Sky Cover

Seminar to NWS/NCEP/EMC

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Special Thanks

- Robert Aune
- Jeffrey Craven
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- James Nelson III
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- Anthony Schreiner

Motivation

- "Cloud Feedbacks in the Climate System: A Critical Review" (G. Stephens 2005)
  - Global circulation and numerical weather prediction models are weakened through the use of cloud parameterizations.
  - Cloud parameterizations are built on assumptions and empirical formulations that are difficult to evaluate.
  - Using observational methods to assess the performance of cloud parameterizations is "important element in the road map to progress."
  - "The blueprint for progress must follow a more arduous path that requires a carefully orchestrated and systematic combination of model and observations."

Problem Statement

- **Problem: There is the lack of an observational method through which to verify the behavior of cloud parameterizations in climate and weather models, which are useful in examining cloud feedbacks.**
- There are two parts to solving this problem.

1. Produce a sky cover analysis which is representative of current conditions and suitable for use as validation
2. Determine the relationship between sky cover as purported by the analysis and related atmospheric quantities in a cloud-resolving model

Objective

What

- Improve the analysis and short-term forecasts of sky cover across the continental United States, Hawaii, and adjacent coastal areas using geostationary satellite and in-situ surface observations
- Understand relationship between sky cover and atmospheric quantities

How

- Use linear and/or mixed integer optimization to minimize the mean absolute difference between multi-source sky cover observations and short-term numerical weather prediction forecasts of cloud and moisture variables

Defining Sky Cover

- The Federal Meteorological Handbook (FMH) No. 1 defines sky cover as "the amount of the celestial dome hidden by clouds and/or obscurations".
- The National Weather Service (NWS) defines sky cover as "amount of opaque clouds (in percent) covering the sky" over a one-hour period.
- The NWS produces their routine sky cover forecast as part of the National Digital Forecast Database (NDFD).

Defining Sky Cover

- Effective cloud amount (ECA), the product of fractional cloud cover within the field of view (FOV) and cloud emissivity, is the most common method to assess sky cover from satellite observations.

- The Real-Time Mesoscale Analysis (RTMA) uses an ECA composite from the GOES Sounders as a sky cover analysis.

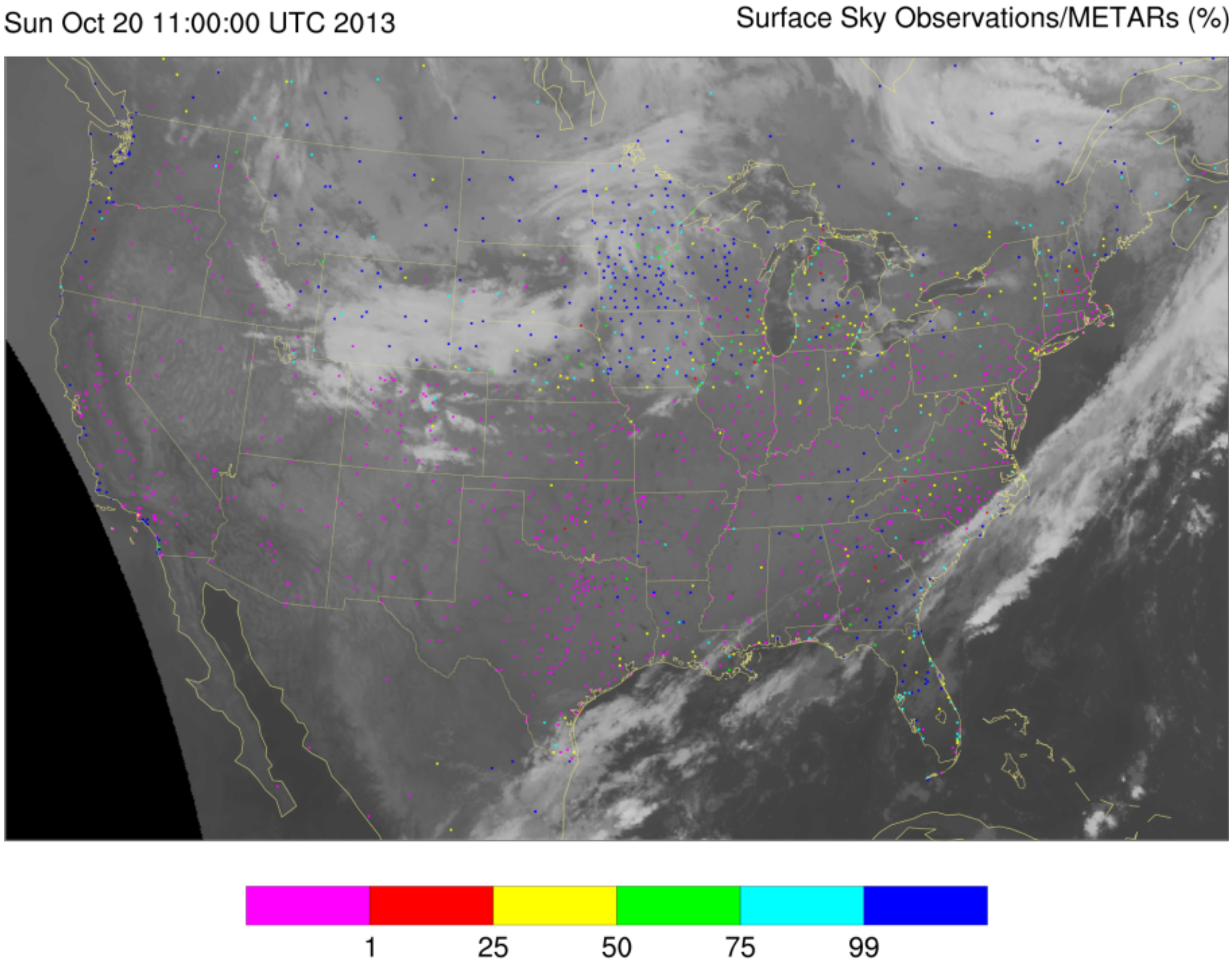
Observing the Sky

There are three primary types of sky observations:

- Space-based imagers (i.e., radiometers onboard low earth-orbiting and geostationary satellites)
- Stationary, surface-based instrumentation (e.g., ceilometers)
- Trained human observer

In-Situ Observations

- **If a surface station reports cloudy, it's cloudy.**
- Strengths:
  - Temporal availability
  - High detectability for low cloud (under 12 kft)
- Weaknesses:
  - Spatial availability
  - Precision (five coverage categories)
  - Poor detectability of high cloud, particularly overnight
  - Automated equipment uses temporal average of detections at fixed point

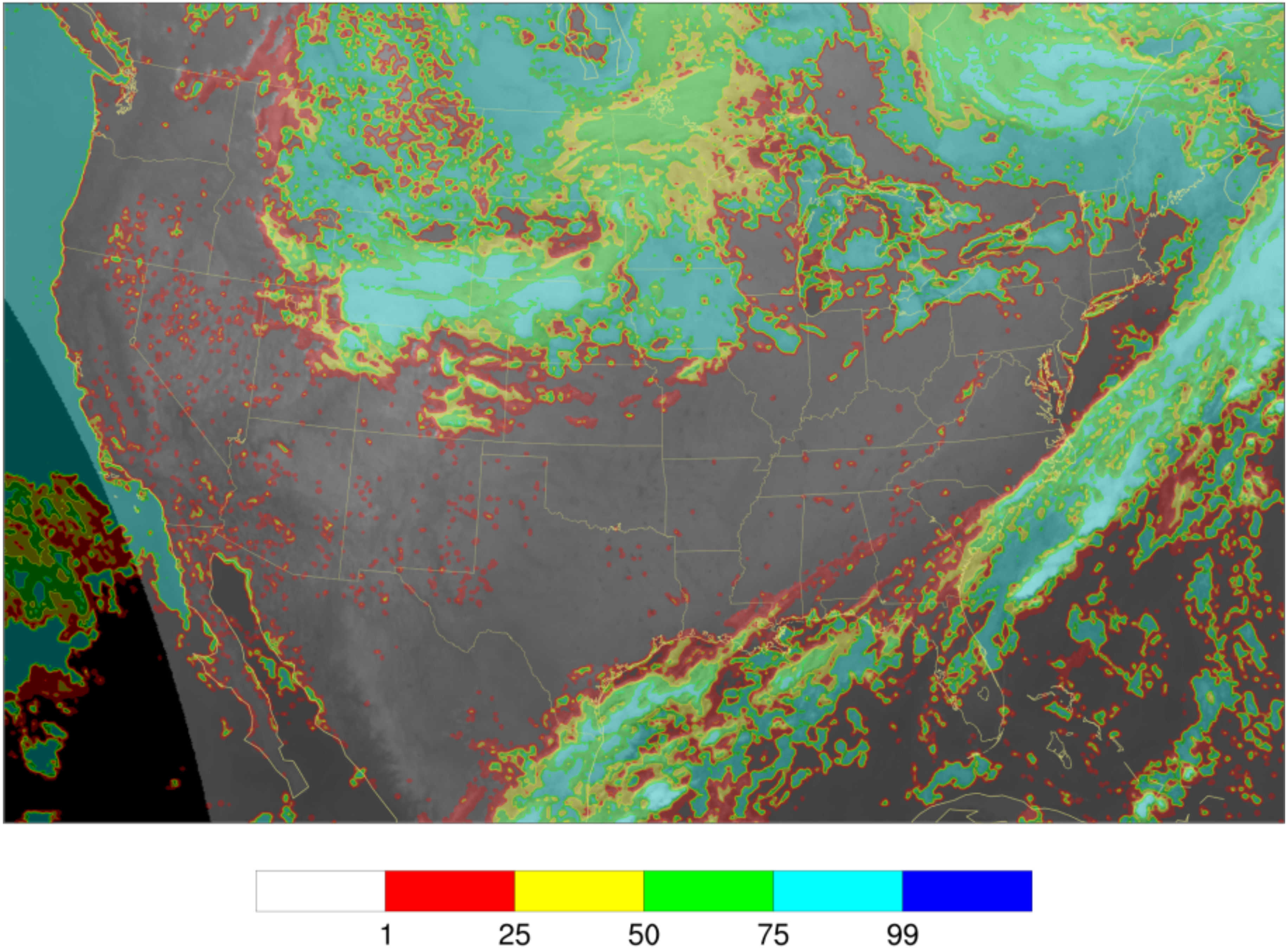

Sun Oct 20 11:00:00 UTC 2013
Surface Sky Observations/METARs (%)
1
25
50
75
99

Satellite Observations

- Strengths:
  - Spatial and temporal coverage (geostationary)
  - Daytime cloud detectability
- Weaknesses:
  - High cloud (ice cloud) masking low cloud (water cloud)
  - Stray light (sunlight entering optics overnight resulting in artificially inflated shortwave bands)
  - Fog or low cloud where infrared brightness temperatures do not vary substantially from background land or water surface (nighttime)

Sun Oct 20 11:00:00 UTC 2013

GOES Imager Effective Cloud Amount (%)

