Linear Optimization as a Solution to Improve the Sky Cover Guess, Forecast

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Defining Sky Cover

- The National Weather Service (NWS) web site defines “sky cover” as “the expected amount of opaque clouds (in percent) covering the sky valid for the indicated hour.”

- No probabilistic component.
- No definition of “opaque cloud” or “cloud”.
- The implication is cloud coverage of the celestial dome (all sky visible from a point observer).

Cirrostratus

How would the NWS classify sky cover for this scene?

Photo source: National Weather Service JetStream, http://www.srh.noaa.gov/jetstream/synoptic/h7.htm

Defining Sky Cover

- Meteorologists have requested a new sky cover product because
  1. purely numerical weather prediction (NWP) methods do not account for radiative transparency of clouds and
  2. current satellite-based techniques and algorithms, used alone or in existing analysis tools, do not match the forecasters' interpretation of the NWS-established definition.

Questions to Answer

- How are cloud scenes represented in a NWP model? How does that compare to the National Digital Forecast Database (NDFD)?
- How are cloud scenes observed on satellite imagery and represented on satellite products?
- What is the predictive skill of NWP model cloud fields? How can that be improved?

Defining Sky Cover

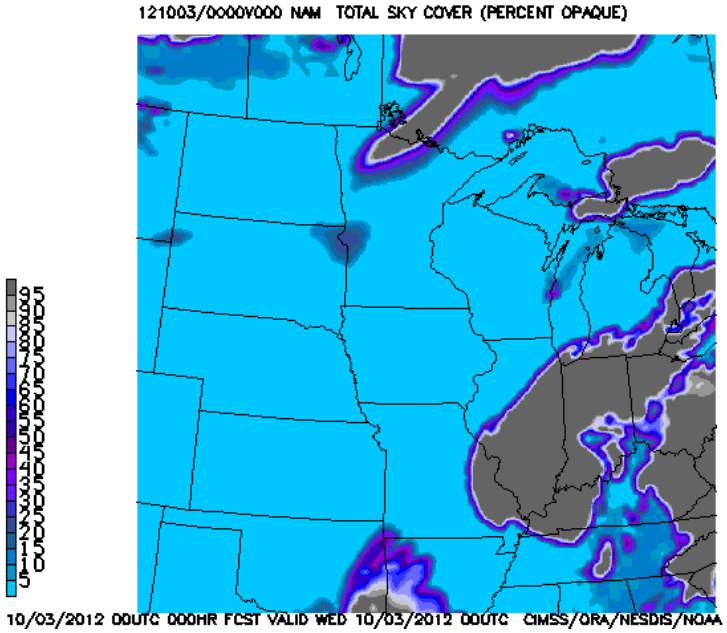
How are cloud scenes represented in a numerical weather prediction (NWP) model? How does that compare to the NDFD?

Sky Cover Representation

- Xu and Randall (1996) developed the semi-empirical cloud fraction formulation found in the Weather Research and Forecast (WRF) model.
  - Cloud fraction varies exponentially according to the grid-averaged condensate mixing ratio.
  - When the grid-averaged relative humidity is 100%, so is the cloud fraction.
  - Total cloud fraction is produced through averaging the maximum fractions from three primary layers (642 hPa, 350 hPa, 150 hPa).

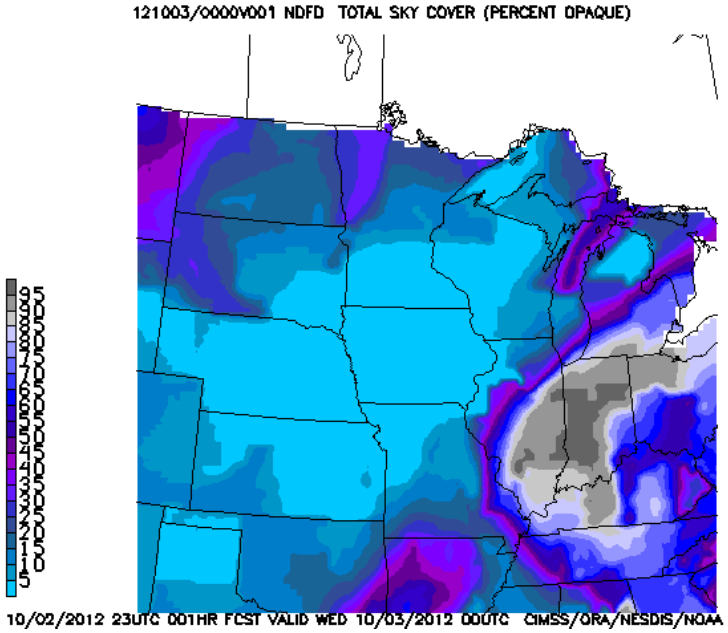
Sky Cover Representation

NAM Analysis



NDFD 1-hour Forecast

Projected onto a 20 km Lambert Conformal grid



Both images valid at 00 UTC on 3 October 2012

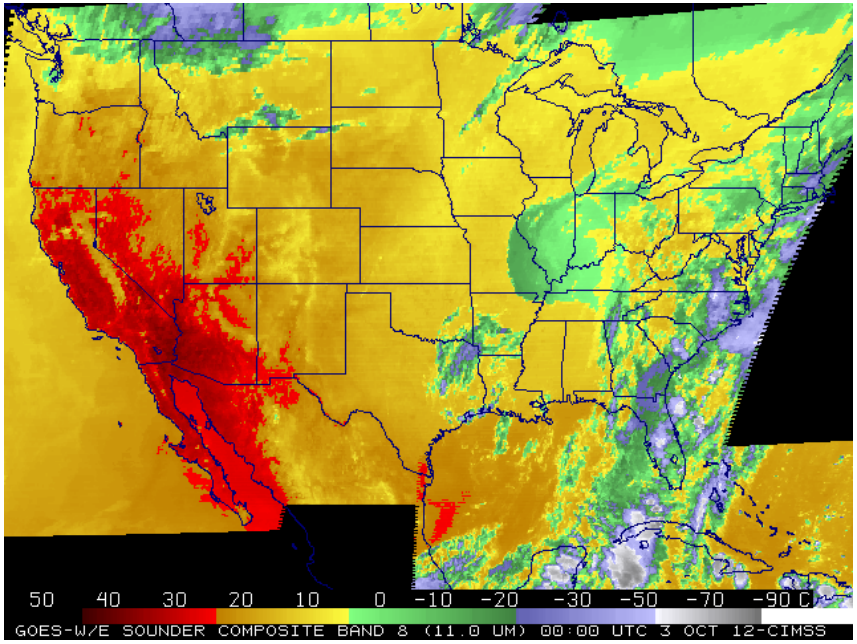
Defining Sky Cover

How are cloud scenes observed on satellite imagery and represented on satellite products?

