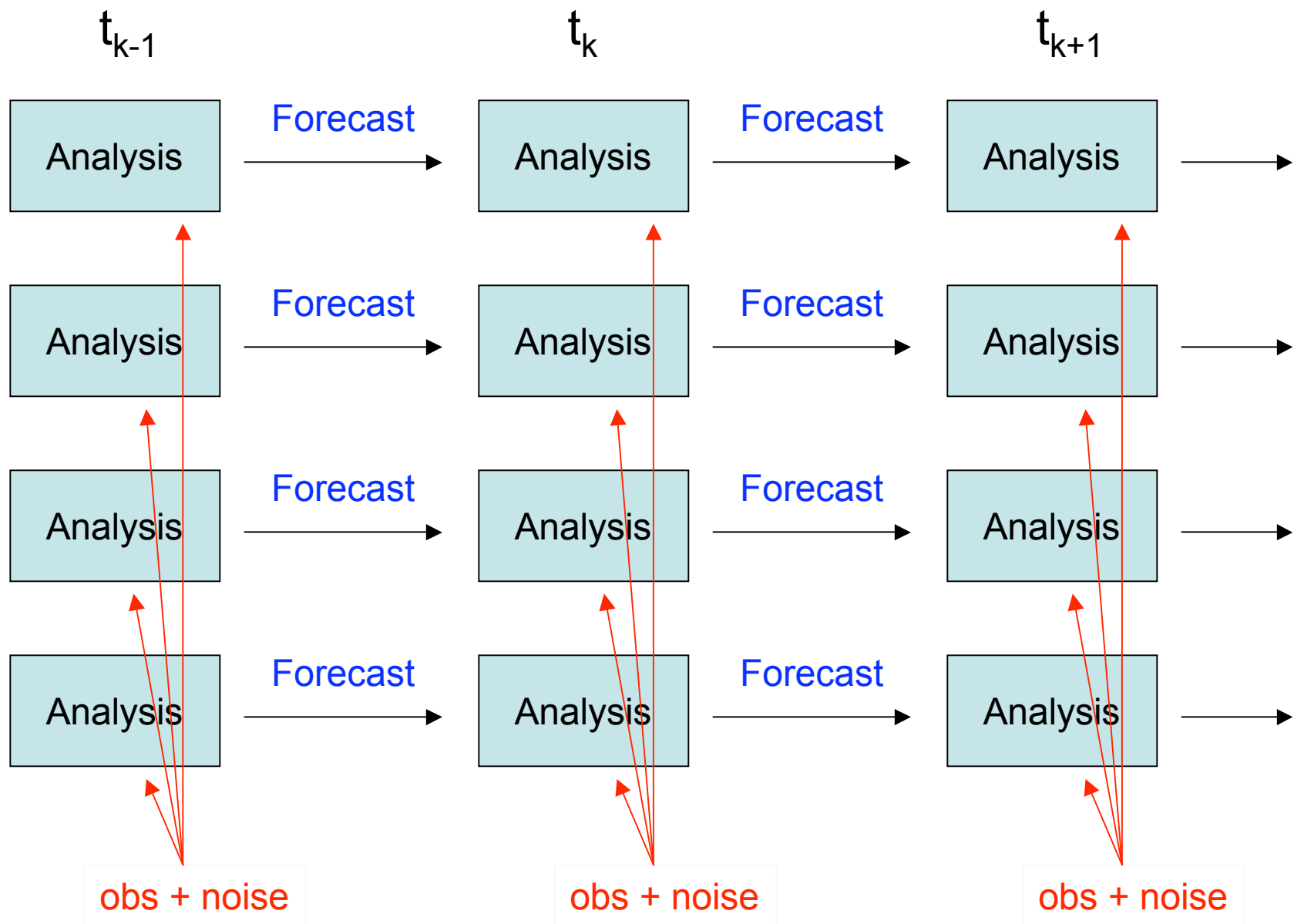
Combines data assimilation and ensemble forecasting

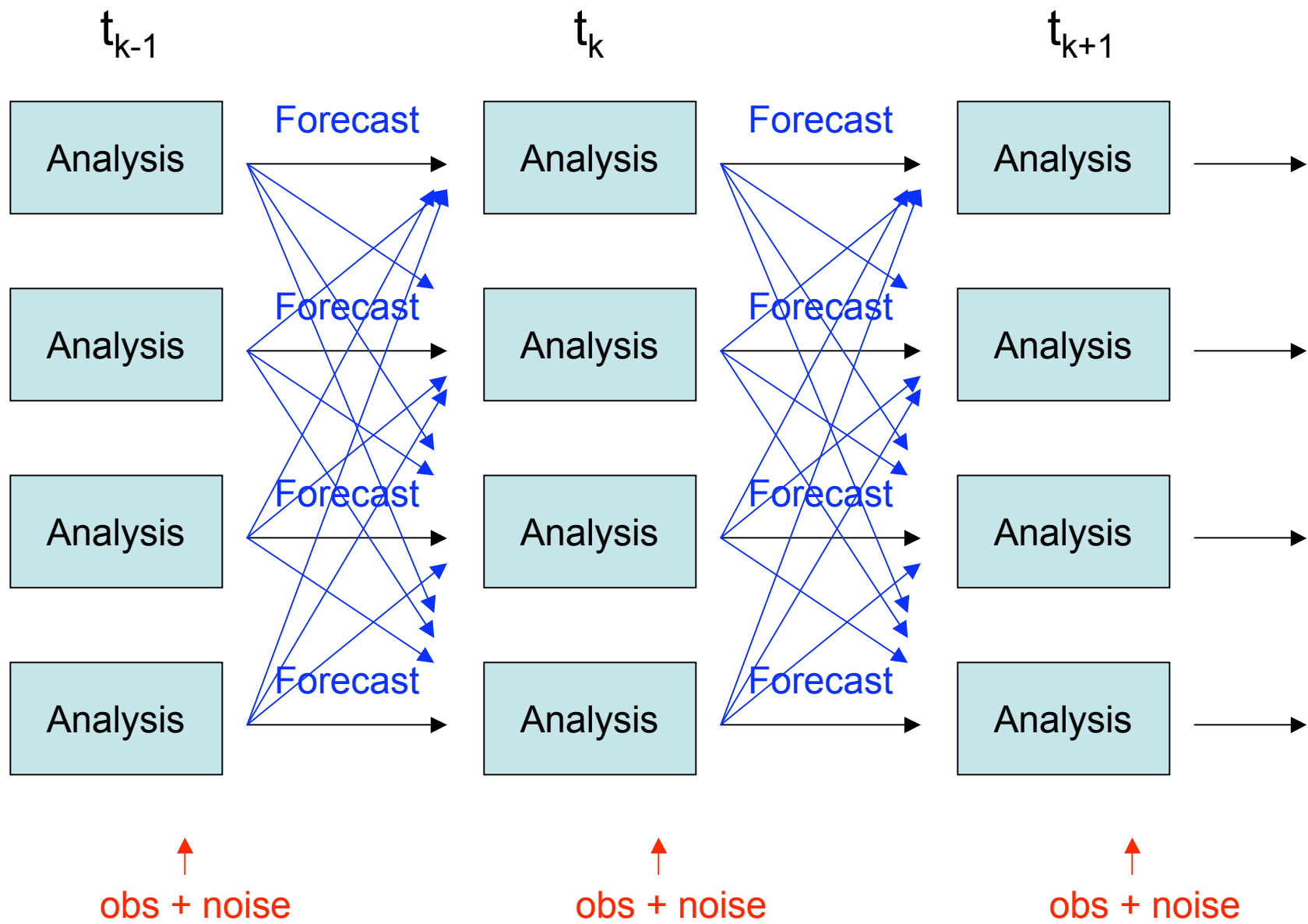
- ▷ analyses *plus* their uncertainty

Uses “flow dependent” forecast-error covariances

- ▷ 3DVar covariances (typically) assumed stationary, isotropic, homogeneous

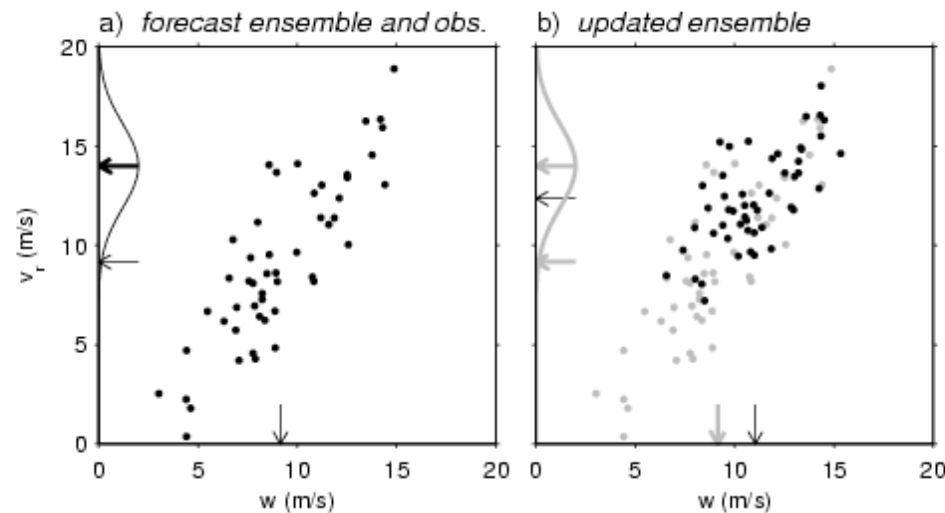






Update Step: Schematic Radar Example

Update w given an observation of v_r



▷ let $v_r^f = \mathbf{H}\mathbf{x}^f$; compute for each member

▷ For each grid point i , estimate from ensemble

$$c_i = (\mathbf{P}^f \mathbf{H}^T)_i = \text{Cov}(w_i^f, v_r^f), \quad d = \mathbf{H}\mathbf{P}^f \mathbf{H}^T + \mathbf{R} = \text{Var}(v_r^f) + \mathbf{R}$$

