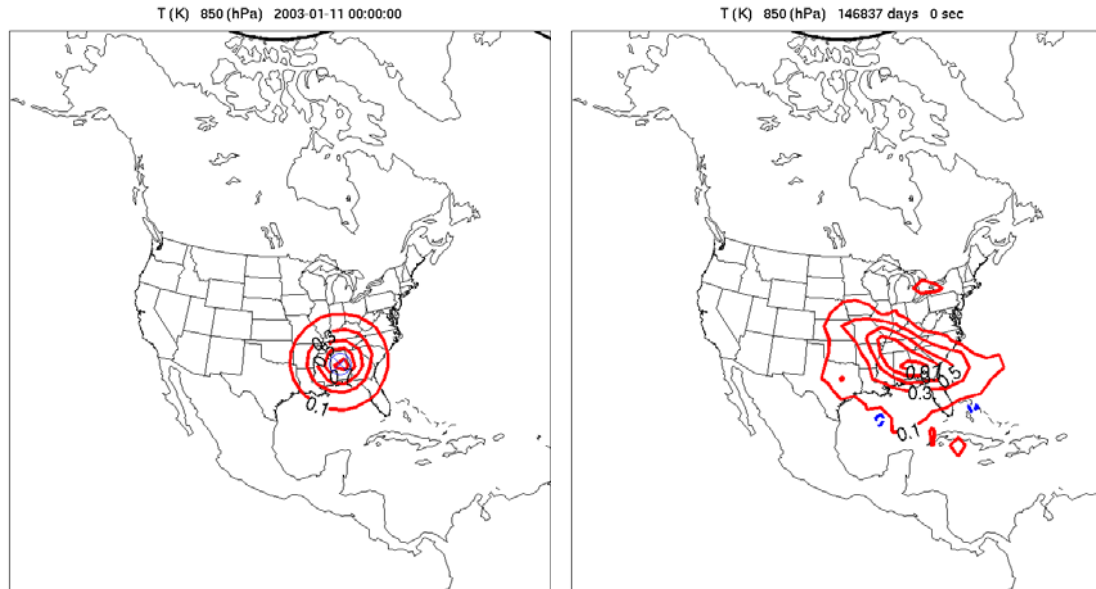


Ensemble Kalman filters for WRF



- ▷ Chris Snyder (MMM and Data Assimilation Initiative)
- ▷ Alain Caya, Jeff Anderson (DAI)
- ▷ Bill Skamarock, Dale Barker (MMM)
- ▷ Greg Hakim, Ryan Torn (U Washington)
- ▷ David Dowell (NSSL), Fuqing Zhang (Texas A&M)

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

Uses “flow dependent” forecast-error covariances

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

EnKFs for WRF

Presently, 3 implementations at different institutions

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

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

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

Issues for this talk

- ▷ How to handle lateral BCs in forecast step?
- ▷ How does EnKF compare with 3DVar?
- ▷ EnKF for convective scales

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

Possible approaches for ensemble BCs

- ▷ ensemble from EnKF on larger domain ('exterior' EnKF)
- ▷ draw BC perturbations from Gaussian with 3DVar covariances
- ▷ draw (scaled) perturbations from climatology
- ▷ other ad hoc approaches

Testing of Lateral BC schemes _____

Assimilate simulated observations, assume perfect model

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

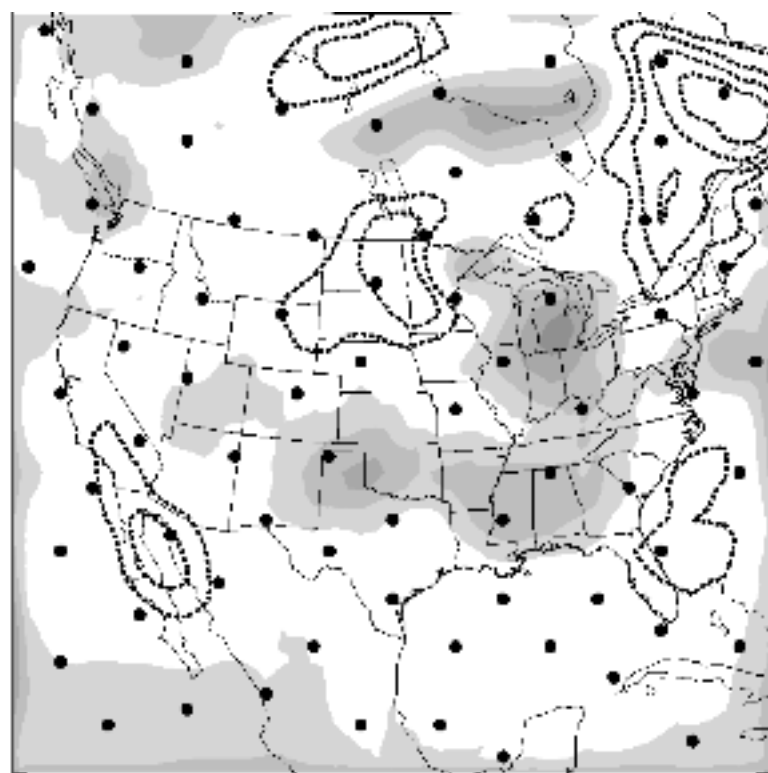
EnKF on larger domain provides standard of reference

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

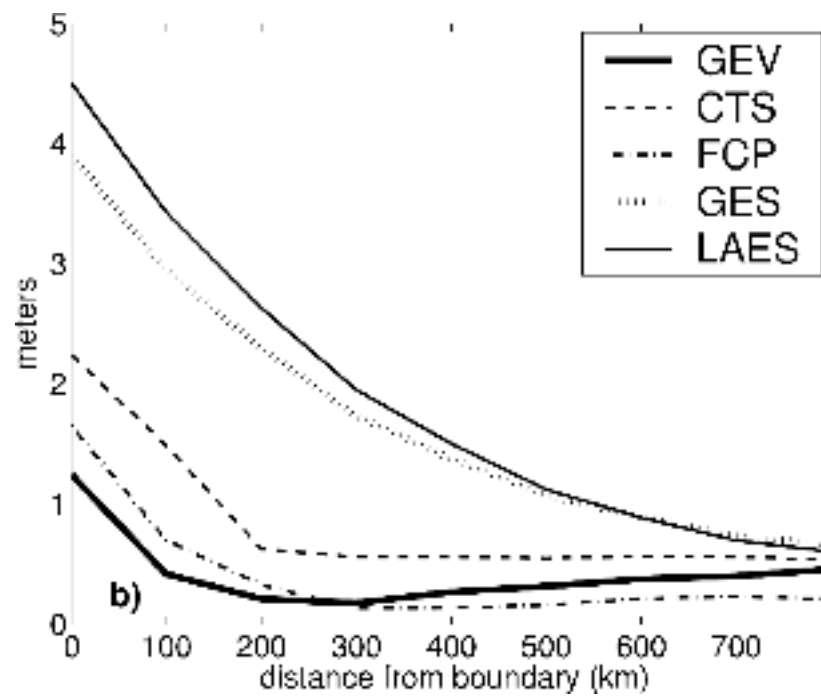
See Torn, Hakim and Snyder (2005)

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



a) 



EnKF/3DVar Comparison ---

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)?

