Lightning data assimilation techniques for convective storm forecasting with application to GOES-R Geostationary Lightning Mapper

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Topics: Severe Weather and Lightning

Program: JCSDA

Two methods of lightning data assimilation are implemented:

1. Using lightning (time/location) to force convection initiation by nudging in water vapor where lightning is observed but convection is absent in the model. Forcing is maintained for 10s of minutes to achieve a model response to sustain the storms. (See Fierro et al. 2012, Mon. Wea. Rev.)

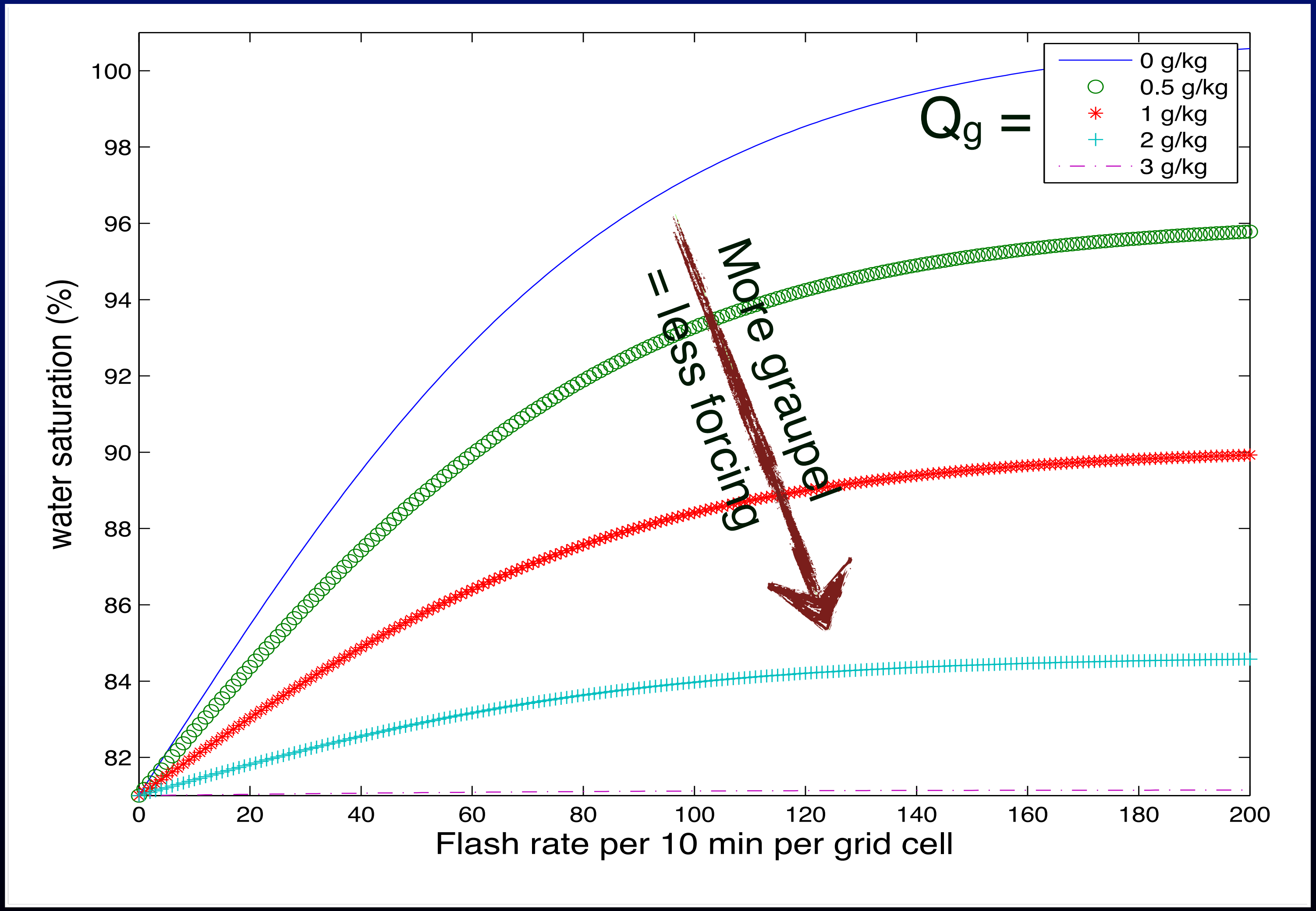
2. Ensemble Kalman Filter to modulate convection (e.g., strengthen or weaken) in the ensemble members. Ensemble covariances provide adjustments to all state variables (e.g., temperature, water vapor, winds, liquid water and ice particles). Pseudo Geostationary Lightning Mapper (p-GLM) data are assimilated on 1-3 minute intervals.

