Evaluating the potential impact of assimilating satellite lightning data utilizing hybrid (variational-ensemble) methods

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1. Introduction and Objectives

- This study demonstrates the utility of lightning data assimilation from the Geostationary Lightning Mapper (GLM) instrument onboard the future GOES-R satellite.

- Why lightning data? The potential benefit of the link between the intensity of deep convection and total lightning flash rates was found (Carey and Rutledge, 2000, Rickenbach et al., 2011).

- Several efforts to incorporate lightning data (Papadopulus et al., 2005, Mansell et al, 2007, Pessi and Bussinger, 2009, Fierro et al., 2012), the majority utilizing nudging techniques.

- All those studies, stressed the importance of utilizing real-time measurements of lightning data to improve the representation of deep convection in numerical weather prediction models.

- One of the goals of this study is to correct the location and intensity of severe thunderstorms during the analysis and short rage (6-hr) forecasts steps.

- To asses how the future GOES-R Geostationary Lightning Maper (GLM) data can assist in correcting the intensity and location of severe weather.

2. Case Study

The April 27-28, 2011 tornado outbreak in the Southeastern United States with special emphasis on the Tuscaloosa tornado

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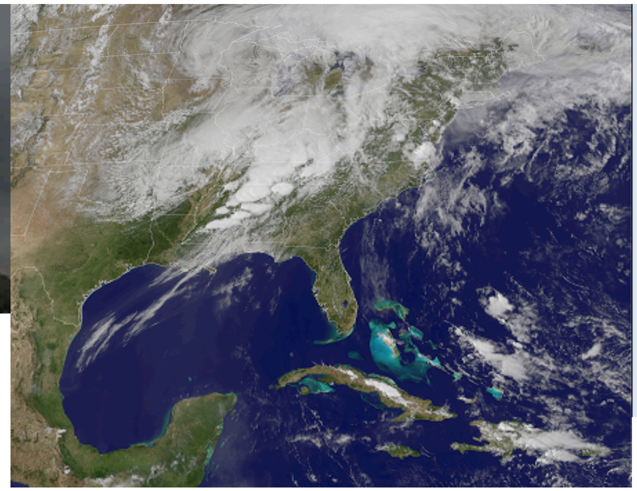

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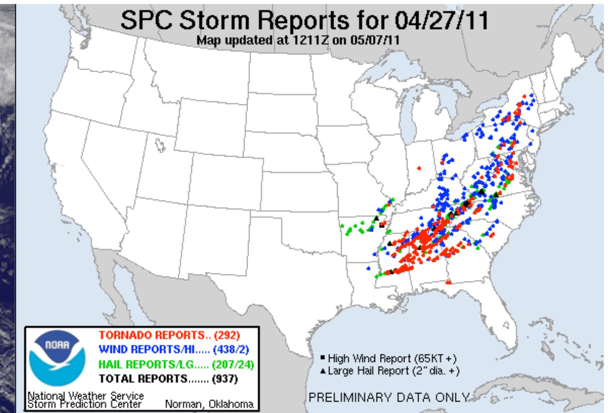

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- Atmospheric conditions created a perfect scenario for severe weather development.
- Cold easterly flow generated atmospheric instability.
- Surface moist air arrived from the Gulf of Mexico.
- Strong vertical wind shear helped create highly organized storms, which developed strong rotation at lower and mid levels.
- In the evening of April 27th a line of severe thunderstorms exploded.
- These exceptionally favorable ingredients ensured a large number and long-lived super-cell thunderstorms capable of producing violent tornadoes ~388) (Hayes, 2011).

3. Data Assimilation and Model Set-up

- The Maximum Likelihood Ensemble Filter (MLEF) is used as a hybrid (variational-ensemble) DA system.