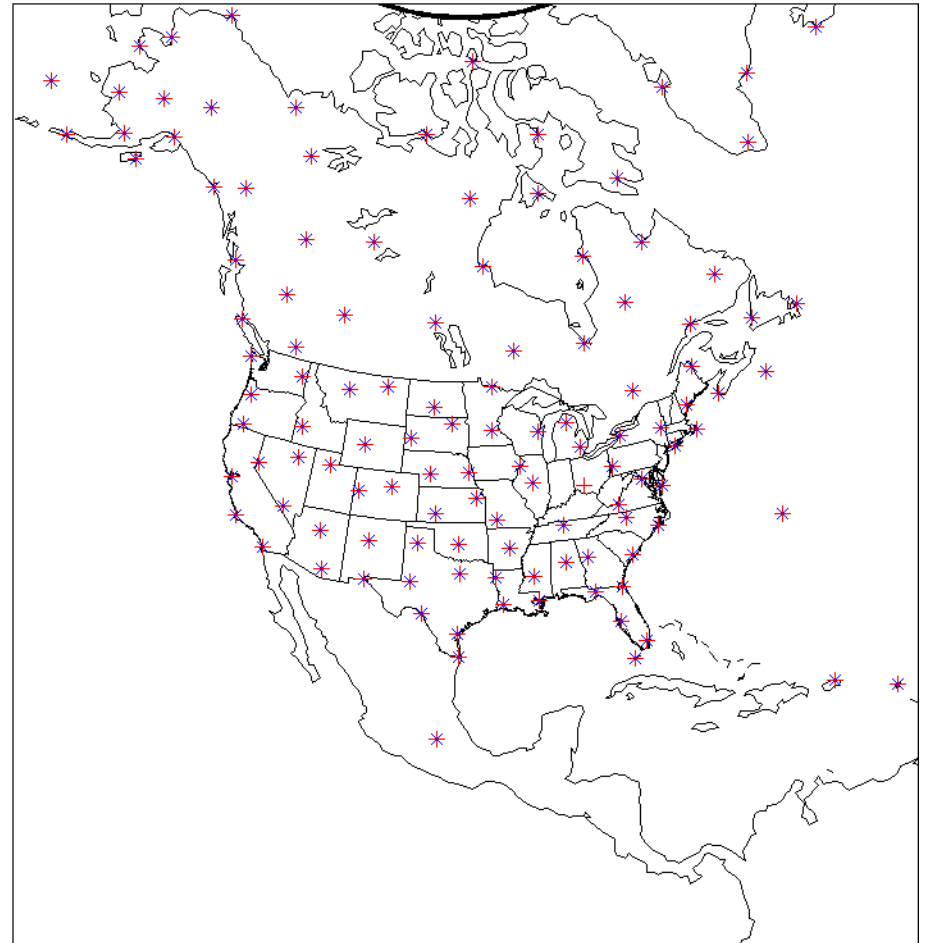
Consider synoptic scales, CONUS domain

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

Compare using same model (WRF), same obs

Experimental Design

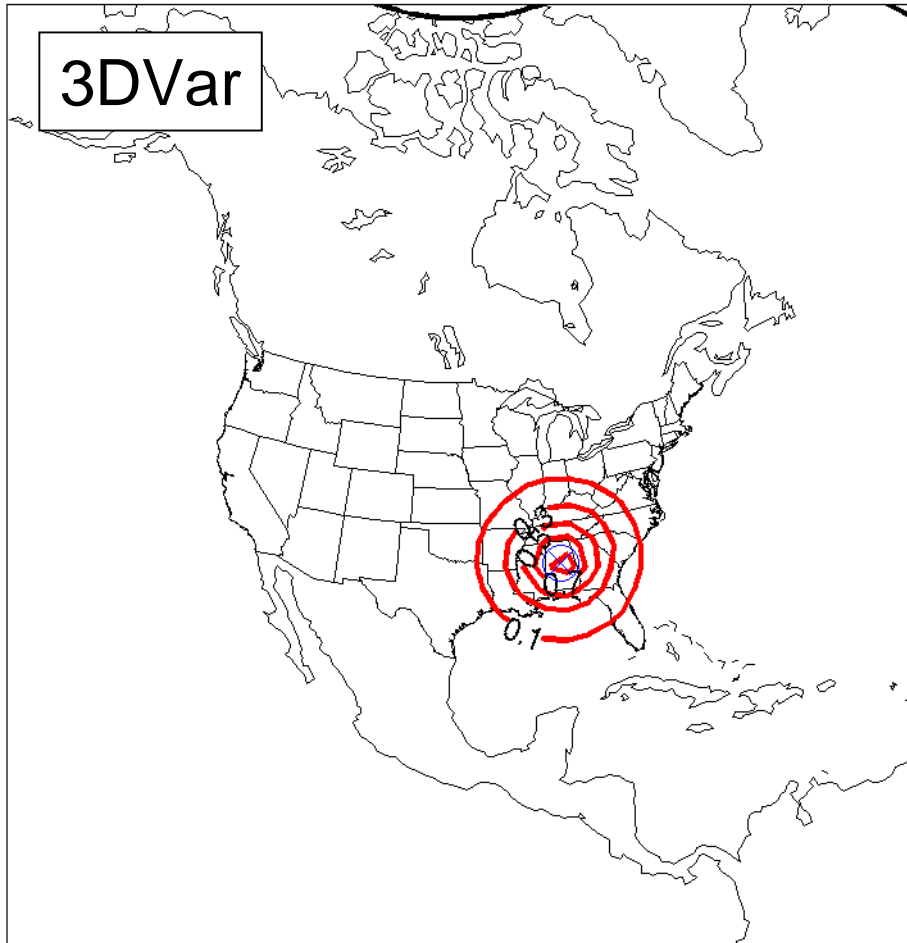
- ▷ again, consider simulated observations and perfect model
- ▷ obs are radiosondes, with u , v , T at mandatory levels every 12 h
- ▷ domain and obs locations shown at right