Lightning assimiation nudging function

Water vapor mixing Q_v within the 0°C to -20°C layer was increased as a function of 9-km gridded flash rates N_{flash} (X) and simulated graupel mass mixing ratio Q_g and saturation vapor mixing ratio Q_{sat}. Increasing Q_v at constant temperature T increases buoyancy (virtual potential temperature θ_v) and ultimately generates an updraft.

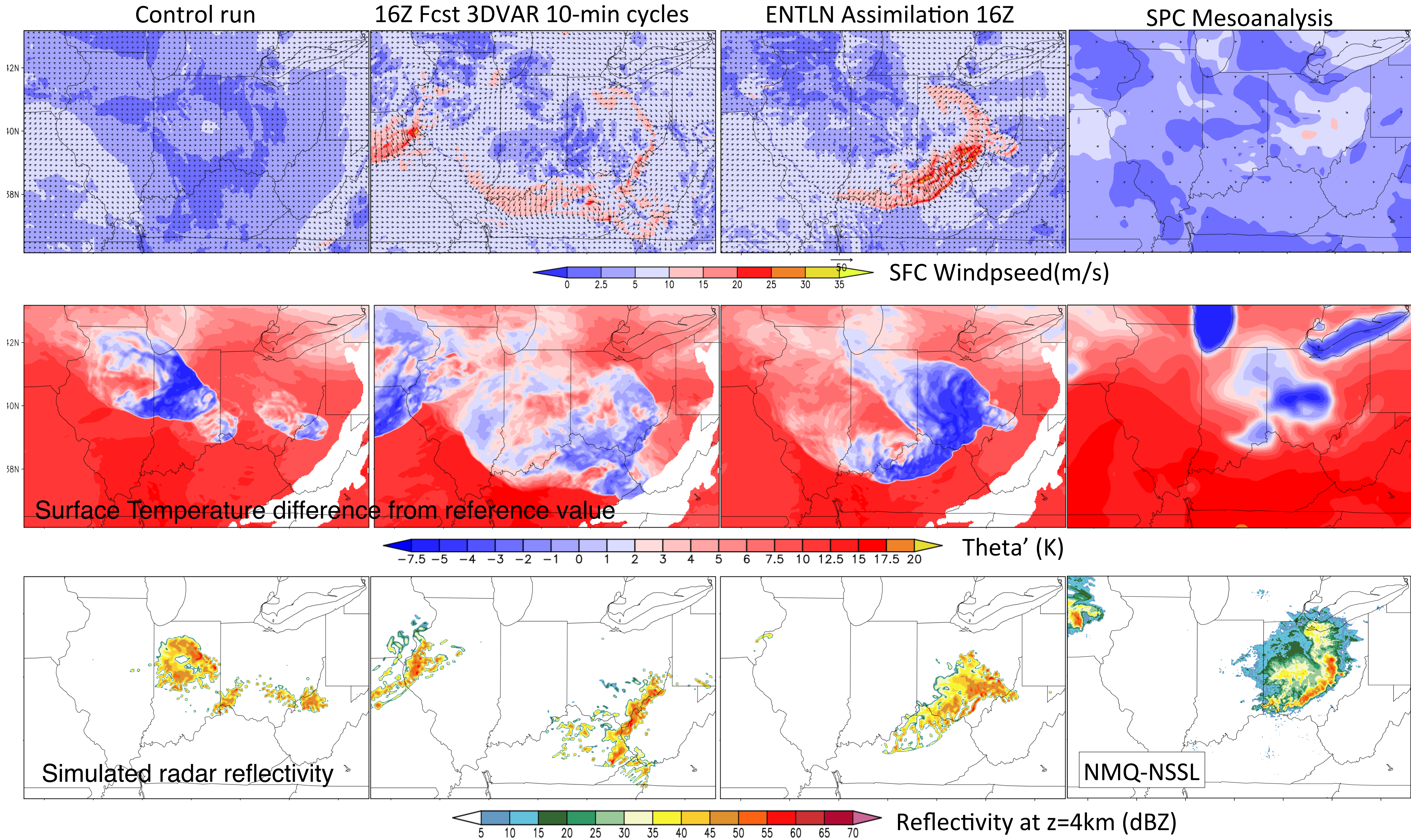
$$Q_v = AQ_{sat} + BQ_{sat}\tanh(CX)\,[1 - \tanh(DQ_g^{\alpha})]$$

- -Only applied whenever simulated RH ≤ A*Qsat and simulated Qg < 3 g/kg.
- -A controls minimum RH threshold (here 81%).
- -B and C control the slope (how fast to saturate)
- -D affects how much water vapor (Qv) is added at a given value of graupel mixing ratio (Qg).