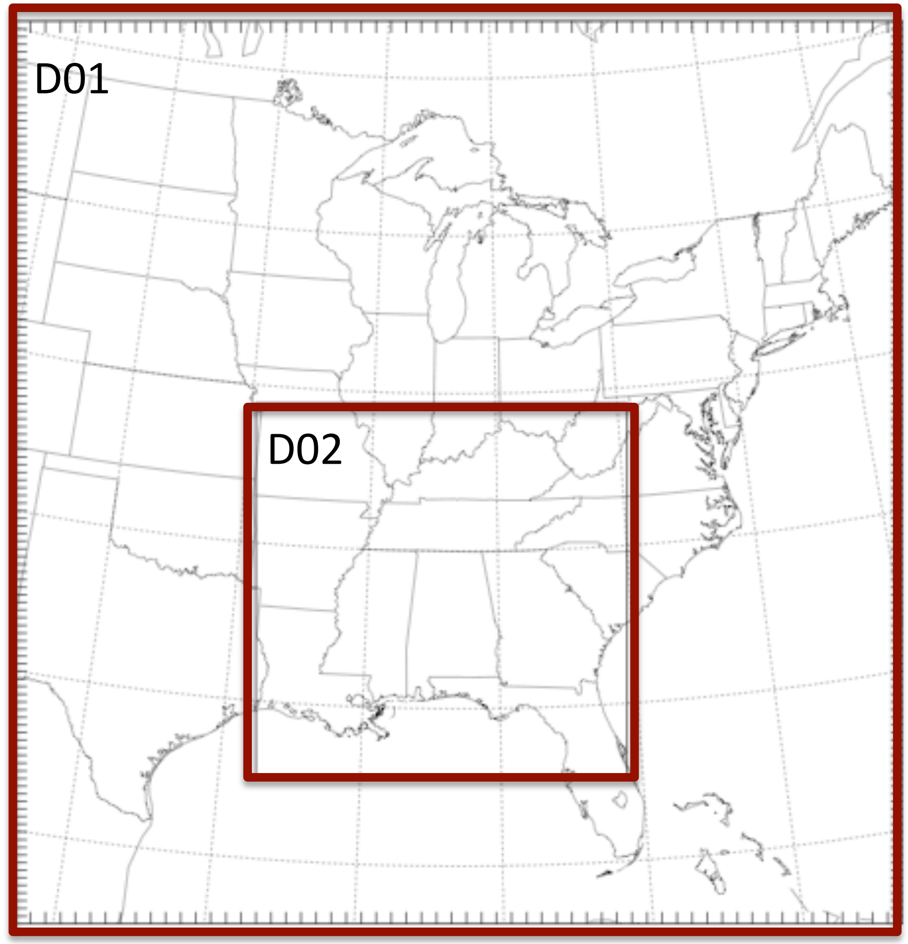
- World Wide Lightning Location Network (WWLLN) data is used as a proxy for future GOES-R GLM data.

- WRF-NMM, resolution --- Two domains at 27 and 9km.

- 32-ensembles at 6-hr assimilation interval.

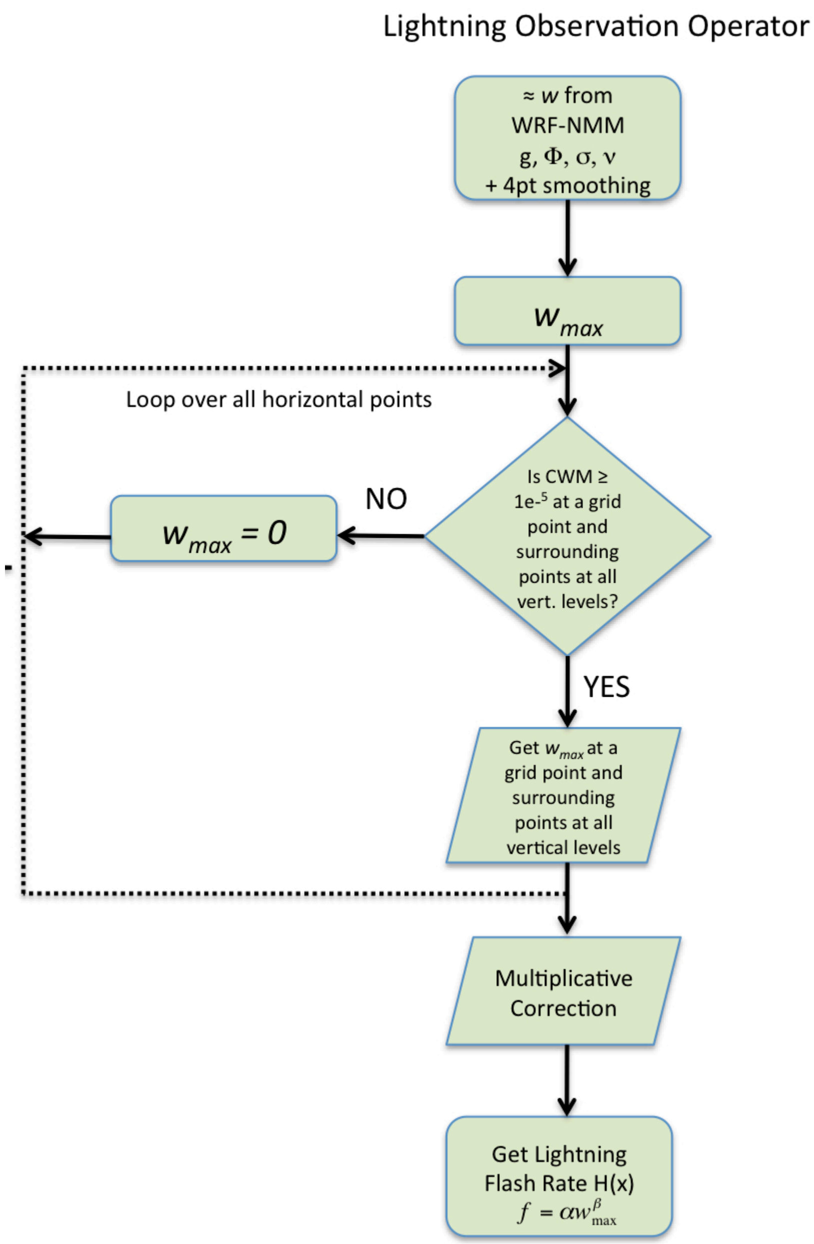
- WWLLN has a 10km location accuracy for lightning strokes.