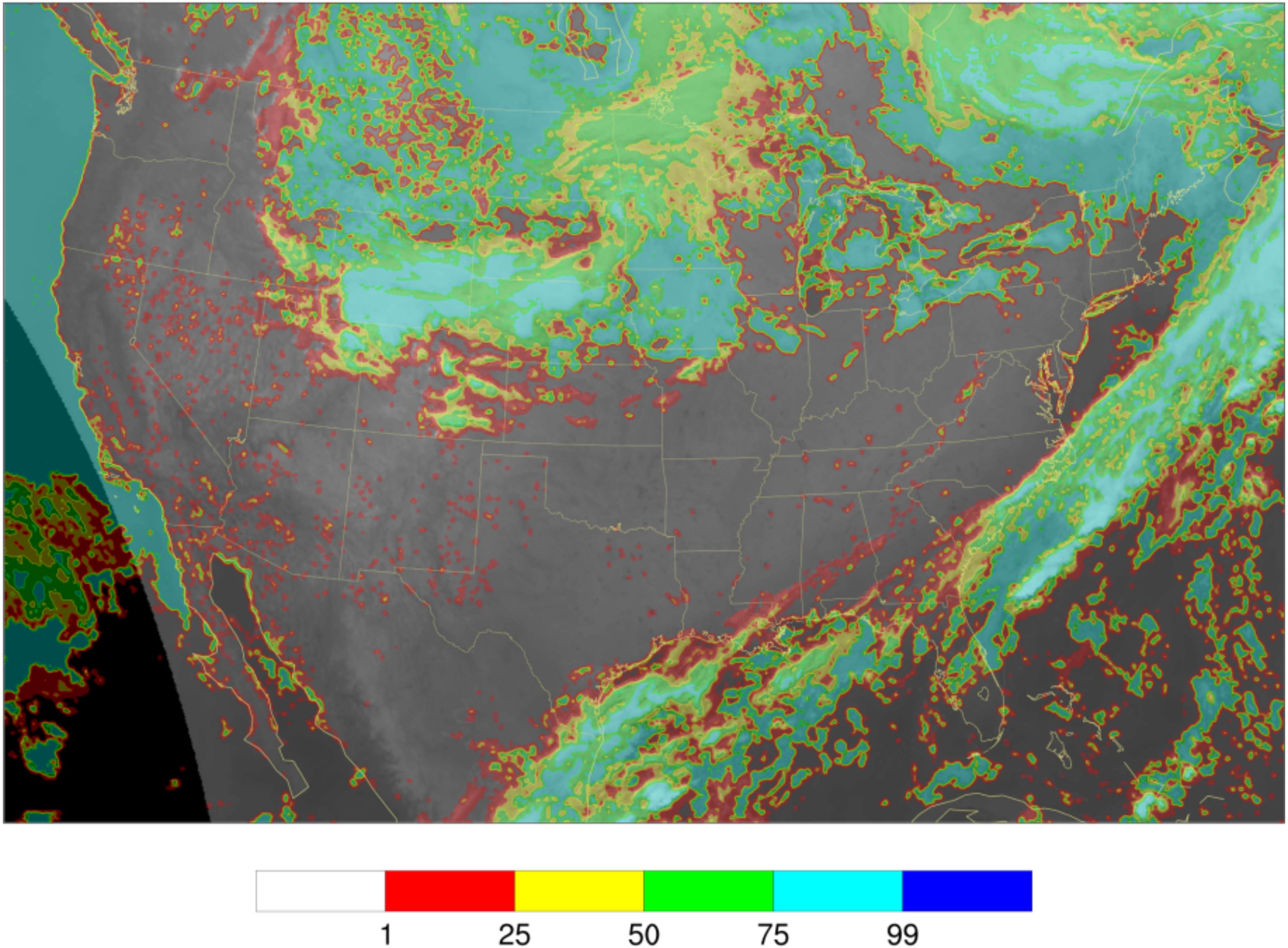


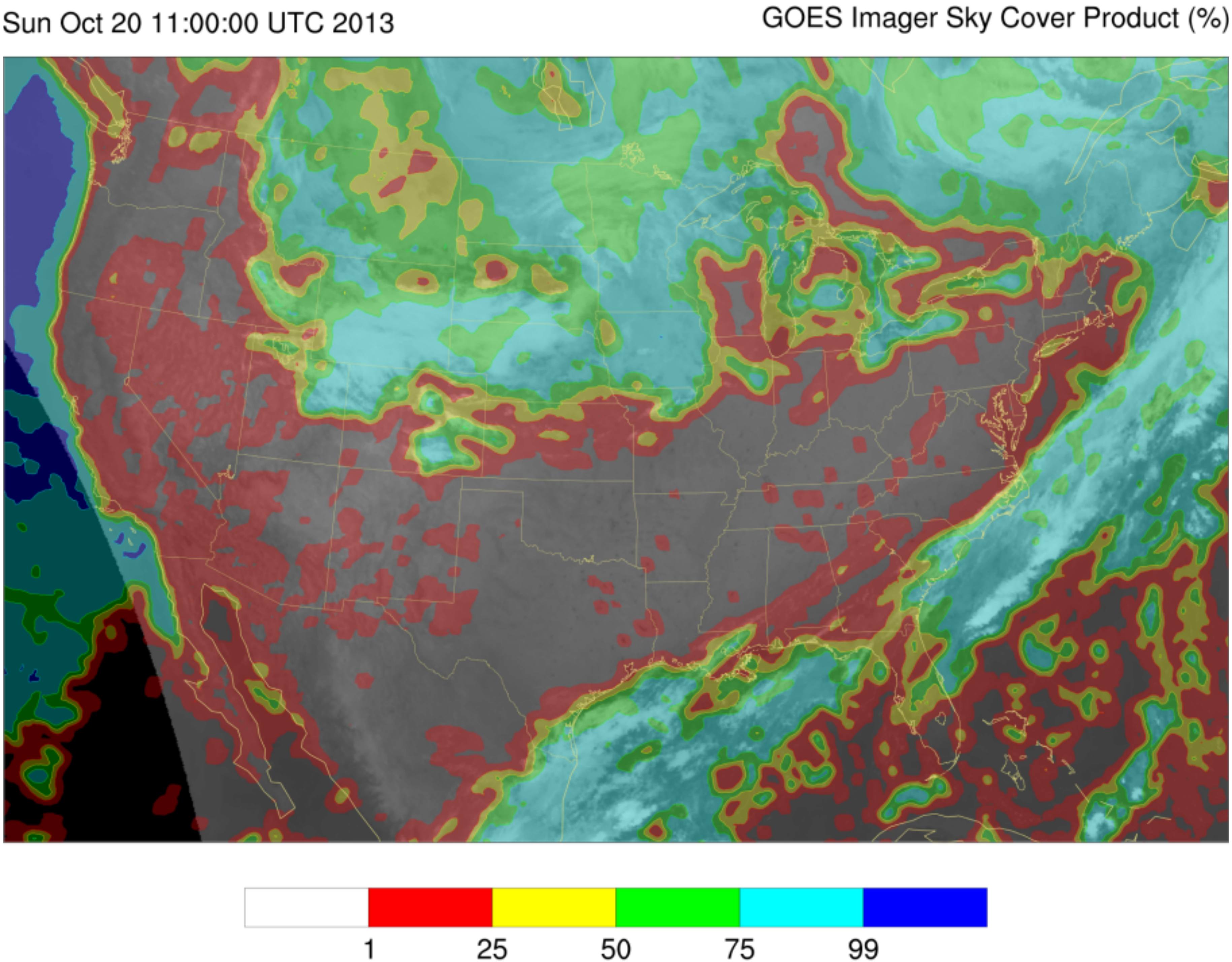
ECA to Sky Cover Product

1. Start with Effective Cloud Amount
2. For each imager (GOES-East and GOES-West) scan, create the celestial dome at each point
   - Average of the standard effective cloud emissivity within a box of 11 by 11 pixels, centered on each grid point
3. Apply corrections if necessary
   - Ice (low emissivity) cloud above water (high emissivity) cloud
   - Overcast scenes
4. Combine all imager scans from both satellites within a one-hour window and average (equal weight for each scan)

Sun Oct 20 11:00:00 UTC 2013

GOES Imager Effective Cloud Amount (%)




Sun Oct 20 11:00:00 UTC 2013
GOES Imager Sky Cover Product (%)
1
25
50
75
99

Blended Sky Cover Analysis

- Where the observation of sky cover from the surface is clear, the blended analysis will assume the value from the satellite sky cover product depending on the corresponding satellite cloud top pressure (CTP). If the CTP value is sufficiently high (low cloud), then the satellite cloud detection is considered false.
- Otherwise, if the value of the nearest surface observation of sky cover is greater than that of the satellite sky cover product, the sky cover value of the surface observation is used in the blended analysis.
- In other instances where both observations are available, a weighted average is performed.

Blended Sky Cover Cases

Satellite Observation at Test Point	Satellite Observation at Closest Surface Station	Surface Observation at Closest Site	Blended Result
Clear	Clear	Clear	Clear
Clear	Clear	Cloudy	Cloudy
Clear	Cloudy	Clear	Clear/Satellite
Clear	Cloudy	Cloudy	Clear
Cloudy	Clear	Clear	Cloudy/Satellite
Cloudy	Clear	Cloudy	Cloudy
Cloudy	Cloudy	Clear	Cloudy/Satellite
Cloudy	Cloudy	Cloudy	Cloudy

Blended Sky Cover Cases

Satellite Observation at Test Point	Satellite Observation at Closest Surface Station	Surface Observation at Closest Site	Blended Result
Clear	Cloudy	Cloudy	Clear
Cloudy	Clear	Clear	Cloudy/Satellite

These cases occur when there is a spatial gradient in the sky cover.

Blended Sky Cover Cases

Satellite Observation at Test Point	Satellite Observation at Closest Surface Station	Surface Observation at Closest Site	Blended Result
Clear	Clear	Cloudy	Cloudy

This case occurs when the cloud is indistinguishable from the underlying or surrounding land or water surface, generally during overnight hours. This result is common in scenes involving low cloud.

Blended Sky Cover Cases

Satellite Observation at Test Point	Satellite Observation at Closest Surface Station	Surface Observation at Closest Site	Blended Result
Cloudy	Clear	Clear	Cloudy/Satellite
Cloudy	Cloudy	Clear	Cloudy/Satellite

These cases occur when there is high cloud at both the test site and closest surface station, which is above the height of detectability for ceilometers.