29 June 2012 Derecho Event

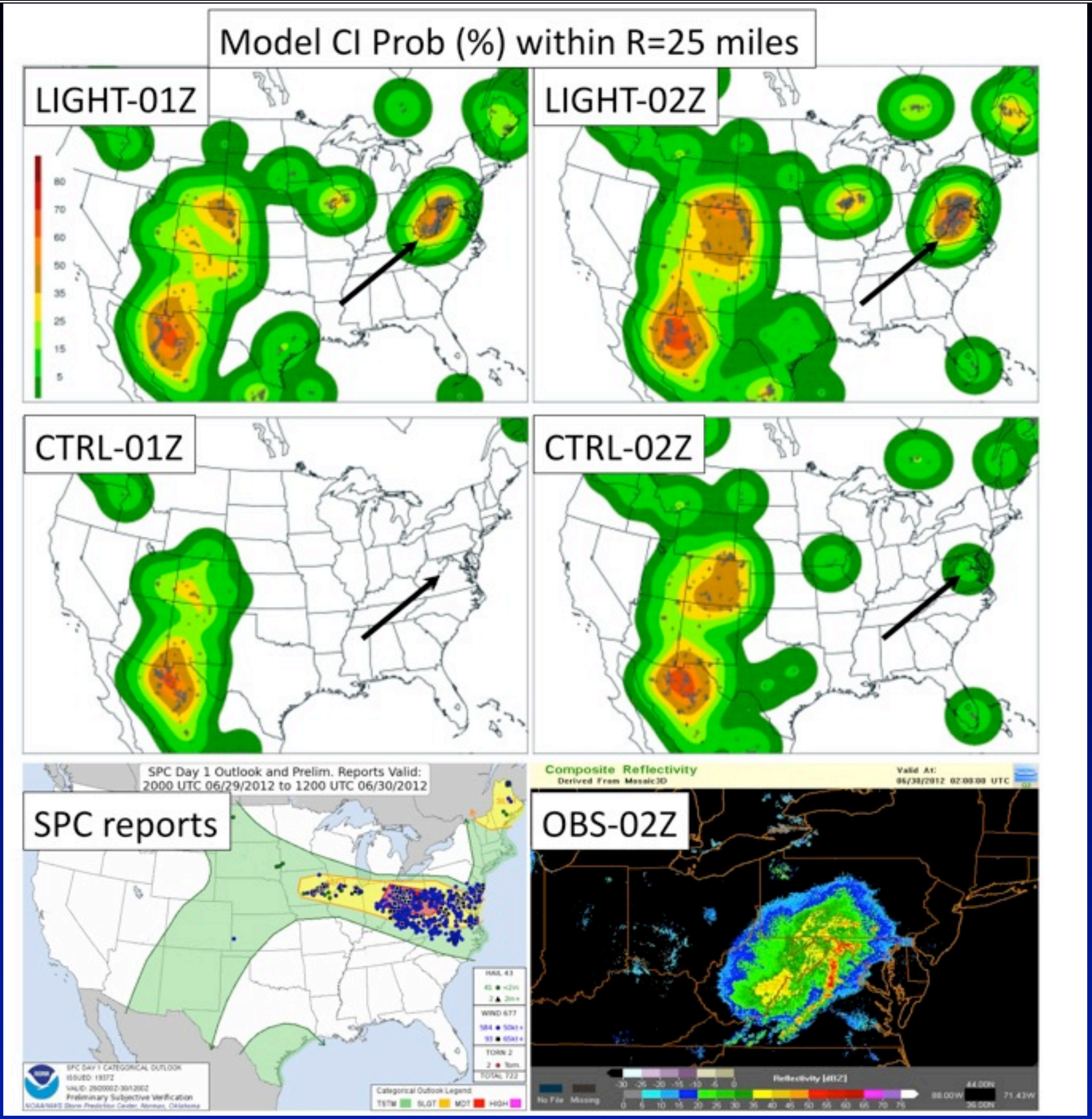
Comparison of 3-km resolution forecasts at 22 UTC: No Assimilation (Control, 14 UTC starting time), 3D-var assim. of radar data (10-minute cycling, 14-16UTC), and lightning (ENTLN system) assimilation (14-16 UTC).



