Incorporation of GOES-R lightning data assimilation into the NCEP Gridpoint Statistical Interpolation System for use in the GFS

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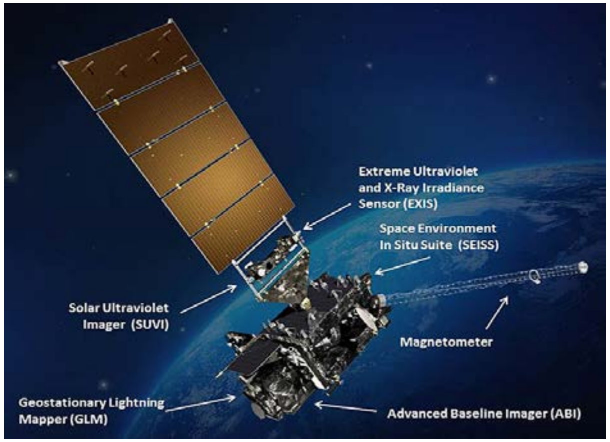
Introduction

- We have previously developed a nonlinear lightning observation operator suitable for GDAS (based on maximum vertical velocity) (Apodaca et al. 2014)

- We are currently focusing on adding this particular operator in the GSI framework (used as a 3DVAR DA system, Hybrid-GSI (possible)

- Preparing this capability for future GOES-R GLM observations

- Development of a lightning data assimilation interface with experimental network lightning data as a proxy for future GLM



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GSI processing of GOES-R lightning data

- Converting geo-located lightning strikes into BUFR format
- Create an adequate read subroutine (read_light.f90)
- Processing of lightning data through the nonlinear observation operator algorithm by comparing the guess to observations (setup_light.f90, setuprhsall.f90)
- Further processing of lightning observations inside the inner-loop minimization: tangent linear and adjoint of observation operator (intlight.f90)

3DVAR GSI cost function

$$J = \frac{1}{2}\left[(\mathbf{x} - \mathbf{x}_b)^T \boldsymbol{B}^{-1} (\mathbf{x} - \mathbf{x}_b) + (y_{obs} - H[\mathbf{x}])^T \boldsymbol{R}^{-1} (y_{obs} - H[\mathbf{x}]) \right]$$

J is called the cost function of the analysis (penalty function)

J_b is the background term;

J_o is the observation term.

The dimension of the model state is n and the dimension of the observation vector is p.

- $\boldsymbol{x}_t$ is the true model state – Set of control variables: **T, Q, U, V, Z**
- $\boldsymbol{x}_b$ background model state (dimension n)
- $\boldsymbol{x}_a$ analysis model state (dimension n)
- $\boldsymbol{y}$ vector of observations (dimension p)
- H observation operator (from dimension n to p) – **Lightning**
- $\boldsymbol{B}$ covariance matrix of the background errors ($\boldsymbol{x}_b - \boldsymbol{x}_t$) (dimension n × n)
- $\boldsymbol{R}$ covariance matrix of observation errors ($\boldsymbol{y}$ – H[$\boldsymbol{x}_t$]) (dimension p × p)

(Based on 2013 GSI tutorial – Ming Hu)

Non-linear lightning Observation Operator (setuplight.f90)

Starts by calculating vertical velocity (w_{max}) from a modified version of the non-hydrostatic continuity equation (Janjic et al. 2010), suitable for GFS

$$w = \frac{1}{g}\frac{\partial \Phi}{\partial t} = \frac{1}{g}\left[\mathbf{v} \bullet \nabla_{\sigma}\Phi + \dot{\sigma}\frac{\partial \Phi}{\partial \sigma} \right]$$

Horizontal Advection

where: $$\mathbf{v} \cdot \nabla_{\sigma}\Phi = u\frac{\partial z_k}{\partial x} + v\frac{\partial z_k}{\partial y}$$

and $$z_k = z_0 + \sum_{1}^{k_{max}} \frac{RT_v}{g}\frac{dP_k}{P_k}$$

Vertical velocity

$$\dot{\sigma} = -\frac{\sigma}{\mu}\left(-\int_0^1 \nabla_{\sigma} \cdot (\mu \mathbf{v}) d\sigma' - \int_0^{\sigma} \nabla_{\sigma} \cdot (\mu \mathbf{v}) d\sigma' \right)$$

(markers: 1 over the first integral, 2 over the second integral)

$$\mu = \frac{1}{\sigma} \qquad \sigma = (p_s - p_t)$$

and $$\frac{\partial \Phi}{\partial \sigma} = -\mu\frac{RT_v}{P}$$ **Hypsometric equation**

