Development and Research of GSI-based EnVar System to Assimilate Radar Observations for Convective Scale Analysis and Forecast

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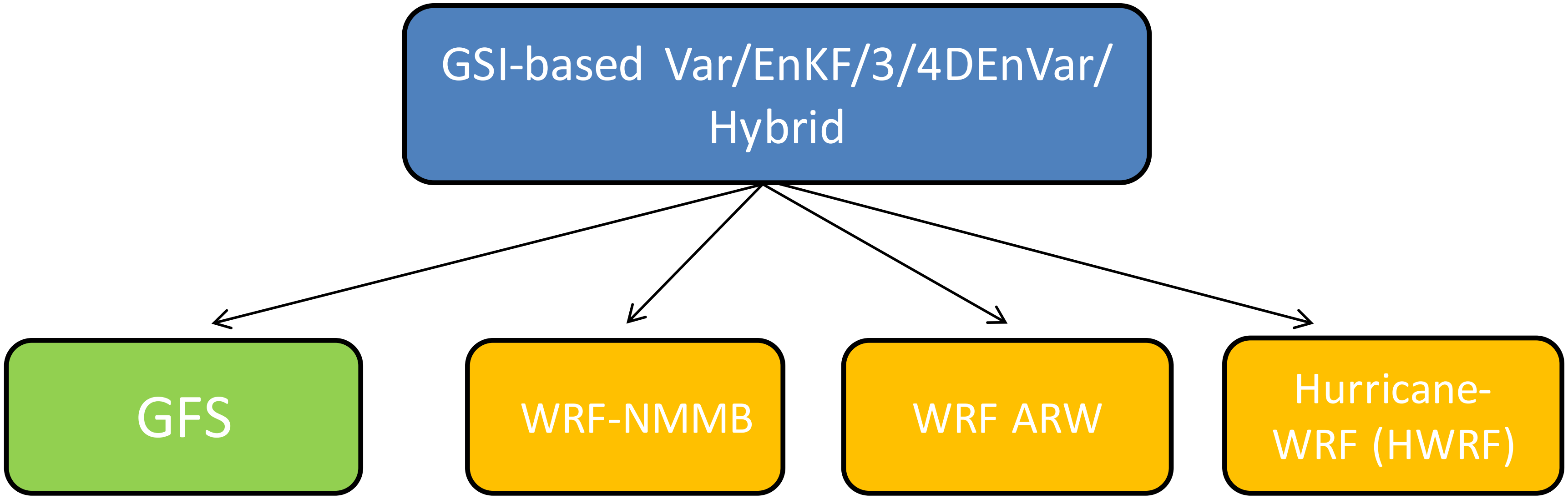
Acknowledgement
Jacob Carley (NOAA/NCEP)
Nusrat Yussouf (NOAA/NSSL)
Lou Wicker (NOAA/NSSL)

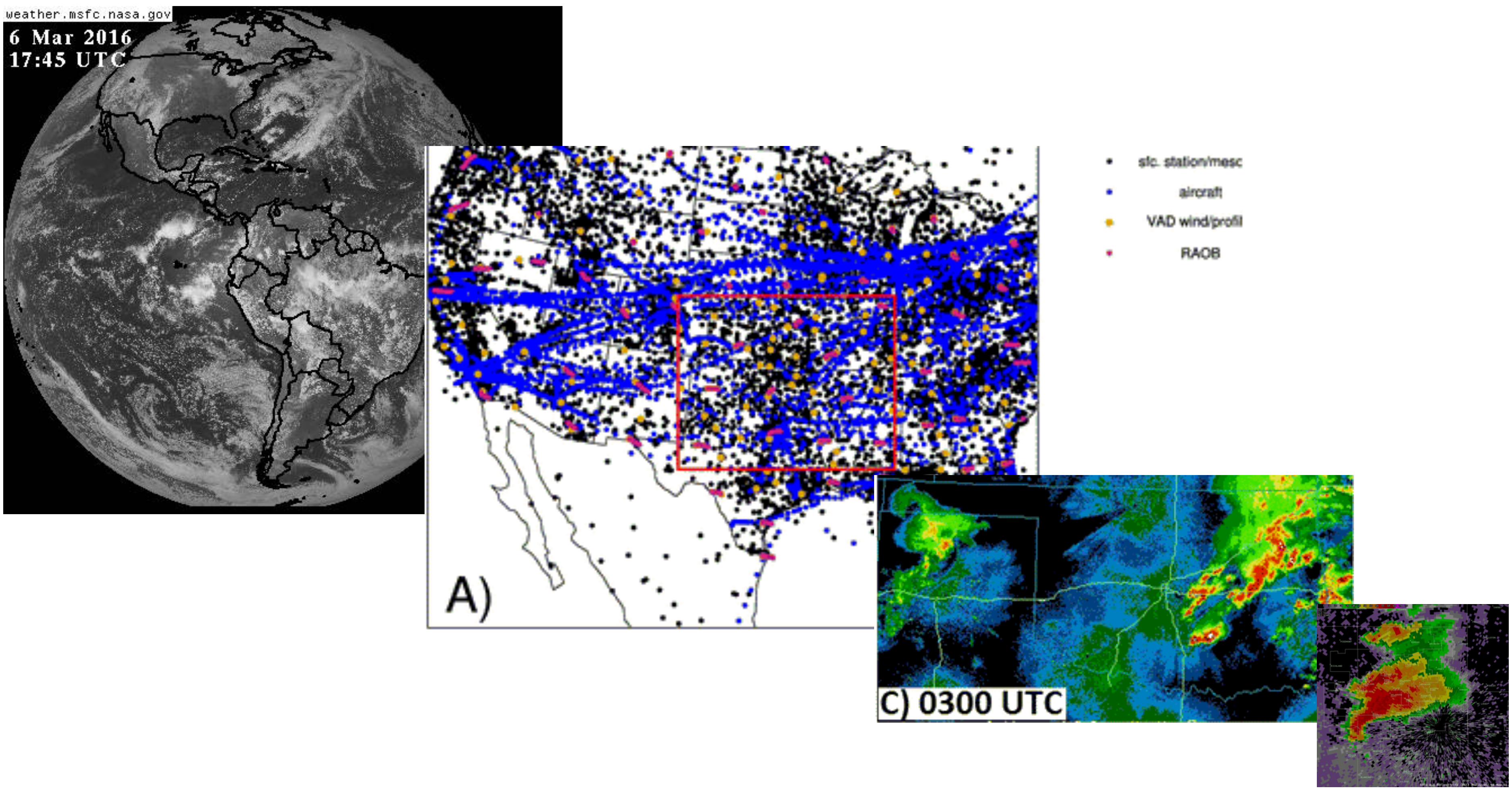
The 7th EnKF Data Assimilation Workshop
May 23-27, 2016, Boulder, CO

GSI-based Var/EnKF/EnVar/Hybrid for global and regional modeling systems



- GSI based Hybrid was implemented operationally at NCEP since 2012.
- Significant improvement from both 3DEnVar and 4DEnVar hybrid was found for GFS forecast in various experiments (e.g., Wang et al. 2013; Wang and Lei 2014; Kleist and Ide 2015; Mahajan et al. 2016)
- Research and development are being made for convective scale regional models.

Why further development is needed for convective scales?



Why further development is needed for convective scales?

- Convective scale analysis and forecasting is a multi-scale problem, requiring an accurate estimate of both the synoptic/mesoscale environment and the convective scale details.

- Convective scale observations (i.e., radar, satellite radiances) require unique observation operators that are often complex and nonlinear.

- Inclusion of additional state variables (e.g., hydrometeors, W) are required.

- Accurate cross-variable covariance is especially important.

- Comparison study among Var, EnKF, 3DEnVar, 4DEnVar and Hybrid for convective scales is still limited.

Development so far for convective scales

- GSI-based Var, EnKF, 3DEnVar, 4DEnVar and Hybrid are extended to work with convection-resolving models such as WRF ARW (Johnson et al. 2015; Wang et al. 2016).
- Vertical velocity and hydrometeor state variables are added.
- Radar radial velocity and reflectivity observation operators are implemented.
- Capability to use storm scale perturbations to treat model errors is added.
- For direct assimilation of reflectivity observations in GSI based EnVar, a method without tangent linear (TL) and adjoint of the nonlinear operator is proposed and implemented (Wang et al. 2016).