Sky Cover Representation

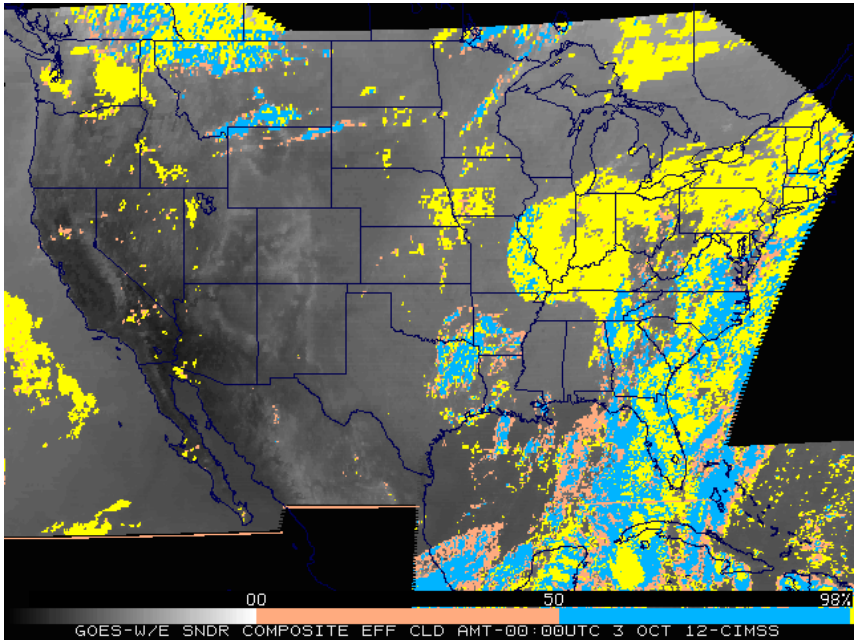
IR Window, Band 8 (11.0 µm)

GOES-14/15 (East/West) Sounder Composite



Effective Cloud Amount

A measure of the opacity ("radiative thickness") of a cloud



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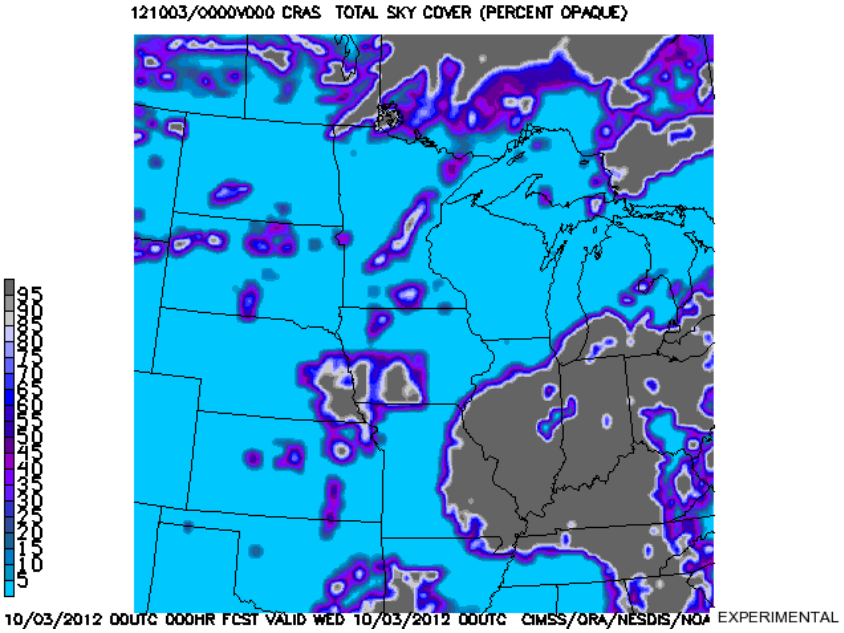
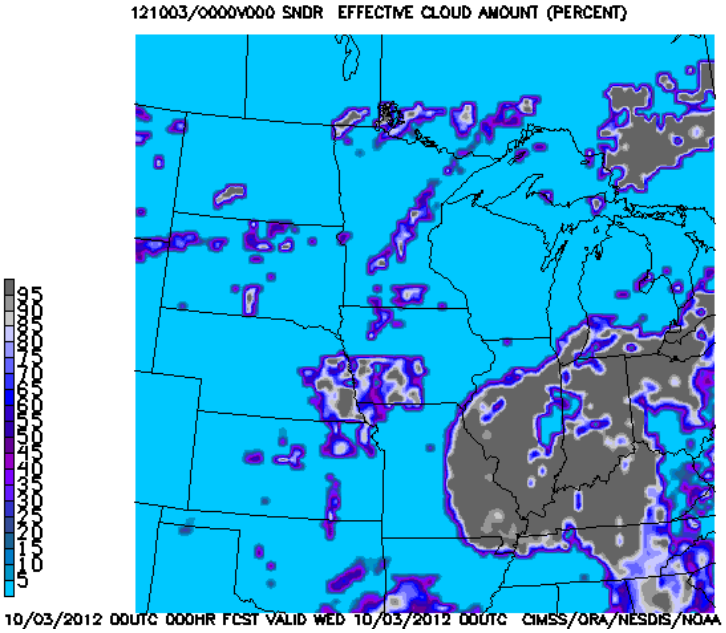
Sky Cover Representation