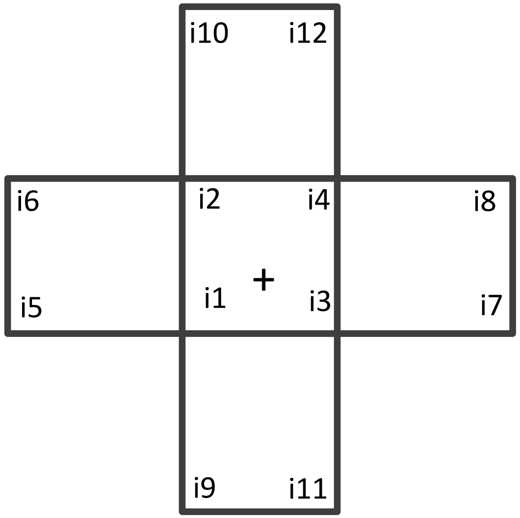
Using material surface boundary conditions ($\dot{\sigma} \equiv d\sigma/dt = 0$ at $\sigma = 0$)

1. Hydrostatic surface pressure tendency

2. Vertical velocity in sigma coordinate

Non-linear lightning Observation Operator (setuplight.f90)

To obtain the value of each control variable and it's perturbed value at observation location we use the following schematic:



Once the value of *w* is known, we proceed to find it's maximum value (w_{max}) along a vertical column above the observation location

An empirical relationship between lightning flash rate and vertical velocity is used (Price and Rind, 1992)

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

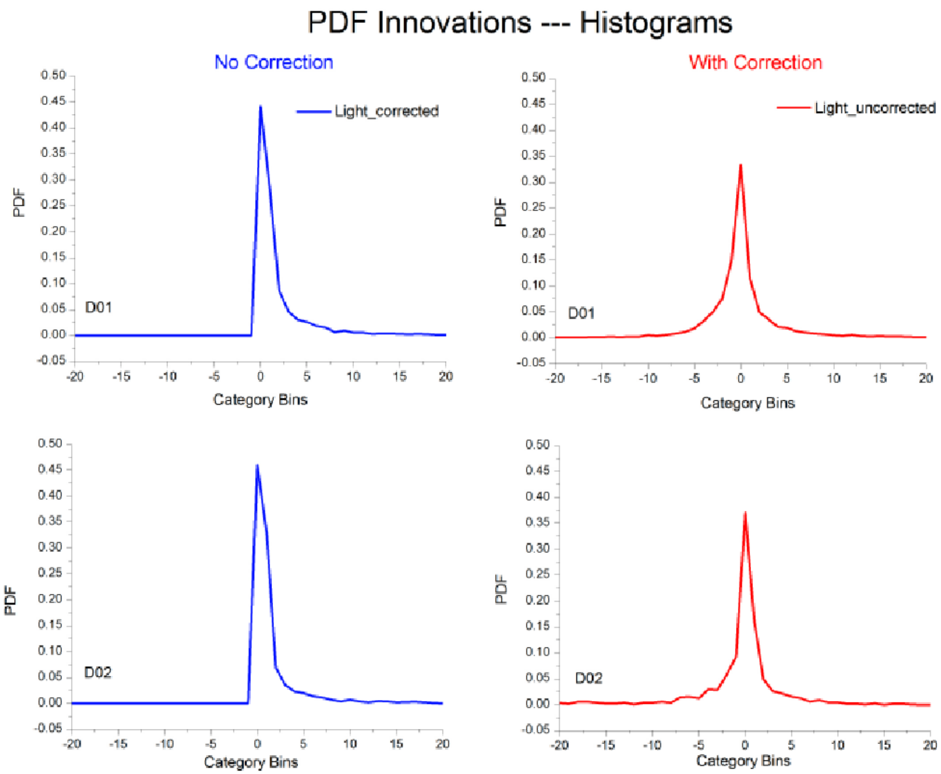
c = 5e^{-6} ®= 4.5 – parameters based on Satellite climatologies

Non-linear lightning Observation Operator (setuplight.f90)

Bias correction for lightning flash rate as in Apodaca et al. 2014

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

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



- Statistics of normalized innovation vectors $R^{-1}[y - H(x_b)]$, or PDF innovations before and after) correction.
- The skewed histograms on the left implicitly indicate that the values of observed lightning flash rates are considerably larger than the guess, a situation that required a correction.
- Need to find an optimal parameter that would minimize the previous cost function

Tangent Linear Model (TL) and Adjoint (AD) (intlight.f90)

• The tangent linear of the observation operator H consists of the partial derivatives of *H* with respect to all of its inputs (control variables), expressing the variations of *H* in the vicinity of the background x_b.