Issue with TL of nonlinear reflectivity operator in EnVar

Wang et al. 2016

- GSI-based EnVar cost function (Wang 2010)

$$J(\mathbf{a}) = 0.5(\mathbf{a})^{T}\mathbf{A}^{-1}(\mathbf{a}) + 0.5(\mathbf{y}^{o'} - \mathbf{Hx}')^{T}\mathrm{R}^{-1}(\mathbf{y}^{o'} - \mathbf{Hx}')$$

$$\Delta_{\mathbf{a}} J_{o} = \mathbf{D}^{T}\mathbf{H}^{T}\mathbf{R}^{-1}(\mathbf{Hx}' - \mathbf{y}^{o\prime})$$

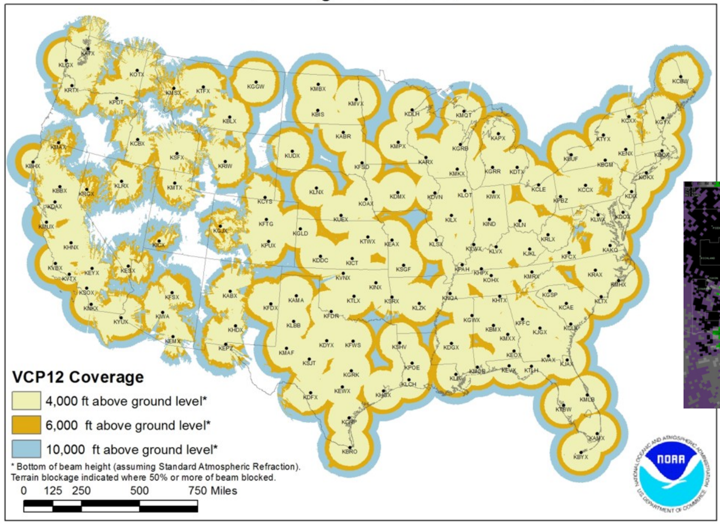
$$\mathbf{x}' = \sum_{k=1}^{K}(\mathbf{a}_{k} \circ \mathbf{x}_{k}^{e})$$

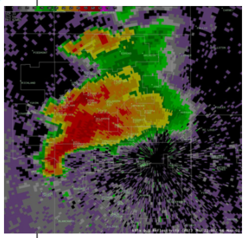
- Nonlinear radar reflectivity operator

$$H(q_r, q_s, q_g) = Z_{dB} = 10\log Z_e$$

$$Z_e = Z_r + Z_s + Z_g$$

$$Z_g = 4.33 \times 10^{10}(\rho q_g)^{1.75}$$

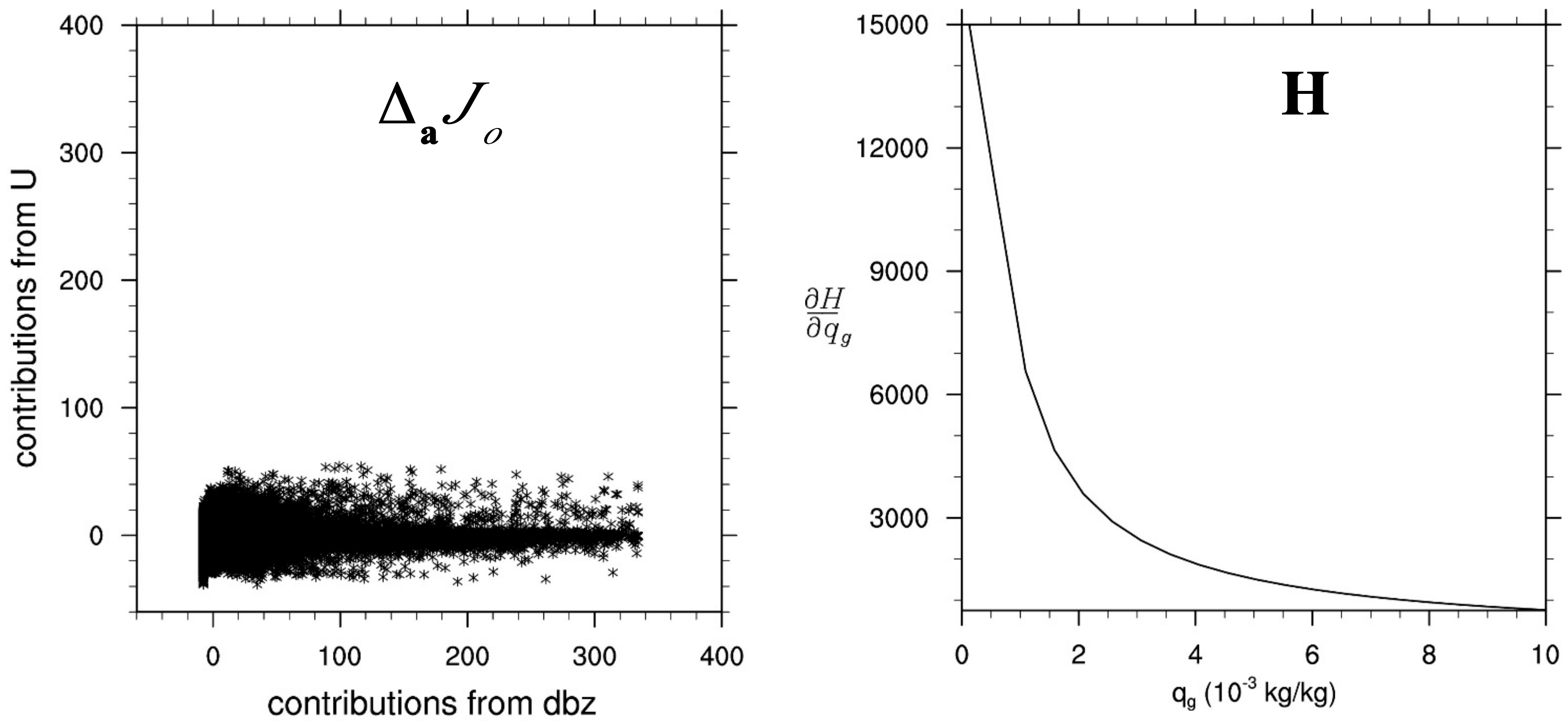




Issue with TL of nonlinear reflectivity operator in EnVar

Wang et al. 2016

- Use hydrometeor mixing ratio as state variable



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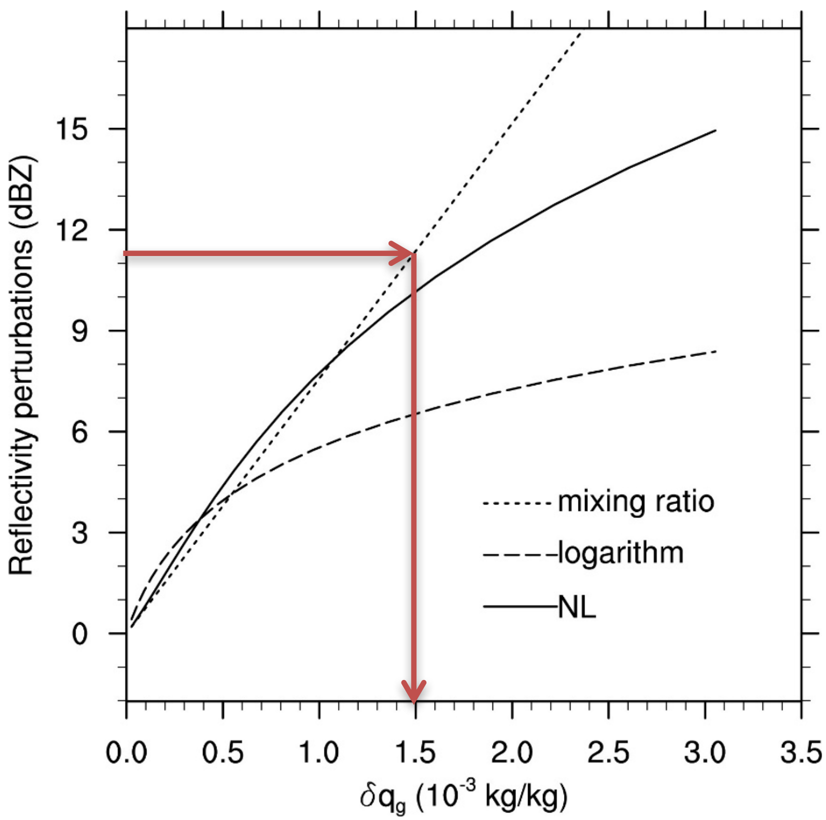
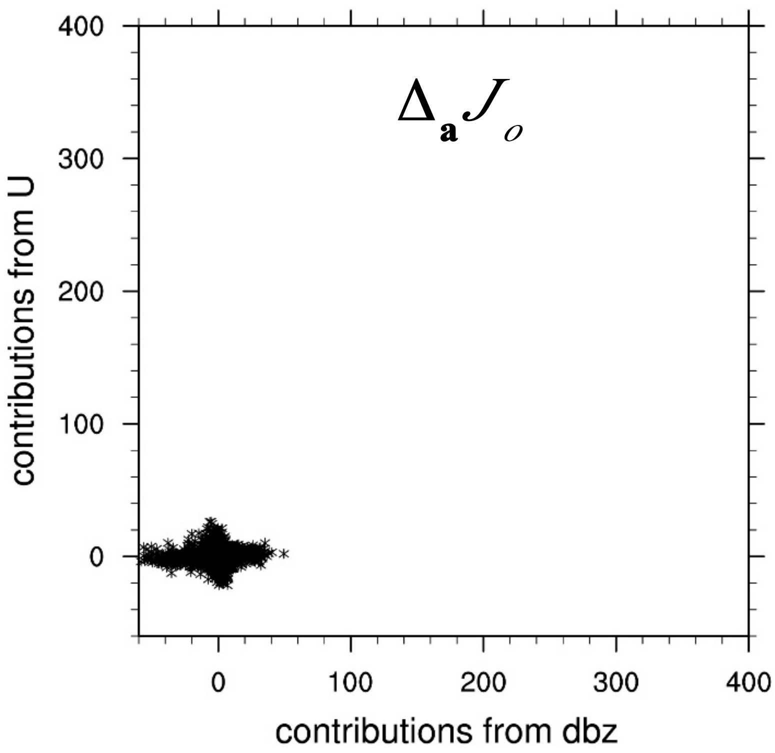