- Control variables: T, Q, PD (P_{surf} - P_{top}), U, V, CWM.



- Two experiments: with assimilation of lightning data (LIGHT) and without it (NODA).

3.1. Lightning Observation Operator Development



- Starts with the calculation of maximum vertical velocity from WRF-NMM (W_{max})

$$w = \frac{1}{g}\left(\frac{\partial \Phi}{\partial t} + v \cdot \nabla_{\sigma}\Phi + \dot{\sigma}\frac{\partial \Phi}{\partial \sigma}\right)$$

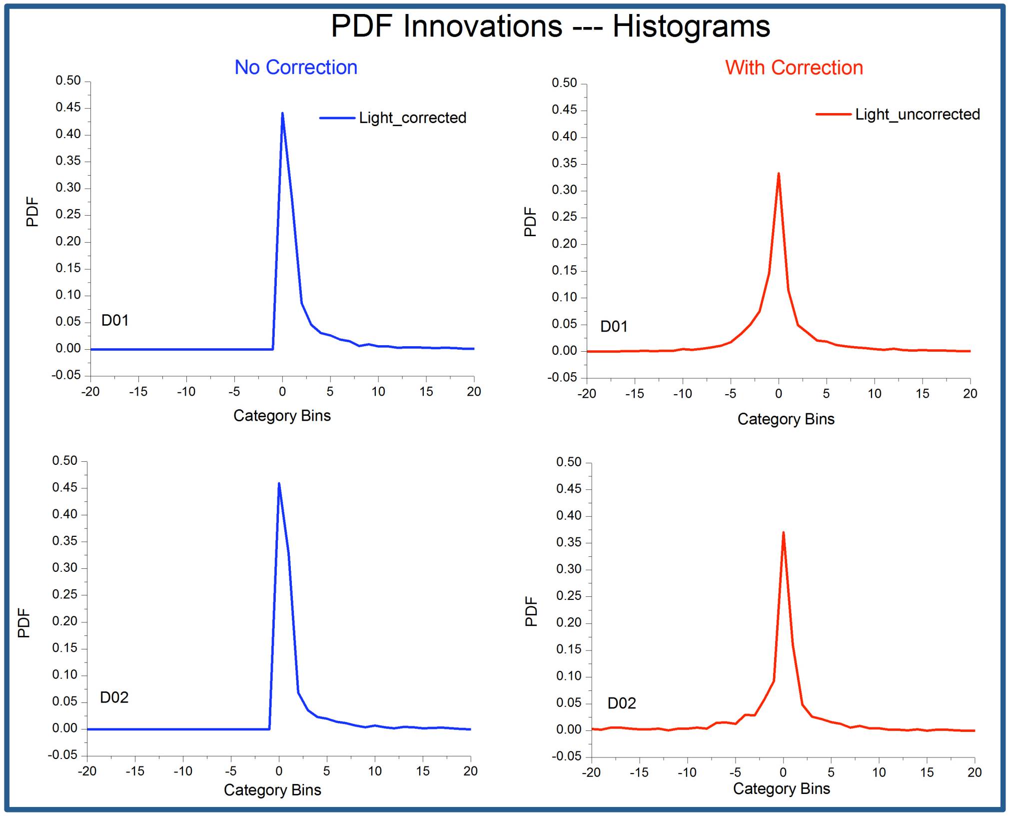
- The algorithm calculates w_{max} at grid points and surrounding points along a vertical column where clouds are present.