CRAS Analysis

CIMSS Regional Assimilation System



Effective Cloud Amount

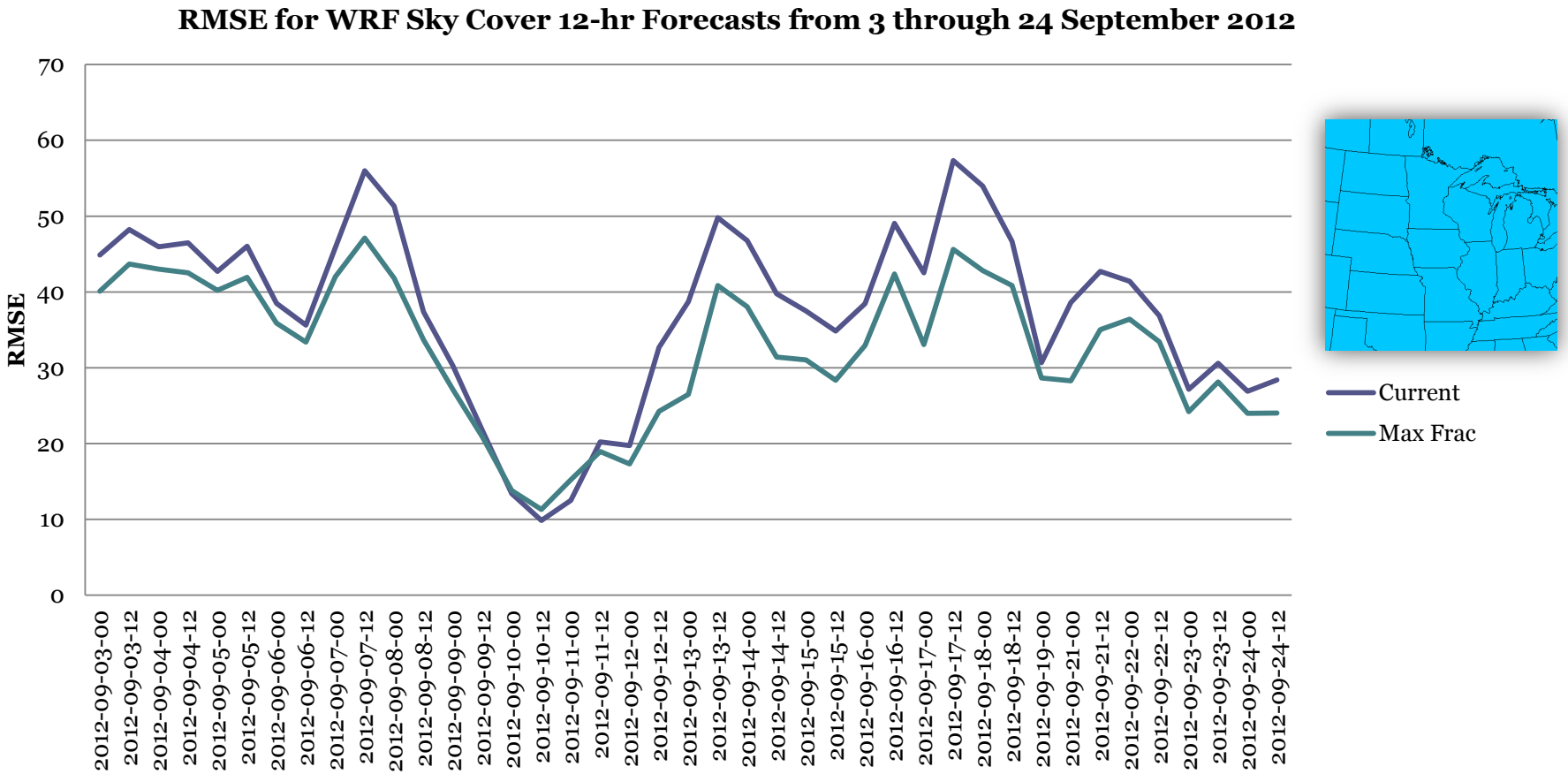


Both images valid at 00 UTC on 3 October 2012

Defining Sky Cover

What is the predictive skill of NWP model cloud fields?
How can that be improved?

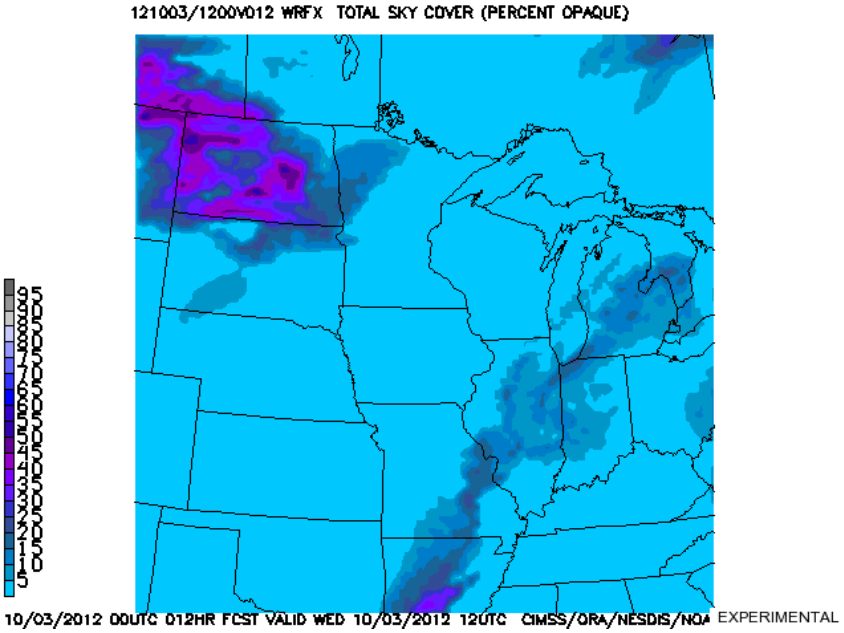
Performance (3—24 Sept. 2012)



Performance (3—24 Sept. 2012)