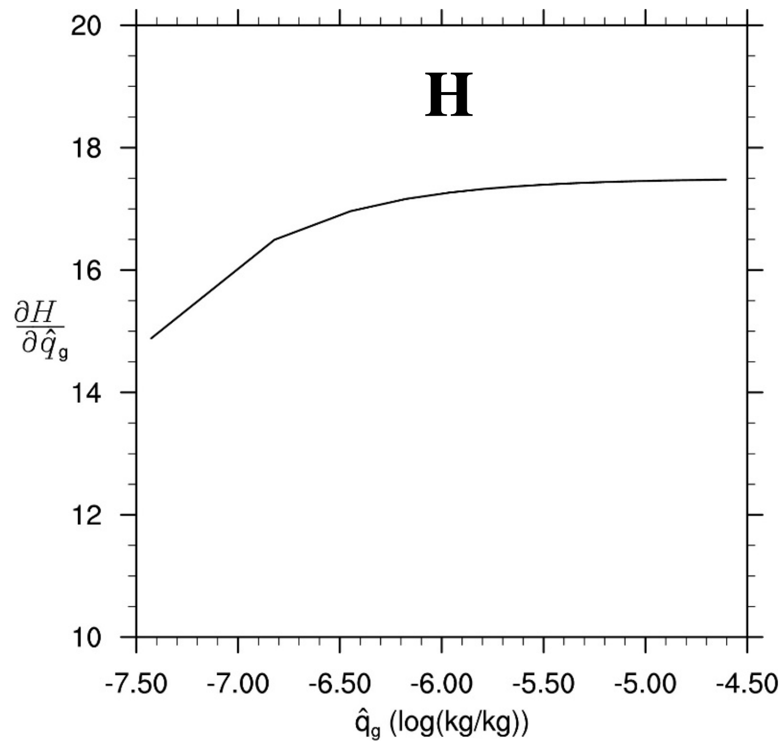
$$\Delta \mathbf{y} = H(\mathbf{x} + \Delta \mathbf{x}) - H(\mathbf{x}) = \mathbf{H}\Delta \mathbf{x}$$

Issue with TL of nonlinear reflectivity operator in EnVar

Wang et al. 2016

- Use logarithm of hydrometeor mixing ratio as state variable





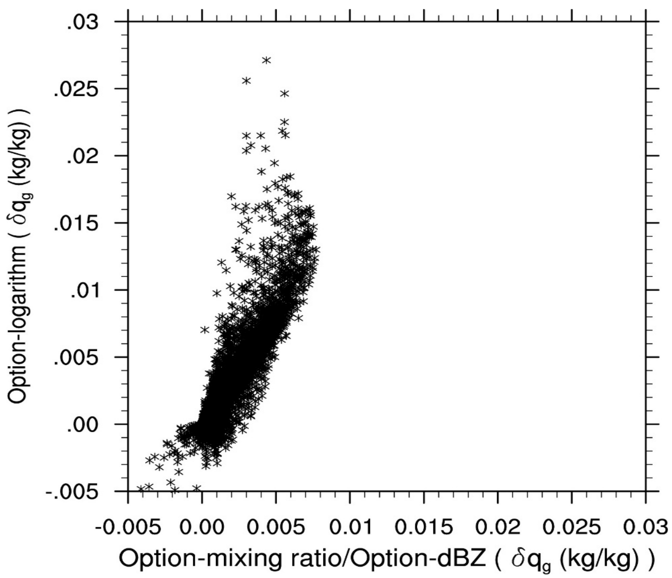
Issue with TL of nonlinear reflectivity operator in EnVar

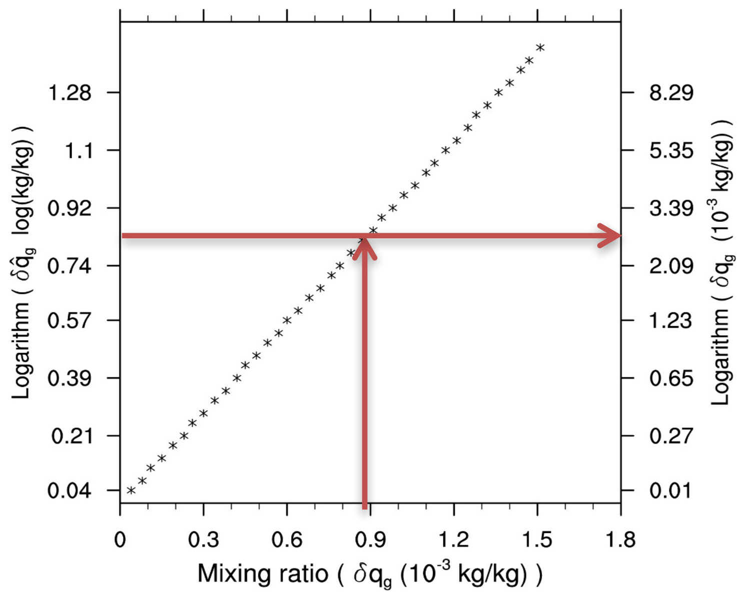
Wang et al. 2016

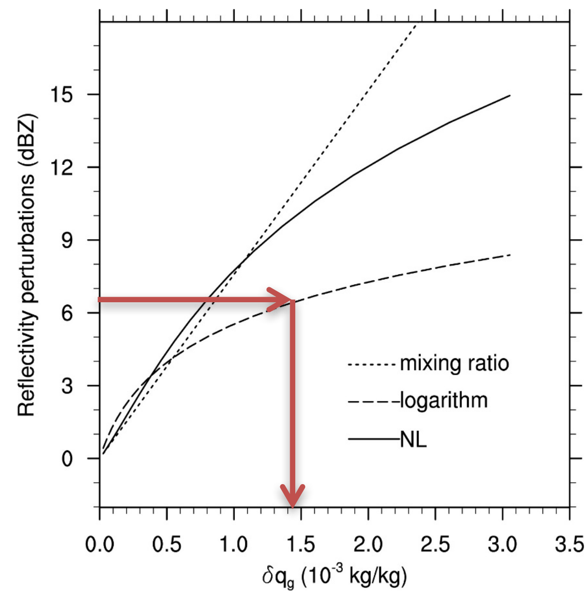
- Use logarithm of hydrometeor mixing ratio as state variable

$$\delta \mathbf{x} = \frac{\mathbf{P}^b\mathbf{H}^T}{\mathbf{H}\mathbf{P}^b\mathbf{H}^T + \mathbf{R}}(\mathbf{y} - \mathbf{H}\mathbf{x}_b)$$

$$\Delta \mathbf{y} = H(\mathbf{x} + \Delta \mathbf{x}) - H(\mathbf{x}) = \mathbf{H}\Delta \mathbf{x}$$