▷ update each member at i th grid point,

$$w_i^a = w_i^f + (\hat{c}_i / \hat{d})(v_r - v_r^f + \epsilon) \quad \epsilon \sim N(0, \mathbf{R})$$

EnKFs for WRF

Presently, 3 implementations at different institutions

- ▷ typically, 20–100 members
- ▷ deterministic/square-root versions of EnKF
- ▷ serial processing of observations, with covariance localization
- ▷ parallel computations on linux clusters with slow interconnect

Real-time implementation at UW

- ▷ <http://www.atmos.washington.edu/~enkf/enkfp.py.cgi>

At NCAR, use the Data Assimilation Research Testbed (DART)

- ▷ http://www.cgd.ucar.edu/DAI/hawaii_release.html

Initial issues

- ▷ Lateral BCs in forecast step?
- ▷ Are EnKF analysis increments balanced?
- ▷ How does EnKF compare with 3DVar?

Lateral BCs

In limited-area model, lateral BCs a source of uncertainty

- ▷ ensemble forecasts require ensemble of lateral BCs
- ▷ global ensemble schemes not designed/tuned for very short range

Approaches for ensemble BCs

- ▷ preferred: ensemble from EnKF on larger domain
- ▷ ad hoc: draw BC perturbations from Gaussian with 3DVar covariances or from (scaled) perturbations from climatology

Ad-hoc approaches inferior, but not horrible

- ▷ Torn et al. (2005),
http://www.atmos.washington.edu/~hakim/papers/torn_etal_2005.pdf

EnKF/3DVar Comparison ---

Performance of EnKF for LAM?

- ▷ WRF 3DVar as benchmark

Importance of EnKF's 'flow dependent' covariances?

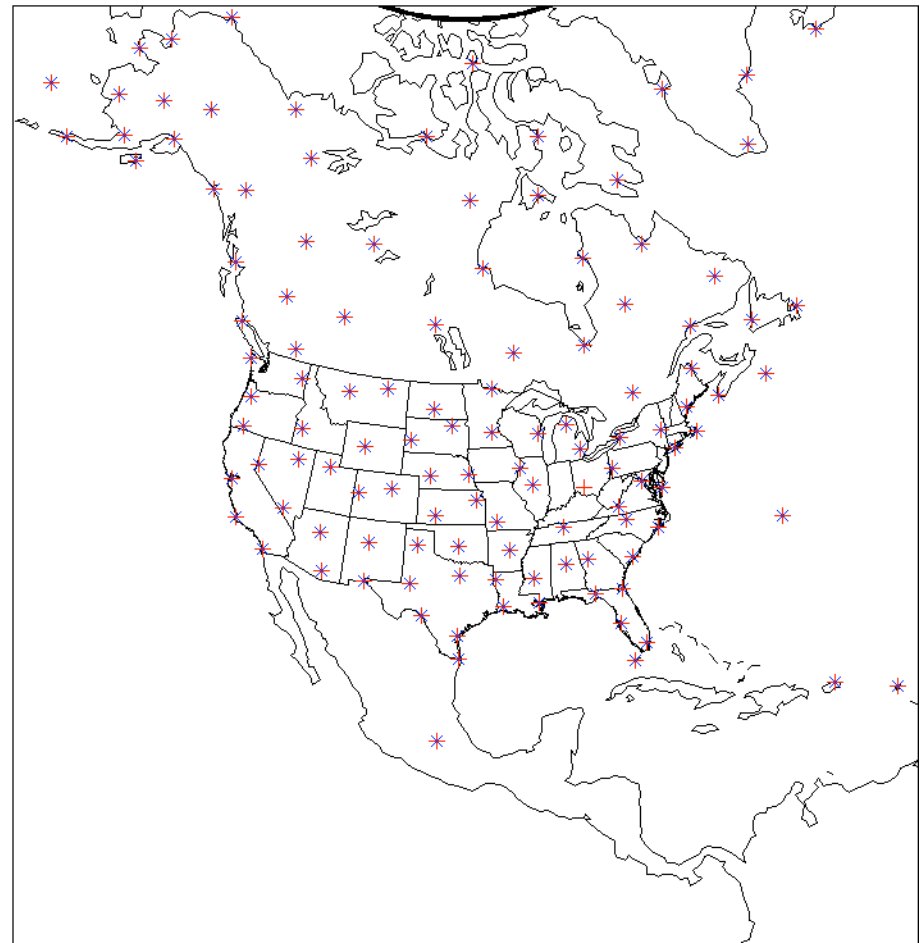
- ▷ in LAM, benefits suppressed by ad hoc treatment of BC uncertainty
- ▷ enhanced by local effects (e.g. orography)?

Consider synoptic scales, CONUS domain

- ▷ balances assumed in 3DVar best suited to such flows
- ▷ degree of imbalance in EnKF, 3Dvar analyses?

Experimental Design

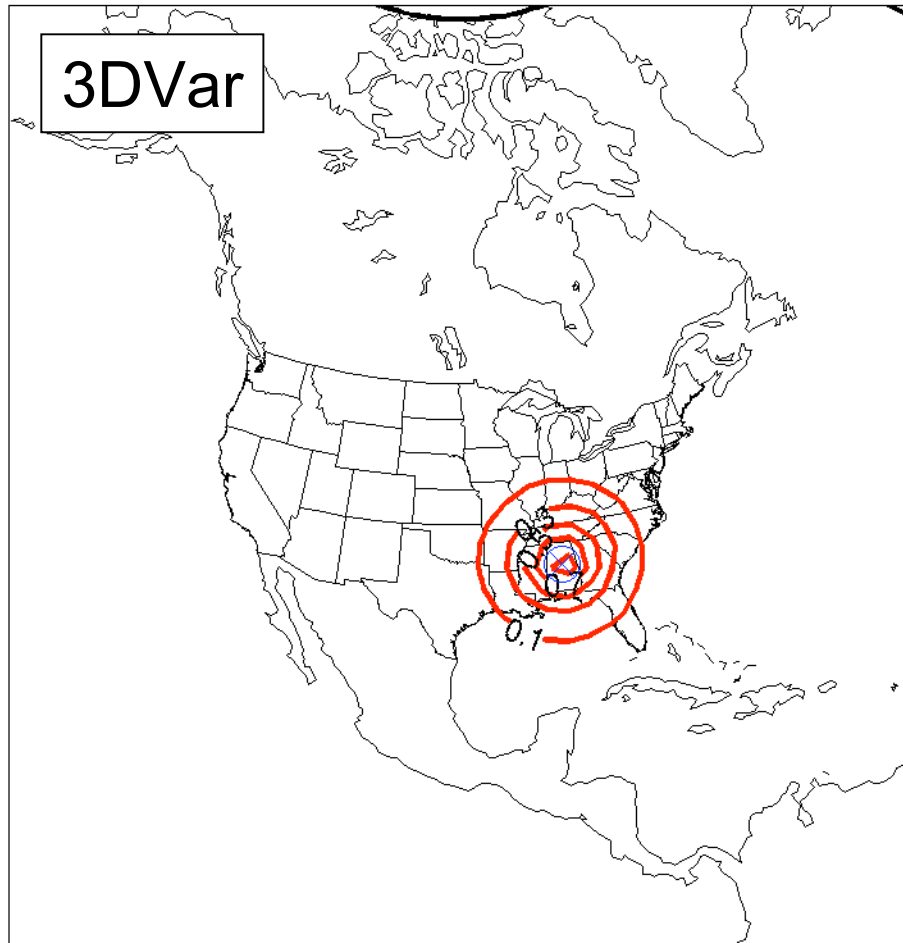
- ▷ obs from NA rawinsonde network
- ▷ domain (200 km) and obs locations shown
- ▷ assimilate u, v, T every 12h
- ▷ LBCs from GFS analyses
- ▷ cycle for Jan 2003