• H is sometimes referred to as the Jacobian of *H*. If *H* varies significantly with x_b then *H* is non-linear.

• Needed for the incremental formulation of XD-Var and the adjoint.

• But also, for complex observation operators, study of the Jacobian highlights observation sensitivities to input model variables at specific points (quantified as information content).

(Based on Isaksen, 2013)

Tangent Linear (TL) and Adjoint (AD) of the forward model (intlight.f90)

In order to minimize the cost function we need to take the gradient (TL) wrt the control variables using finite differencing

$$\frac{\partial J}{\partial \boldsymbol{x}} = \boldsymbol{B}^{-1}(\boldsymbol{x} - \boldsymbol{x}_b) + \boldsymbol{K}^T \boldsymbol{R}^{-1}\left[K(\boldsymbol{x}) - y_{obs}\right]$$ (Based on Zupanski, 2008)

The elements of the Jacobian matrix (jac_***x***'s) are calculated at each quadrant surrounding the observation location using 4-12 points

In the end the TL of the lightning flash rate is interpolated to observation location

```
flashrate_tl = w1*flashratei1_tl + w2*flashratei2_tl &
             + w3*flashratei3_tl + w4*flashratei4_tl
```

where w_1-w_4 are interpolation weights

$\boldsymbol{K}^T$ is the adjoint of the forward lightning observation operator

Data assimilation applications for weather analysis and prediction

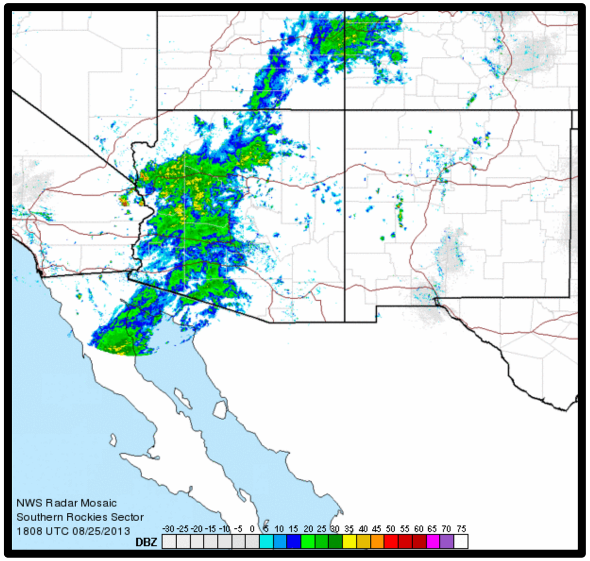
Lightinng DA for tropical cyclones

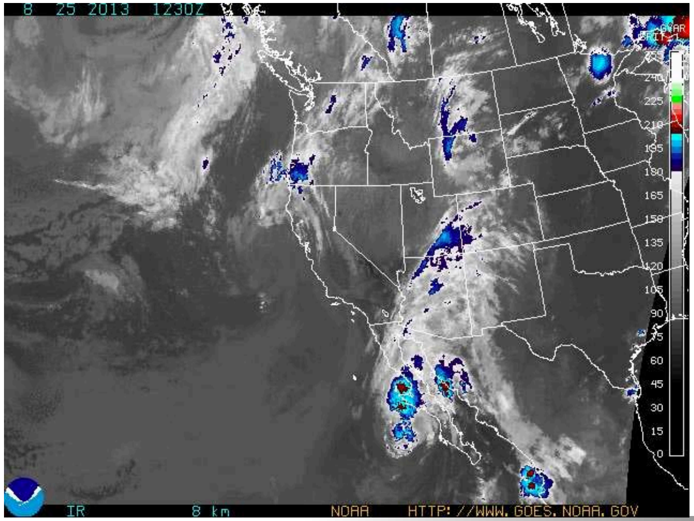
- **Tropical Storm Ivo** (August 22-25, 2013) making landfall on the Baja California peninsula during late NAM season

- Ivo's remnants triggered flash floods over the Southwest United States on the afternoon of the 26th of August (Nevada, Colorado)