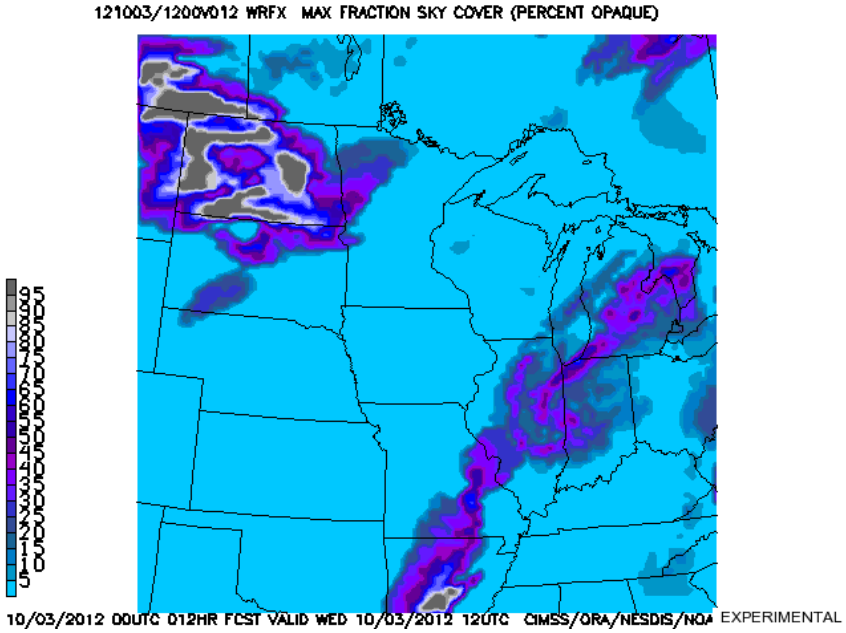
Current WRF Output

Mean RMSE: 37.5%



Maximum Fraction Output

Mean RMSE: 32.4%



Both images valid at 12 UTC on 3 October 2012

Defining Sky Cover

What is the predictive skill of NWP model cloud fields?
How can that be improved?

Types of Numerical Tools

- Numerical Weather Prediction
  - Mathematical models which predict the future state of the atmosphere
- Statistical Model
  - Relates random variables to other variables
- Linear Programming/Optimization (LP)
  - Applies mathematical method to a linear model in an attempt to find the ideal solution
    - Solves an objective function
    - Requires a list of linear relationships

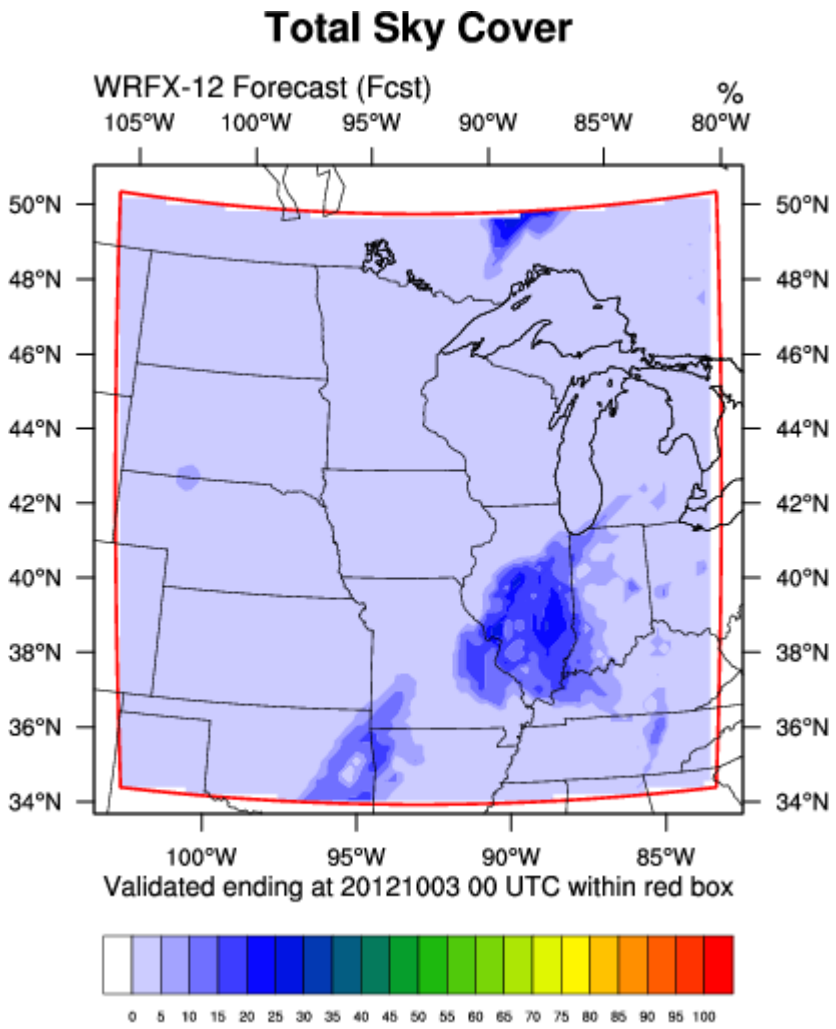
Linear Model

$$\min w = \sum_{i=1}^{n} \left| x_j a_i^j + z_j - b_i \right|$$

$$0 \leq x_j a_i^j + z_j \leq 100$$

$$x_j \geq 0$$

- The LP objective is to minimize the absolute difference between the human-produced "truth" (the NDFD 1-hour forecast) and the NWP 12-hour forecast (no NWP analysis available).