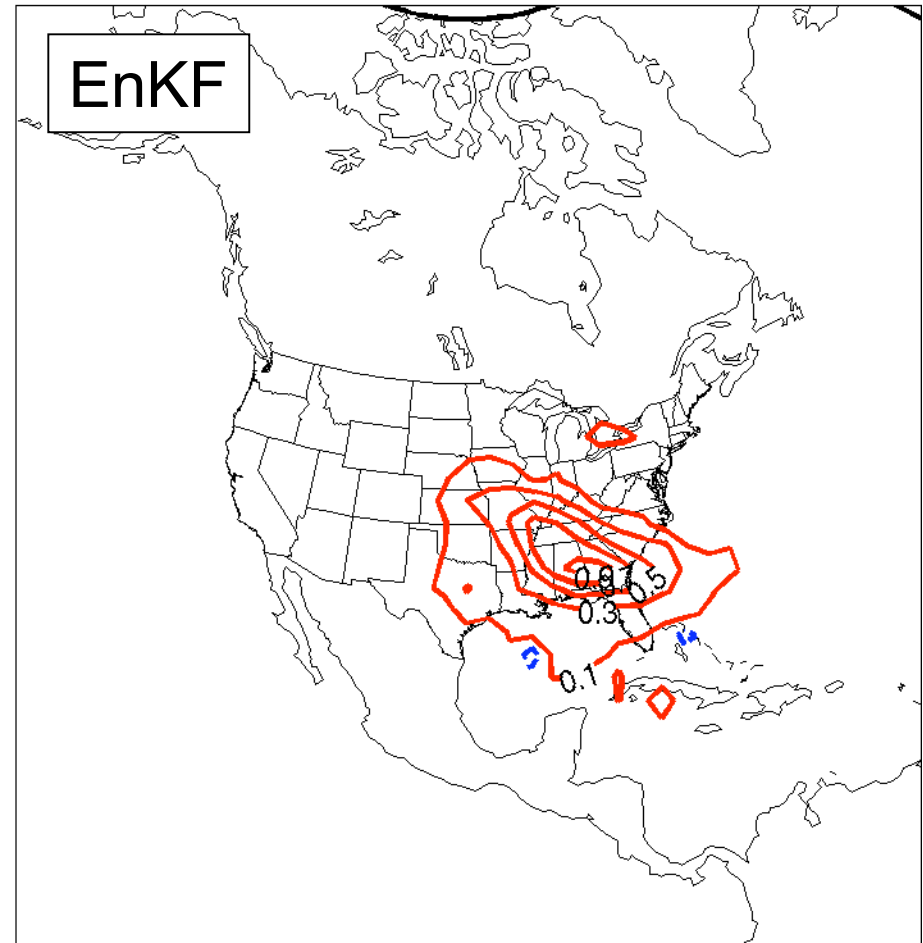
EnKF/3DVar Comparison

- ▷ T analysis increment, day 10, single T observation at 850 mb

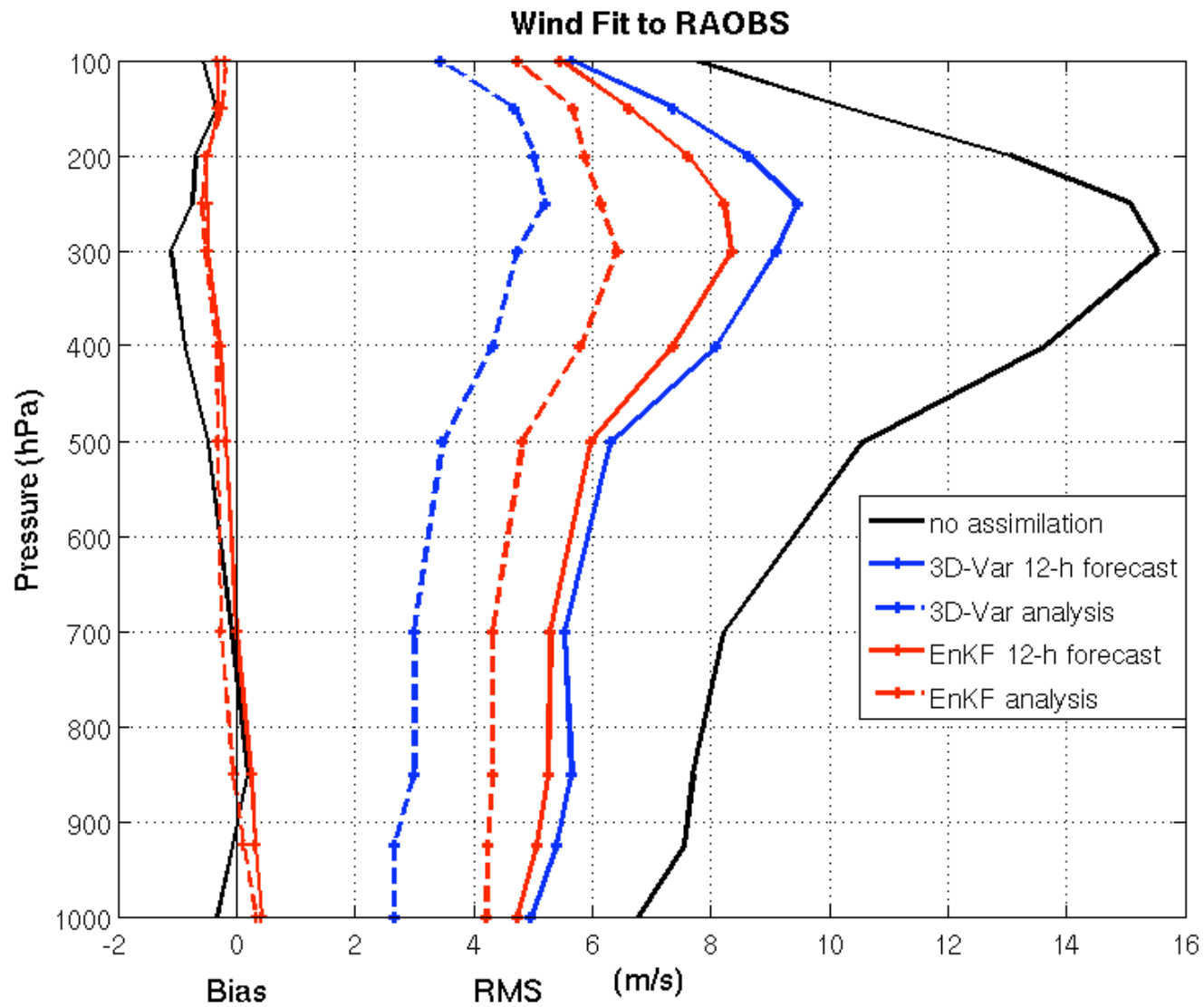
T(K) 850 (hPa) 2003-01-11 00:00:00



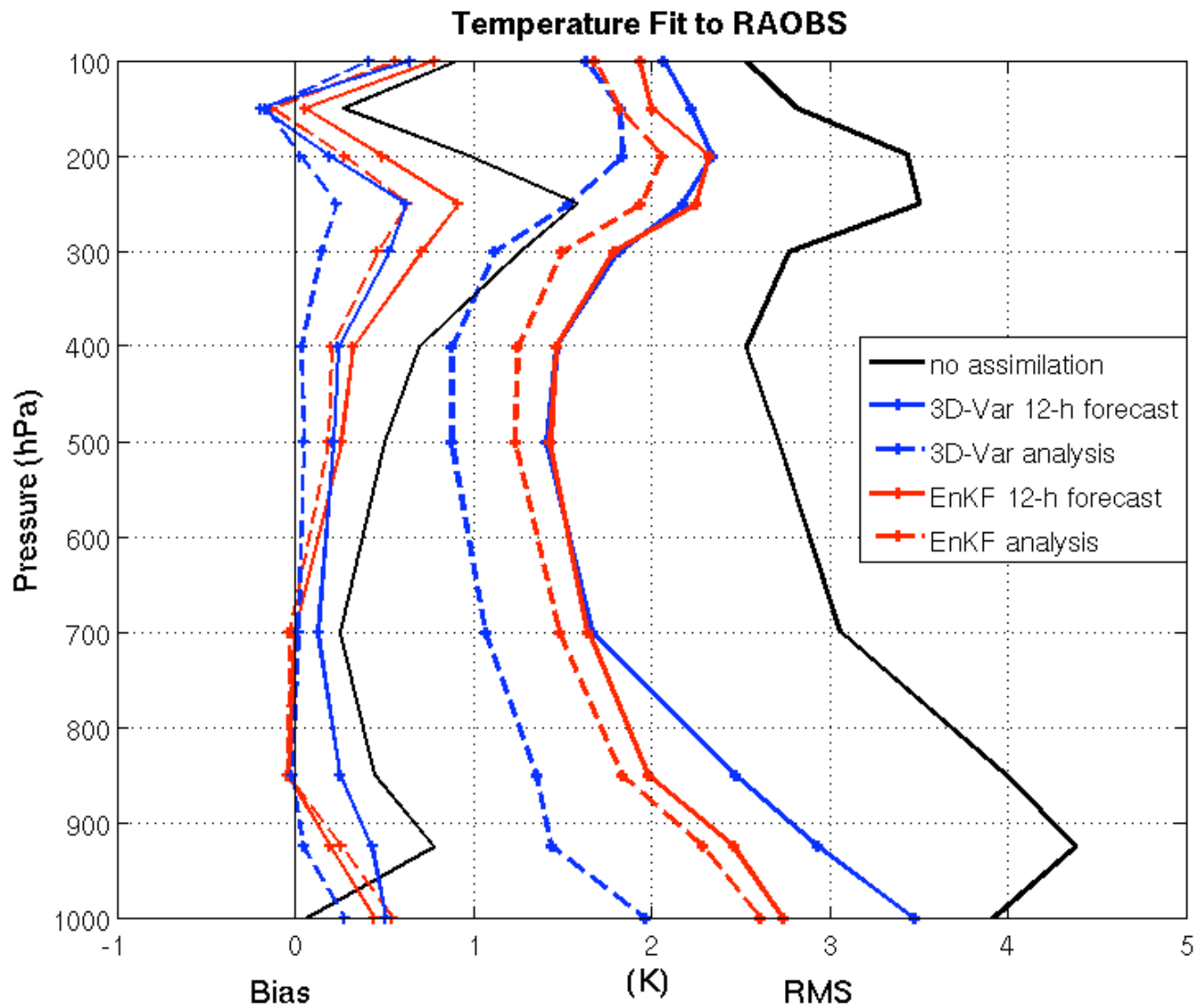
T(K) 850 (hPa) 146837 days 0 sec



EnKF/3DVar Comparison



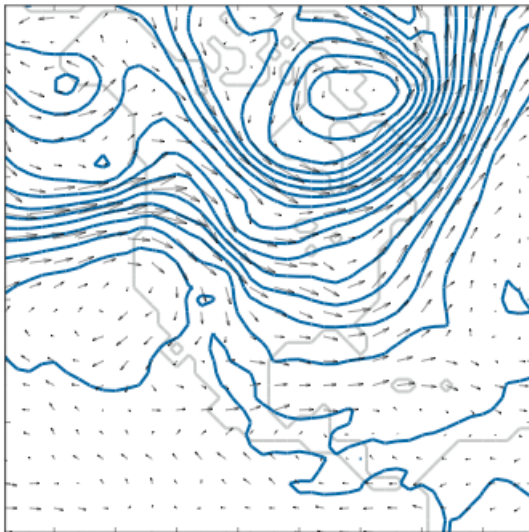
EnKF/3DVar Comparison



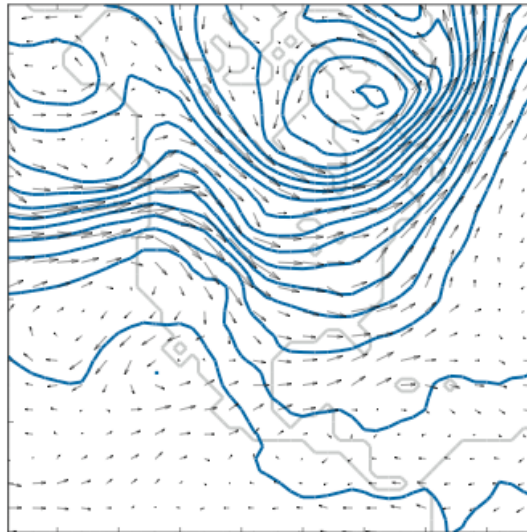
Comparison with GFS Analysis _____

- ▷ 500-hPa heights and winds, 00UTC 31 January
- ▷ EnKF (left; $\Delta = 60$ m), GFS (center), difference (right; $\Delta = 20$ m)

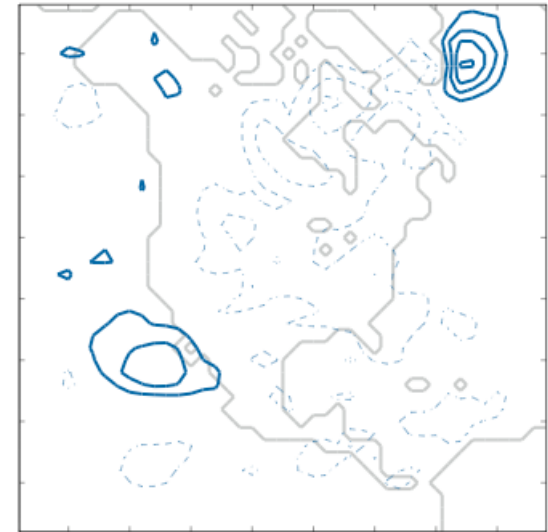
EnKF geopotential and winds at 500 hPa