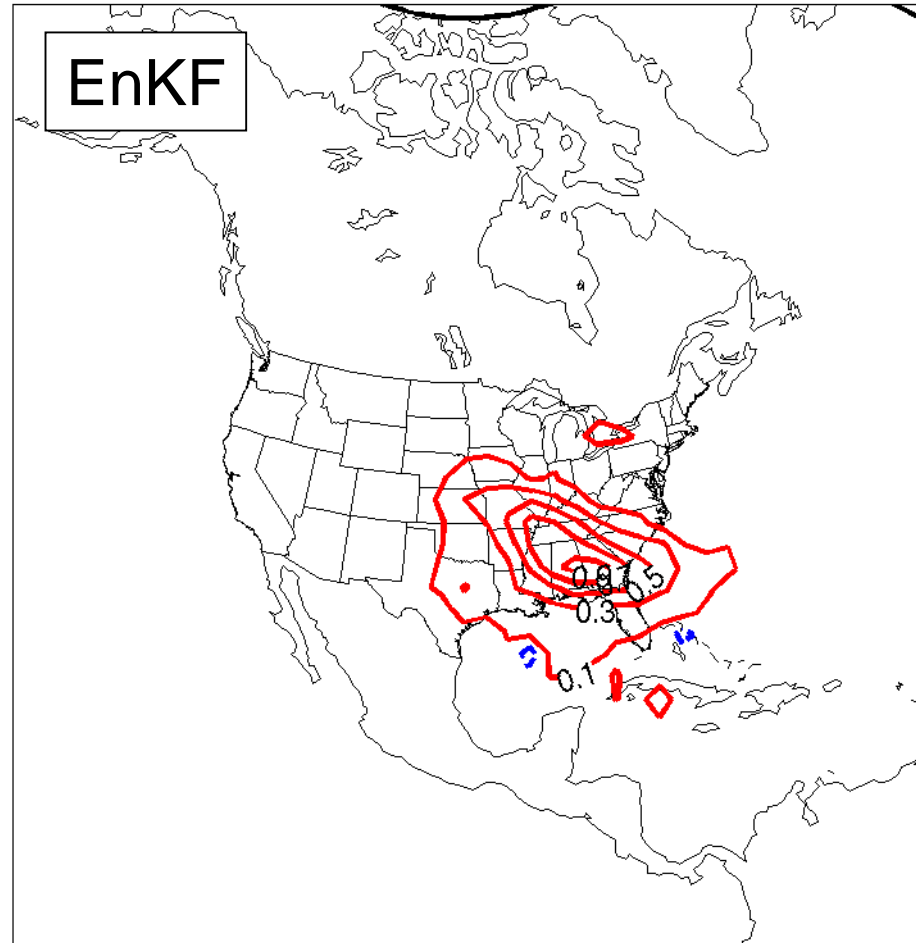
EnKF/3DVar Comparison

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

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

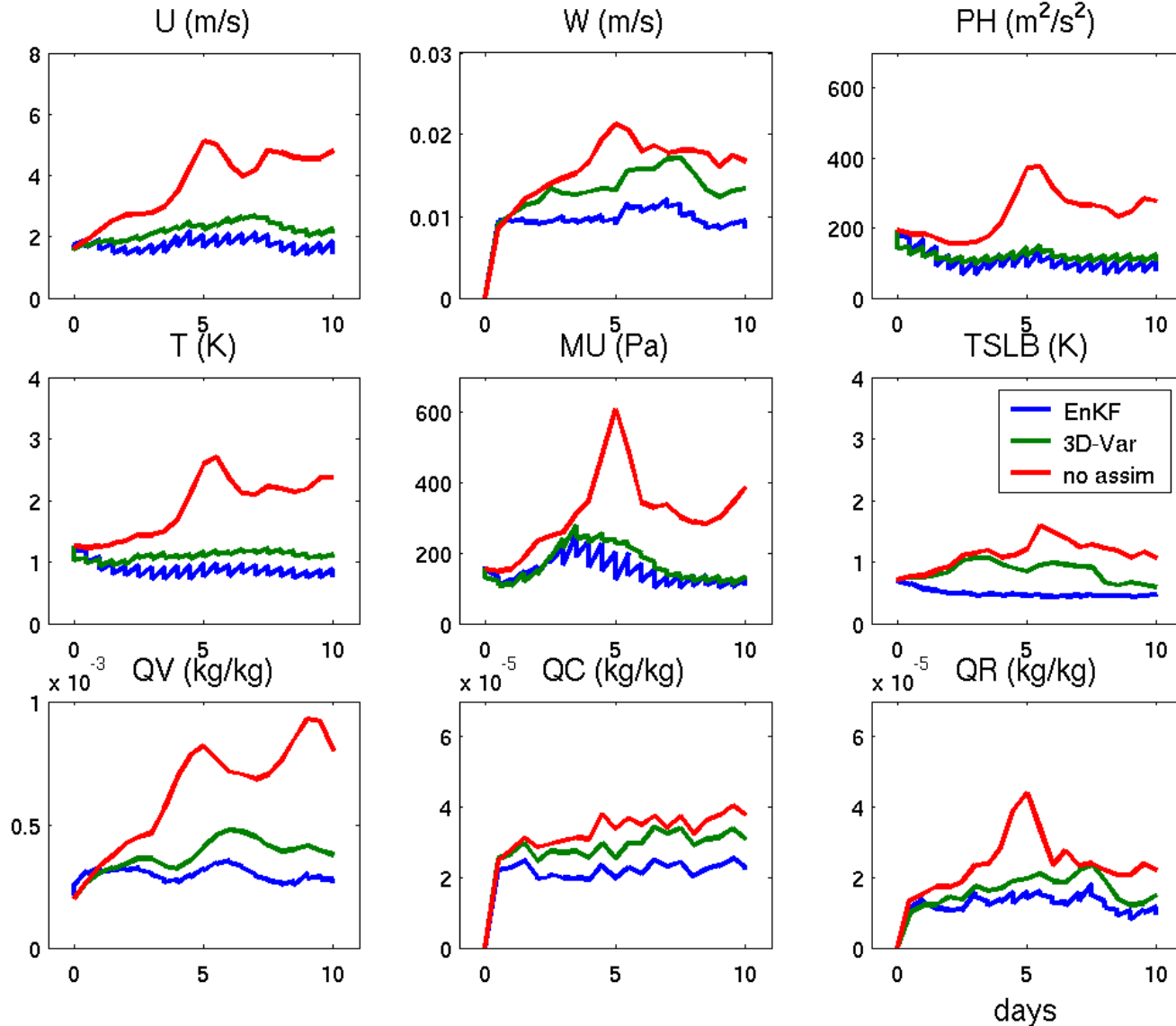


T (K) 850 (hPa) 146837 days 0 sec



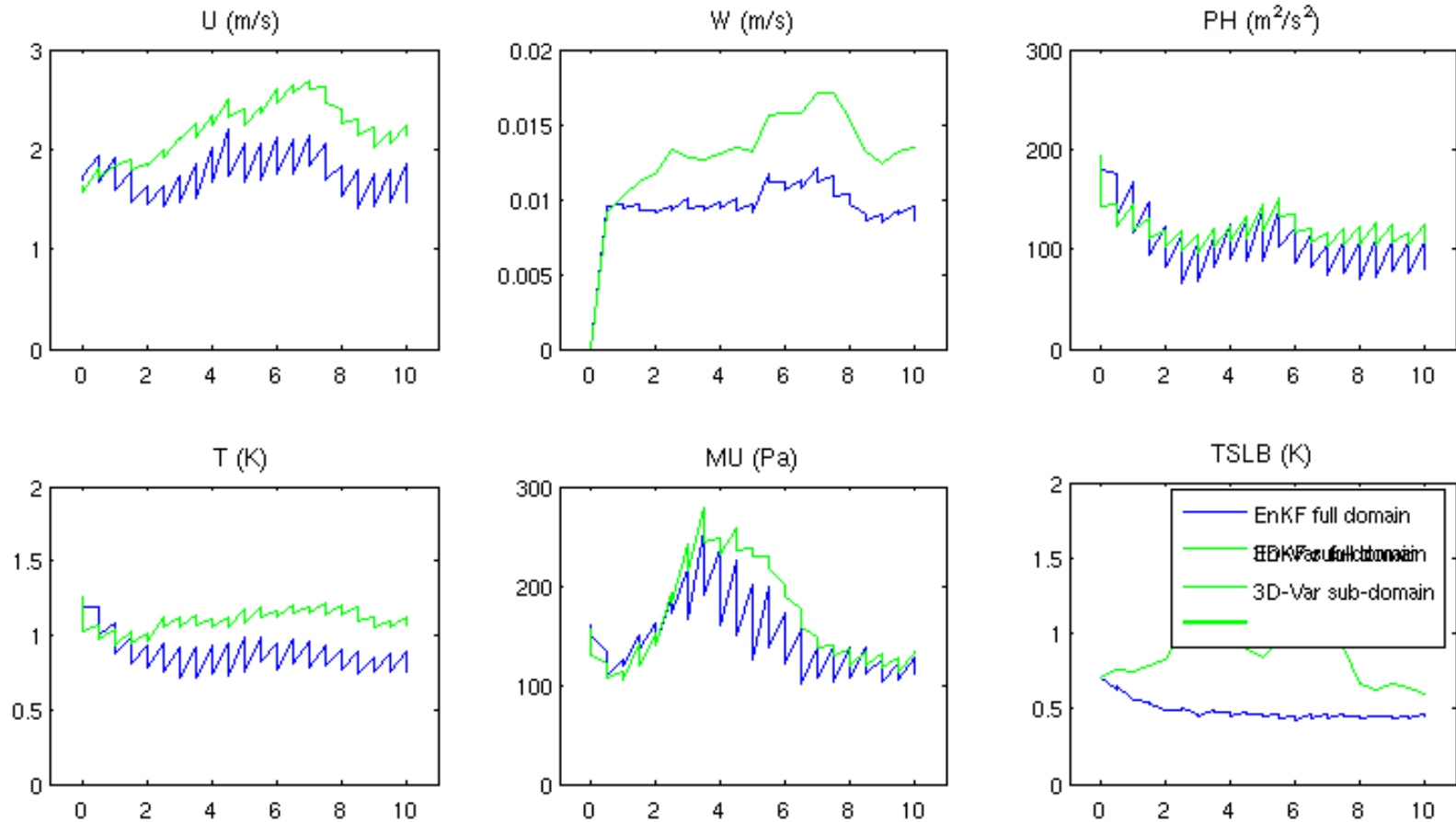
EnKF/3DVar Comparison

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



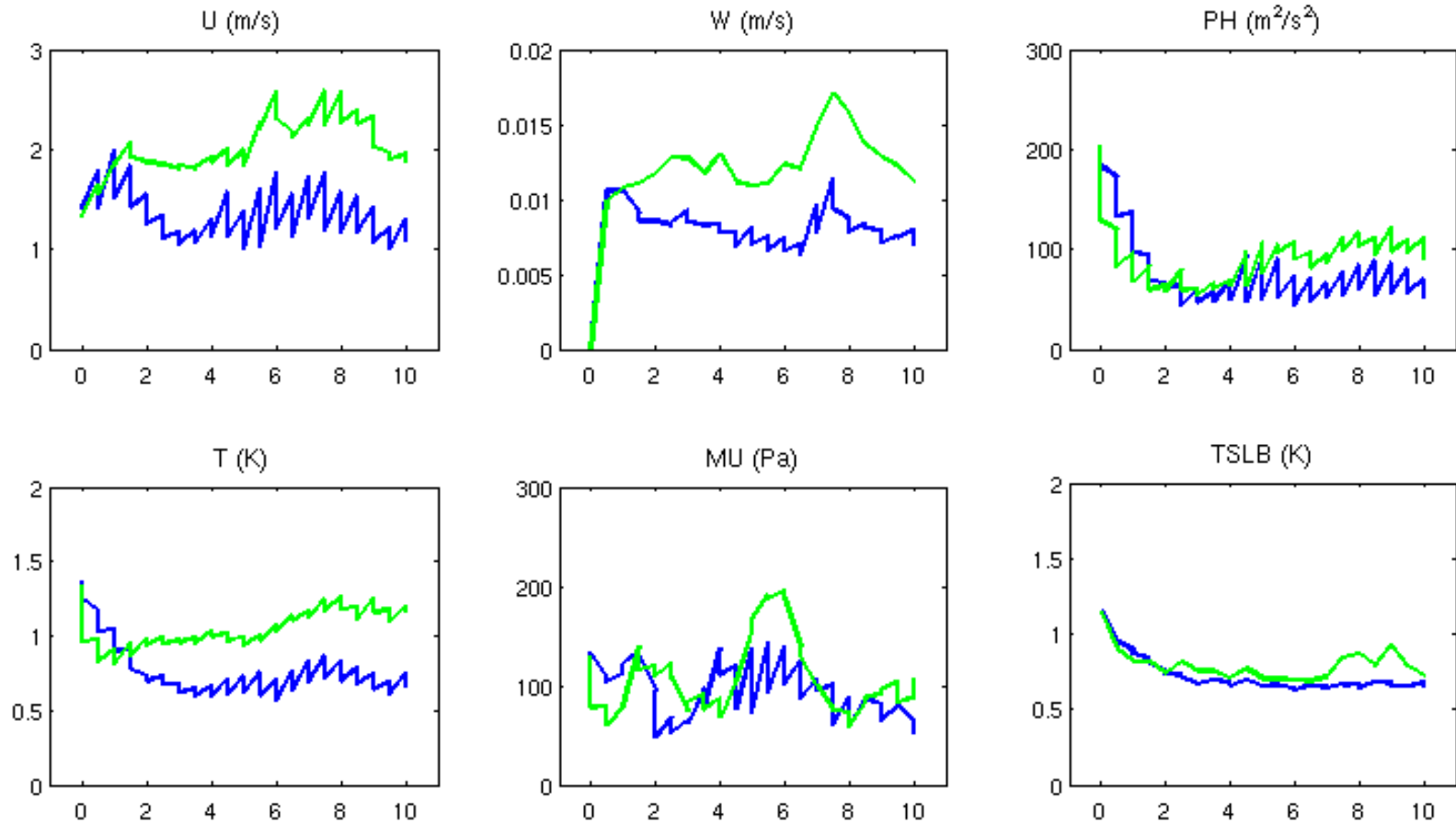
EnKF/3DVar Comparison

▷ rms errors on inner 1/4 of domain



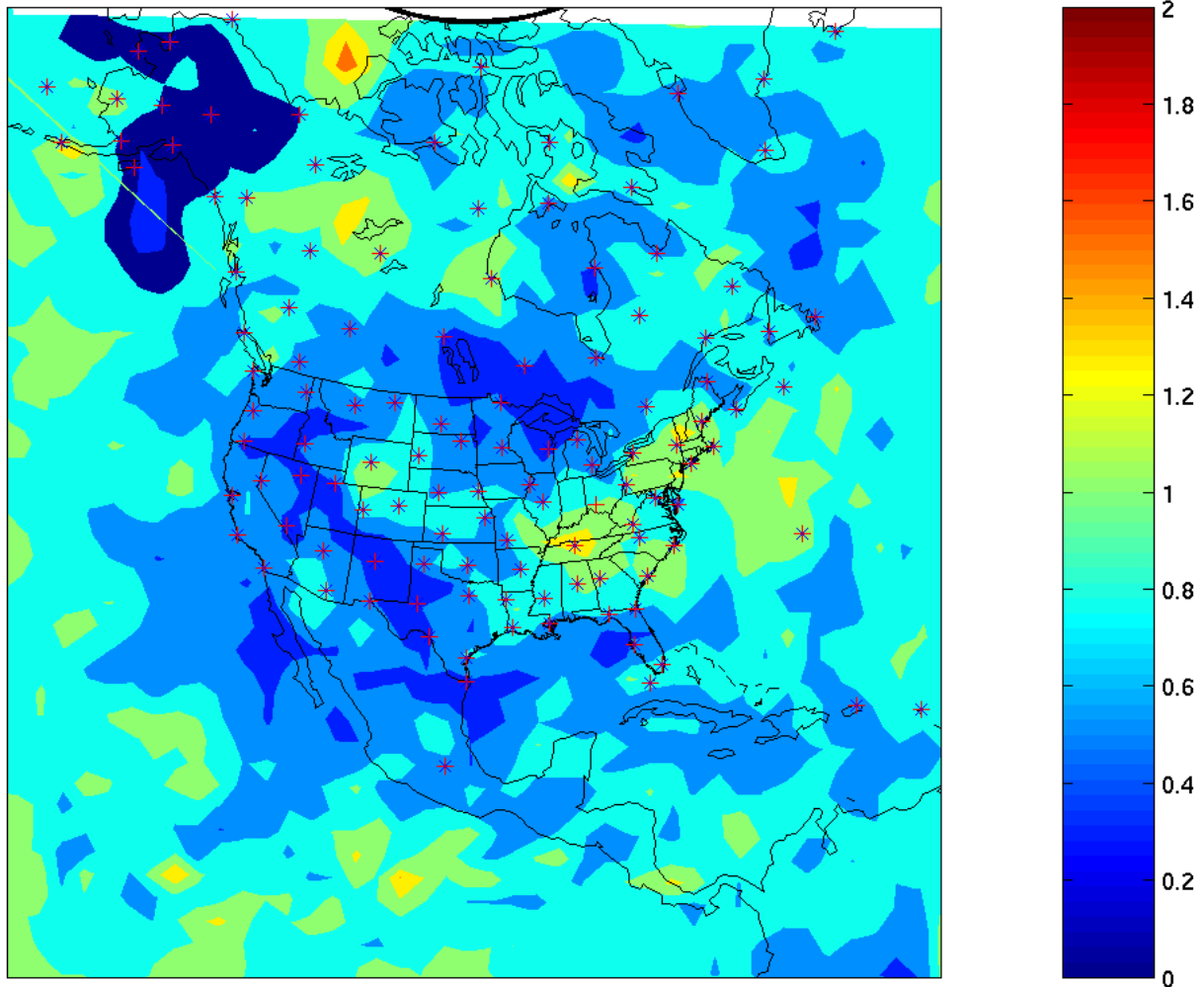
EnKF/3DVar Comparison

▷ 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