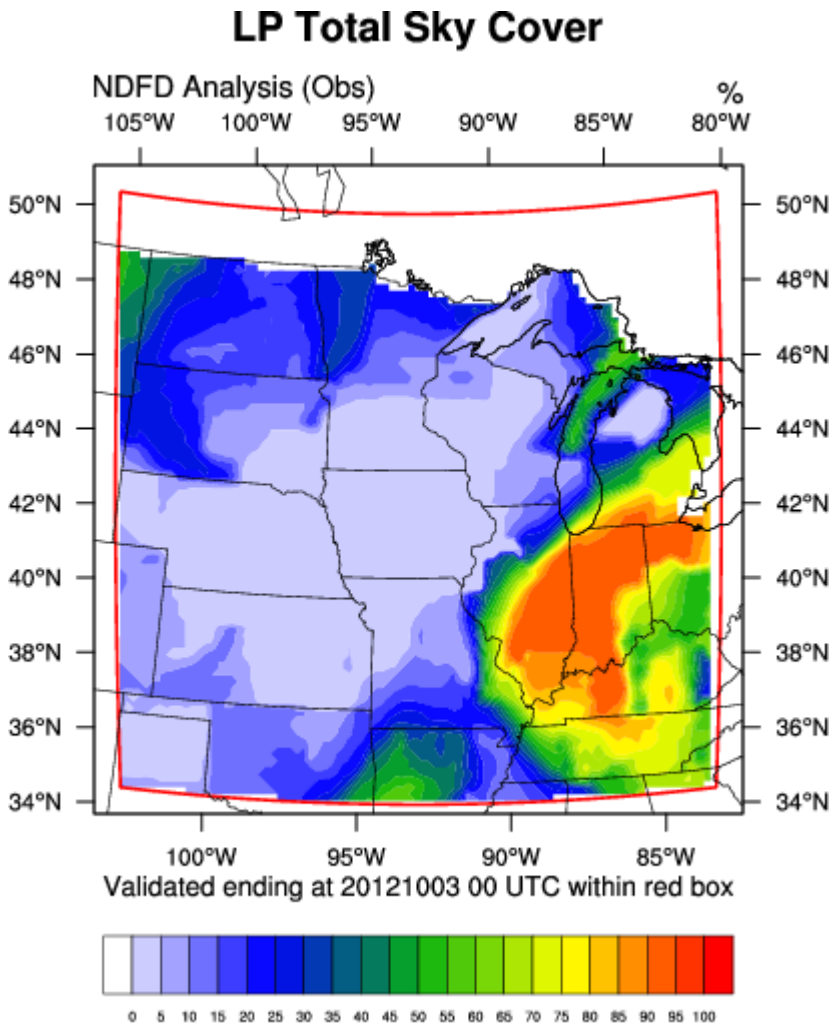
WRF Total Sky Cover Output

a_i is a point on a two-dimensional grid of the 12-hour sky cover forecast, obtained from a WRF model.

$$\min w = \sum_{i=1}^{n} \left| x_j a_i^j + z_j - b_i \right|$$

$$0 \le x_j a_i^j + z_j \le 100$$

$$x_j \ge 0$$



NDFD Sky Cover 1-hr Forecast

b_i is a point on a re-projected two-dimensional grid of the 1-hour sky cover forecast (analysis) obtained from the human-produced NDFD.

$$\min w = \sum_{i=1}^{n} \left| x_j a_i^j + z_j - b_i \right|$$

$$0 \le x_j a_i^j + z_j \le 100$$

$$x_j \ge 0$$

Linear Model

$$\min w = \sum_{i=1}^{n} \left| x_j a_i^j + z_j - b_i \right|$$

$$0 \leq x_j a_i^j + z_j \leq 100$$

$$x_j \geq 0$$

- b_i is used as truth to calculate the coefficient x_j and scalar z_j adjustments (variables) for each cloud classification (six total at approximately 20% increments).

Linear Model

$$\min w = \sum_{i=1}^{n} \left| x_j a_i^j + z_j - b_i \right|$$

$$0 \leq x_j a_i^j + z_j \leq 100$$

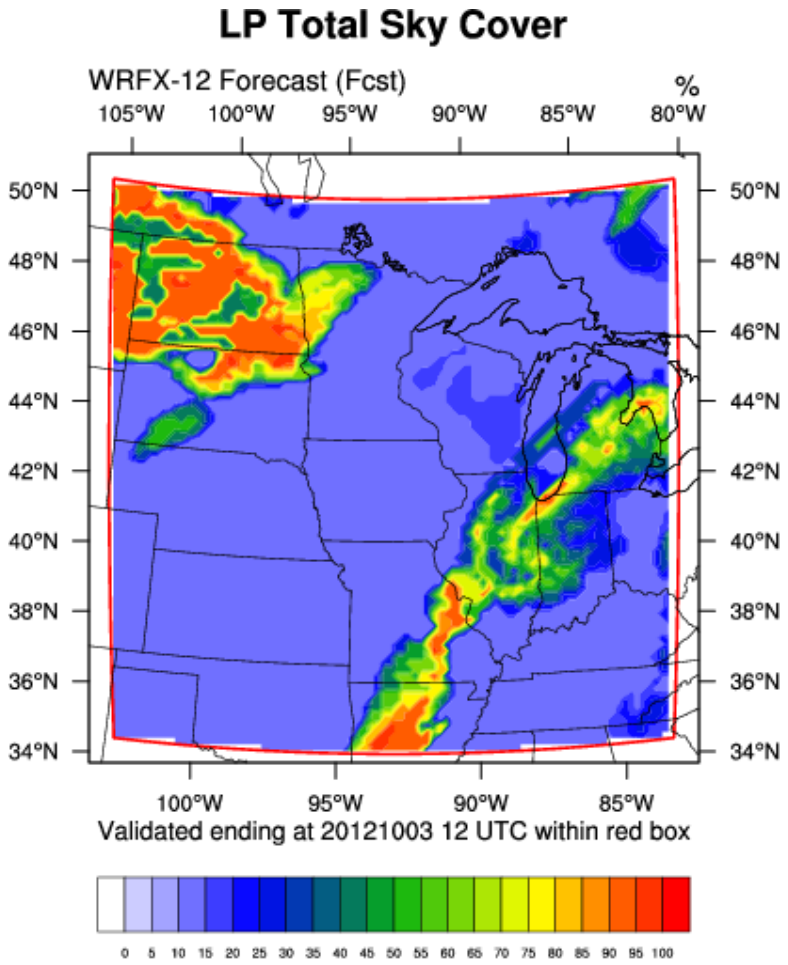
$$x_j \geq 0$$

- The value of the adjusted sky cover fraction must fall within physical meteorological values (between 0% and 100%). The value of the coefficient must be nonnegative.

Apply Results: Procedure

- The process employed in this project for staging and using background data is as follows:
  - Initialize the WRF model at time t = -12 (hours).
  - Obtain the 12-hour forecast from the model initialized at t = -12.
  - Obtain the analysis from t = 0.
  - Run linear program to minimize the objective function comparing the 12-hour forecast and analysis both valid at t = 0.
  - Initialize the WRF model at time t = 0.
  - Apply fixed variable values from the linear program (a coefficient and scalar) to WRF model output at t = 12, t = 24, and t = 36. Calculate skill.