Real -time implementation into WRF-NSSL 4-km CONUS runs

A quasi-operational system has been set up as a parallel forecast to the daily NSSL convection-allowing forecasts (4-km horizontal grid spacing). Lightning data (ENTLN) are assimilated for the first two hours of forecast to nudge in deep convection.

Here again is the 2012 Derecho event in terms of convection initiation (CI) probability. The lighting assimilation spins up the ongoing severe convection (arrow) that fails to emerge from the initial condition alone in the control case.



Ensemble Kalman Filter (EnKF) Assimilation

EnKF offers a means to an observation to adjust all state variables via covariances with a corresponding simulated observation (here, lightning flash extent rates) from the ensemble members. It cannot generate convection by itself, but can modulate convection forced by other means or help to suppress spurious deep convection.

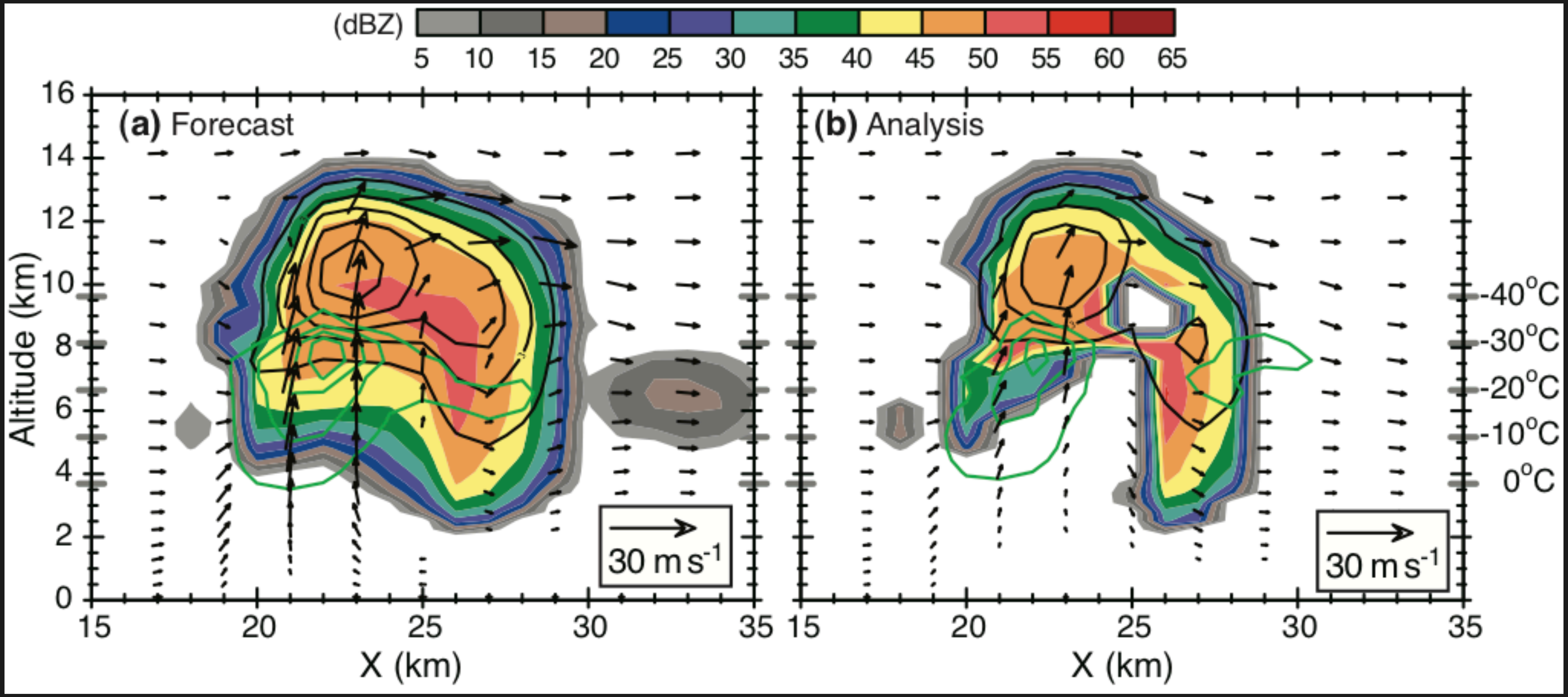


Figure: Observing Systems Simulation Experiment (OSSE): Example of a single lightning assimilation cycle damping a spurious storm cell in an ensemble member. Reduced updraft (vectors) and graupel mass (black contours) and radar reflectivity