- Total cloud condensate (cloud water, rain and snow) above a threshold used to detect clouds.

- An empirical relationship between lightning flash rate and vertical velocity is used (Price and Rind, 1992) $f = c\alpha_{opt} w_{\max}^{\beta}$

$c=5e^{-6}$, α_{opt}=correction parameter, $\beta=4.5$

3.2. Lightning Observation Operator Correction



- Necessary correction as the PDF Innovation histograms from previous experiments showed positive bias and skeweness

- Assume a multiplicative correction to the lightning observation operator $h(x) \rightarrow \alpha h(x)$, where α is the unknown multiplication parameter

- The cost function will include an adjustable parameter $\alpha < 0$

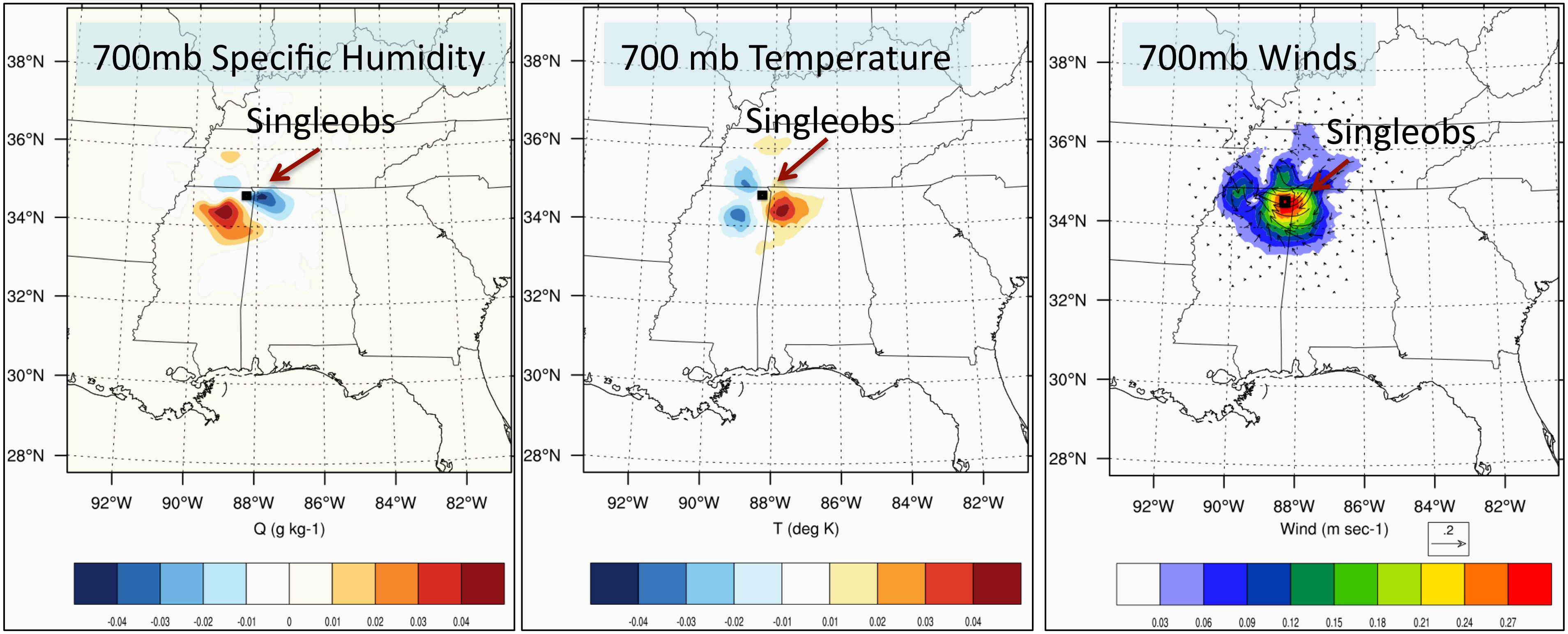
$$J(\alpha) = \frac{1}{2}[\log(\alpha) - \log(\alpha_0)]^T W^{-1}[\log(\alpha) - \log(\alpha_0)]$$
$$+\frac{1}{2}[\log(y) - \log(\alpha h(x))]^T R_L^{-1}[\log(y) - \log(\alpha h(x))]$$

