Evaluating the potential impact of lightning data assimilation utilizing hybrid variational-ensemble methods

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Introduction & Goals

- This study demonstrates the utility of assimilating lightning data from the GLM instrument onboard the future GOES-R for severe weather applications
- Proxy lightning DA into a NWP model with a hybrid variational-ensemble DA system is investigated
- Case Study: April 28-29, 2011 tornado outbreak – Southeastern, United States (Tuscaloosa, Alabama)
- The goal is to correct the intensity and location of severe thunderstorms during the analysis and short-time (6-hr) forecast steps

DA & Model System Set-up

- WRF-NMM, resolution --- 27 and 9km
- The Maximum Likelihood Ensemble Filter (MLEF) is used as a hybrid variational-ensemble DA system
- 32-ensembles at 6-hr assimilation interval
- Lightning data from the World Wide Lightning Location Network (WWLLN) -- 10km location accuracy
- Control variables: T, Q, U, V, PD, PINT, CWM
- 2 experiments with lightning data assimilation (LIGHT) and without data assimilation (NODA)

Lightning Observation Operator

- Starts by calculating maximum vertical velocity (w_{max}) from WRF-NMM

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

- An empirical relationship between lightning flash rate and vertical velocity is used

$$f = c\alpha_{opt} w_{max}^{\beta}$$

$c=5e^{-6}$, α_{opt}= correction parm., β= 4.5

- Flow diagram of the MLEF DA system and Obs. Opt. shown in Figure 1

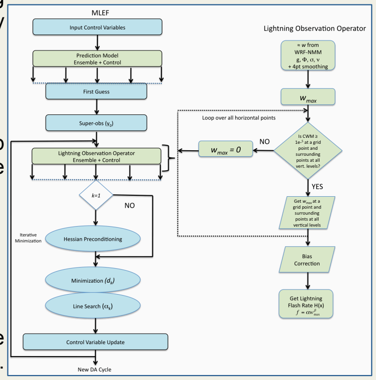

Figure 1. Flow chart of the MLEF DA system and lightning observation operator

Observation Operator Correction

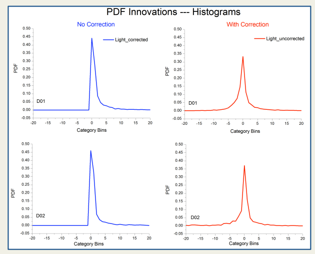

Figure 2. PDF Innovations – histograms, before and after correction. Before correction (left), the innovation vector was skewed and positively biased. After correction (right) it was normalized.

- 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 have 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 = obs. error covariance, α_0 = guess value, W = guess uncertainty matrix
- Search for the optimal parameter $\alpha_{opt} > 0$ that minimizes the cost function
- With a typical guess value of α_0= 1, the solution becomes (1), where N_{obs} = # of observations, $diag(R_L)=r_0$ and $diag(W)=w_0$

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

R E S U L T S

Synoptic Representation

- The following contour plots, correspond to the LIGHT experiment at April, 28 0000UTC, the touch-down time of the Tuscaloosa, Alabama tornado
- The region of strongest winds (Fig. 3a) coincides with the area where the lightning observations are located (Fig. 7b) (ellipses)
- By assimilating lightning, the analysis increased making advection and absolute vorticity at 850mb go up (Figure 3b,c)
- The wind difference, suggests that stronger vorticity is being advected into the region of high CAPE gradient (dry-line) (Figure 4)
- CAPE at forecast, exists in the place of observed strong CAPE gradient (Figure 4)

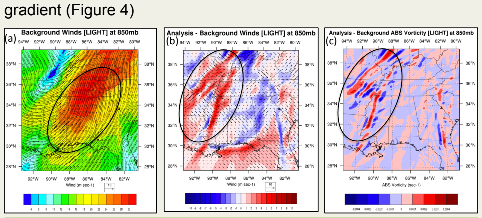

Figure 3. (a) Background winds at 850mb, (b) wind difference [A-B] and (c) absolute vorticity difference [A-B] (LIGHT)

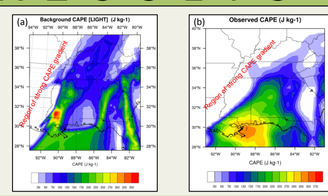

Figure 4. (a) background and (b) observed CAPE (LIGHT experiment)

Statistics

- RMS errors are calculated from a super-obed domain containing all the lightning observations at 10km resolution
- From Figure 5a,b, LIGHT achieves a better fit in the assimilation, only partially kept in the forecast
- Improving dynamical balances could positively impact forecast RMS errors

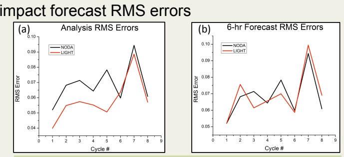

Figure 5. Analysis (a) and (b) observed CAPE (light experiment)

Rodgers Information Content of Observations

- Use information theory (e.g. entropy) as an objective, pdf-based quantification of information (Rodgers 2000; Zupanski et al. 2007):

Entropy $H\{X\} = -\int p(x)\log(p(x))dx$

Change of entropy due to observations $\Delta H = H\{X\} - H\{X|Y\}$

ΔH assumes a Gaussian PDF $\Delta H = d_s = trace\left[I - P_a P_f^{-1}\right]$

Ensemble: In realistic ensemble methods d_s can be computed exactly in ensemble subspace

$$P_a = P_f^{1/2}\left(I + Z^T Z\right)^{-1} P_f^{T/2} \quad Z = R^{-1/2}HP_f^{1/2} \quad Z^T Z = U\Lambda U^T \quad d_s = \sum_i \frac{\lambda_i^2}{1+\lambda_i^2}$$

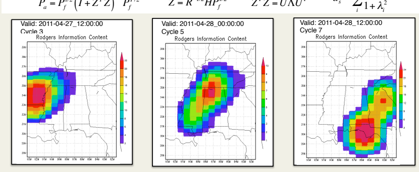

Figure 6. Rodgers information content during cycles 3, 5 and 7

- Time-dependent covariance P^f shows direct relationship to obs.

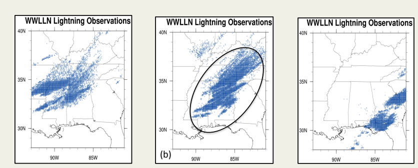

Figure 7. Lightning observations during assimilation cycles 3, 5 and 7

Summary & Future Work

- The assimilation of lightning data adds new information to the system
- Lightning DA impacts winds, advection and absolute vorticity
- Time-dependent forecast error covariance (P_f) follows the observations throughout the assimilation period
- Will include operational observations to constrain the fit in the analysis and to test combined GLM and ABI observations from the future GOES-R

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