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

- ▷ OSSE for synoptic-scale flow
- ▷ EnKF analysis errors 20–30% smaller than those of 3DVar
- ▷ Advantage of EnKF increases with distance from lateral boundaries.

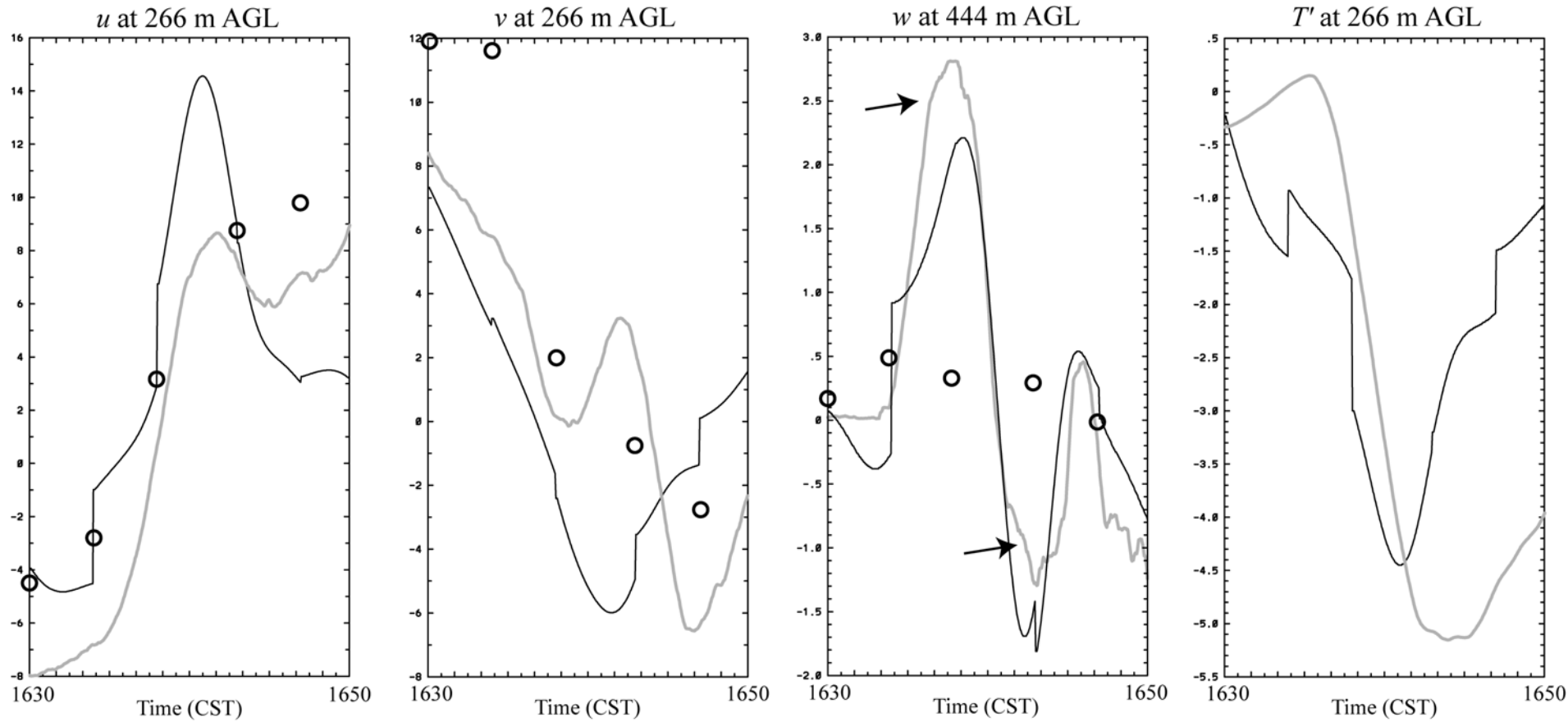
EnKF for Convective Scales ---

Present status

- ▷ proof of concept with simulated supercell (Snyder and Zhang 2003)
- ▷ case study with real radar observations (Dowell et al 2004)
- ▷ comparison with 4DVar (Caya et al 2004)

Comparison Against Tower Observations

▷ obs (grey), EnKF analysis (black), dual-Doppler (circles)