Pseudo-GLM EnKF Assimilation

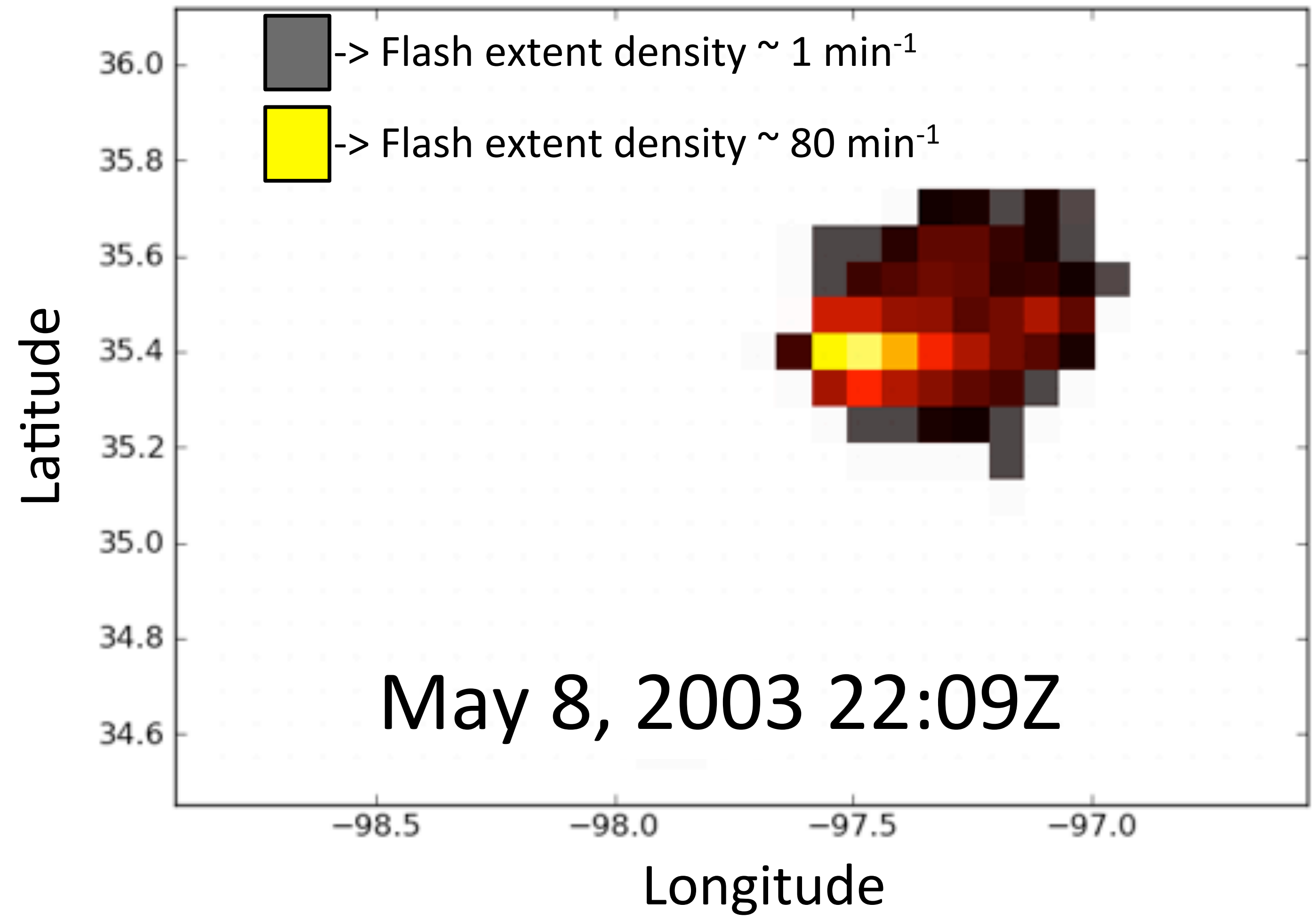
P-GLM flash extent density observations were generated from Lightning Mapping Array (LMA) data, using a flash separation algorithm (MacGorman et al 2008) to specify individual flashes.