Apply Results: Test Case

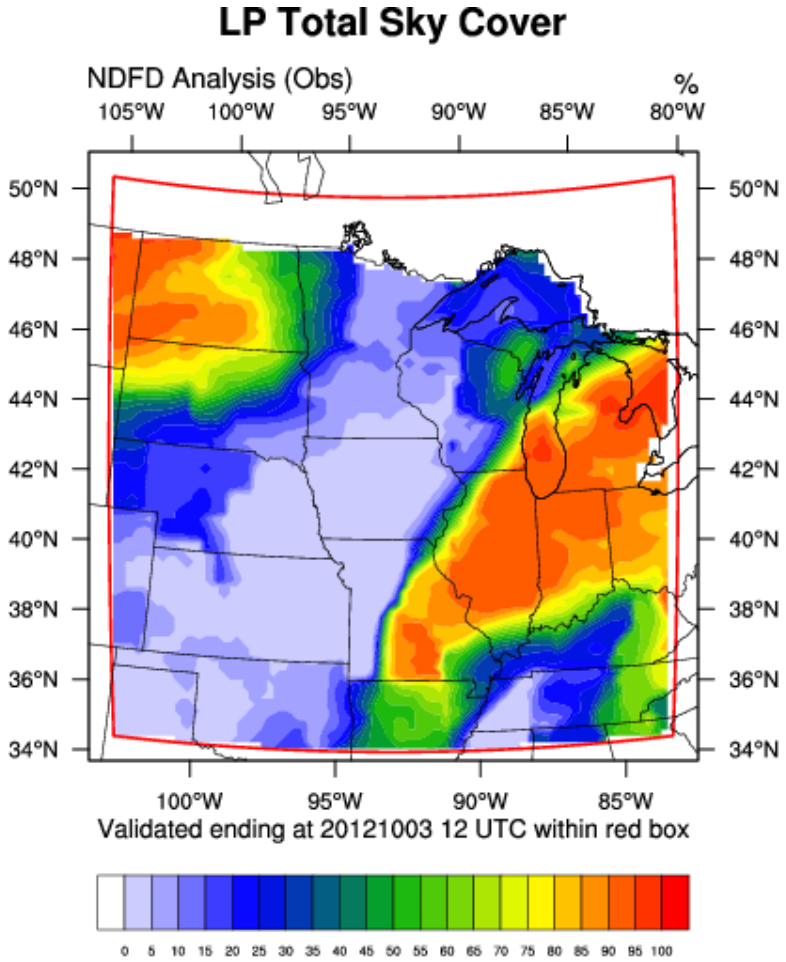


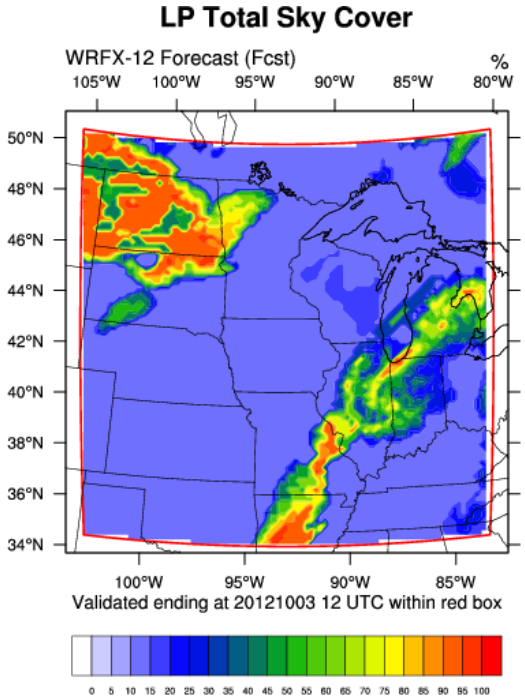
$$x_j a_i^j + z_j$$

Fraction (%)	*Coefficient (x)*	*Scalar (z)*
$0 \le a_i < 20$	4.4	12.0
$20 \le a_i < 40$	0	93.0
$40 \le a_i < 60$	1.0	0
$60 \le a_i < 80$	1.0	0
$80 \le a_i < 95$	1.0	0
$95 \le a_i \le 100$	1.0	0

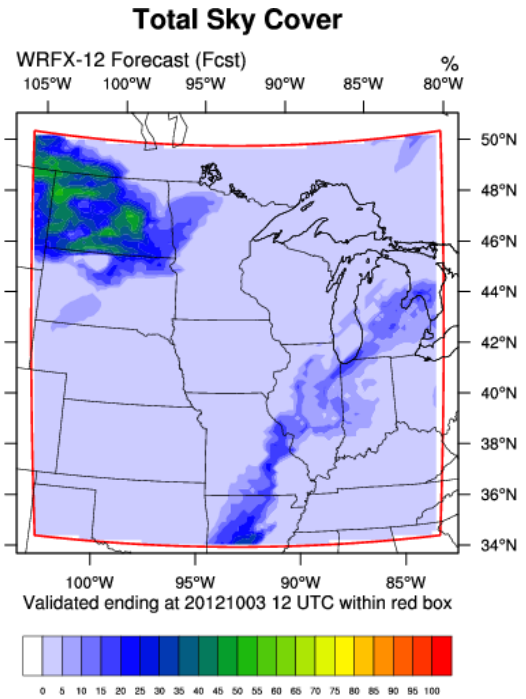
Applied to forecast output from model initialized at 00 UTC on 3 October 2012