NCEP/AVN geopotential and winds at 500 hPa

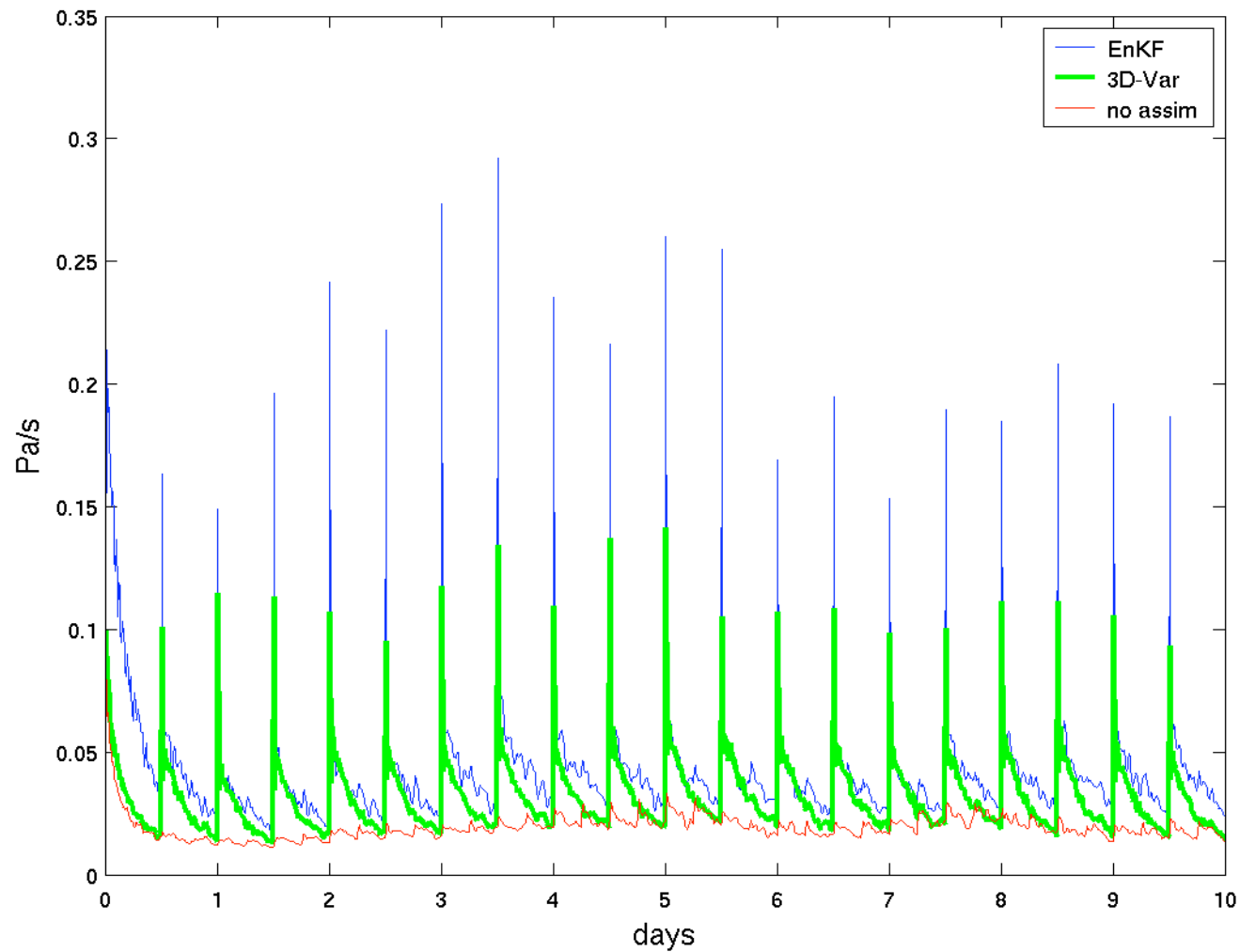


EnKF - AVN geopotential at 500 hPa



EnKF/3DVar Comparison

▷ rms $\partial p_s / \partial t$ as function of t



Conclusions ---

Lateral boundary conditions

- ▷ BC perturbations from 'exterior' EnKF preferred, but not essential
- ▷ scaled perturbations drawn (randomly) from 3DVar background covariances and from climatology both perform acceptably

Comparison with 3DVar

- ▷ in OSSEs, EnKF analysis errors 20–30% smaller than for 3DVar
- ▷ for real obs, EnKF obs-minus-forecast diffs noticeably smaller
- ▷ balance of increments comparable to 3DVar