- Where R_L = observation error covariance, α_0 = guess value and W = guess uncertainty matrix
- Search for the optimal parameter $a_{opt} > 0$ that minimizes the cost function

- With a typical guess value of $a_0 = 1$, the solution becomes (1), where
- N_{obs} = # of observations, *diagonal* $(R_L) = r_0$ and *diagonal*$(W) = w_0$

$$\alpha_{opt} = \exp\left[\frac{\frac{1}{N_{obs}}\sum_{i=1}^{N_{obs}}\log\left(\frac{y}{h(x)}\right)_i}{1+\frac{r_0}{w_0}}\right]$$

4. Results --- Singleobs test



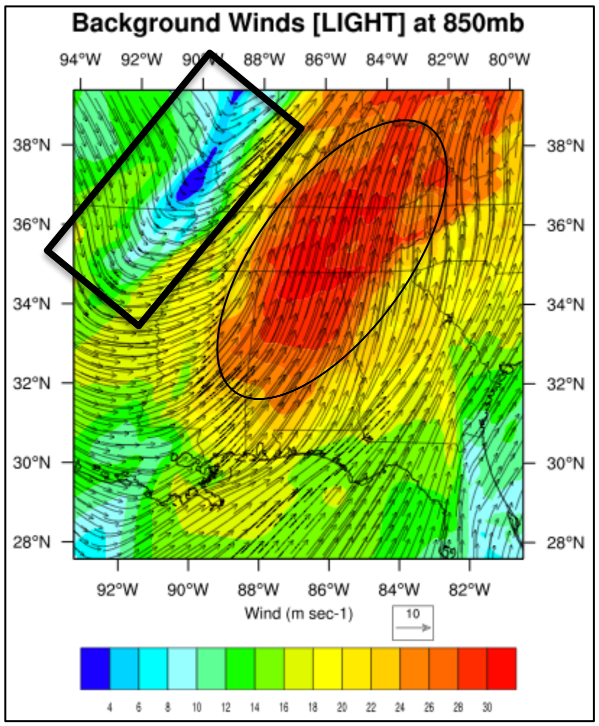
- Analysis increments – SPECIFIC HUMIDITY, TEMPERATURE, WIND at 700mb.
- Location of the single observation (35.01°N, 87.60°W).
- Dipoles of positive and negative analysis increments at either end of the single observation in SPECIFIC HUMIDITY and TEMPERATURE, but with opposite signs.
- 700mb WINDS: positive analysis increment, maximum values coincide with the region of positive temperature increment and cyclonic circulation around the location of the singleobs