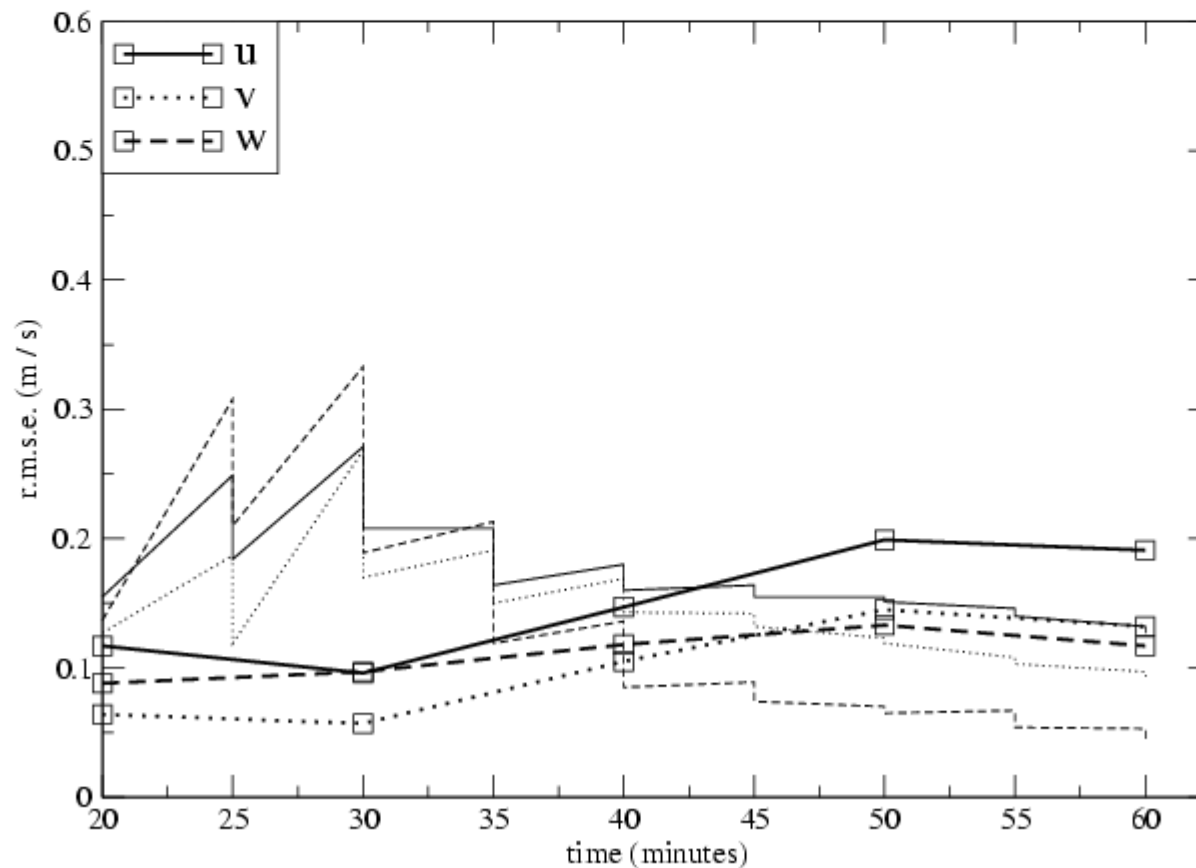
EnKF for Convective Scales ---

Present status

- ▷ proof of concept with simulated supercell (Snyder and Zhang 2003)
- ▷ case study with real radar observations (Dowell et al 2004)
- ▷ comparison with 4DVar (Caya et al 2004)

Comparison with 4DVar

- ▷ rms errors over entire domain; obs of both v_r and reflectivity
- ▷ EnKF (thin) and 4DVar (thick w/ boxes)



EnKF for Convective Scales ---

Present status

- ▷ proof of concept with simulated supercell (Snyder and Zhang 2003)
- ▷ case study with real radar observations (Dowell et al 2004)
- ▷ comparison with 4DVar (Caya et al 2004)

Ongoing work

- ▷ assimilation of reflectivity, particularly low reflectivity
- ▷ further case studies, particularly including mesoscale variability
- ▷ comparisons with WRF variational schemes

Why the EnKF? ---

Ensemble-based covariance model requires few assumptions

A flexible research tool

- ▷ easy to implement and maintain—no adjoints needed
- ▷ appears to be applicable to variety of scales and domains with relatively little tuning
- ▷ basic parallelization is straightforward
- ▷ easily accomodates nested-grid models

Basis for a unified EF/DA system

- ▷ provides estimates of analysis and forecast uncertainty

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, 2004: A comparison between the 4D-Var and the ensemble Kalman filter techniques for radar data assimilation. *Mon. Wea. Rev.*, accepted.

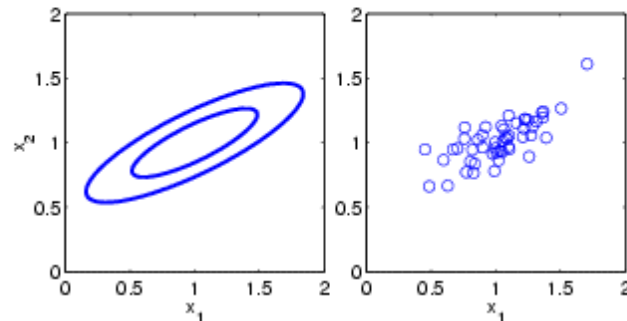
Tong, M. and M. Xue, 2004: Ensemble Kalman filter assimilation of Doppler radar data compressible nonhydrostatic model: OSS experiments. *Mon. Wea. Rev.*, accepted.

Dowell, D., L. J. Wicker, and D. J. Stensrud, 2004: High Resolution analyses of the 8 May 2003 Oklahoma City Storm. Part II: EnKF data assimilation and forecast experiments. *Preprints, 22nd Conference on Severe Local Storms*, Hyannis, MA.