- Using WRF-NMM and ARW for initial testing

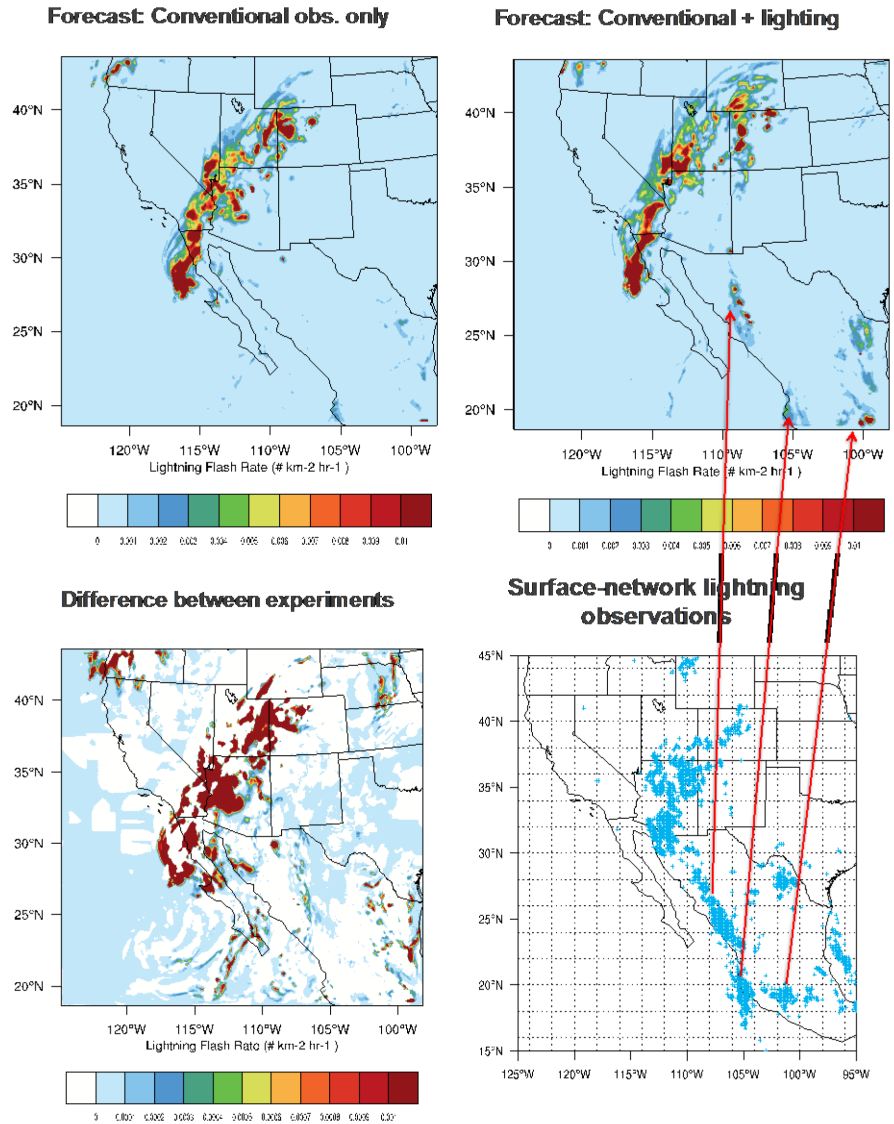
NWS Radar Mosaic for Ivo Remnants





GOES-West Satellite Image of TS-Ivo

Lightning DA for tropical cyclone Ivo, August, 2013



Forecast of lightning flash rates

The assimilation of lightning data (CONV+LIGHT) improved the forecast of lightning in several areas as compared to conventional observations (CONV-only)