Why the EnKF? ---

Ensemble-based covariance model requires few assumptions

- ▷ appears to be applicable to variety of scales and domains with relatively little tuning
- ▷ e.g. convective scales (Snyder and Zhang 2003; Dowell et al. 2004; Caya et al. 2005)

A flexible research tool

- ▷ easy to implement and maintain—no adjoints needed for model or obs operators
- ▷ basic parallelization is straightforward
- ▷ easily accomodates nested-grid models
- ▷ facilitates use of unconventional obs

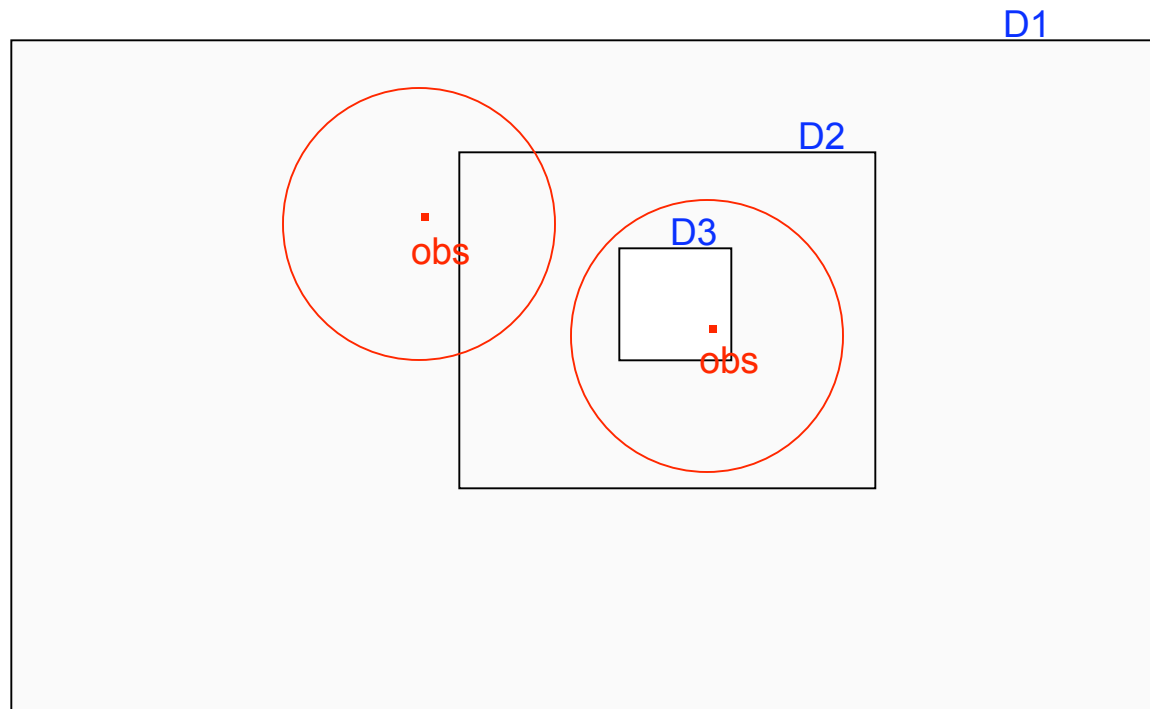
Basis for a unified EF/DA system

- ▷ provides estimates of analysis and forecast uncertainty

EnKF Analyses Across Multiple Domains _____

Have implemented EnKF for multiple, nested domains

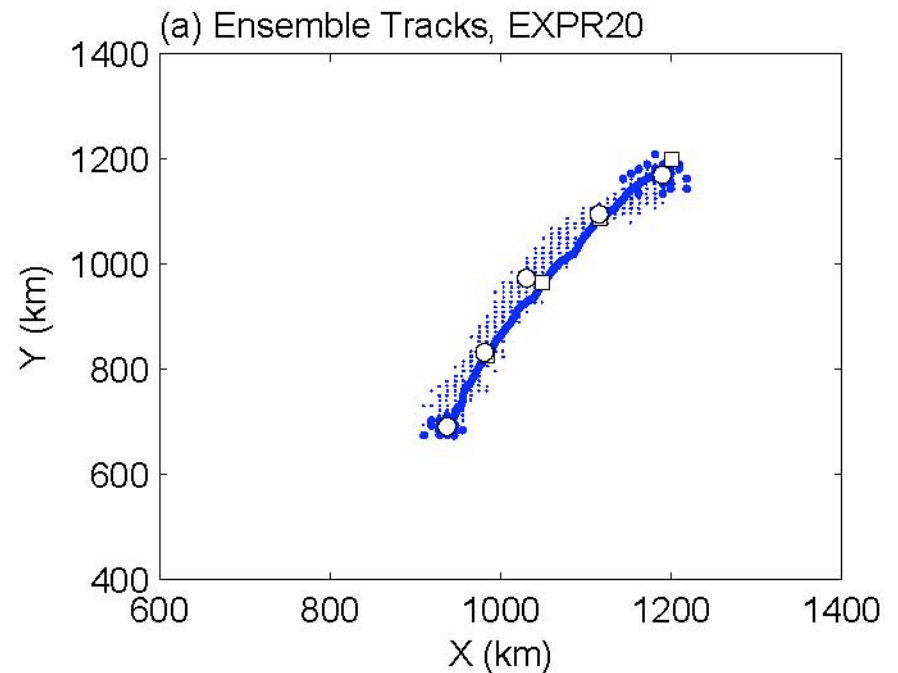
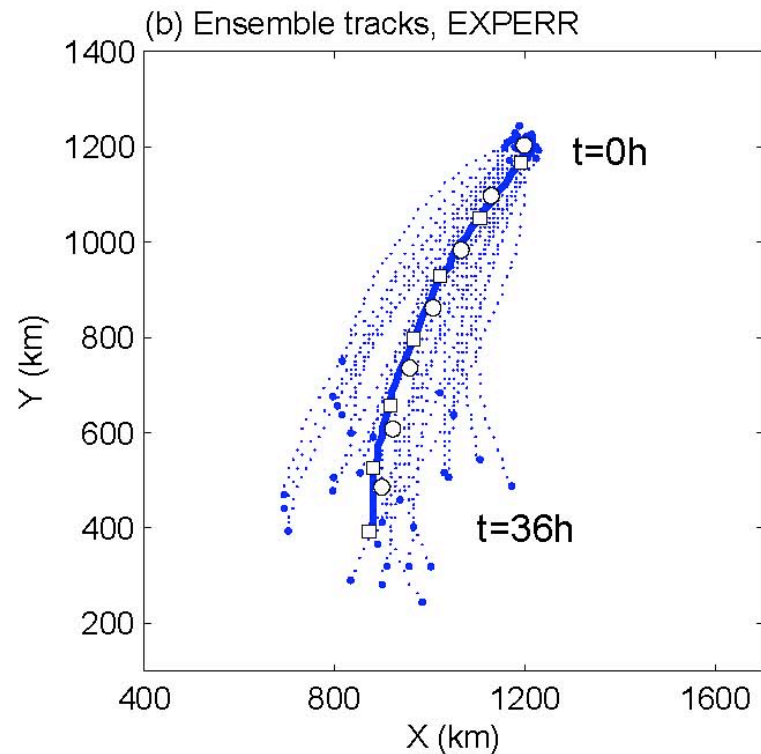
- ▷ innovations calculated using finest available grid
- ▷ all grid points w/in localization radius are updated
- ▷ minor extension to code



Assimilation of Vortex Position

Have frequent obs of hurricane position

- ▷ analyzed vortex should be consistent with these
- ▷ to use in EnKF, simply need “position” operator