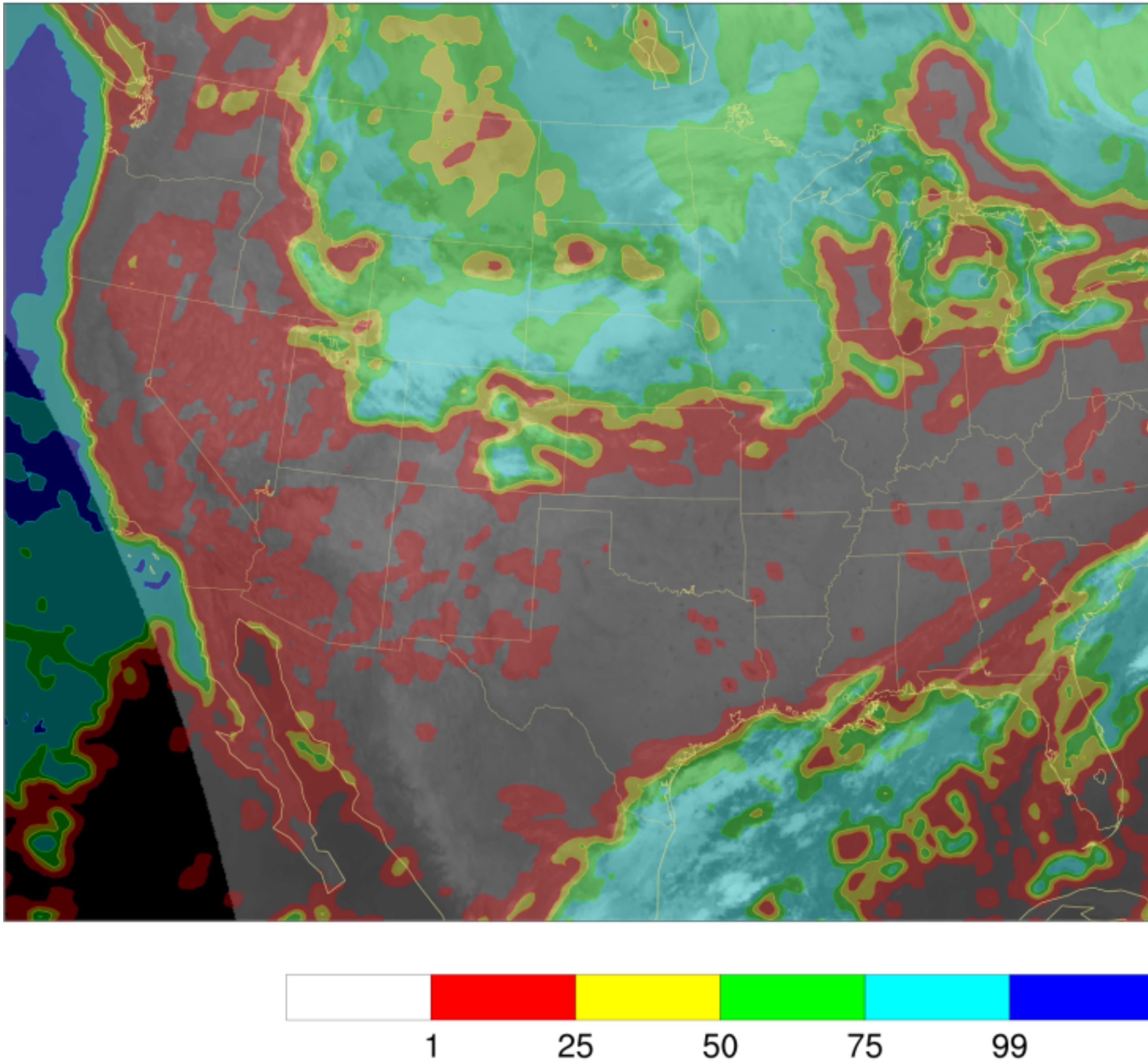
Blended Sky Cover Cases

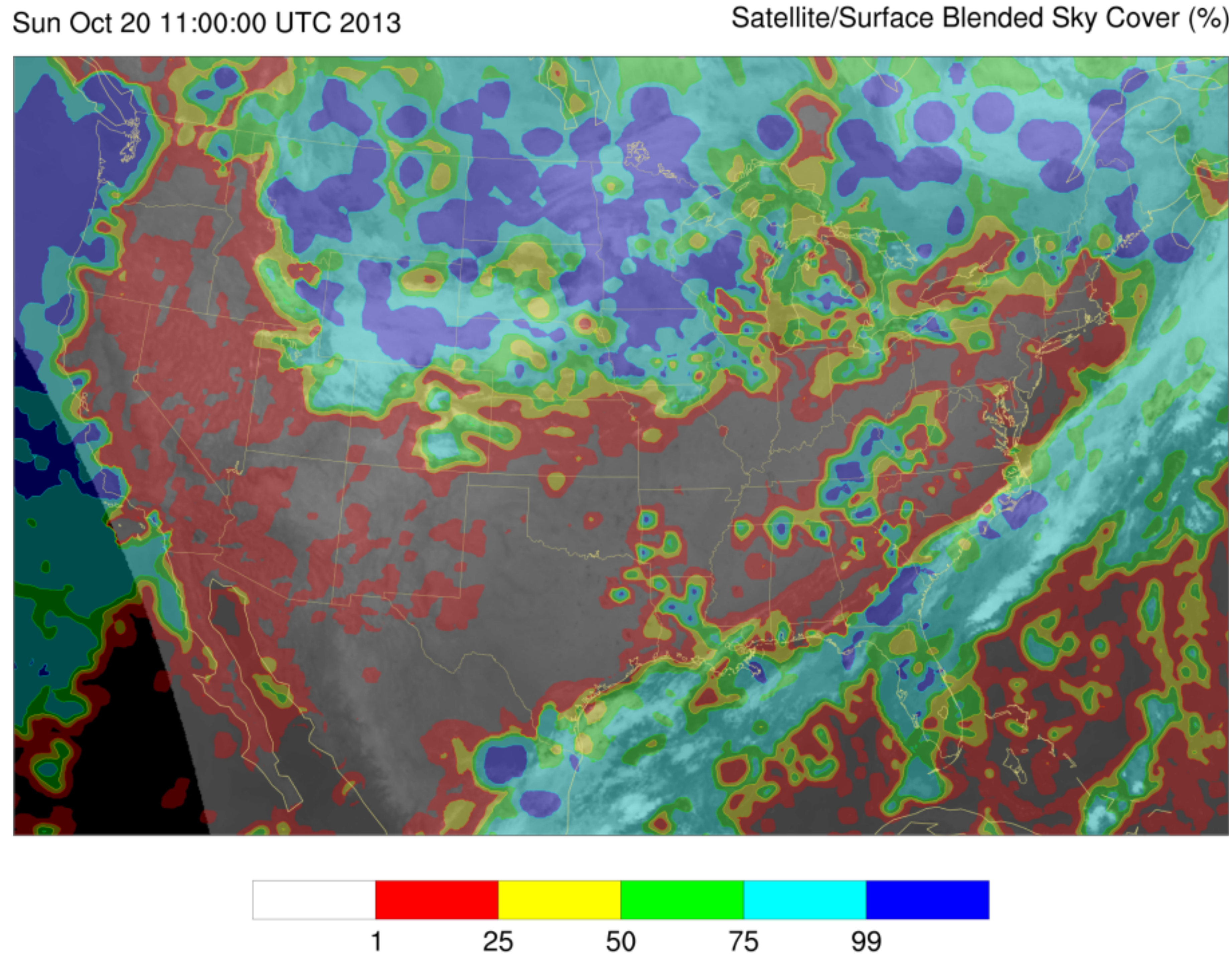
Satellite Observation at Test Point	Satellite Observation at Closest Surface Station	Surface Observation at Closest Site	Blended Result
Clear	Cloudy	Clear	Clear/Satellite

This case occurs when there is high cloud at the closest surface station, which is above the height of detectability for ceilometers, but not at the test point. This is a spatial gradient in sky cover resulting from high cloud.

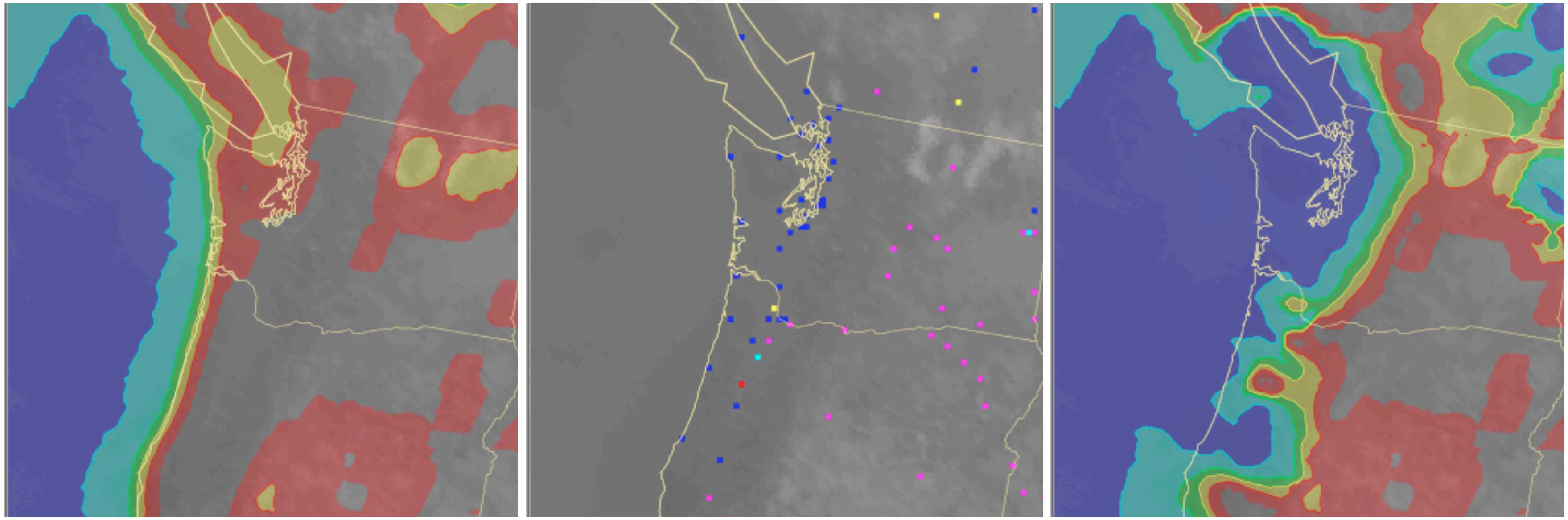
Sun Oct 20 11:00:00 UTC 2013

GOES Imager Sky Cover Product (%)




Sun Oct 20 11:00:00 UTC 2013
Satellite/Surface Blended Sky Cover (%)
1
25
50
75
99

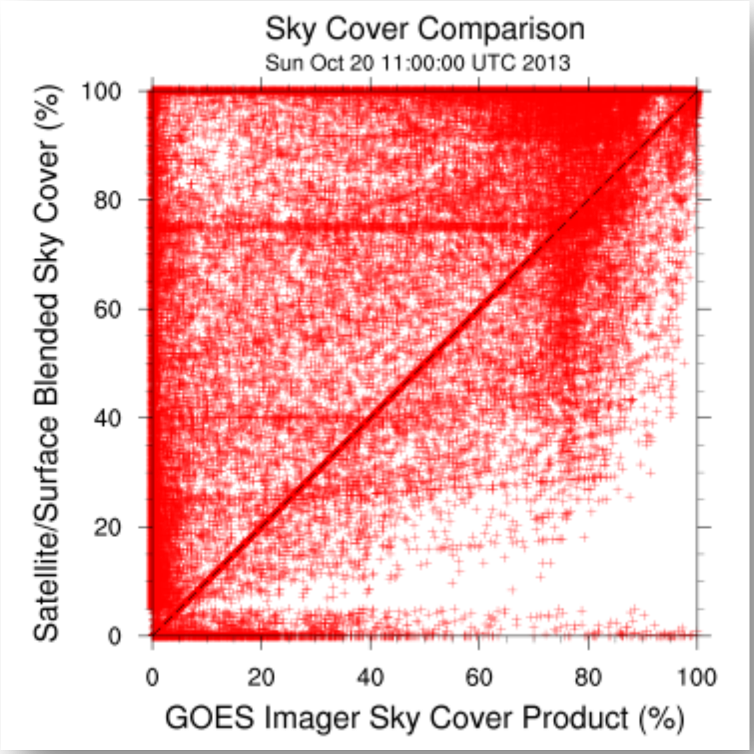
Value of Multiple Sources



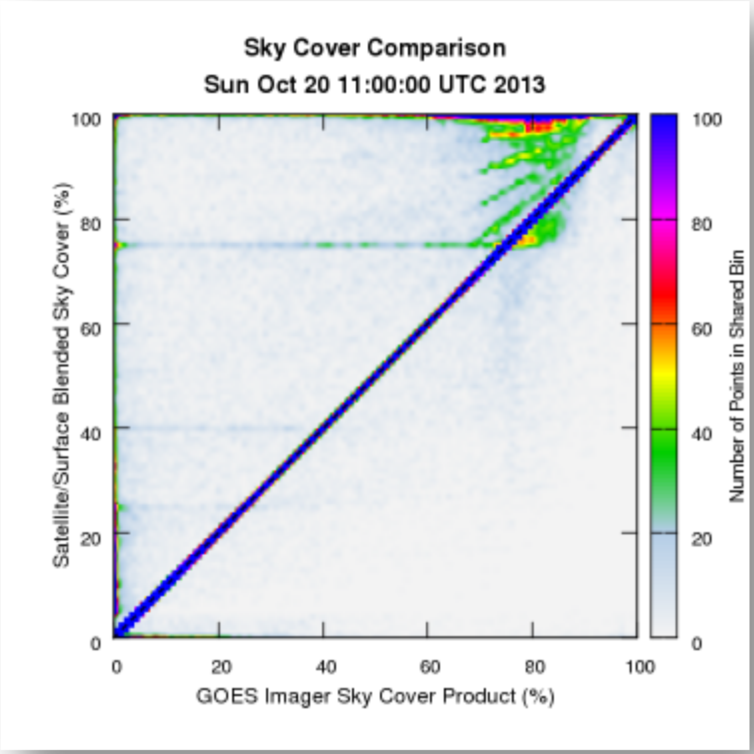
Each panel in the three-panel plot is valid at 11 UTC on 20 October 2013.

The left panel shows the estimated sky cover from the GOES-West imager. The middle panel shows the point surface observations (both manual and automated). The right panel shows the blended product, using both satellite and in-situ observations (as shown In the two leftmost plots).