Various linear relationships between graupel mass and flash rate, graupel echo volume and flash rate, and non-inductive charging and flash rate were tested. Good results for strong and weak convection tests were found with the relationship:

FED = (0.017)*(graupel volume)

Here, graupel volume is the sum of grid cells with graupel mixing ratio > 0.5 g/kg in a 16-km box centered on the p-GLM pixel.

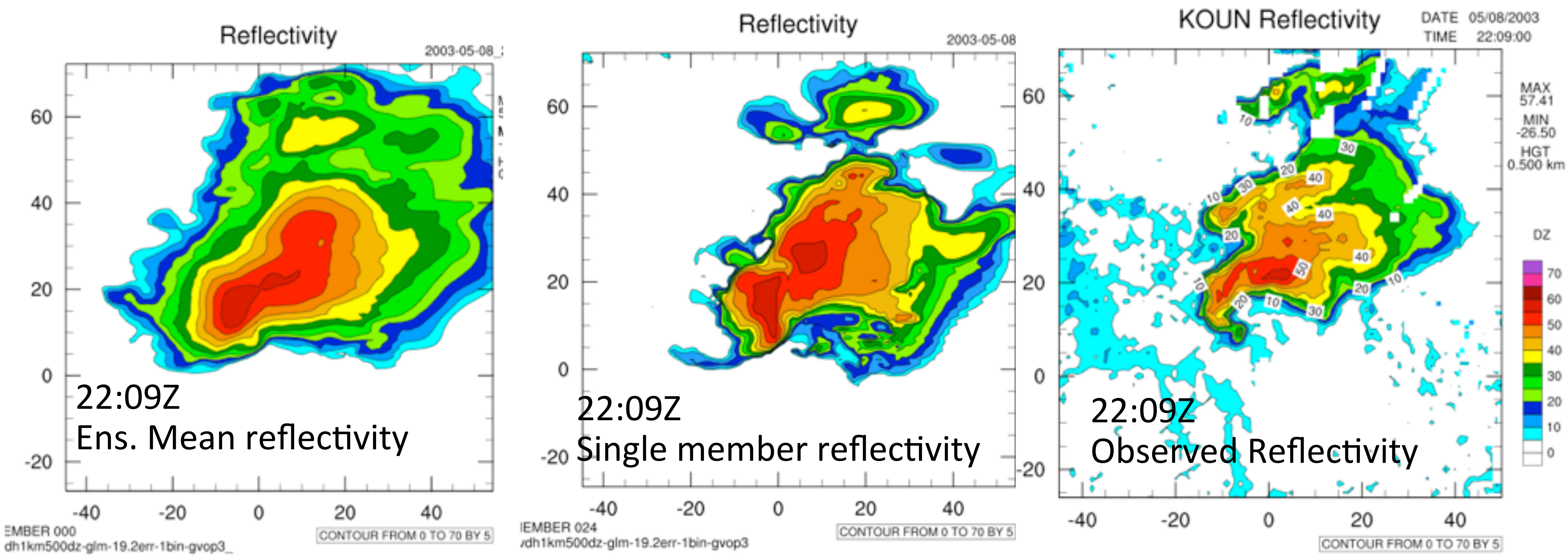
Ensemble has 40 members at 1-km horizontal resolution. Comparison assimilation tests with radar radial velocity were also performed.



Example of pseudo-GLM Flash extent density (FED) derived from Oklahoma LMA data.