The Ensemble Kalman Filter (EnKF) ---

Monte-Carlo approach

- ▷ work with samples rather distributions

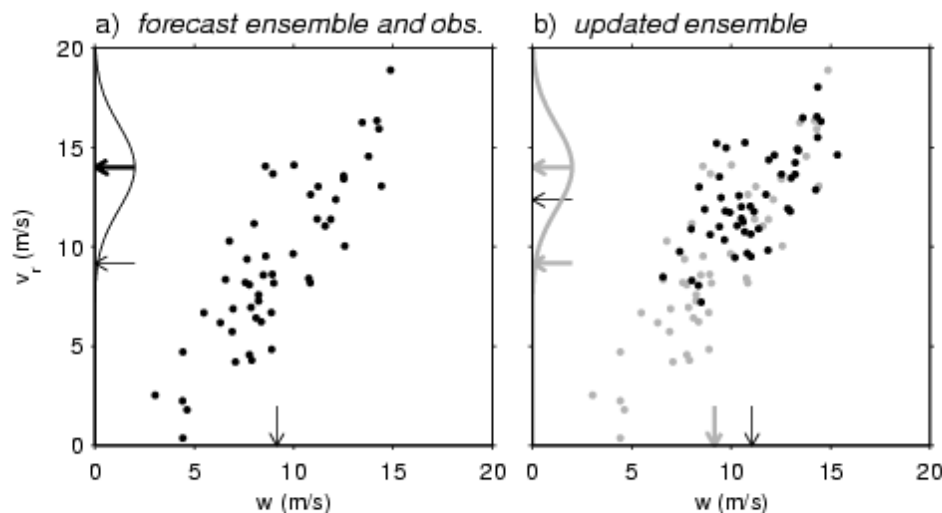


Sequential method: given ensemble at $t = t_k$,

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

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,

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

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

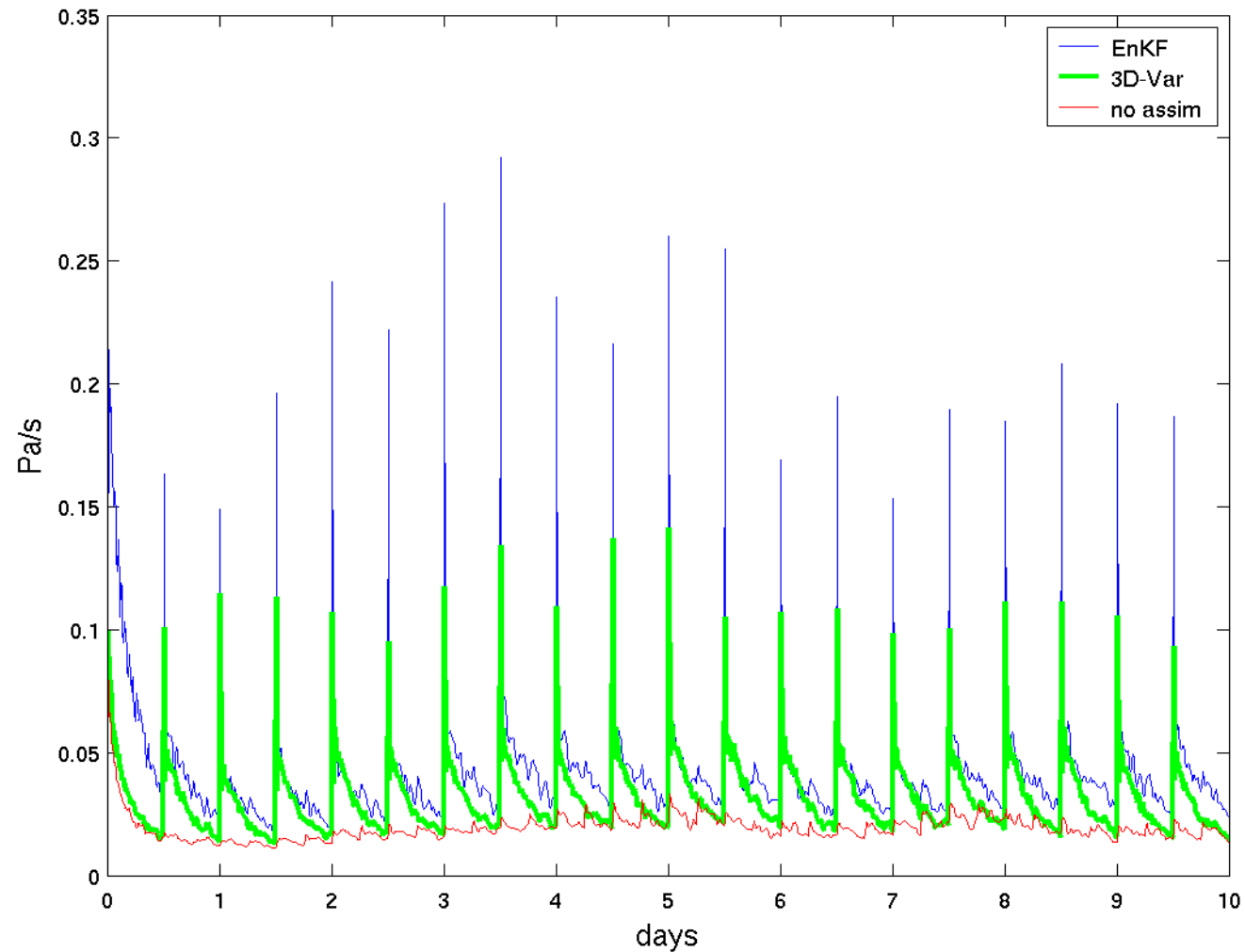
- ▷ experiment extends over 10 days
- ▷ 200 km grid spacing
- ▷ obs are columns of u , v , T at locations of NA radiosondes, every 12 h
- ▷ 40 members in EnKF
- ▷ covariance localization of 2500 km
- ▷ construct ICs for 41 ensemble members by adding 3DVar perturbations to GFS analysis from 00 UTC 1 January 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

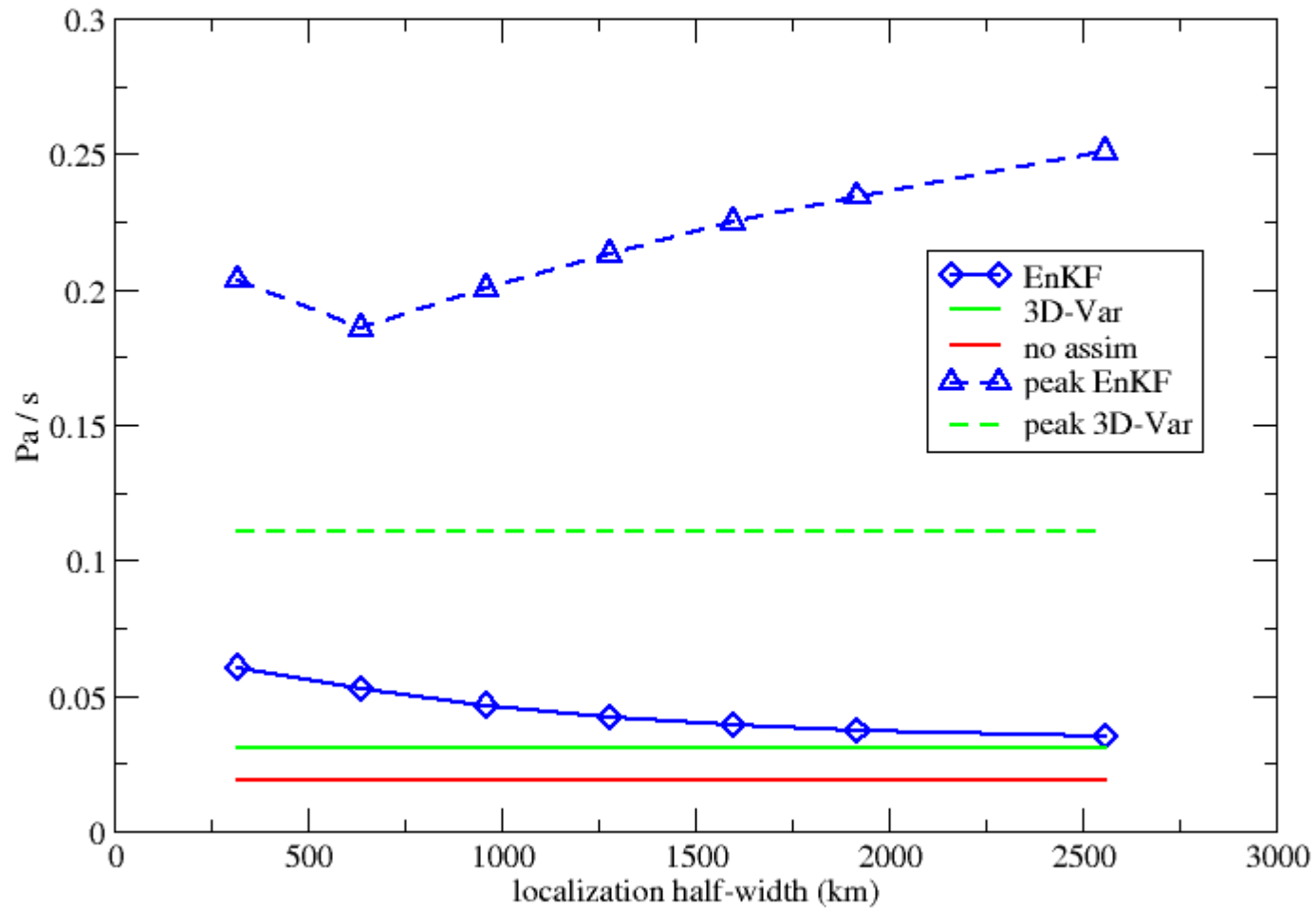
- Construct $N+1$ initial states
 - AVN analysis (1 Jan 03) + perturbations drawn randomly from 3DVar covariances
- Construct $N+1$ lateral BC's
 - AVN analyses (1-10 Jan 03) + perturbations
 - Perturbations are deviations from Jan climatology, scaled by 0.2
- EnKF uses first N initial states and LBCs;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

EnKF/3DVar Comparison

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



10-day average of rms surface pressure tendency



8 May 2003, Oklahoma City Case ---

More advanced radar (KOUN)

- ▷ clear-air observations in PBL

More sophisticated model

- ▷ higher resolution and reduced dissipation
- ▷ four-class microphysical scheme (following LFO)
- ▷ TKE turbulence scheme
- ▷ still ignores mesoscale variations, surface processes