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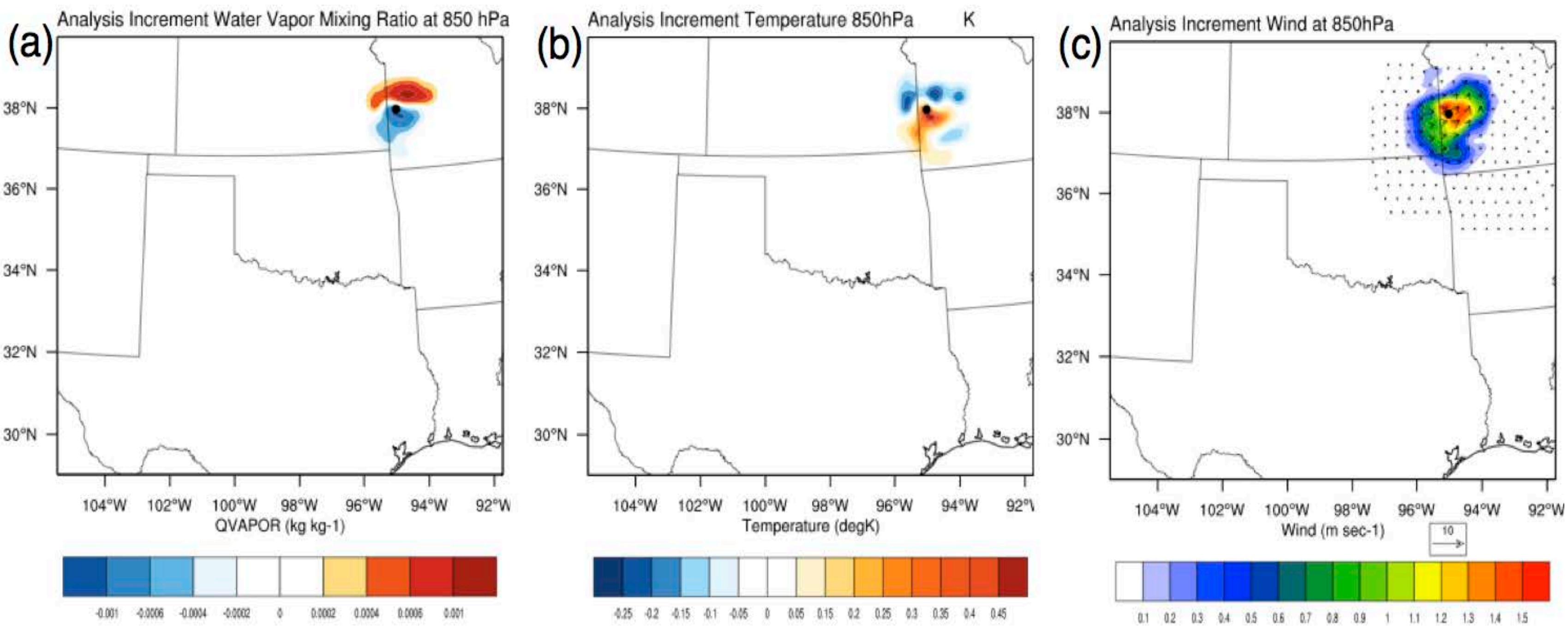
Impacts on surface precipitation for TC remnants

- Initial assessment of the impact of lightning data on 24-hr accumulated precipitation indicates most of the impact occurring over the ocean, at the location of the tropical cyclone

- GOES-R data will provide a valuable opportunity for observing and verifying forecasts of precipitation at very high resolution

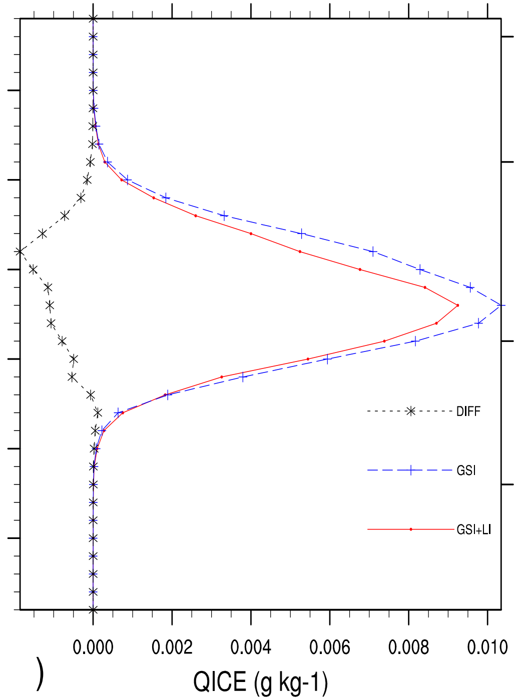
Single-OBS test - Lightning DA for the Moore, OK tornado – May, 2013

Testing an observation operator with an explicit link to cloud microphysics for cloud-resolving models



- Analysis increments ($\boldsymbol{x}_a - \boldsymbol{x}_b$) of temperature, humidity and wind at 850 hPa
- Updates to the environment around the storm

Impacts on the vertical structure of ice-phase and liquid species



(a)) (c)

Pressure (h Pa)

- The assimilation of lightning data impacted cloud hydrometeors – shown: ice, snow, rain mixing ratios as shown in vertical profiles (below)
- (CONV+LIGHT) red lines, produced less ice and snow, but more rain mixing ratio as compared to (CONV-only)
- Some WRF microphysics schemes are know for over predicting solid-phase hydrometeors

Future work

- Complete GSI processing of new GOES-R lightning observations
- Evaluate the sensitivity of the Jacobian matrix elements to model specifications
- Complete the deliverables for NCEP
- Commence testing in GFS for severe weather applications

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