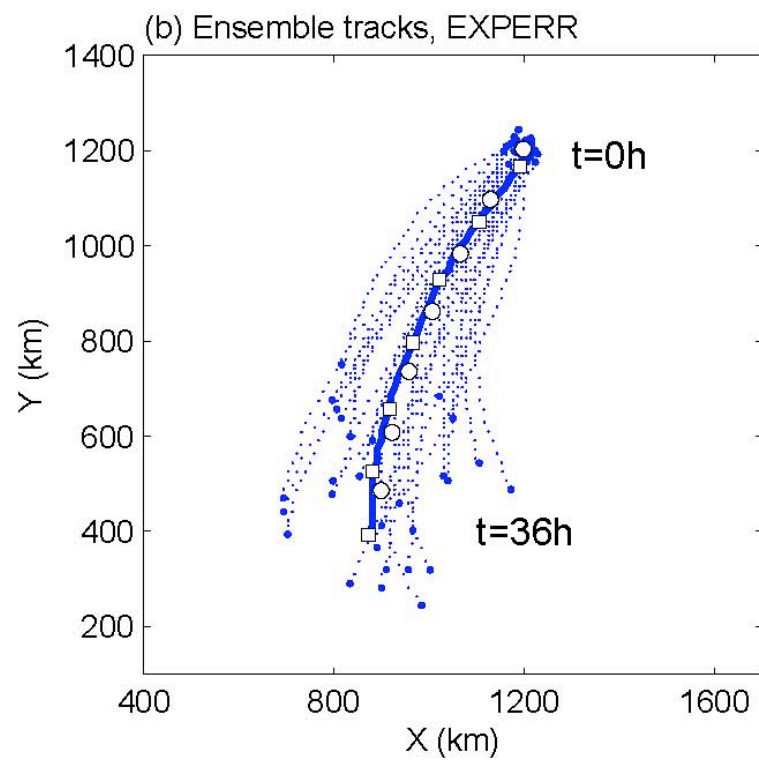
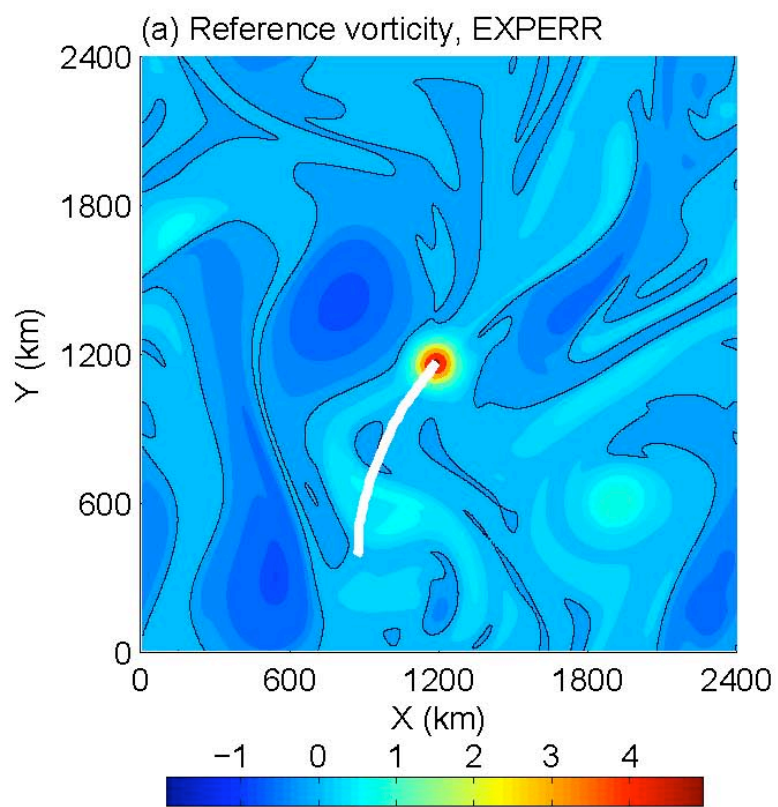


Courtesy of Yongsheng Chen (MMM)

<http://box.mmm.ucar.edu/individual/snyder/Papers/ChenSnyder2005.pdf>

References

- Snyder, C. and F. Zhang, 2003: Assimilation of simulated Doppler radar observations with an ensemble Kalman filter. *Mon. Wea. Rev.*, **131**, 1663–1677.
- Bengtsson T., C. Snyder, and D. Nychka, 2003: Toward a nonlinear ensemble filter for high-dimensional systems. *J. Geophys. Research*, **108(D24)**, 8775–8785.
- Zhang, F., C. Snyder and J. Sun, 2004: Impacts of initial estimate and observations on convective-scale data assimilation with an ensemble Kalman filter. *Mon. Wea. Rev.*, **132**, 1238–1253.
- Dowell, D., F. Zhang, L. Wicker, C. Snyder and N. A. Crook, 2004: Wind and thermodynamic retrievals in the 17 May 1981 Arcadia, Oklahoma supercell: Ensemble Kalman filter experiments. *Mon. Wea. Rev.*, **132**, 1982–2005.
- Caya, A., J. Sun and C. Snyder, 2005: A comparison between the 4D-Var and the ensemble Kalman filter techniques for radar data assimilation. *Mon. Wea. Rev.*, accepted.
- Torn, R. D., G. J. Hakim, and C. Snyder, 2005: Boundary conditions for limited-area ensemble Kalman filters. *Mon. Wea. Rev.*, submitted.
- Chen, Y., and C. Snyder, 2005: Assimilating vortex position with an ensemble Kalman filter. *Mon. Wea. Rev.*, to be submitted.



Testing of Lateral BC schemes _____

Assimilate simulated observations, assume perfect model

- ▷ CONUS domain
- ▷ observations of column dry-air mass ($\sim p_s$)

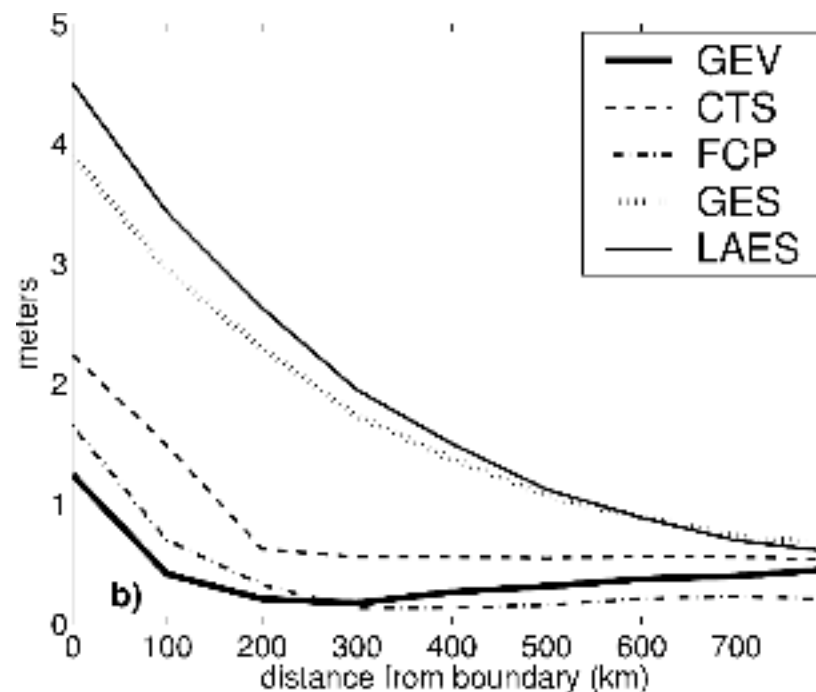
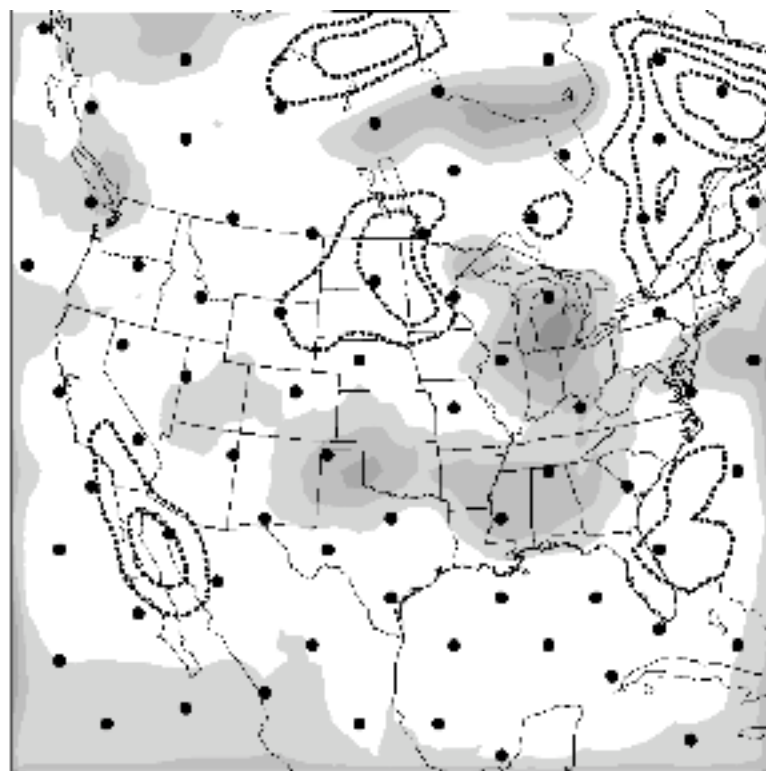
EnKF on larger domain provides standard of reference

Compare: ensemble BCs from larger-domain EnKF, from 3DVar perturbations, and from climatological perturbations

See Torn, Hakim and Snyder (2005)