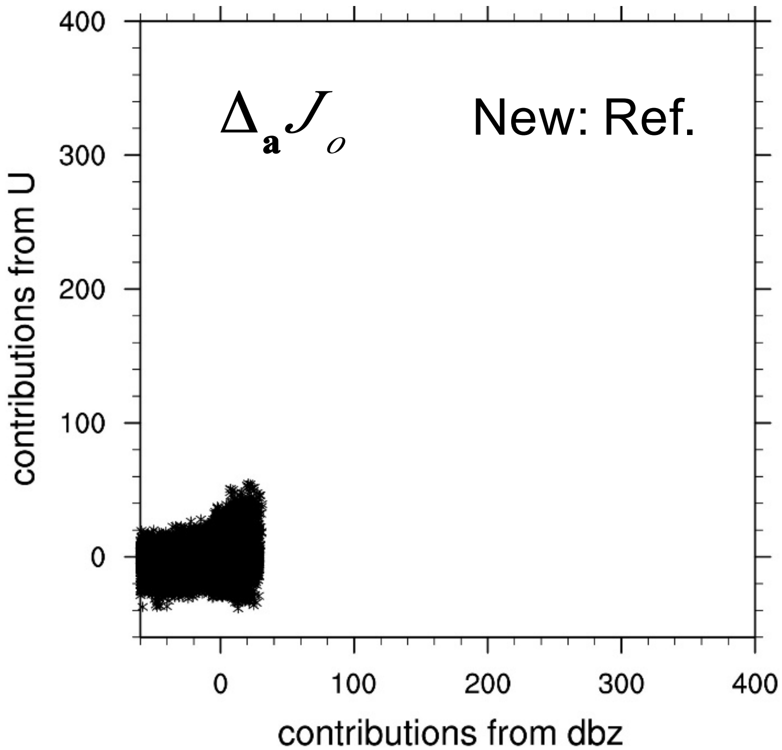


Anomalously large increment

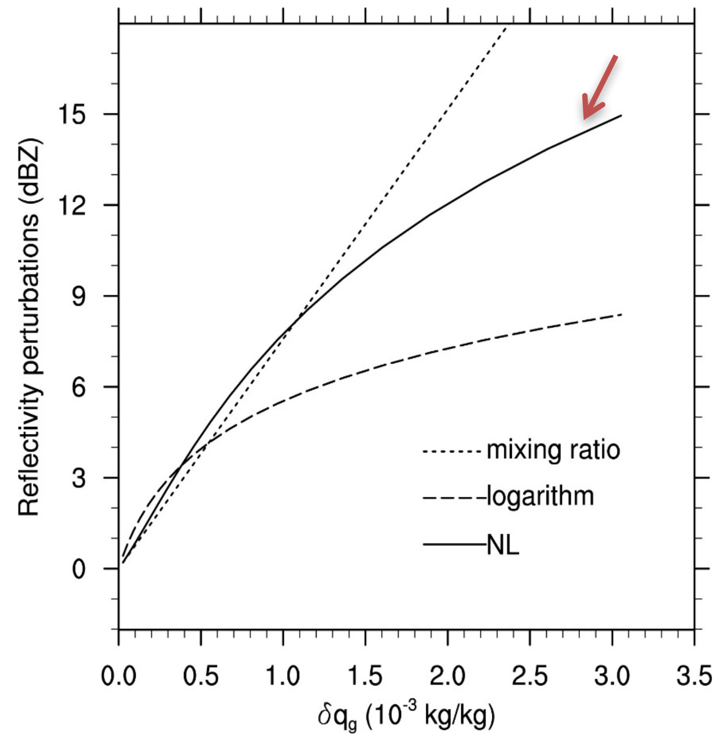
GSI-based EnVar without tangent linear (TL) and adjoint of the nonlinear reflectivity operator

Wang et al. 2016

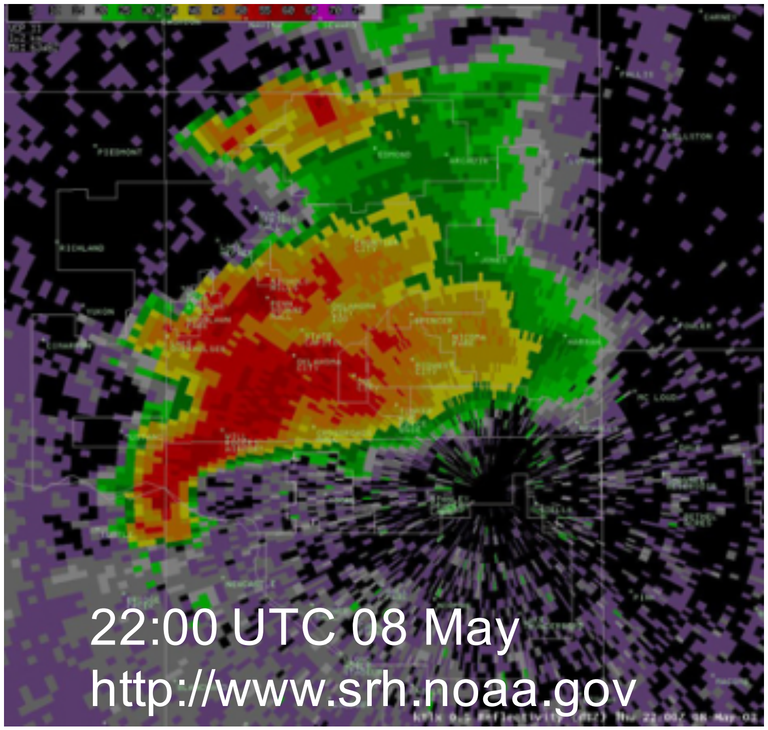
- Use reflectivity as state variable

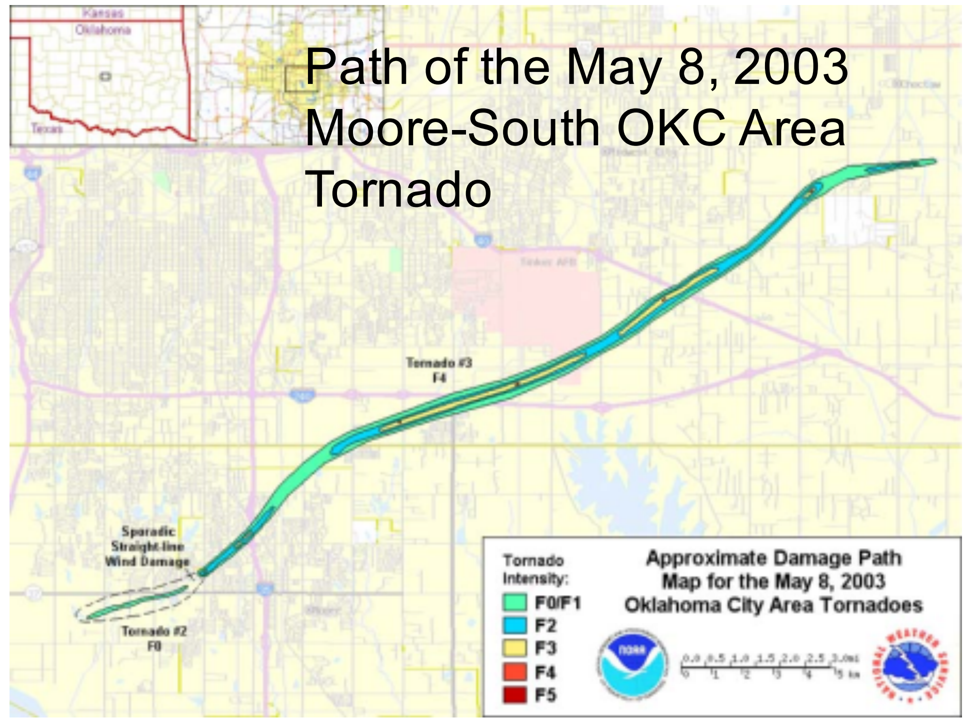


$$\Delta \mathbf{y} = H(\mathbf{x} + \Delta\mathbf{x}) - H(\mathbf{x}) = \mathbf{H}\Delta\mathbf{x}$$



May 8th 2003 OKC Tornadic Supercell



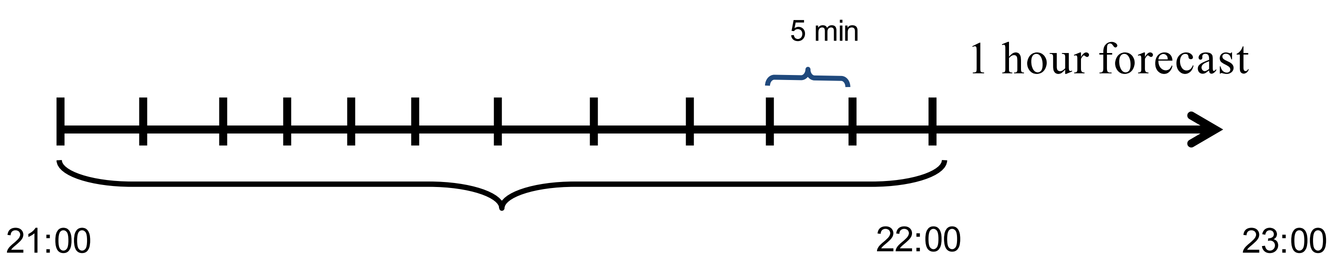


- An isolated supercell case that produced F-4 intensity tornadoes in Moore and Oklahoma City (OKC) during about 2210—2240 UTC.
- Supercell maintained well beyond 2300 until about 0000 UTC.