Case Study

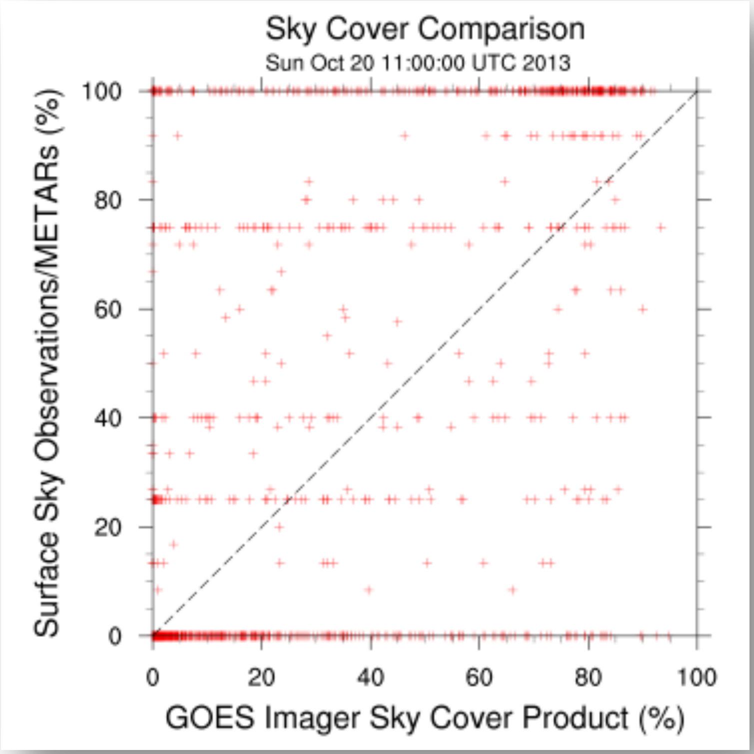


Sky Cover Comparison
Sun Oct 20 11:00:00 UTC 2013
Satellite/Surface Blended Sky Cover (%)
GOES Imager Sky Cover Product (%)
0
20
40
60
80
100

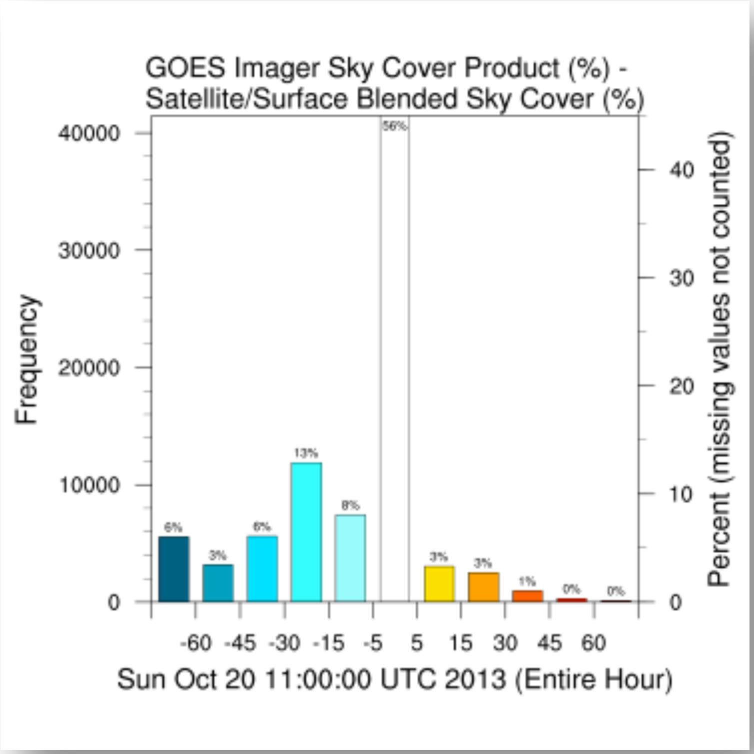


Sky Cover Comparison
Sun Oct 20 11:00:00 UTC 2013
Satellite/Surface Blended Sky Cover (%)
GOES Imager Sky Cover Product (%)
Number of Points in Shared Bin
0
20
40
60
80
100

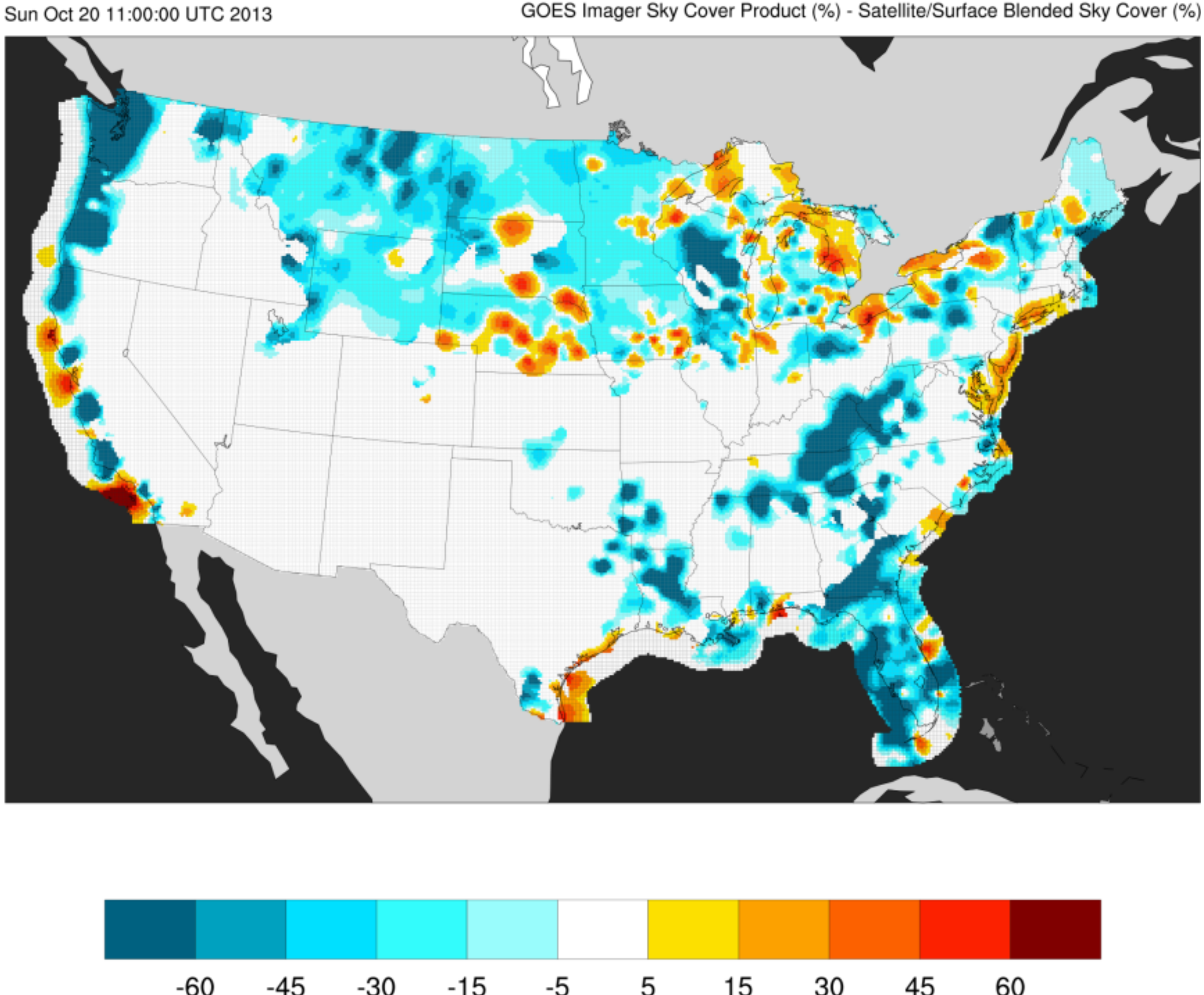
Case Study



Sky Cover Comparison
Sun Oct 20 11:00:00 UTC 2013
Surface Sky Observations/METARs (%)
GOES Imager Sky Cover Product (%)
0
20
40
60
80
100



GOES Imager Sky Cover Product (%) -
Satellite/Surface Blended Sky Cover (%)
Frequency
Percent (missing values not counted)
0
10000
20000
30000
40000
10
20
30
40
6%
3%
6%
13%
8%
56%
3%
3%
1%
0%
0%
-60
-45
-30
-15
-5
5
15
30
45
60
Sun Oct 20 11:00:00 UTC 2013 (Entire Hour)


Sun Oct 20 11:00:00 UTC 2013
GOES Imager Sky Cover Product (%) - Satellite/Surface Blended Sky Cover (%)
-60
-45
-30
-15
-5
5
15
30
45
60

Blended Sky Cover Analysis

The advantages of the blended analysis creation process are that it:

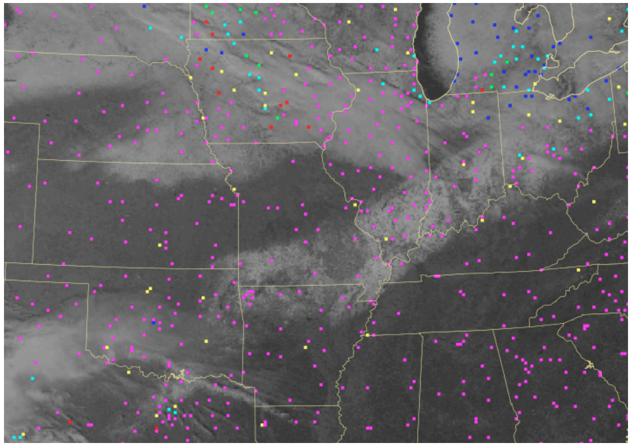
- Evaluates all available data and leverages strengths of multiple observational sources
- Preserves cloud gradients
- Adequately resolves diurnal cumulus fields (not missing, not bimodal)
- Is a temporally continuous and spatially contiguous field (available hourly over the contiguous United States)

Influence of Snowpack on Blended Sky Cover Analysis

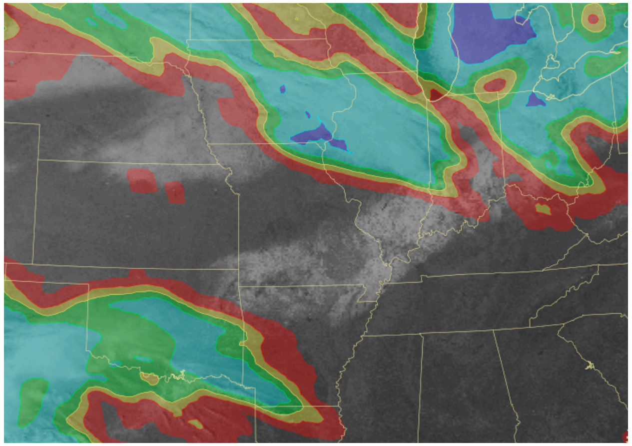
Case Study from 12 December 2013 and 13 December 2013

12 December 2013, 18 UTC

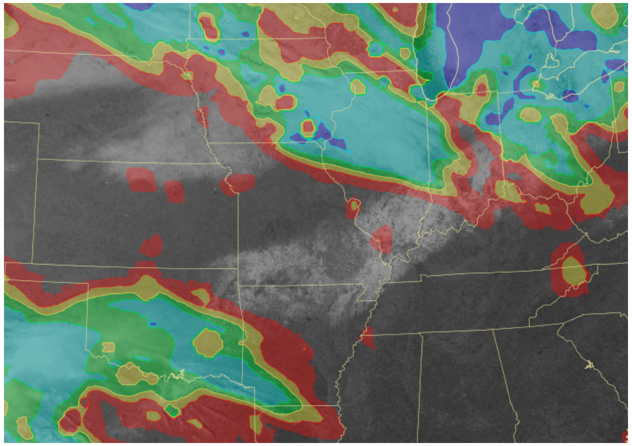
- **Other than along the snowpack edge, the satellite sky cover product does not contain false cloud detections over or near the snowpack.**
- **The surface observations add detail to the blended analysis and add cloud cover where the satellite sky cover product does not indicate such.**