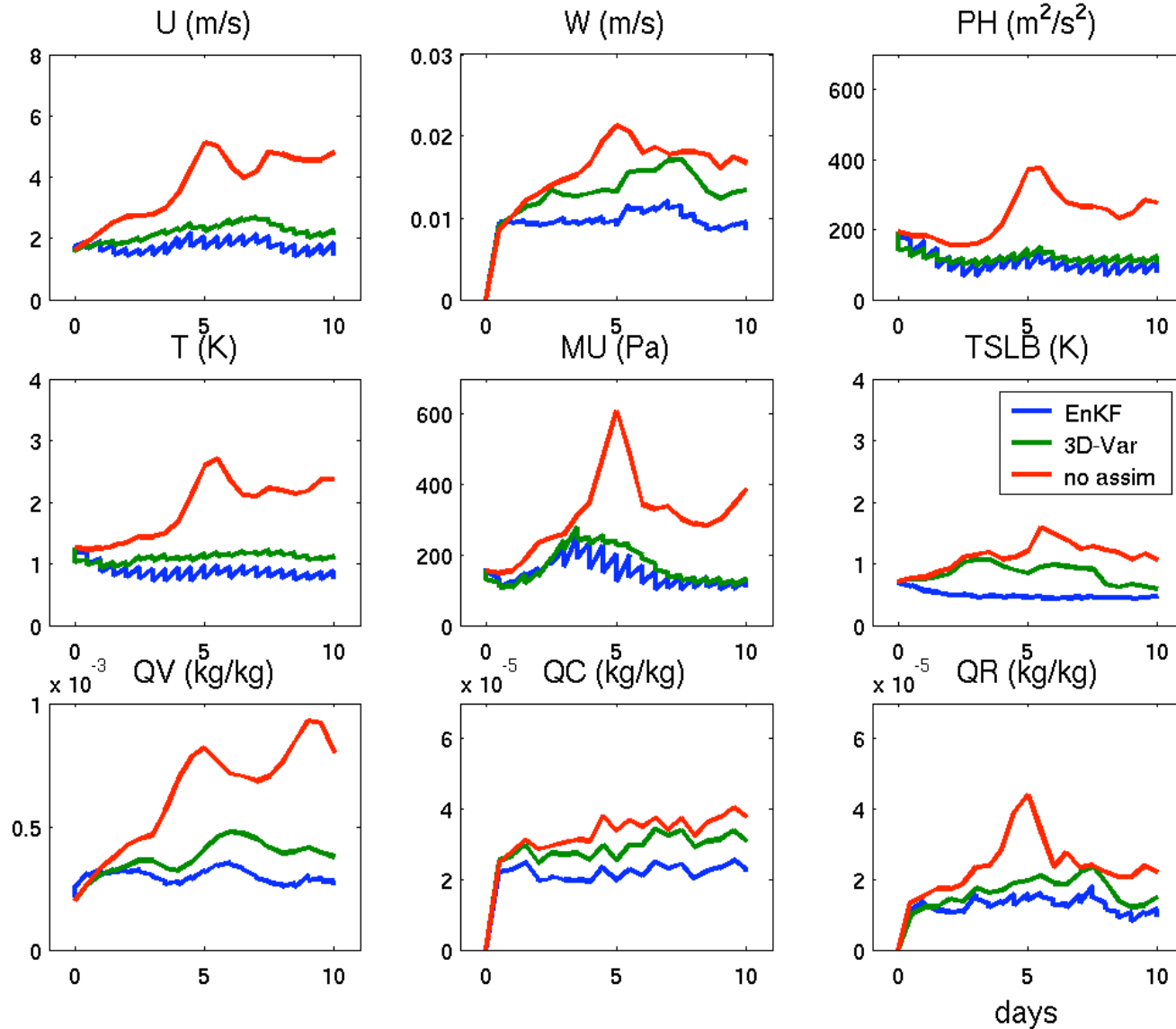
Testing of Lateral BC schemes

- ▷ (left) Difference in time-averaged, rms height error at 500 mb between large-domain EnKF and EnKF with 3DVar LBC perturbations
- ▷ (right) As above, but summed over all grid points a given distance from the boundary and for various LBC schemes