Experiment design

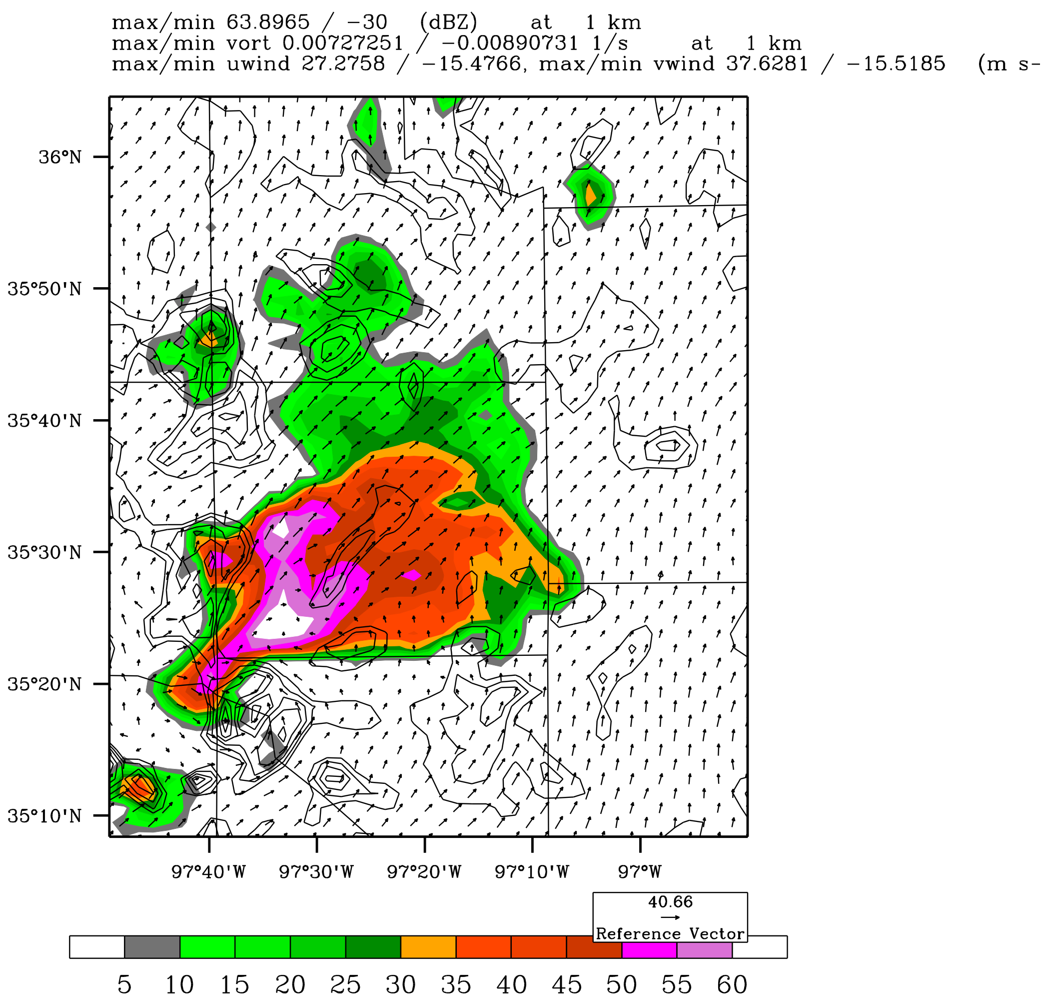
Wang et al. 2016

- **Model**: WRF-ARW 2km
- **Observation**: radar radial wind and reflectivity from KTLX
- **IC and LBC ensemble**: A 45-member ensemble downscaled from a mesoscale ensemble at 2100 UTC.