Surface Observations of Sky Cover

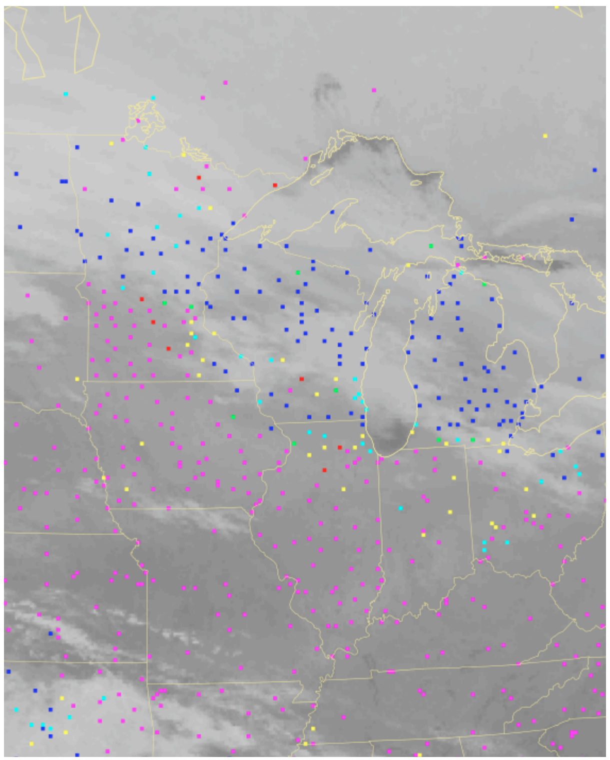


Satellite Sky Cover Product

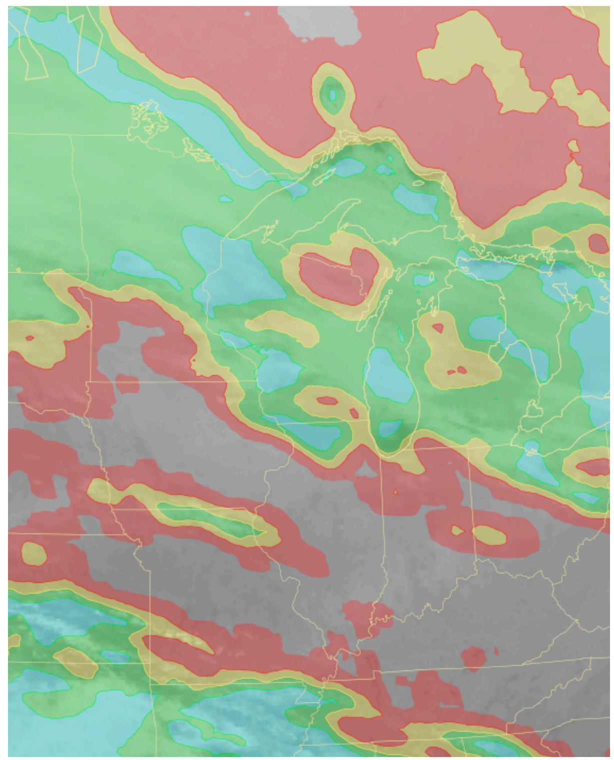


Blended Sky Cover Analysis

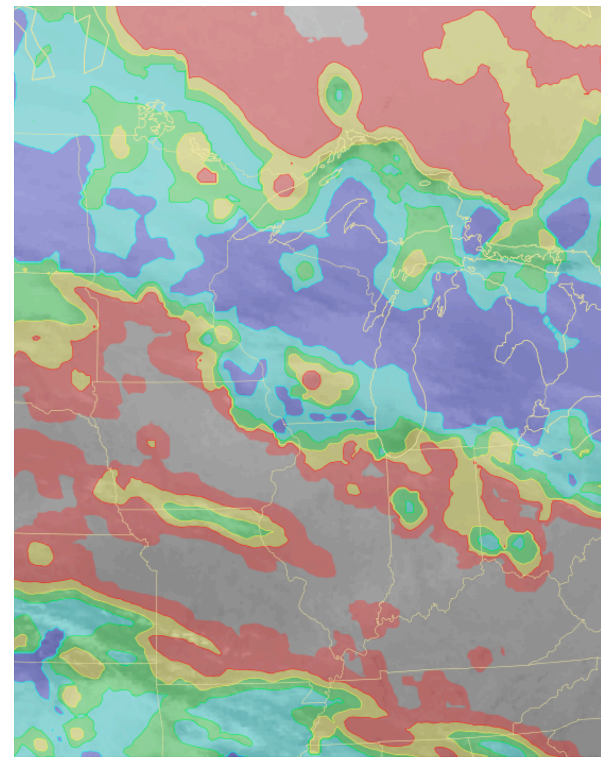
13 December 2013, 6 UTC



Surface Observations of Sky Cover

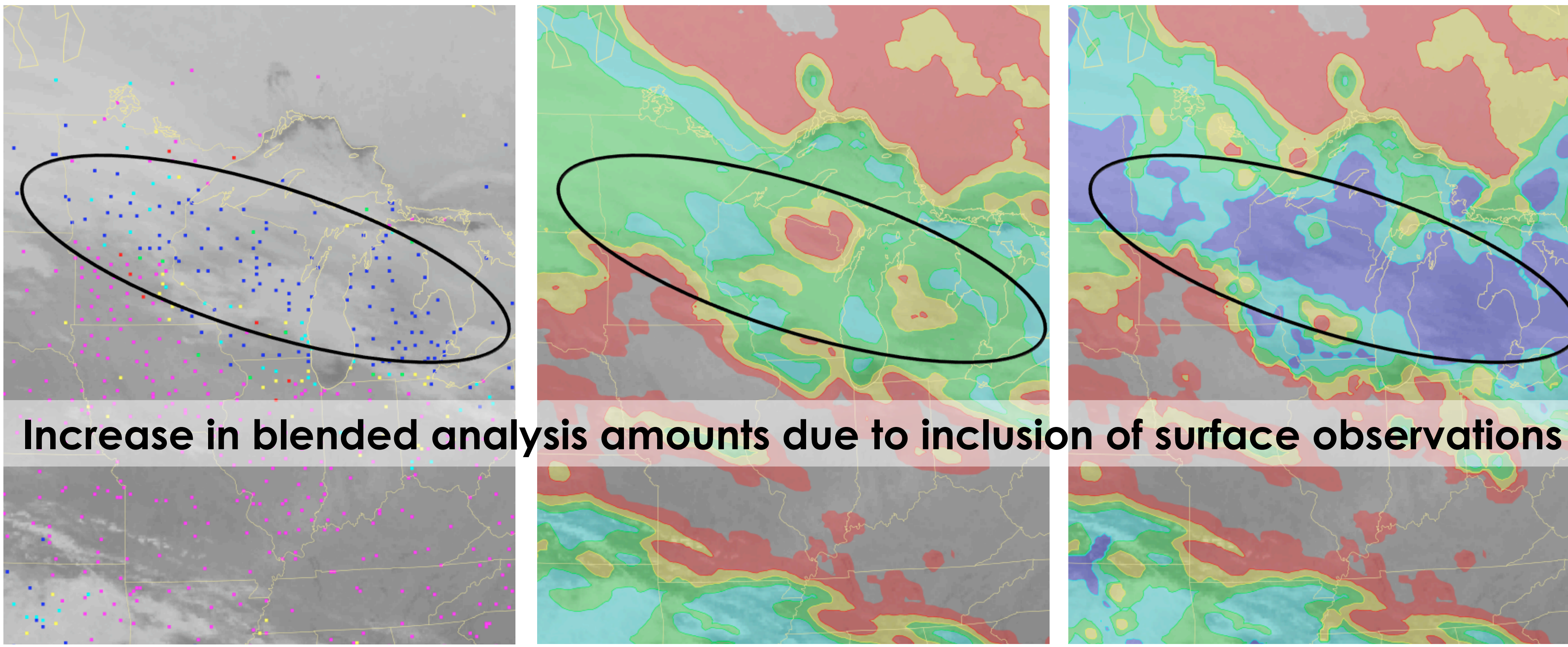


Satellite Sky Cover Product



Blended Sky Cover Analysis

13 December 2013, 6 UTC

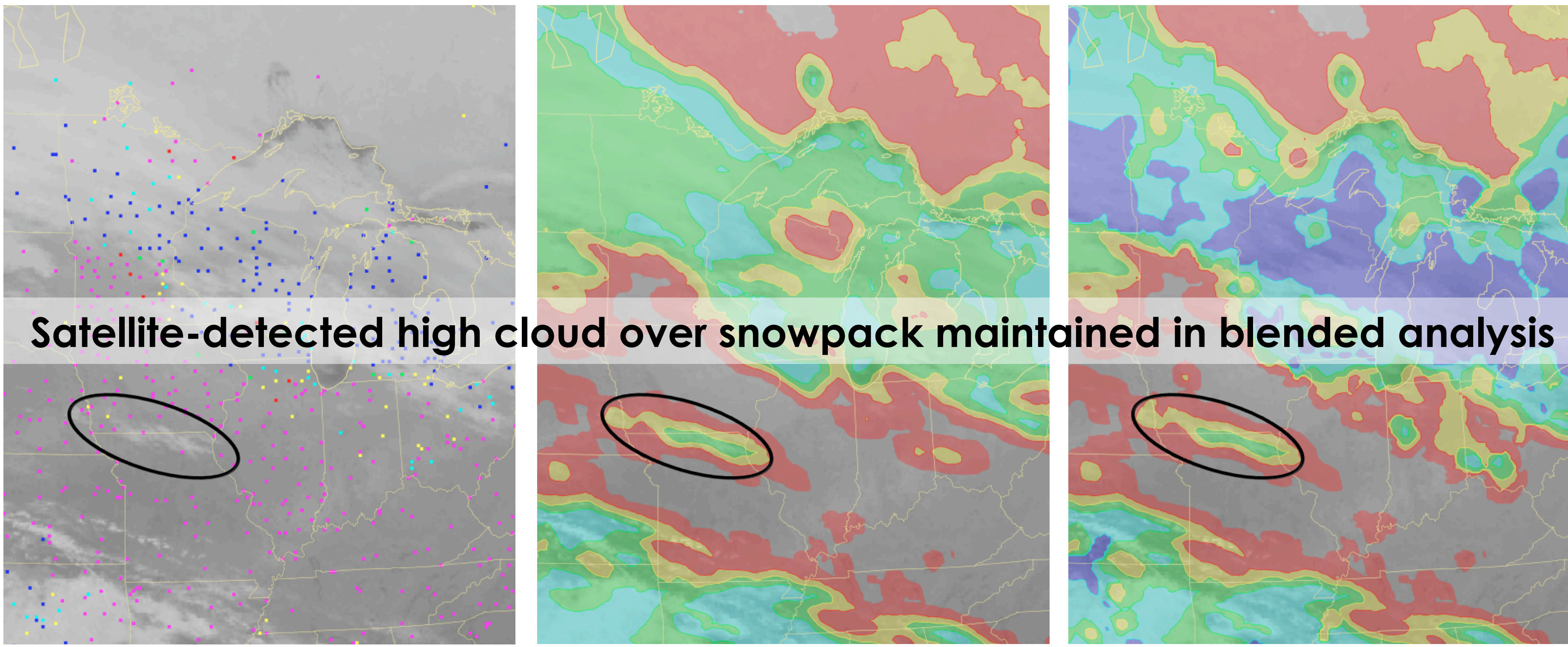


Surface Observations of Sky Cover

Satellite Sky Cover Product

Blended Sky Cover Analysis

13 December 2013, 6 UTC



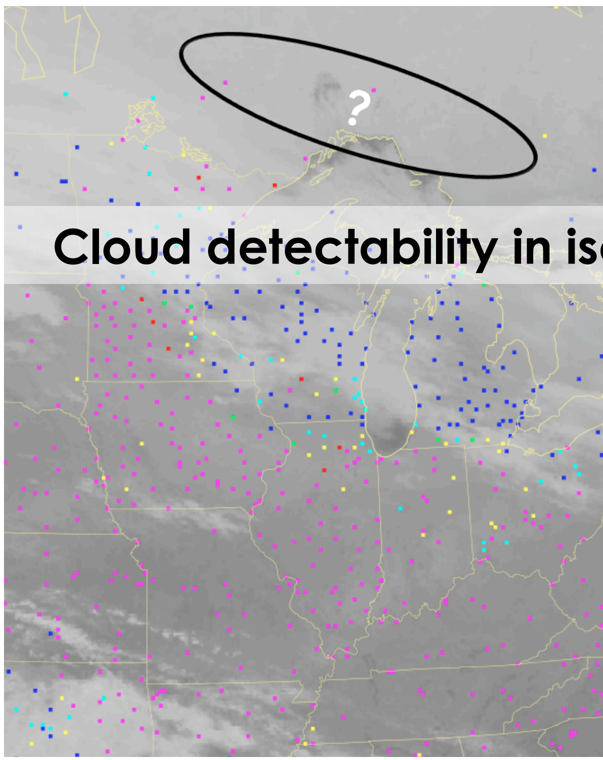
Surface Observations of Sky Cover

Satellite Sky Cover Product

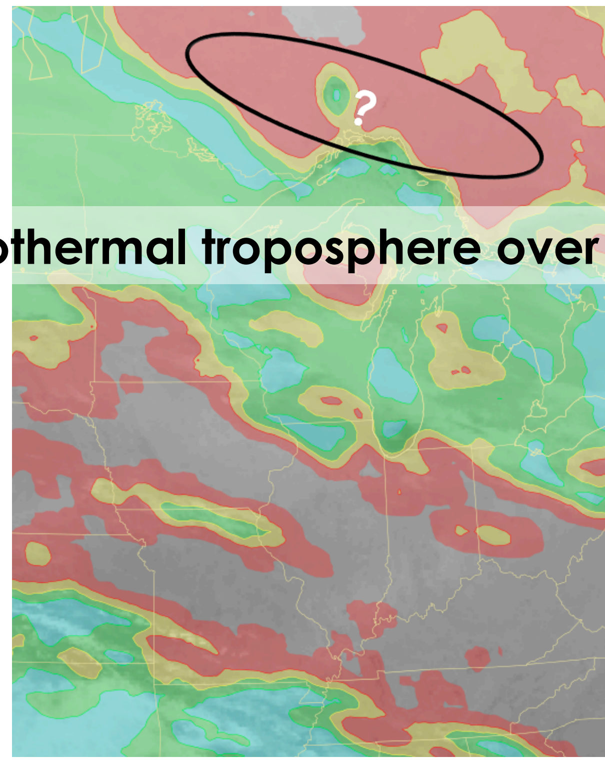
Blended Sky Cover Analysis

13 December 2013, 6 UTC

Cloud detectability in isothermal troposphere over snowpack is challenging



Surface Observations of Sky Cover



Satellite Sky Cover Product

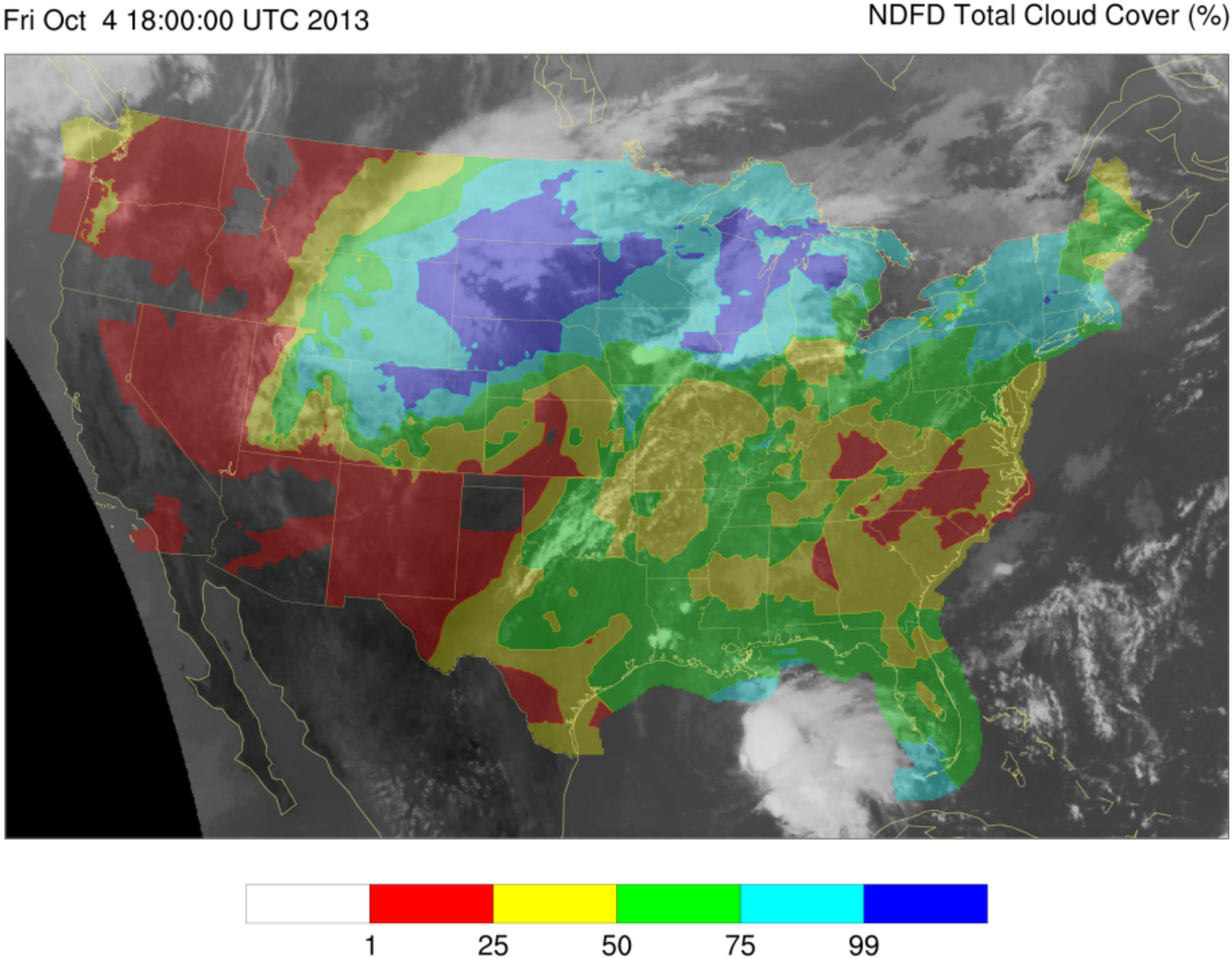
Blended Sky Cover Analysis

Forecasting Sky Cover

The NWS' NDFD contains the gridded operational forecast for sky cover. Issues with the national one-hour forecast include:

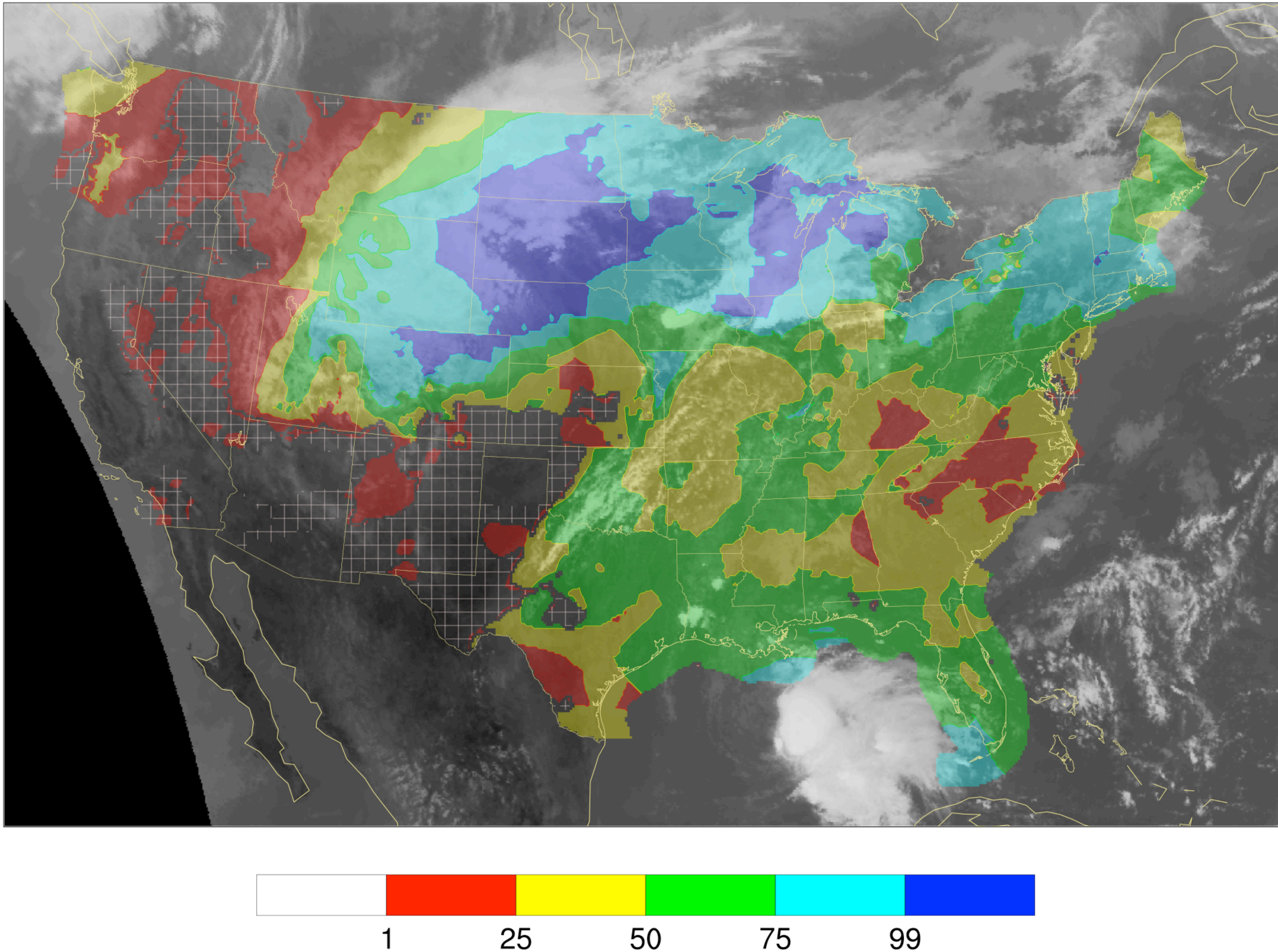
- Clear areas with non-zero cloud cover
- Vastly different cloud classifications for similar cloud scenes
- Lack of spatial continuity between forecast areas
- Temporal trends do not match observations
- Update frequencies vary by forecast office

The NDFD is generally based on output from weather prediction models.


Fri Oct 4 18:00:00 UTC 2013
NDFD Total Cloud Cover (%)
1
25
50
75
99

Fri Oct 4 18:00:00 UTC 2013

NDFD Total Cloud Cover (%)



How can an optimization methodology contribute to solving problems in the atmospheric sciences?

An observational method for creating and validating analyses

Cloud Schemes

- Diagnostic schemes
  - Cloud quantities are diagnosed from other model variables during model execution or post-processing
- Prognostic schemes
  - Cloud cover, water vapor, and condensate variables are interconnected, dependent, and advanced/calculated during model execution
- Hybrid scheme
  - Condensate variables are prognostic, but cloud cover is diagnostic
    - Global Forecast System (GFS) and Weather Research and Forecast (WRF) models

Cloud Schemes

- Relative humidity schemes
  - Primary assumption is that cloudiness is represented through the sub-grid scale variability of the relative humidity field
- Statistical schemes
  - Employ the use of a probability density function (PDF) with respect to total water (sum of mixing ratios)
  - Most PDFs are unimodal, varying shape and skewness
- There is either a critical relative humidity threshold or assumption about the subgrid-scale temperature and/or humidity behavior that is a central component of the approach/scheme in all implementations.