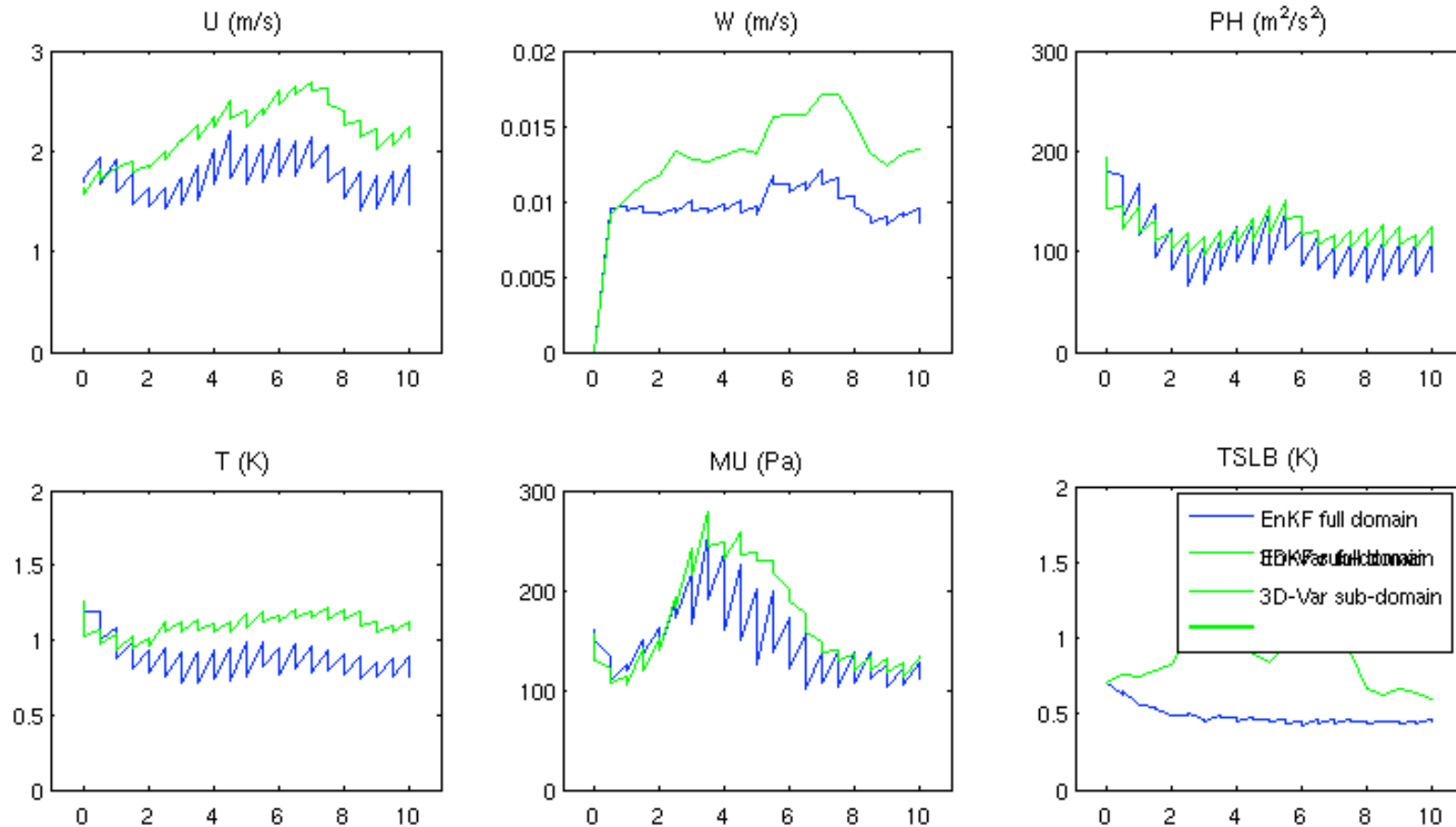
EnKF/3DVar Comparison

▷ rms errors (both first guess and analysis) over entire domain



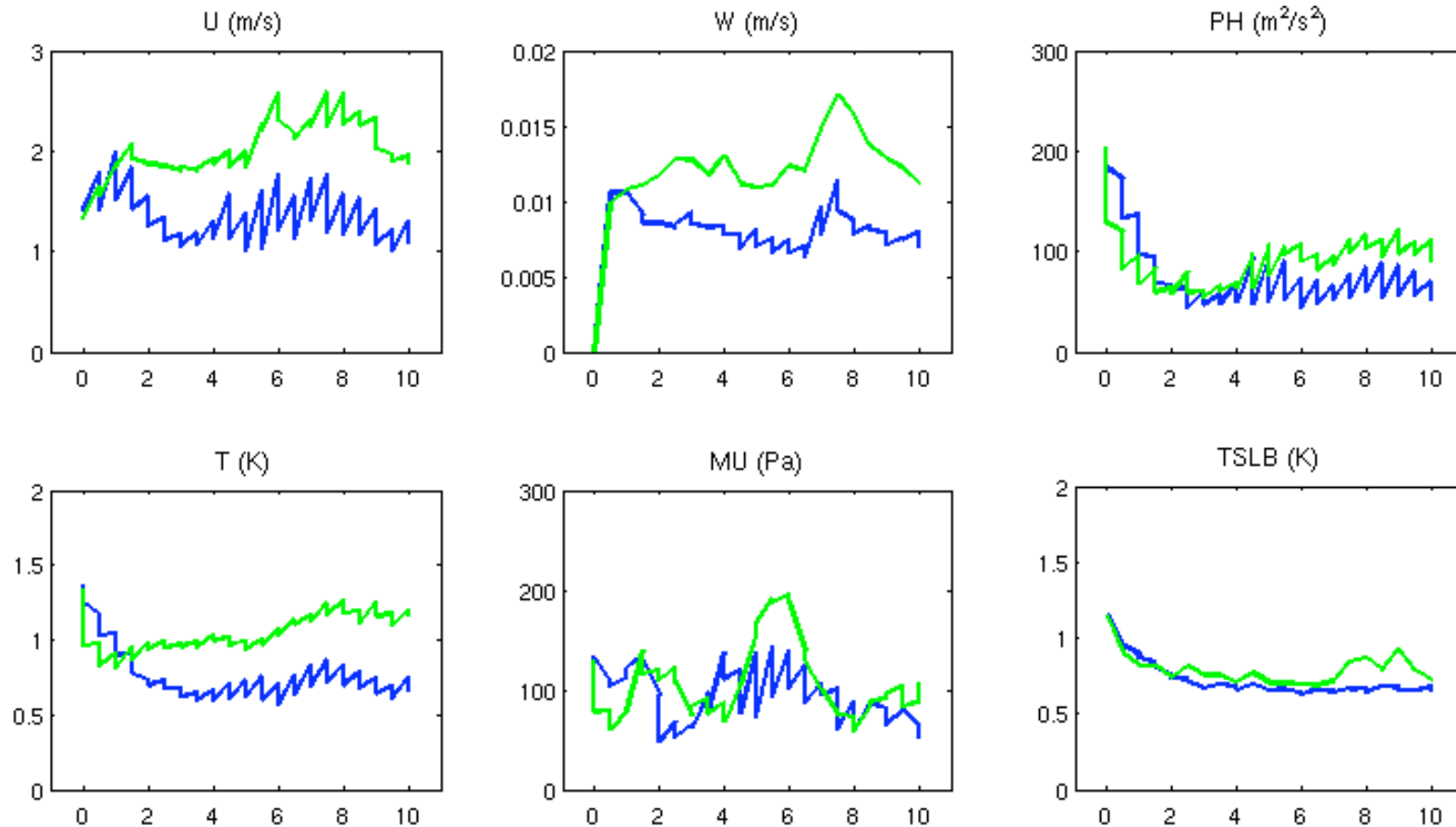
EnKF/3DVar Comparison

▷ rms errors on inner 1/4 of domain



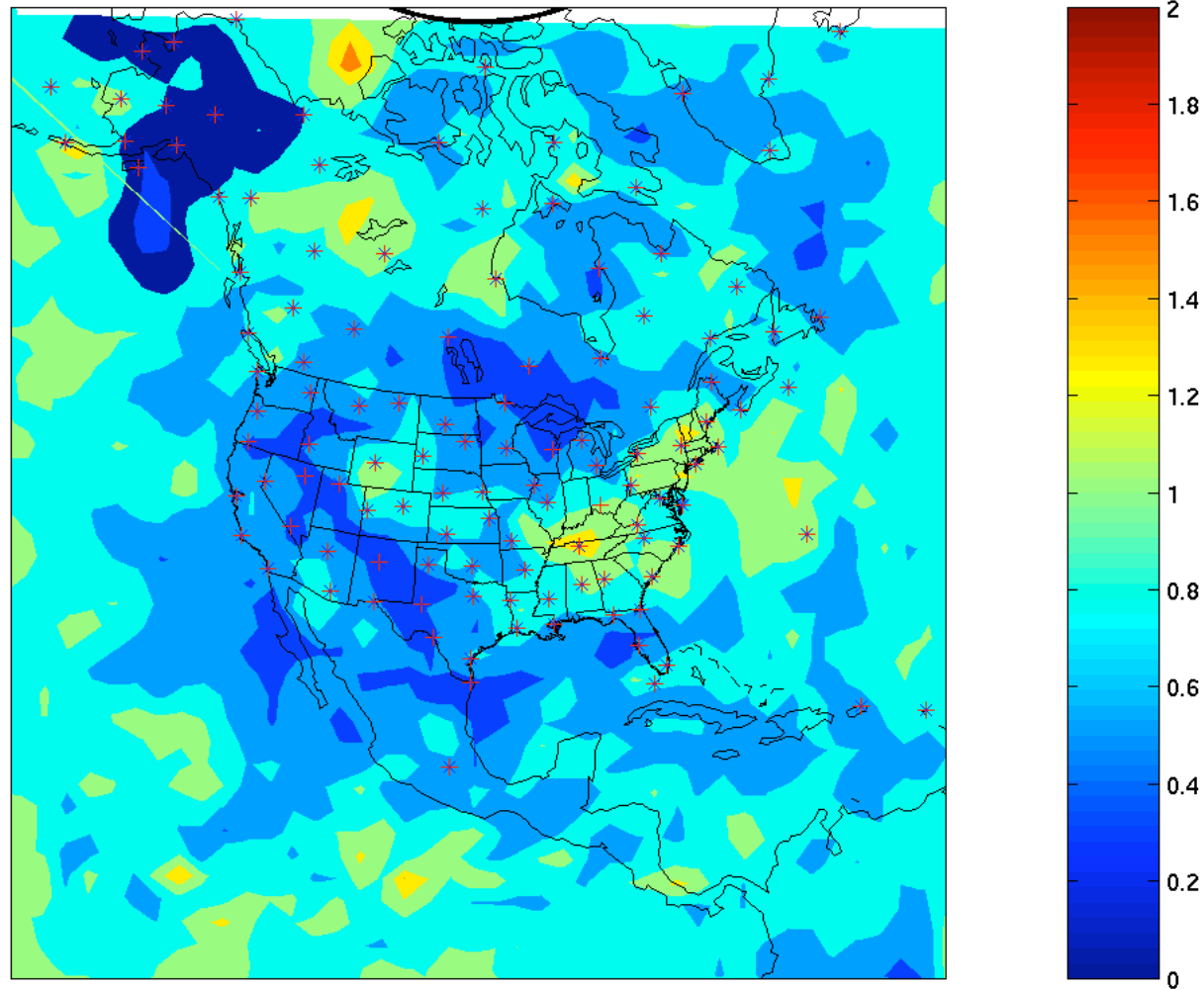
EnKF/3DVar Comparison

▷ rms errors on inner 1/4 of domain



EnKF/3DVar Comparison

- ▷ Ratio of time-av'd EnKF rms T error to that of 3DVar at 500 mb



Details

Lateral BC experiments

- ▷ experiment extends over 15 days
- ▷ 100 km grid spacing
- ▷ 250 μ obs, spaced roughly every 500 km
- ▷ obs assimilated every 6 h
- ▷ truth run initialized with NCEP GFS analysis from 18 UTC 18 March 2003, and uses lateral BCs from subsequent GFS analyses
- ▷ 100 members in EnKF
- ▷ covariance localization of 3000 km

Details

3DVar comparisons

- ▷ experiment extends over 10 days
- ▷ 200 km grid spacing
- ▷ obs are columns of u , v , T at locations of NA radiosondes, every 12 h
- ▷ 40 members in EnKF
- ▷ covariance localization of 2500 km
- ▷ construct ICs for 41 ensemble members by adding 3DVar perturbations to GFS analysis from 00 UTC 1 January 2003; thus, 1st EnKF analysis approximates 1st 3DVar analysis.
- ▷ construct ensemble of 41 lateral BCs by adding climatological perturbations scaled by 0.2 to subsequent GFS analyses
- ▷ truth run uses 41st IC and lateral BCs

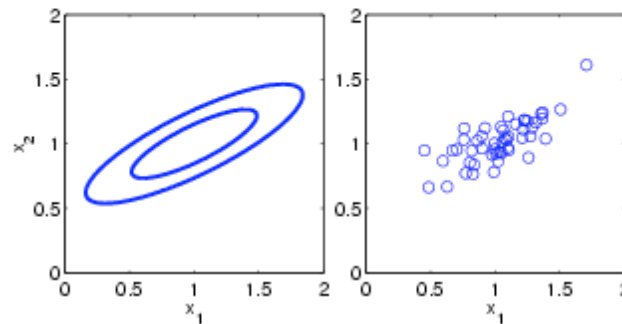
Initializing “True” State and Ensemble

- Construct N+1 initial states
 - AVN analysis (1 Jan 03) + perturbations drawn randomly from 3DVar covariances
- Construct N+1 lateral BC's
 - AVN analyses (1-10 Jan 03) + perturbations
 - Perturbations are deviations from Jan climatology, scaled by 0.2
- EnKF uses first N initial states and LBCs; true state use N+1st
 - Ensemble and true state drawn from same pdf

The Ensemble Kalman Filter (EnKF) ---

Monte-Carlo approach

- ▷ work with samples rather distributions



Sequential method: given ensemble at $t = t_k$,

- ▷ forecast each member to t_{k+1} , time of next observations
- ▷ update each member at t_{k+1}
- ▷ continue as above, from $t = t_{k+1}$

10-day average of rms surface pressure tendency