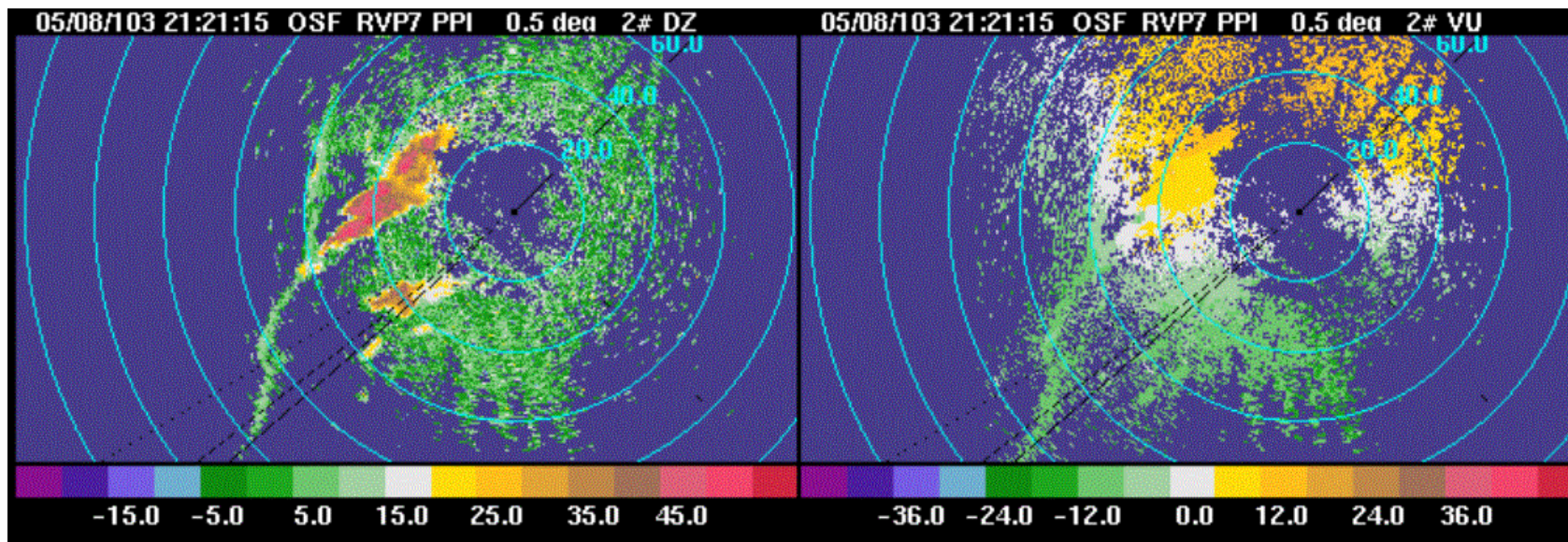
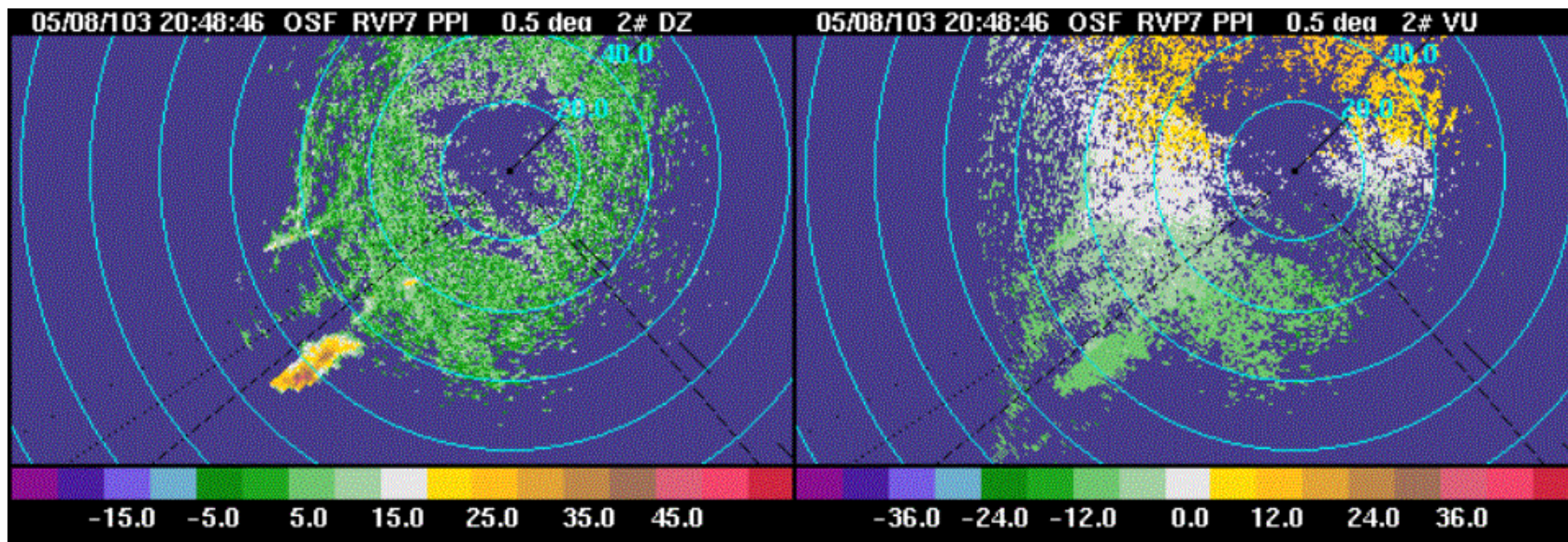
EnKF details

- ▷ 50 members
- ▷ more complete use of reflectivity obs (c.f. Skamarock talk)

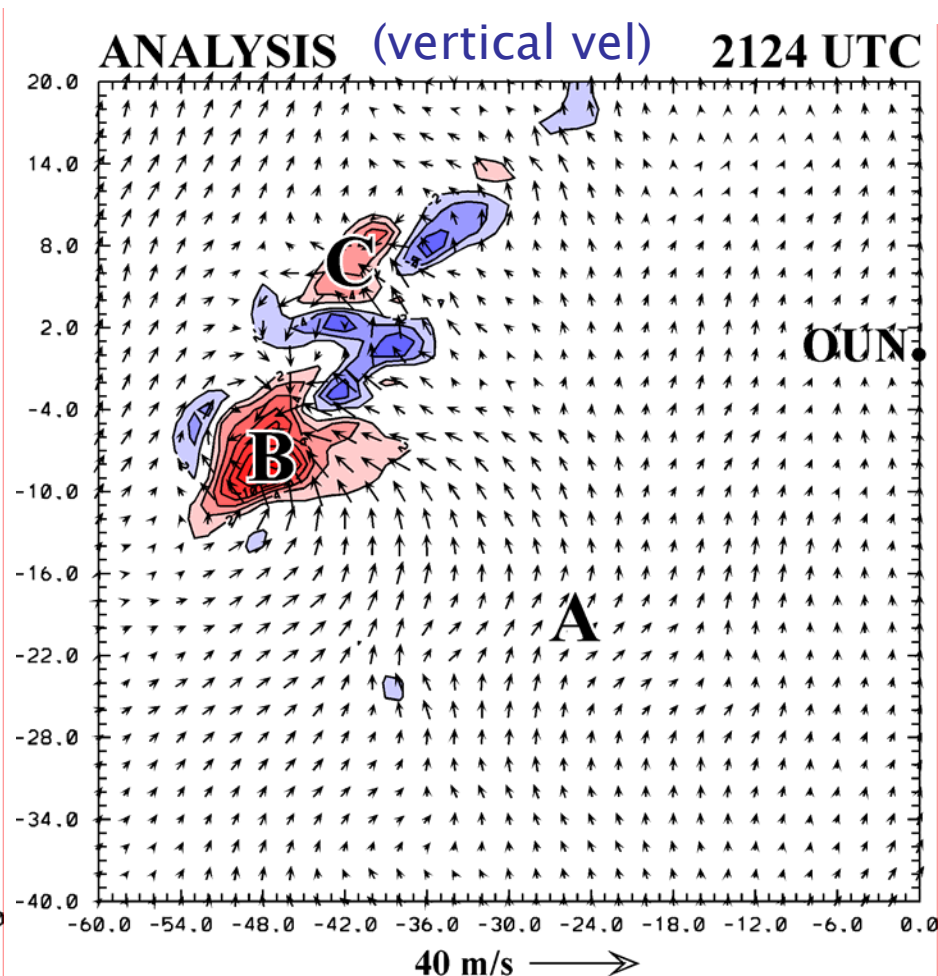
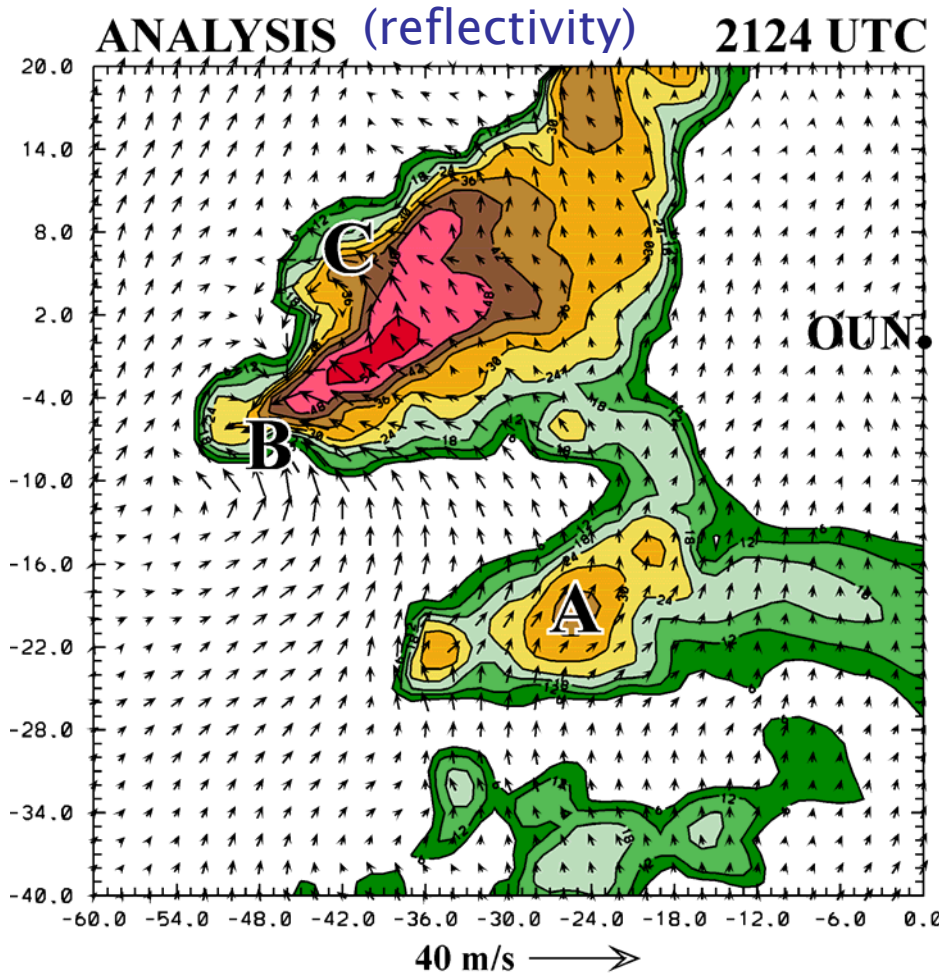
See:

Dowell, D., L. J. Wicker, and D. J. Stensrud, 2004: High Resolution analyses of the 8 May 2003 Oklahoma City Storm. Part II: EnKF data assimilation and forecast experiments. *Preprints, 22nd Conference on Severe Local Storms*, Hyannis, MA.