Relative Humidity Schemes

Slingo (1980)

M = 0.80 for low and high clouds
M = 0.65 for mid-level clouds

$$C = \begin{cases} 0, & \mathrm{RH} < M, \\ ([\mathrm{RH} - M]/[1 - M])^2, & M \le \mathrm{RH} < 1.0, \\ 1, & 1.0 \le \mathrm{RH}, \end{cases}$$

Smith (1990)

RH_{crit} = 0.90 at surface
RH_{crit} = 0.70 at PBL height and above

$$C = \begin{cases} 0, & \overline{q_t}/\overline{q_s} \le \mathrm{RH}_{\mathrm{crit}}, \\ \frac{1}{2}\left[1 + \frac{(\overline{q_t}/\overline{q_s} - 1)}{(1 - \mathrm{RH}_{\mathrm{crit}})}\right]^2, & \mathrm{RH}_{\mathrm{crit}} < \overline{q_t}/\overline{q_s} \le 1, \\ 1 - \frac{1}{2}\left[1 - \frac{(\overline{q_t}/\overline{q_s} - 1)}{(1 - \mathrm{RH}_{\mathrm{crit}})}\right]^2, & 1 < \overline{q_t}/\overline{q_s} < 2 - \mathrm{RH}_{\mathrm{crit}}, \\ 1, & 2 - \mathrm{RH}_{\mathrm{crit}} \le \overline{q_t}/\overline{q_s}. \end{cases}$$

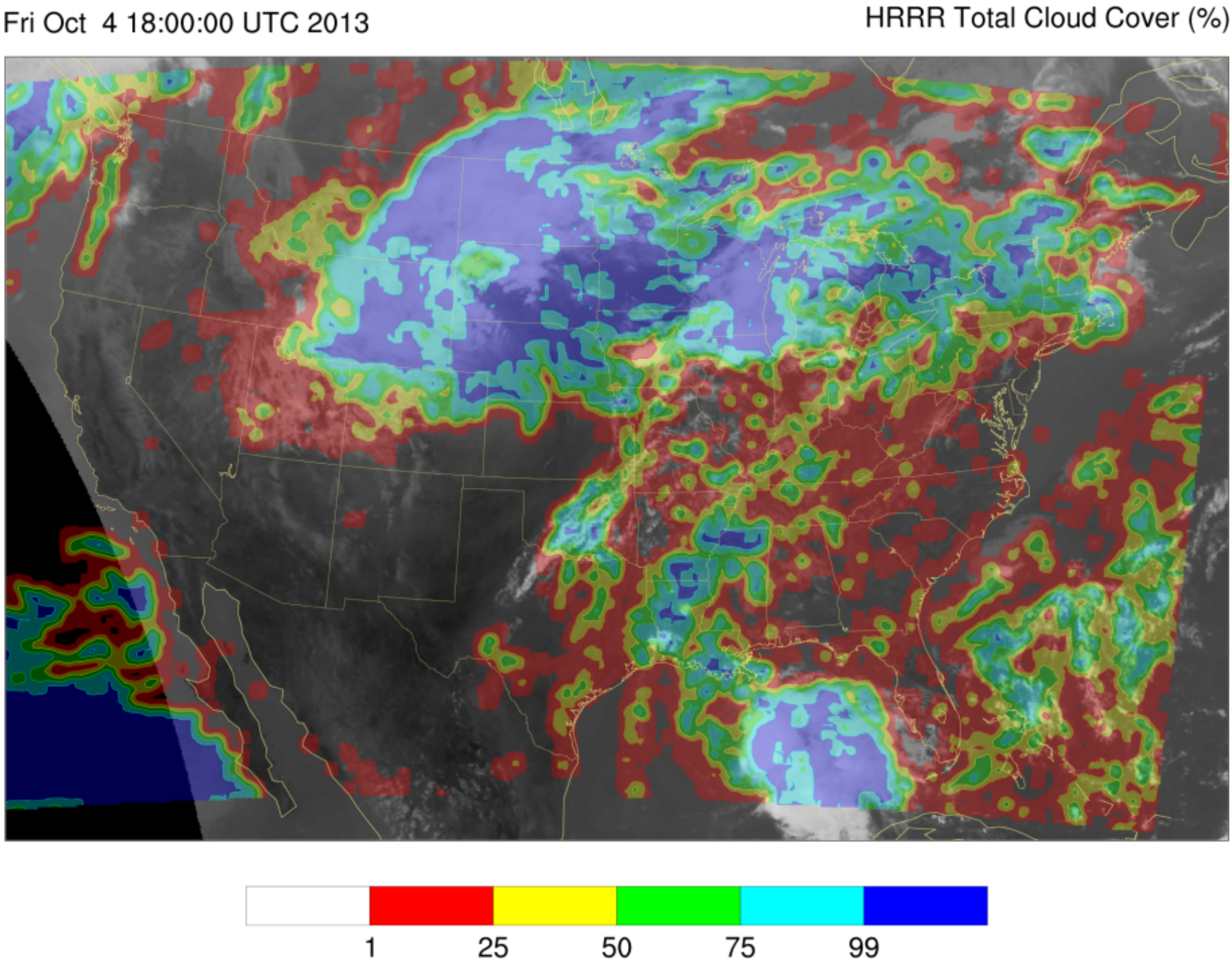
Xu and Randall (1996)

p = 0.25, α_0 = 100, and γ = 0.49

$$C = \begin{cases} (\mathrm{RH})^p[1 - \exp(-\alpha_0 \overline{q}_c/[(\overline{q_s} - \overline{q_v})]^\gamma)], & \mathrm{RH} < 1, \\ 1, & \mathrm{RH} \ge 1, \end{cases}$$

HRRR

- High-Resolution Rapid Refresh (http://ruc.noaa.gov/hrrr/)
- Horizontal resolution of 3 km, 50 vertical levels
- Cloud-resolving numerical weather prediction (NWP) model, no convective parameterization
- Literature available for WRF framework (basis for the HRRR)
  - Advanced Research WRF (ARW) core (v3.4.1+) with Thompson microphysics and RUC/Smirnova land-surface model
- Assimilates GOES cloud products and METARs
- Available hourly in real-time


Fri Oct 4 18:00:00 UTC 2013
HRRR Total Cloud Cover (%)
1
25
50
75
99

Linear, Mixed Integer Optimization

- Optimization is a broader toolset than a regression technique because they can be formulated intelligently (keep the results physical)
- Solution is subject to linear constraint and/or decision structure controlled by integer/binary variable
- Mathematical "tricks" exist to express some cases of non-linearity in linear (for example, absolute value)
- Literature review suggests that the use of optimization in solving problems in the atmospheric sciences is not widespread

Optimizing Sky Cover

- Input fields (subset of points)
  - Truth: Sky cover analysis
  - Components
- Design model (formats: linear, mixed integer, others)
  - Objective using free variable, subject to constraint
  - Terms, matching variables and components
  - Constraints involving terms
- Execute optimizer
  - Commercial solvers (free for academia)
    - CPLEX
    - Gurobi
  - Open source options (slower)

Optimizing Sky Cover

Components:

- Relative Humidity (all levels)
- Cloud Water Mixing Ratio, Cloud Ice Mixing Ratio, Rain Water Mixing Ratio, Snow Mixing Ratio (all levels)
- Absolute Vorticity (200 hPa only), partitioned into positive and negative components

- Pressure levels:
  - 200 hPa
  - 300 hPa
  - 500 hPa
  - 700 hPa
  - 800 hPa
  - 850 hPa
  - 900 hPa
  - 950 hPa
  - 1000 hPa

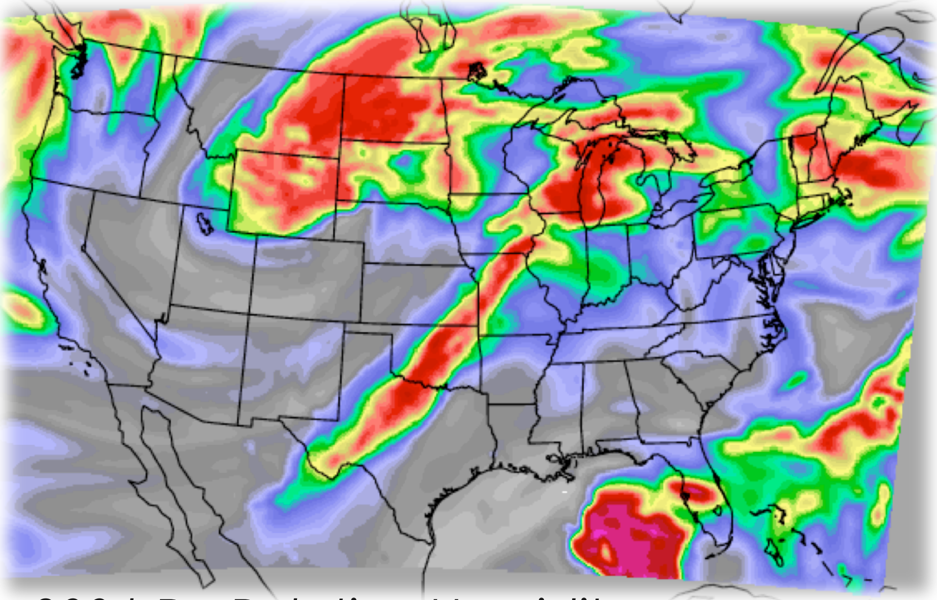
Maclaurin Series

- Though the exponential function is nonlinear, the Maclaurin series (case of Taylor series) for the function e^{-x} is

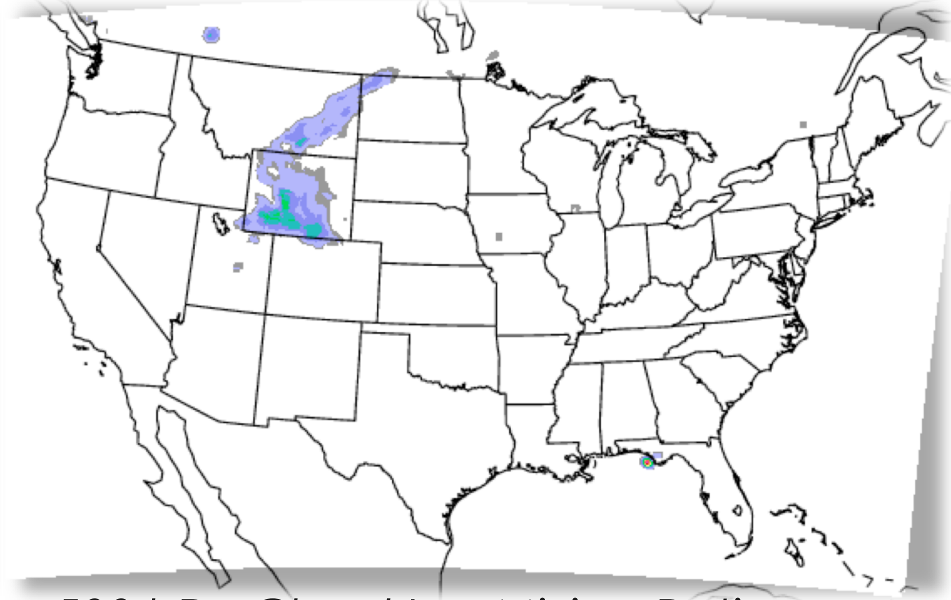
$$e^{-x} = \sum_{n=0}^{\infty} \frac{(-x)^n}{n!} = 1 - x + \frac{x^2}{2!} - \frac{x^3}{3!} + \cdots$$

  where $0 \le x \le 1$ for this application. If higher order terms, where $n \ge 2$, are disregarded, $f(x)=1-e^x$ can be reduced to $f(x) \approx 1-(1-x)=x$, which is linear.

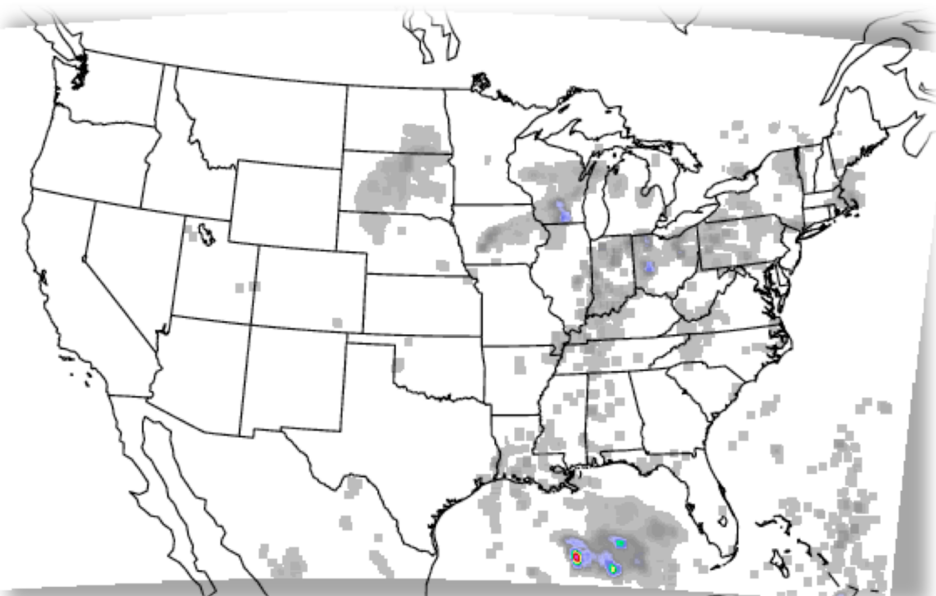
- Such an adjustment is possible because significant error between the approximated value and the actual value arises for $x>1$, where the value of x becomes much larger than the approximated function.