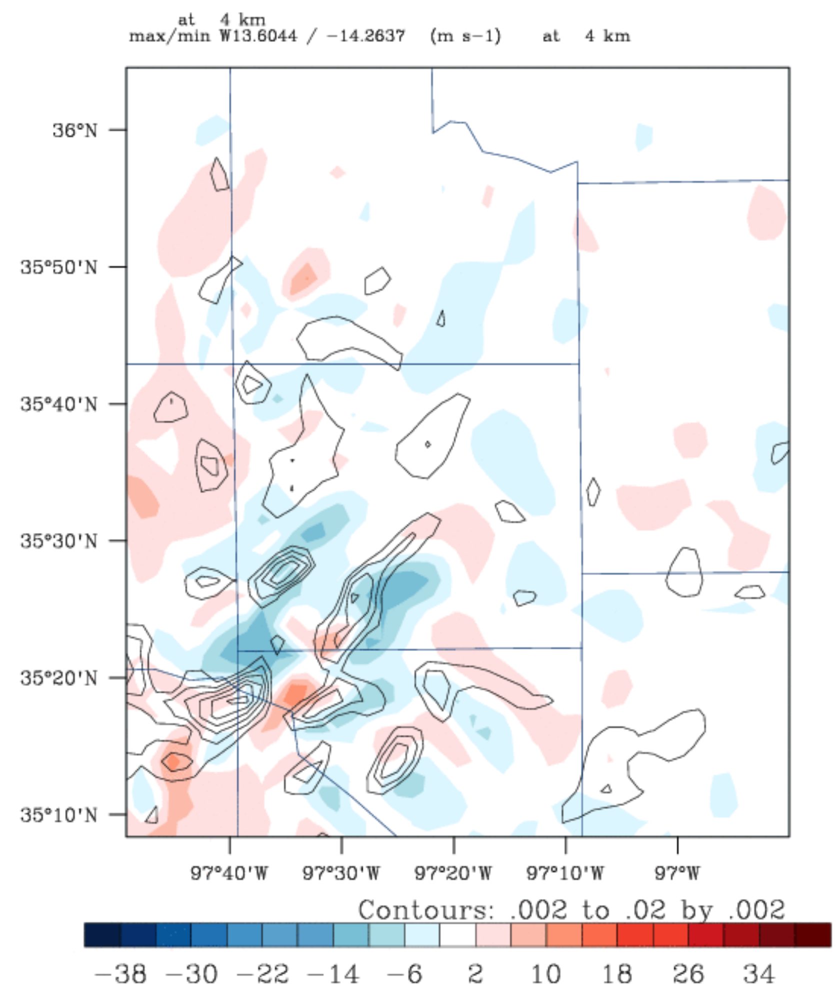


GSI based 3DVar: analysis and 1h forecast from 2200UTC

22:00:00

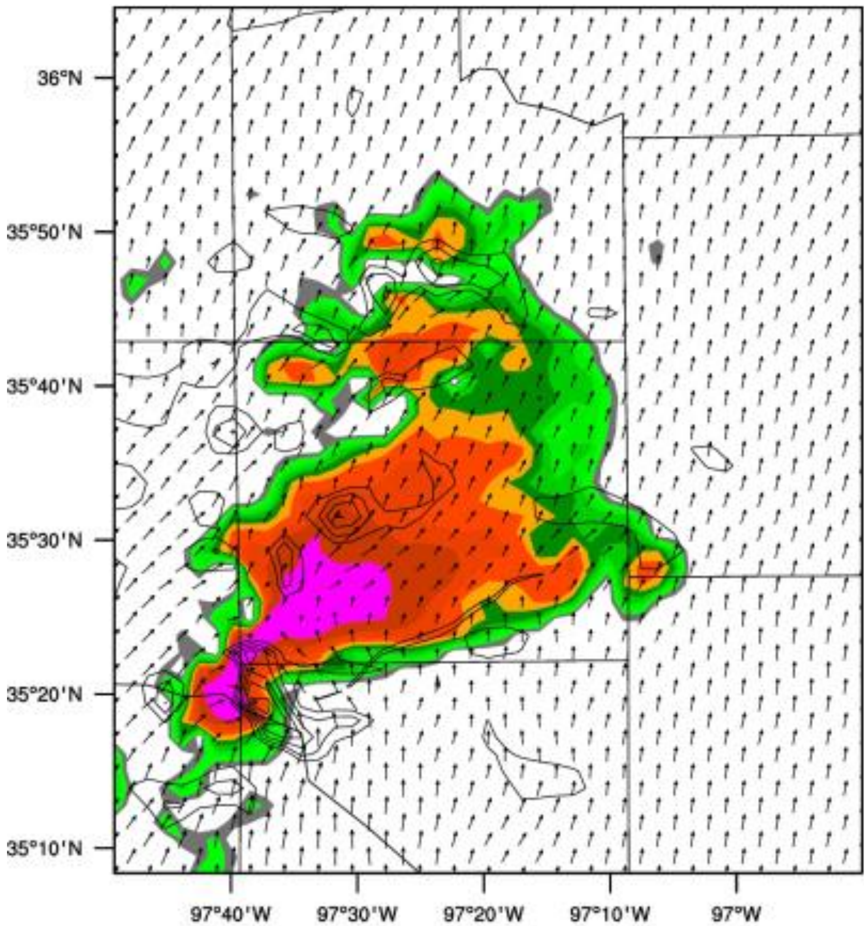


Ref and vorticity at 1 km



W at 4 km

GSI based EnVar: analysis and 1h forecast from 2200UTC



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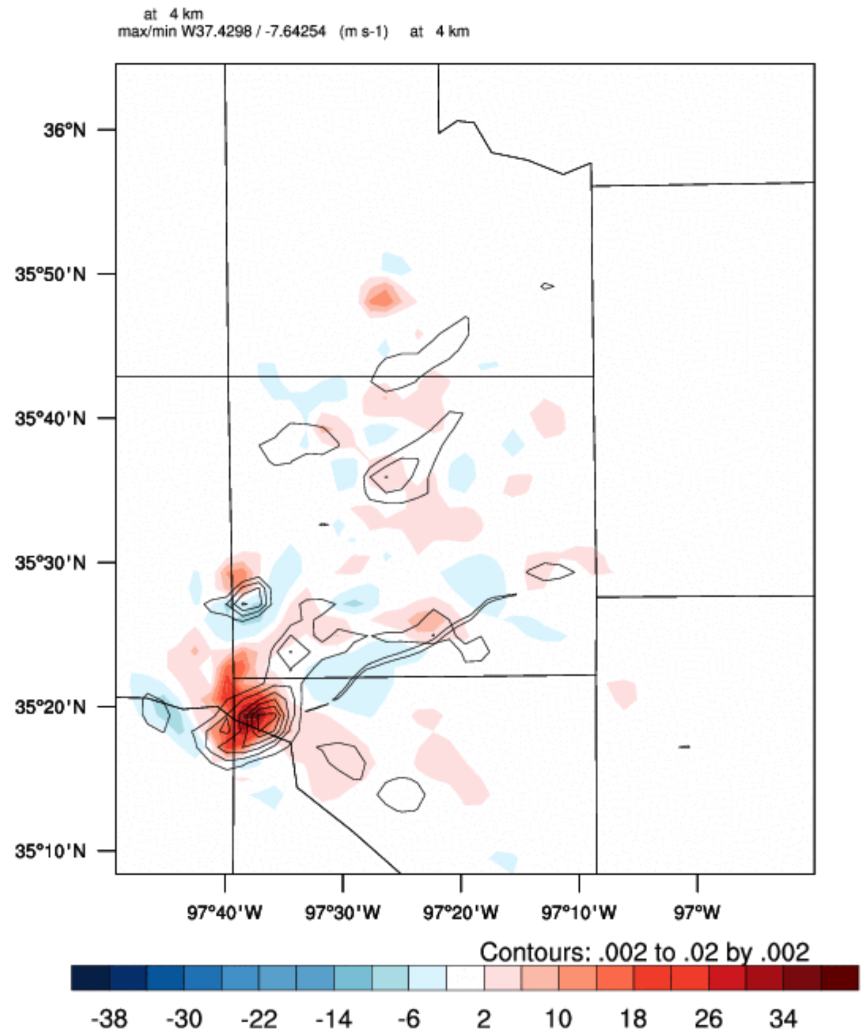
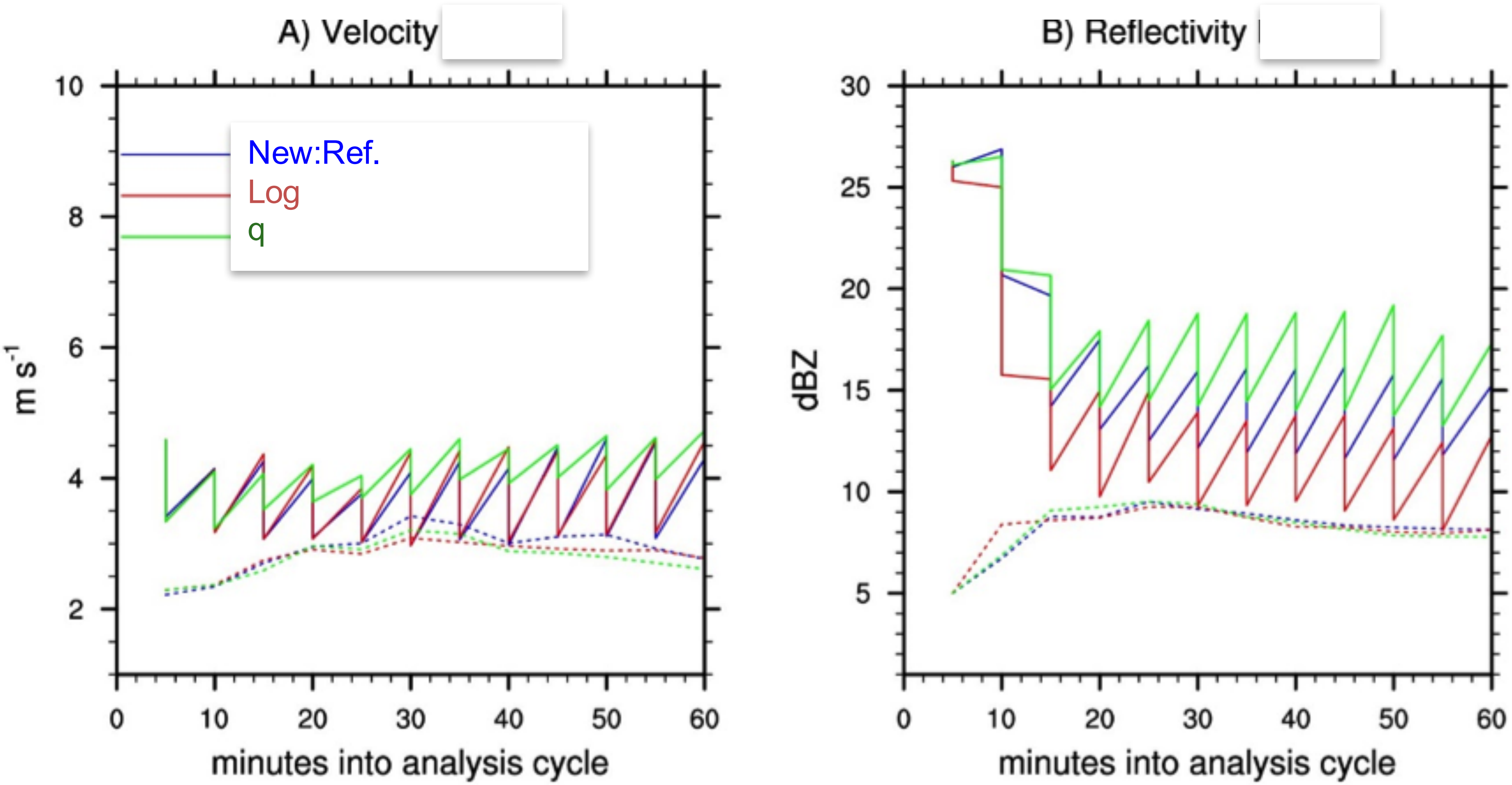
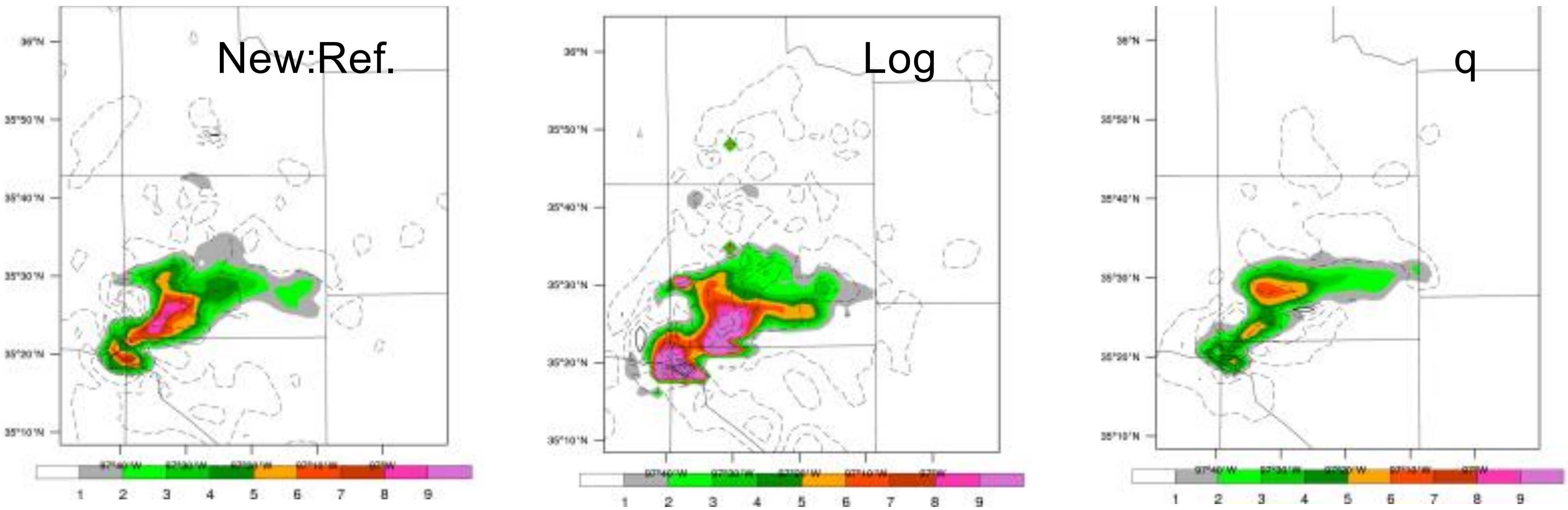