P-GLM EnKF: 8 May 2003 Supercell

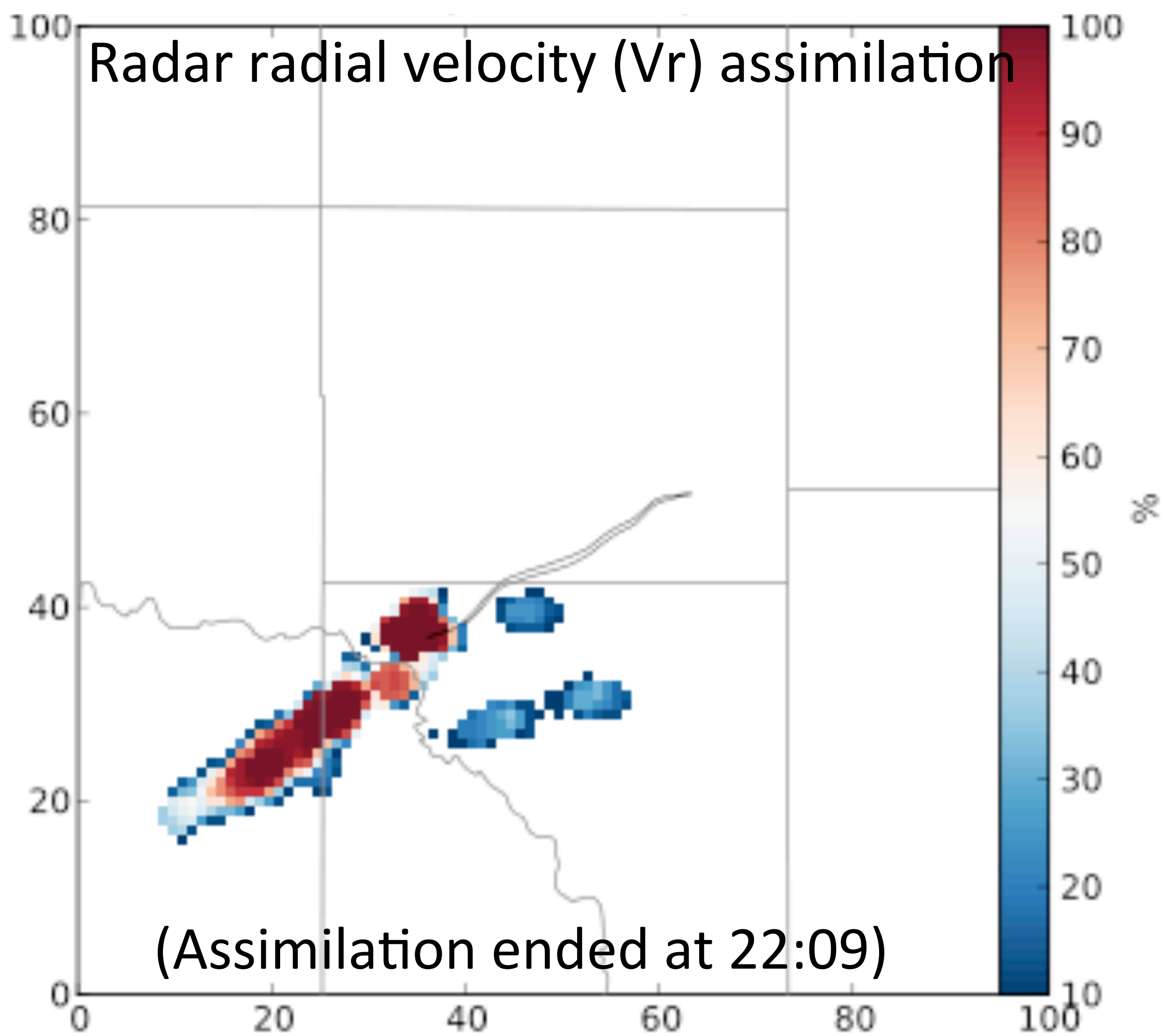
Low-level analysis of radar reflectivity around the time of the first tornado (Moore/Oklahoma City, OK EF4 tornadic storm)