8 May 2003, Oklahoma City Case



8 May 2003, Oklahoma City Case

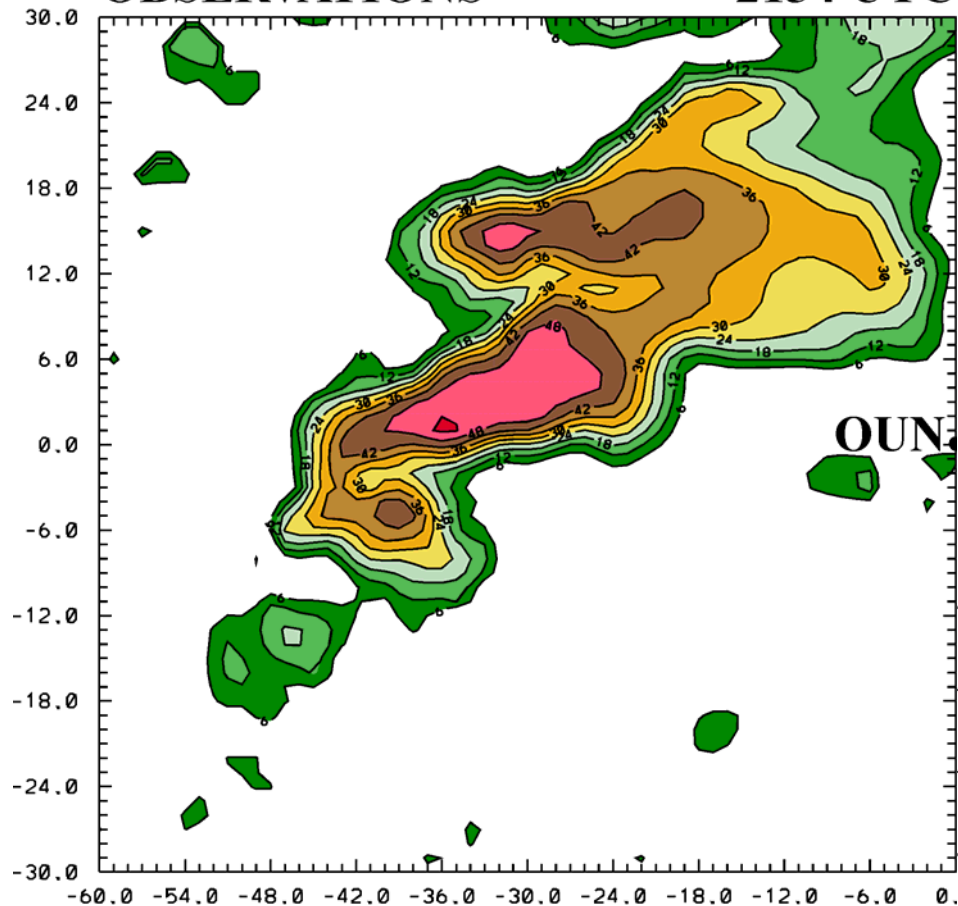


8 May 2003, Oklahoma City Case

reflectivity

OBSERVATIONS

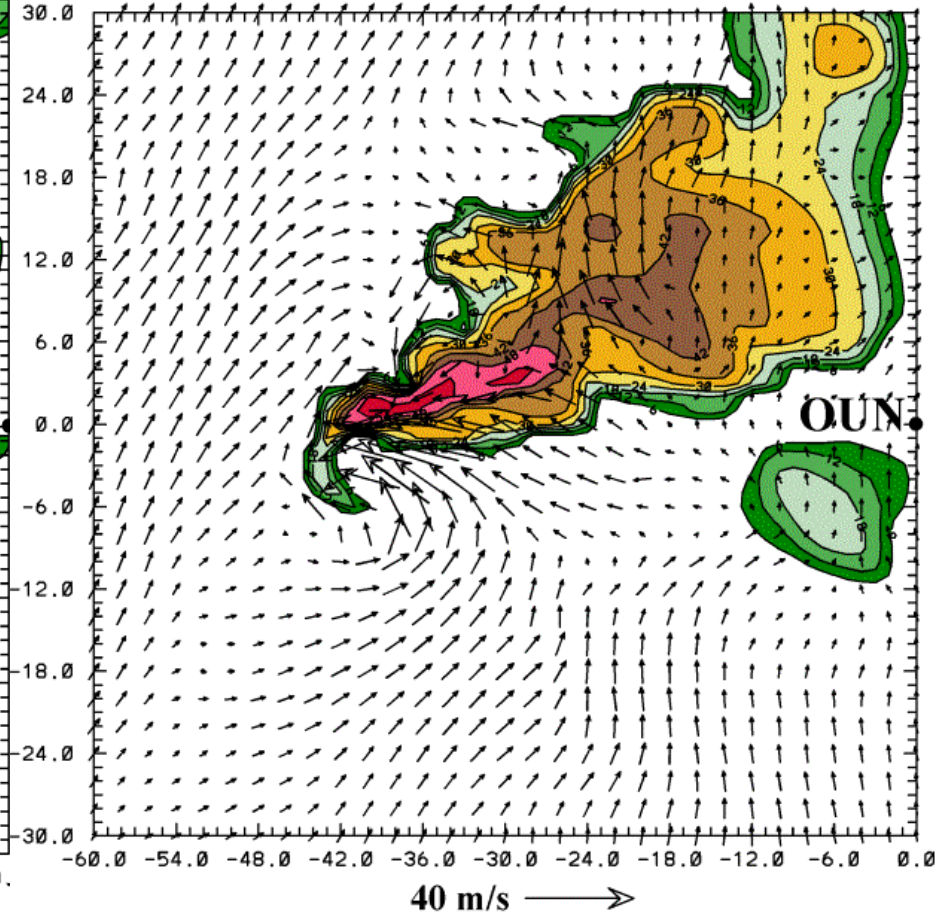
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reflectivity

8-MIN FORECAST

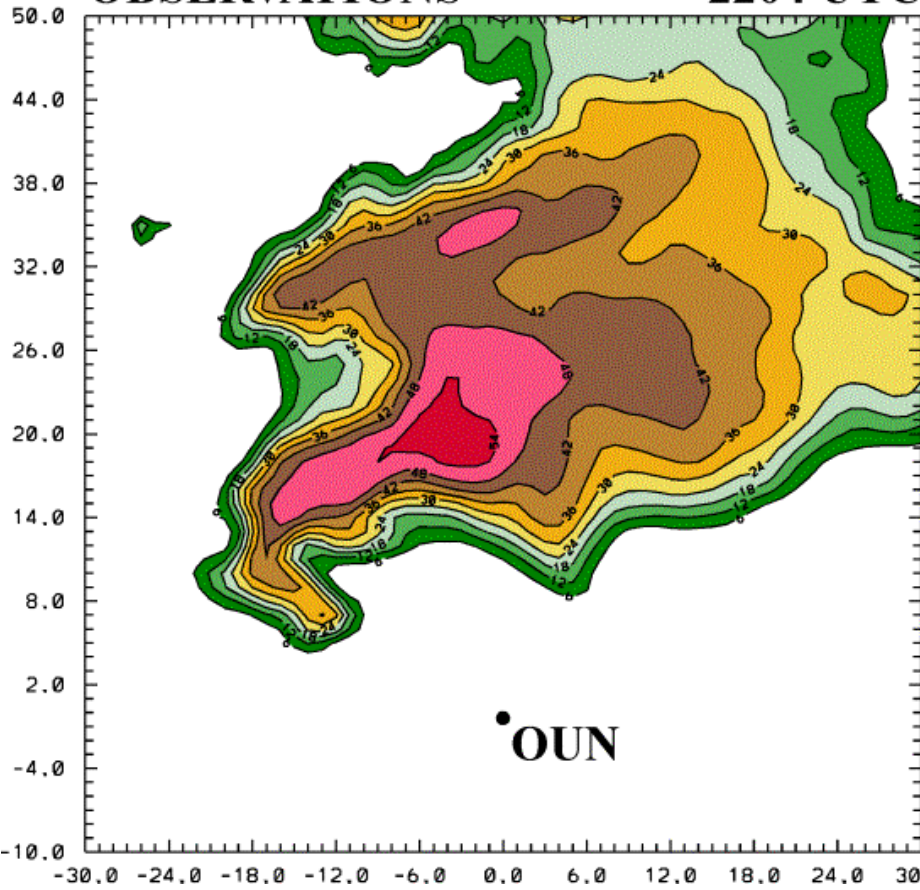
2134 UTC



8 May 2003, Oklahoma City Case

OBSERVATIONS

2204 UTC



38-MIN FORECAST

2204 UTC