W at 4 km

RMS fit to radar observation

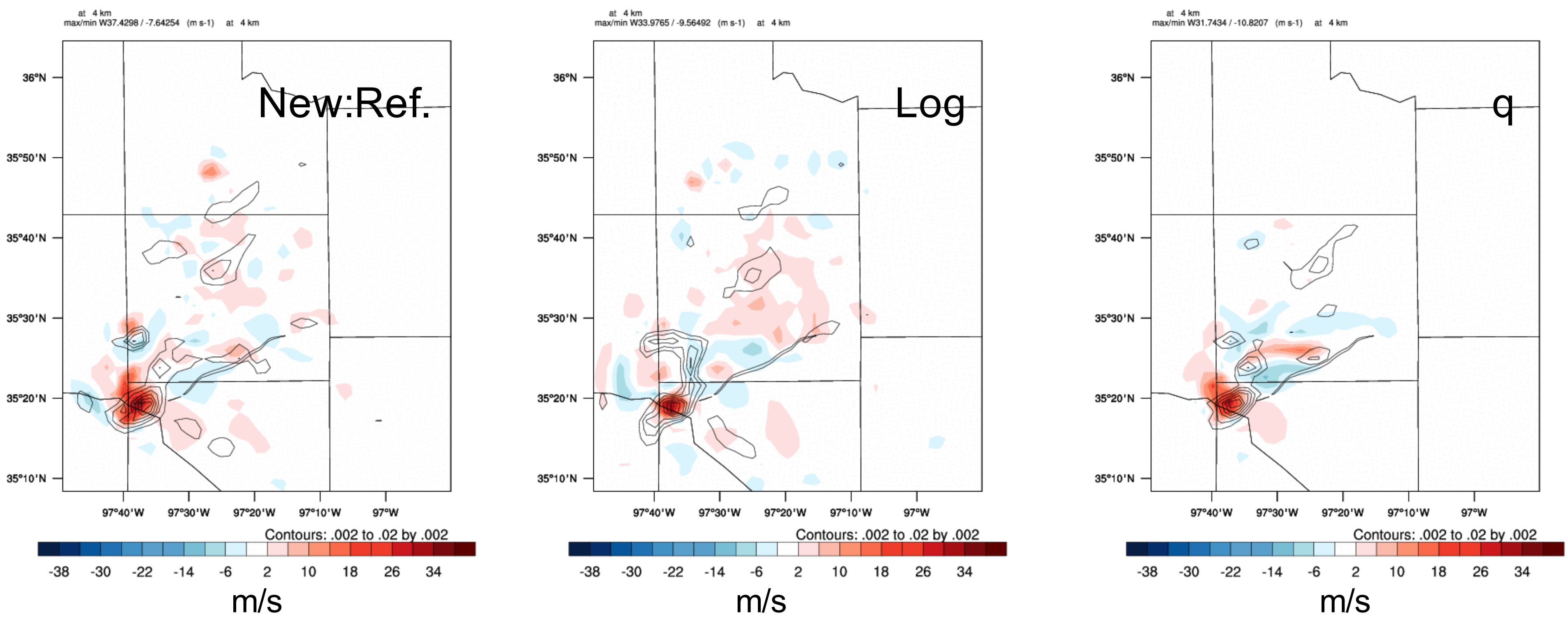


Graupel (q_g) analysis

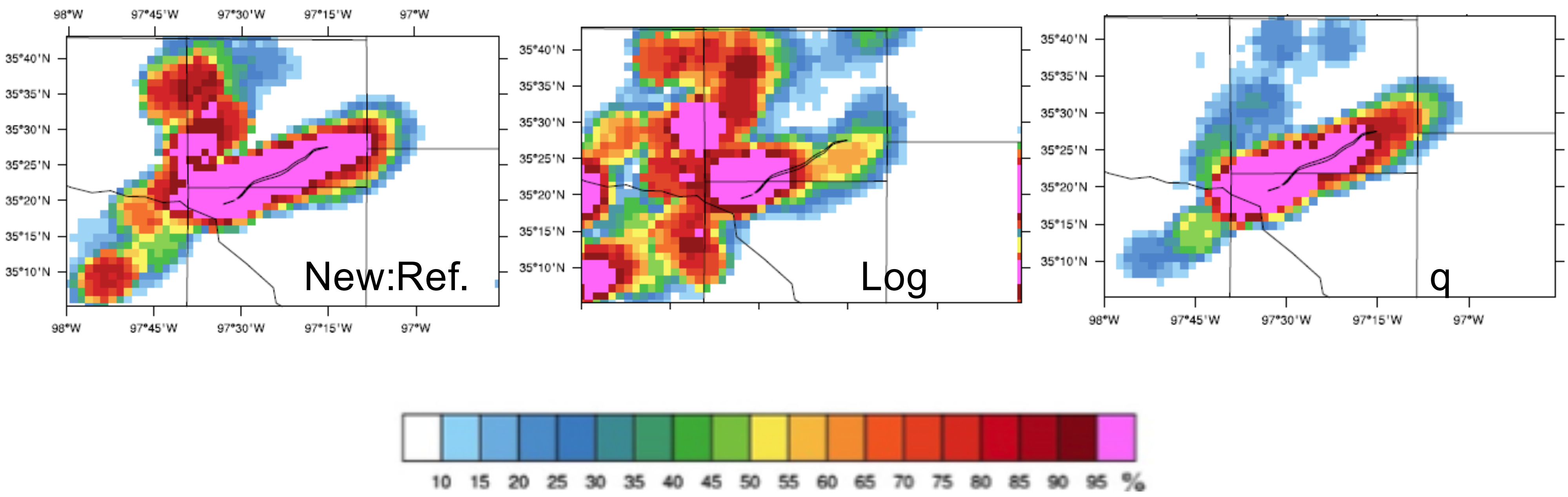


(g/kg)