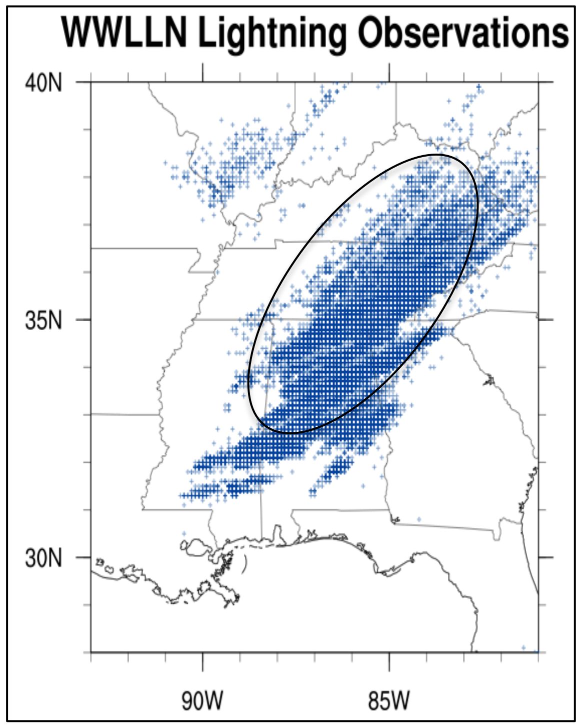
4. Results --- Synoptic Analyses

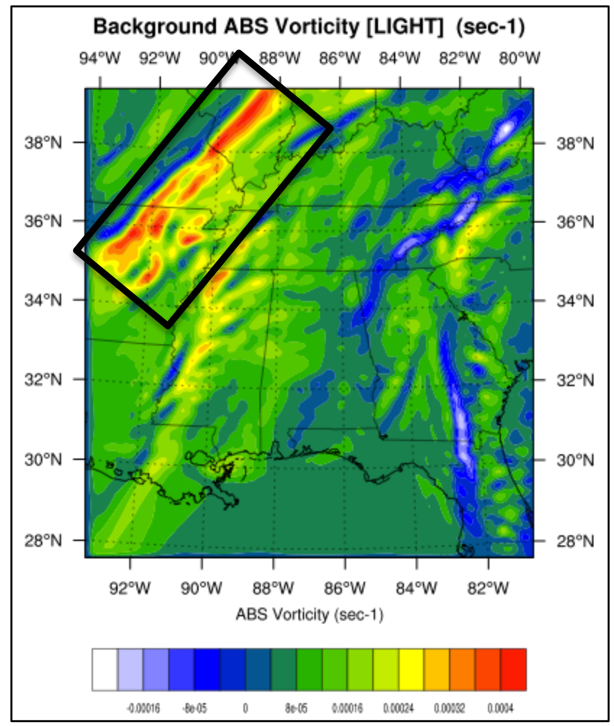
◆ The following contour plots, correspond to the LIGHT experiment at 0000UTC on April, 28, the touch-down time of the Tuscaloosa, Alabama tornado.

◆ The region of strongest winds in the 6-hr forecast (left) coincides with the area where the lightning observations are located (midle) during the same assimilation cycle.

◆ Strong values of absolute vorticity in the background (6-hr forecast), are located to the west of the core of strong winds where cyclonic circulation is observed.