Test Case: Local WRF Model





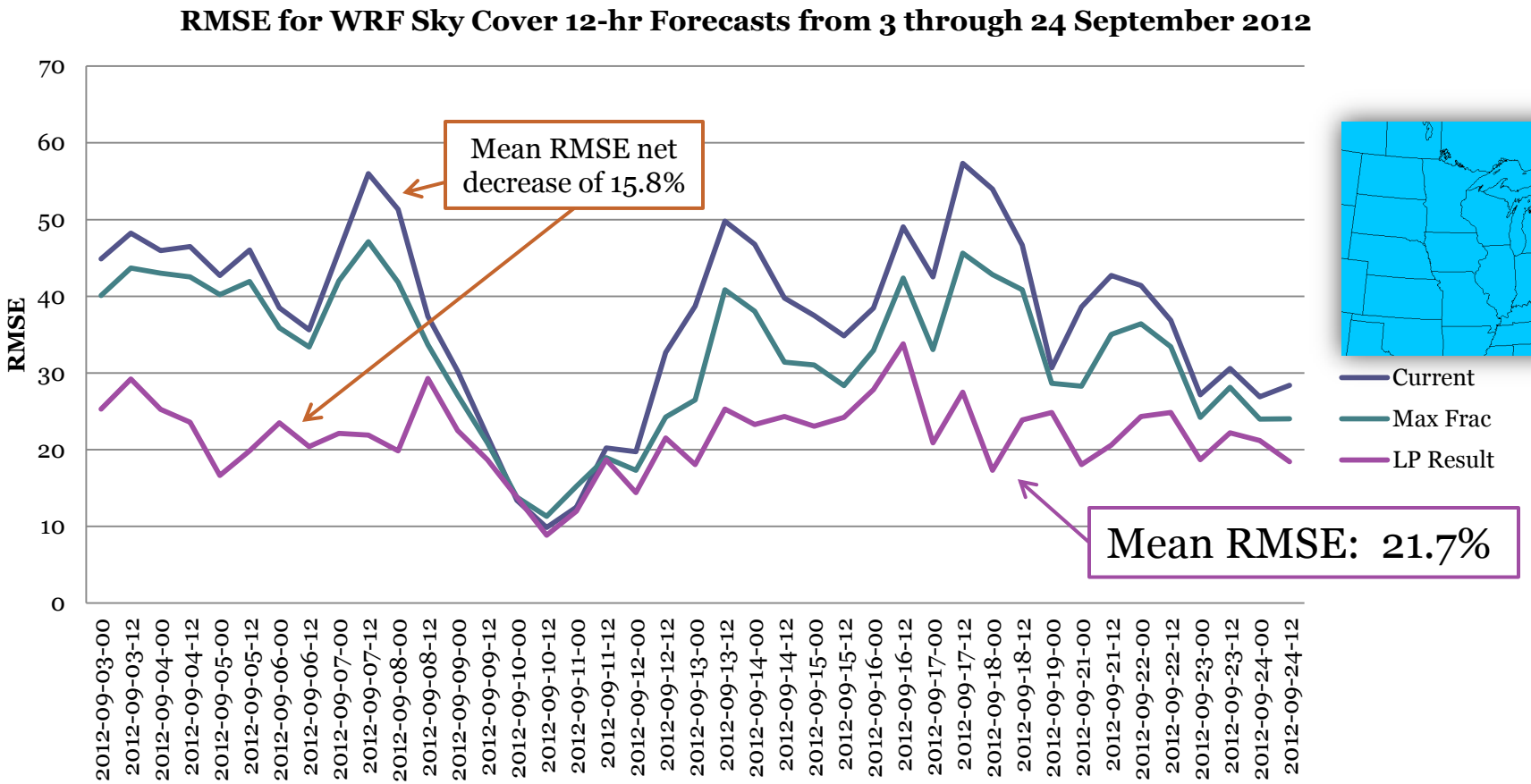
RMSE: 30.5%



RMSE: 45.0%

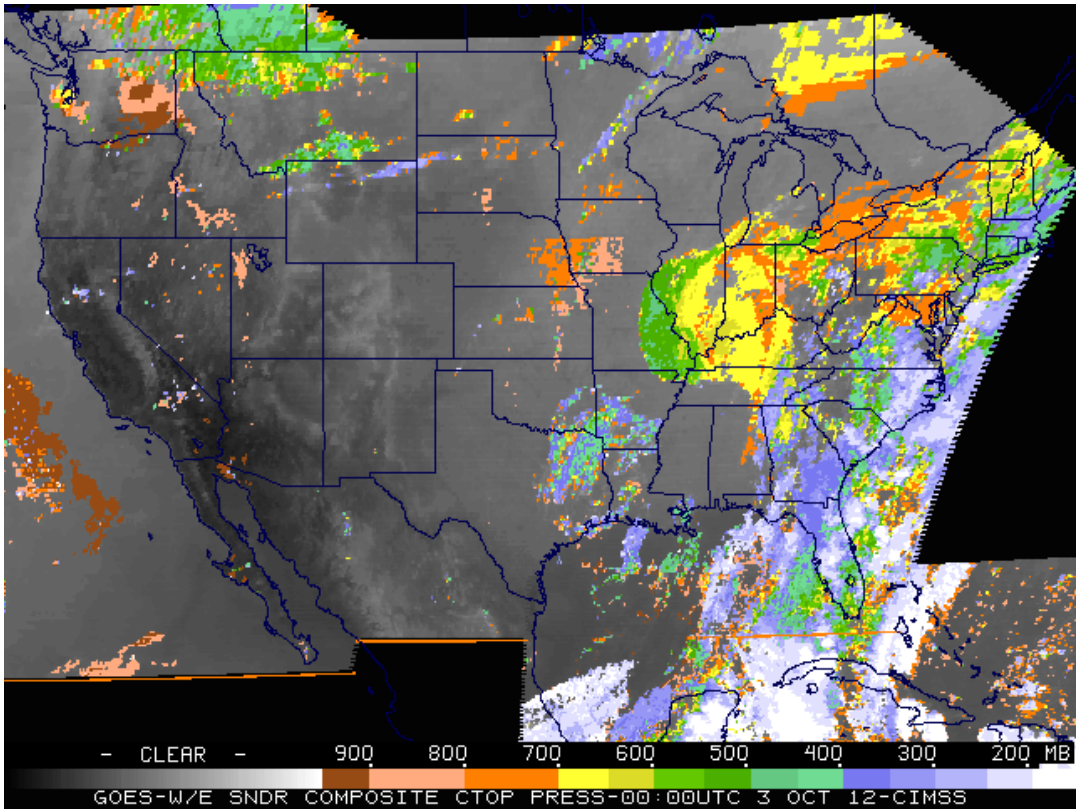
LP produces net RMSE improvement of 14.5%

Performance (3—24 Sept. 2012)



Improving Results

- Decreased performance is a consequence of:
  - Lacking sky cover congruity between forecast areas on NDFD domain
  - Assumption that relative horizontal distribution of model-developed cloud fraction matches NDFD
  - No qualification for cloud forcing or air mass regimes within NWP model (parameterizations and performance)
  - No corroboration between other NWP model output parameters or variables