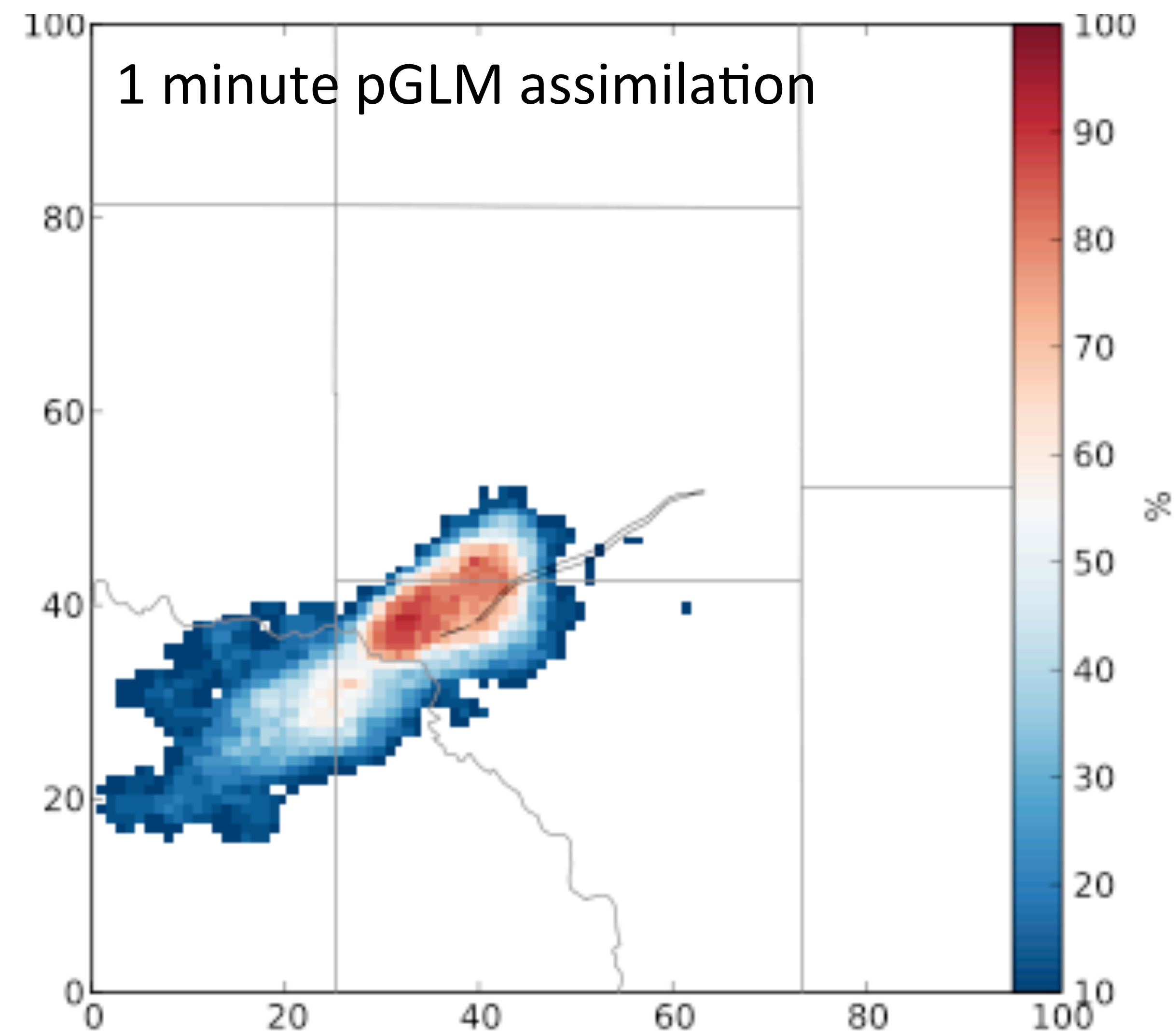


Some broadening of the storms is expected from the 8-km resolution of the pseudo-GLM data. Excessive coverage of high-reflectivity regions is not unexpected, but also not bad for a simple linear observation operator.

P-GLM EnKF: 8 May 2003 Supercell

Probability of Vorticity > 0.016 s^{-1} at 1.75 km model height





EnKF analyses of low-level mesocyclone (indicative of tornado potential) shows supercell storm character in the p-GLM assimilation. Rotation is not as strong as when radar radial velocity is assimilated, but has a similar average track and increases in probability near the time of the observed tornado formation. Forecast tests are planned but not yet executed.

Summary:

Lighting effectively identifies deep convection and is useful for forcing convection in the early hours of a forecast. Sustained nudging of water vapor forms updrafts and allows storms to develop in a balanced manner within the model. For simple convection initiation, it is more efficient, e.g., than 3D-VAR radar analysis.

The Ensemble Kalman Filter method can modulate convection (e.g., strengthen or weaken) or help suppress spurious storms using lightning or radar data. It requires an ensemble, which is computationally expensive, but eliminates the need to develop direct algorithmic adjustments of state variables (updraft, moisture, temperature, etc.) or complex 4D-var adjoint models.

Lightning data can provide enhanced value to radar where available and are especially useful in radar voids (e.g., tropical storms at sea). It can serve as additional input, for example, in short-term (0-1 hr) forecasting of high-impact weather in the Warn-on-Forecast paradigm.

Reference: Fierro, A. O., E. R. Mansell, C.L. Ziegler, and D.R. MacGorman, 2012: Application of a Lightning Data Assimilation Technique in the WRF-ARW Model at Cloud-Resolving Scales for the Tornado Outbreak of 24 May 2011, Mon. Wea. Rev. vol. 120, 2609-2627.