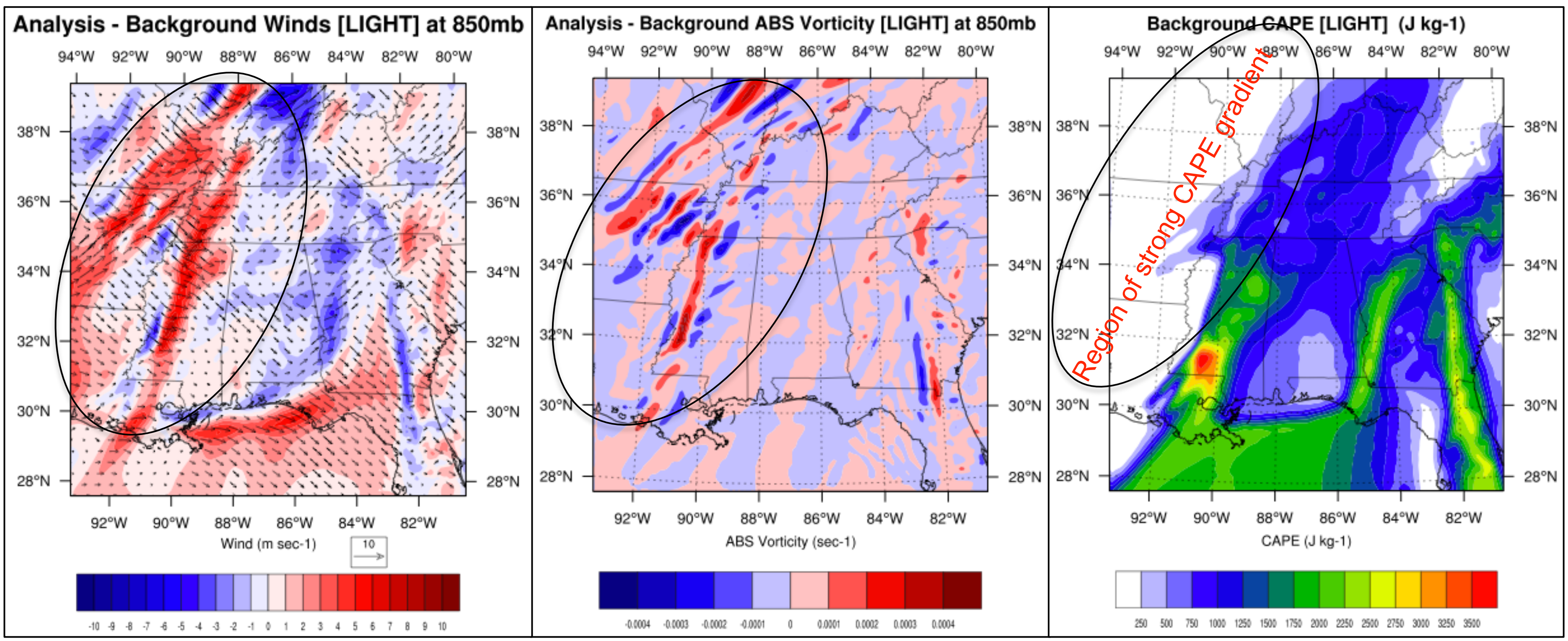






Winds, Vorticity and CAPE

- Wind differences between the analysis and forecast, show that assimilating lightning data increased 850mb winds.
- Similarly, absolute vorticity at 850mb increased.
- The wind difference, suggests that stronger vorticity is being advected into the region of high CAPE gradient (dry-line).
- Not a tornado resolving scale, but impact is noticeable



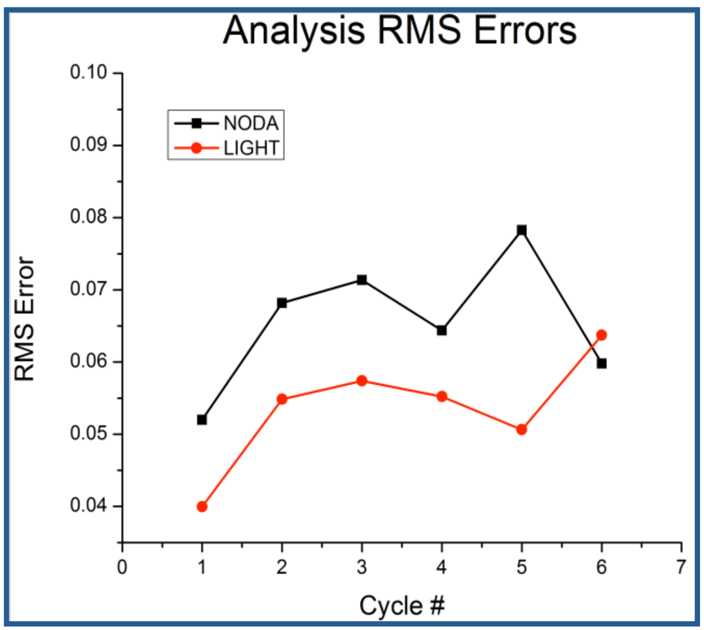
Statistics --- RMS Errors

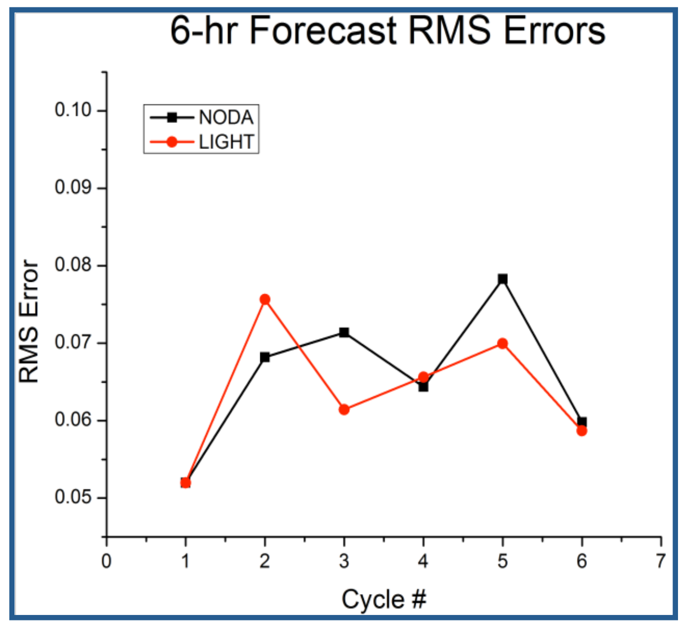
◆ Qualitative comparison may be subjective, statistics can provide useful diagnostics when morphological comparisons fall short.

◆ RMS errors are calculated from a subset domain containing all the lightning observations at 10km resolution to match WRF-NMM 9km resolution.