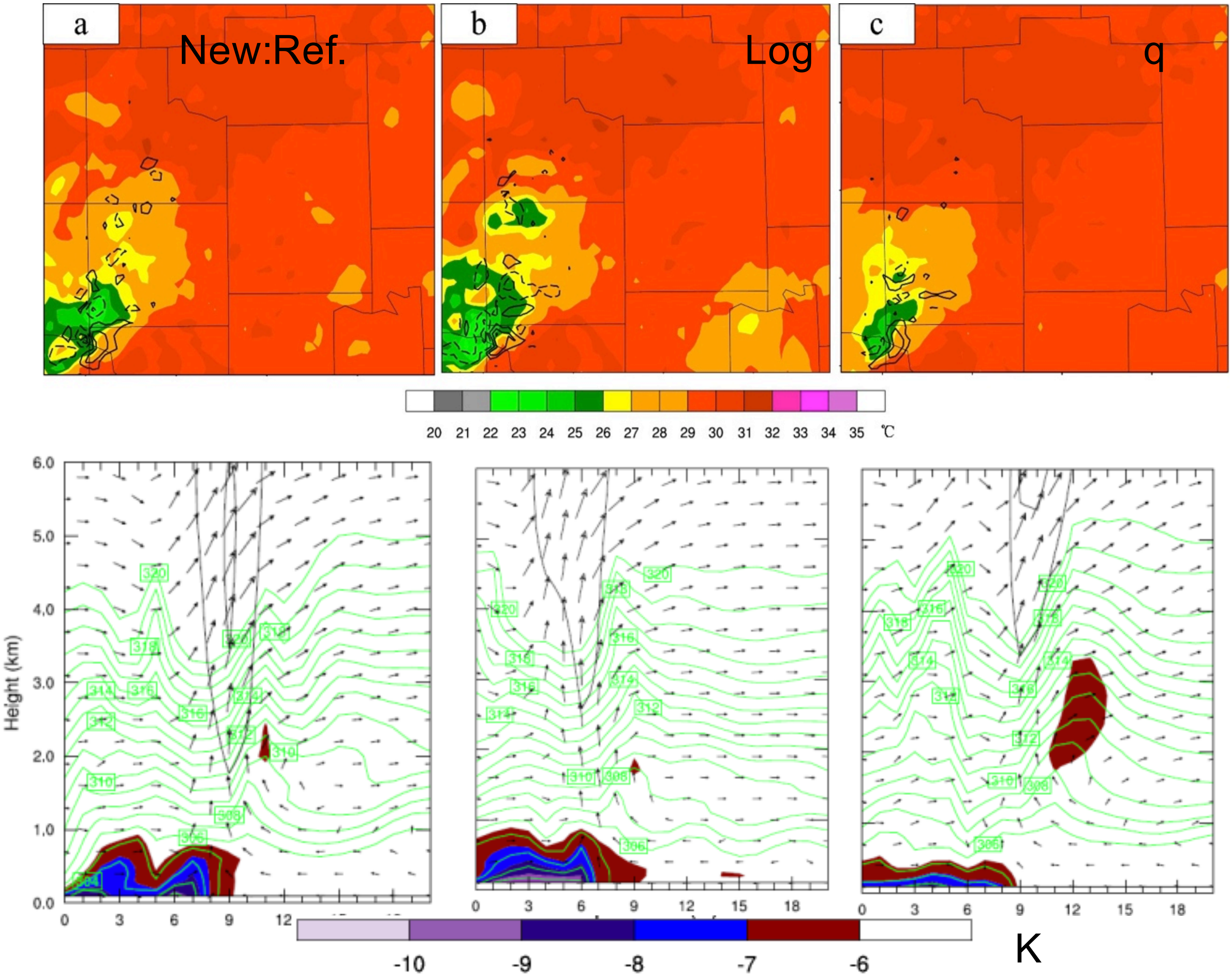
1 hour forecast: w and vorticity at 4km



1 hour forecast: Neighborhood ensemble probability (%) of vorticity at 150 m AGL

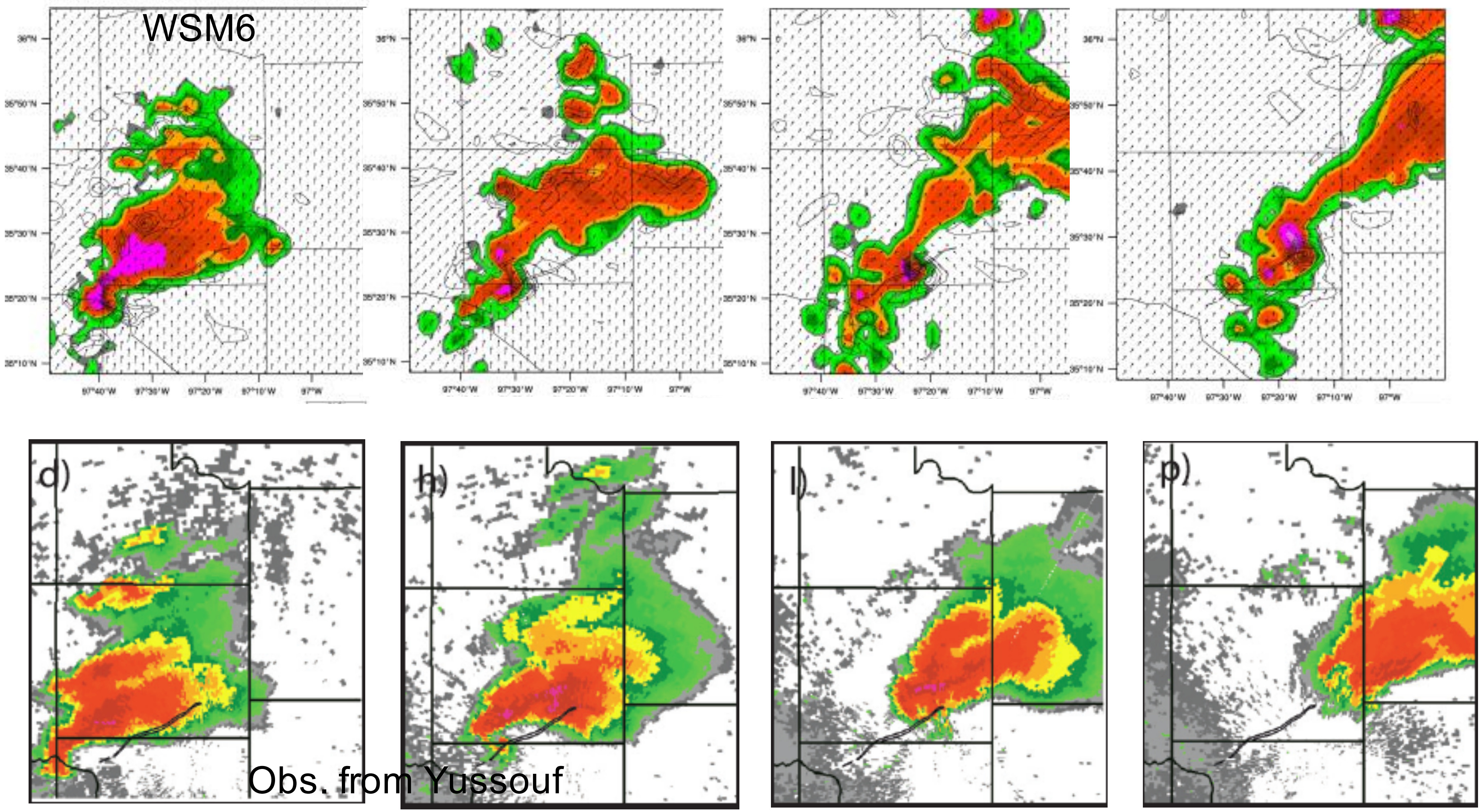


Dynamical factors that impact storm evolution



1 hour forecast: Reflectivity

2200 UTC 2215 UTC 2230 UTC 2245 UTC



Summary

- GSI-based Var/EnKF/EnVar/Hybrid data assimilation system is further developed for convective scale radar data assimilation.
- Experiments for complex mesoscale system and isolated supercell both show improved analysis and forecast by EnKF (Johnson talk next) and EnVar compared to 3DVar.
- For direct reflectivity assimilation in EnVar, issues associated with the use of tangent linear (TL) and adjoint of the nonlinear operator are revealed.
- For direct reflectivity assimilation in EnVar, a method without tangent linear (TL) and adjoint of the nonlinear operator is developed to solve the issues.
- So now 4DEnVar is not only TLA free for forecast model, but also TLA free for nonlinear obs. operator.
- We plan to apply this method to other nonlinear observations (e.g. cloudy radiances) in EnVar.