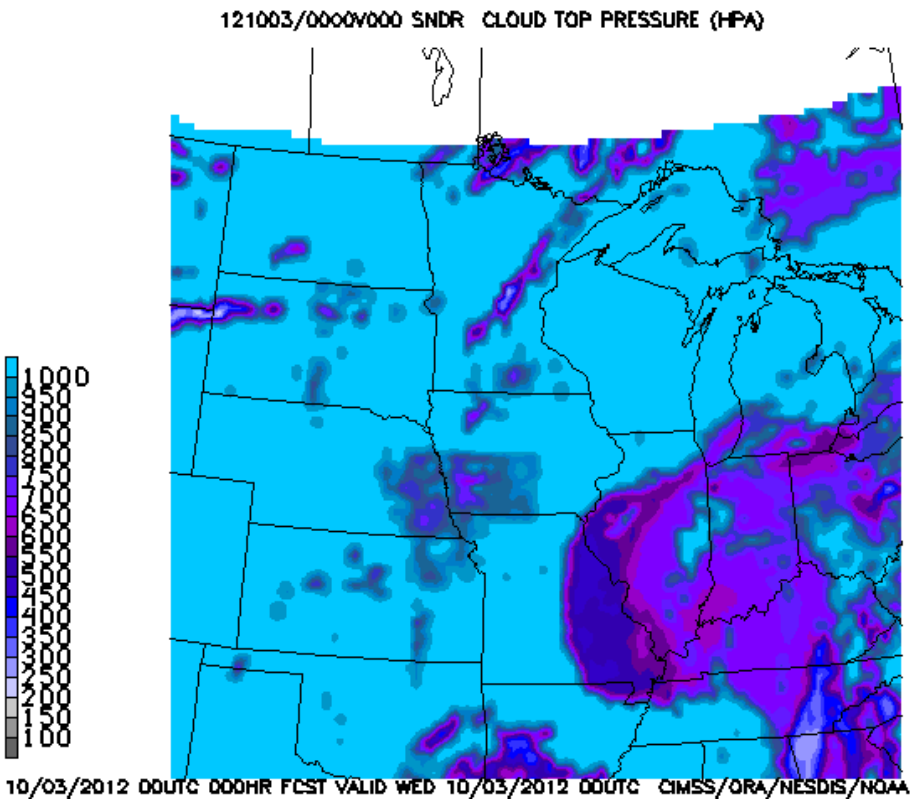


Cloud Top Pressure (CTP)

Considering the best matches, for which 200 hPa deep layer does the effective cloud amount (ECA) analysis best correspond to the NDFD sky cover 1-hr forecast?

The CTP composite from the GOES Sounders provides a cloud height for each corresponding ECA value.

Image valid at 00 UTC on 3 October 2012



Gridded CTP

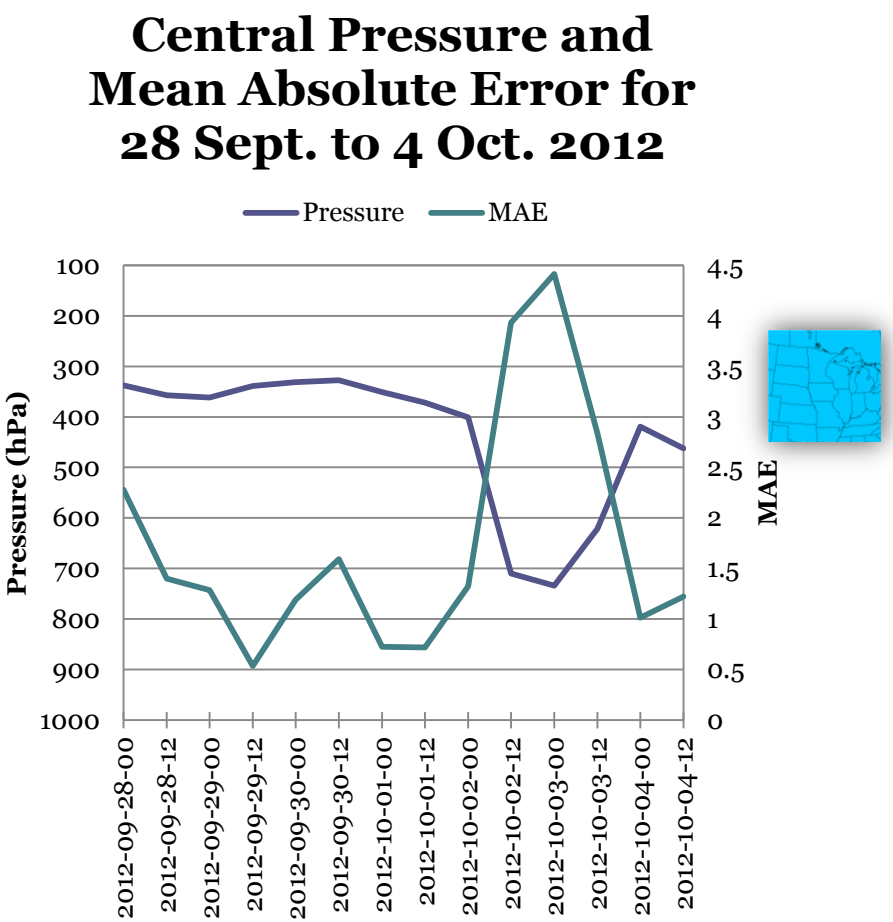
This can be solved through implementing another linear model:

- Objective function is to minimize absolute error between ECA and NDFD.
- At least 250 ECA/NDFD matches must be used. This is approximately 2.5% of all points on the grid (but not all points are considered).
- Clear points are excluded.
- The set of points contributing to the objective function must be within 100 hPa of central pressure level.

Image valid at 00 UTC on 3 October 2012

Improving Results

- Examined ECA-NDFD pairs producing the least amount of collective absolute error
- Trial period suggests lower MAE associated with higher cloud tops (thicker cloud?)
- Available CTPs can vary according to weather scenario and subject to Sounder bias
- Mean central pressure over trial period was 437 hPa (layer from 537 hPa to 337 hPa)
- Mean MAE was 1.7 (%)



Summary of Results

- Sky cover definitions are inconsistent. Model output needs major adjustment to match the NDFD result. The NDFD needs more congruity.
- Linear optimization of model output leads to a reduction in RMSE for subsequent forecasts.
- ECA skill is in question for verifying the NDFD sky cover grid in low-topped cloud regimes.
- Future work will focus on building a celestial dome and time-averaging new geostationary satellite cloud products over a one-hour window.

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