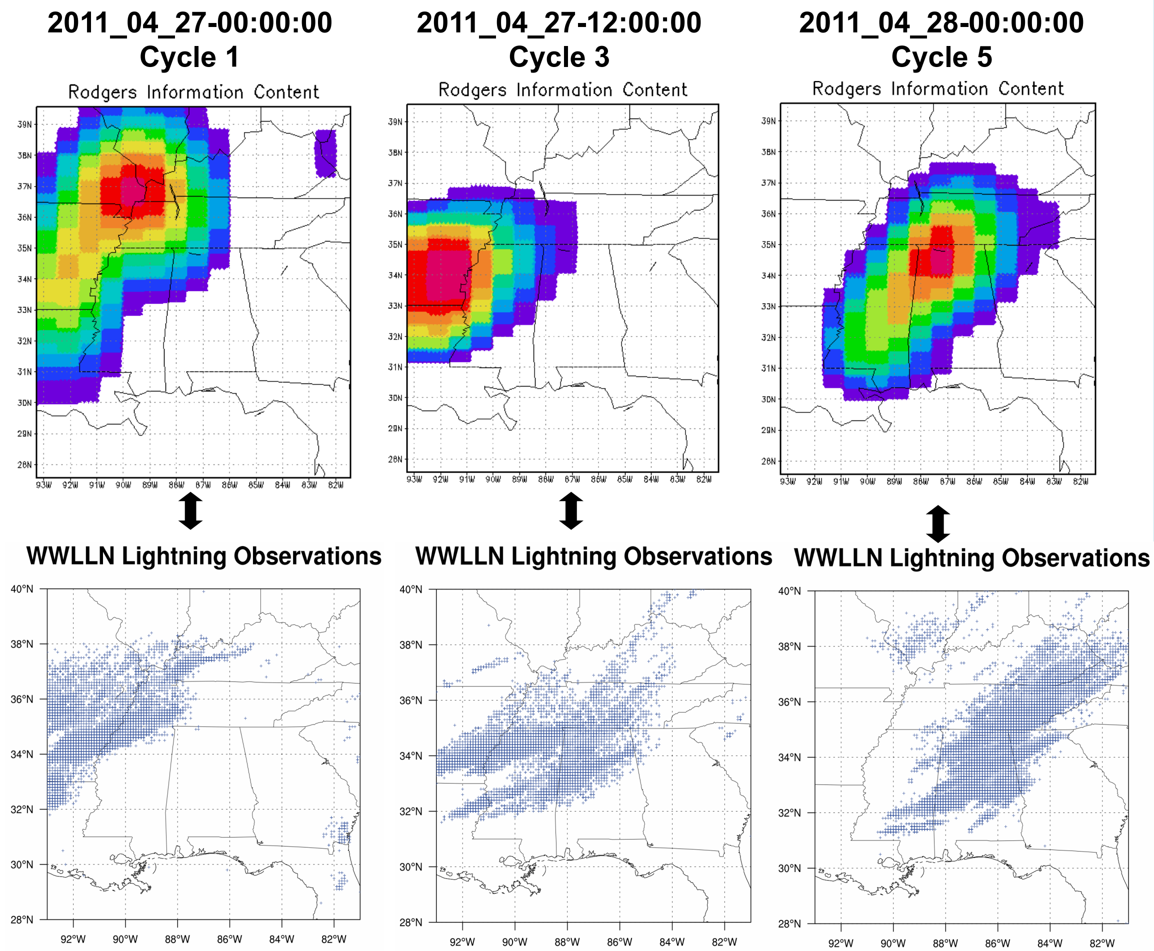
◆ From Figures below for each 6-hr assimilation window, LIGHT achieves a better fit in the assimilation, only partially kept in the forecast.

◆ Improving dynamical balances in the model could positively impact forecast RMS errors.





Results --- Shannon Information Content



◆ Lightning DA is quantified through information theory (ENTROPY) as a PDF-based measure of the use of observations in the system.

◆ The exact flow-dependent change in entropy is computed in ensemble subspace and ultimately time-flow-dependent forecast error covariances (Rodgers, 2000, L'Ecuyer et al. 2006, Zupanki et al. 2007, Zupanski, 2012).

◆ The areas of highest density of lightning observations are in agreement with information content,

implying that time-flow dependent forecast error covariance has a direct relationship to observations throughout the assimilation period.

Summary and Future Work

- The assimilation of lightning is capable of spreading new information into a NWP model
- Lightning DA impacts updrafts, moisture content, temperature, winds, advection and absolute vorticity leading to strengthening of deep convection
- Time-dependent forecast error covariance (P^f) follows the observations throughout the assimilation period
- Even though we aren't using a tornado resolving scale, results are promising
- This methodology can be applied for other lightning measurements, NWP models and case studies
- Will include operational observations to constrain the fit in the analysis and to test combined GLM and ABI observations from the future GOES-R

Acknowledgements and References

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Thanks

Questions?

Happy 2013!