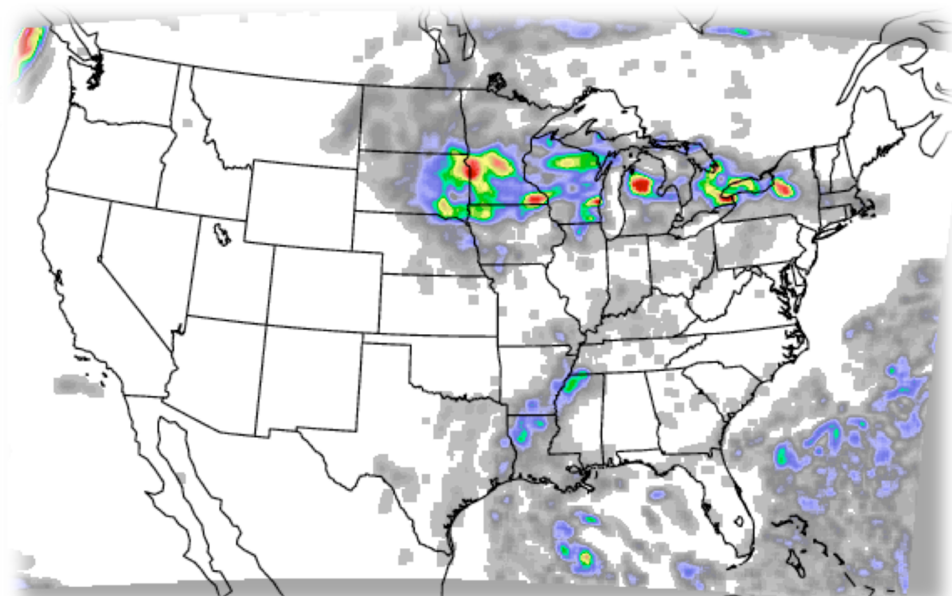
300 hPa Relative Humidity



500 hPa Cloud Ice Mixing Ratio



700 hPa Rain Water Mixing Ratio



900 hPa Cloud Water Mixing Ratio

All images are HRRR model analysis output valid at 18 UTC on 4 October 2013.

Clear Sky Fraction

- The clear sky through an atmospheric column is the product of the clear sky fraction for the layers within the column, such that

$$A_Z = 1 - C_Z = \prod_{i=0}^{N}(1 - C_i) = \prod_{i=0}^{N}(A_i)$$

for $i \in N$ layers in the column, where A_i is the clear sky fraction for layer *i* or the entire column for A_Z, and C_i is the cloud fraction for layer *i* or the entire column for C_Z.

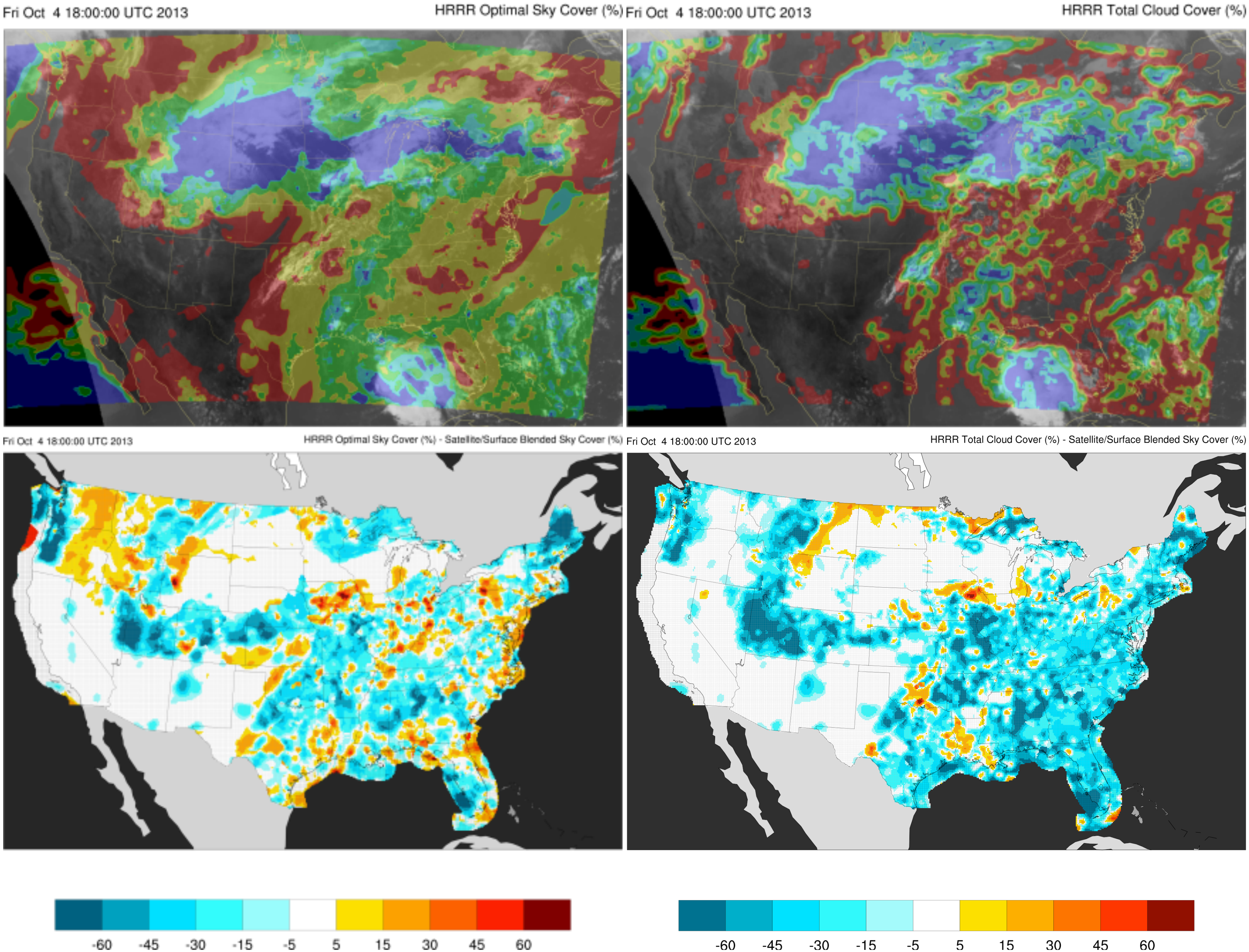
Mixing Ratio and Cloud Fraction

- Since
  - optical depth is a function of the extinction coefficient,
  - the extinction coefficient is proportional to mixing ratio, and
  - given there exists a direct relationship between absorbance and cloud fraction,
  - it is possible to define the cloud cover as the sum of adjusted relative humidity values and adjusted mixing ratio values within a column.
- Therefore, the sum of adjusted mixing ratio quantities is approximated using the same Maclaurin series of e^{-x} as previously.

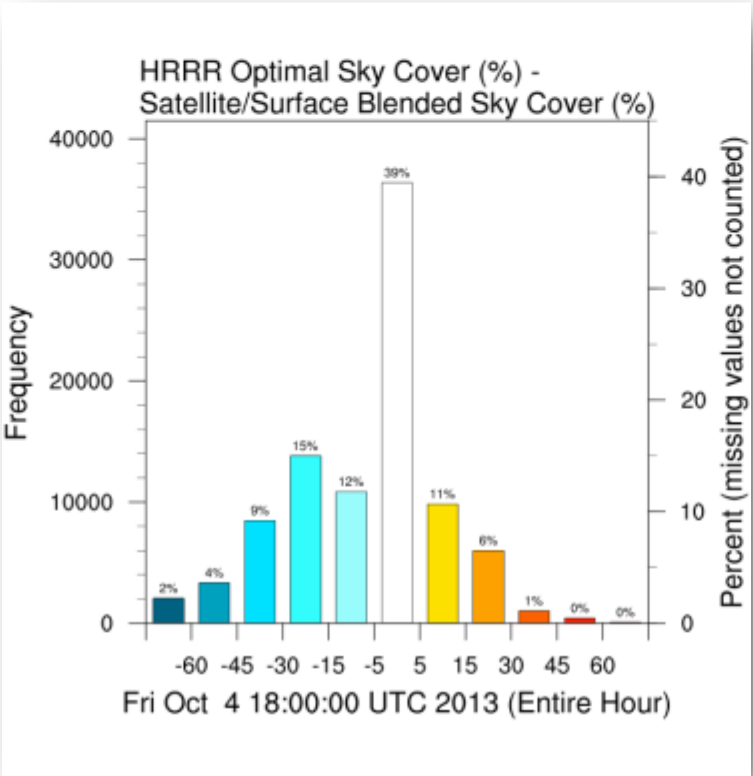
Optimizing Sky Cover

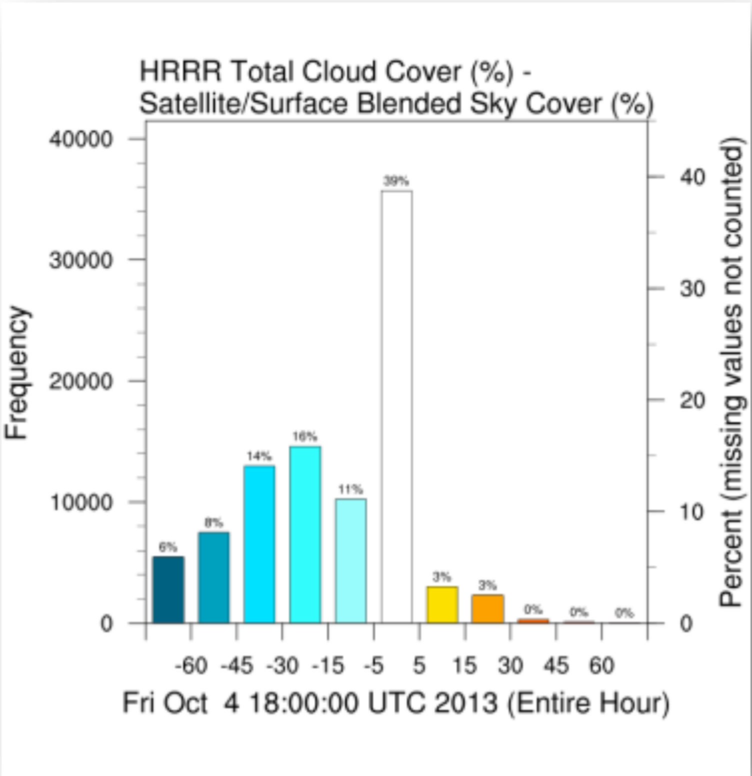
- Optimization objective: Minimize the mean absolute error between the affine expression of adjusted input fields and the truth field

- Terms:
  - Coefficient allowed for 200 hPa positive and negative absolute vorticity ($m_{200}AV_{200}$)
  - Coefficient allowed for relative humidity quantities (m_xRH_x)
  - Threshold allowed for applying coefficient to 1000 hPa relative humidity field ($m_{1000}RH_{1000}$ if $RH_{1000} > RH_T$)
  - Coefficient and scalar allowed for non-zero mixing ratio quantities ($m_yMR_y+b_y$ if $MR_y > 0$, otherwise 0)


Fri Oct 4 18:00:00 UTC 2013
HRRR Optimal Sky Cover (%)
Fri Oct 4 18:00:00 UTC 2013
HRRR Total Cloud Cover (%)
Fri Oct 4 18:00:00 UTC 2013
HRRR Optimal Sky Cover (%) - Satellite/Surface Blended Sky Cover (%)
Fri Oct 4 18:00:00 UTC 2013
HRRR Total Cloud Cover (%) - Satellite/Surface Blended Sky Cover (%)
-60 -45 -30 -15 -5 5 15 30 45 60
-60 -45 -30 -15 -5 5 15 30 45 60

Case Study


HRRR Optimal Sky Cover (%) -
Satellite/Surface Blended Sky Cover (%)
Frequency
40000
30000
20000
10000
0
Percent (missing values not counted)
40
30
20
10
0
2%
4%
9%
15%
12%
39%
11%
6%
1%
0%
0%
-60 -45 -30 -15 -5 5 15 30 45 60
Fri Oct 4 18:00:00 UTC 2013 (Entire Hour)


HRRR Total Cloud Cover (%) -
Satellite/Surface Blended Sky Cover (%)
Frequency
40000
30000
20000
10000
0
Percent (missing values not counted)
40
30
20
10
0
6%
8%
14%
16%
11%
39%
3%
3%
0%
0%
0%
-60 -45 -30 -15 -5 5 15 30 45 60
Fri Oct 4 18:00:00 UTC 2013 (Entire Hour)

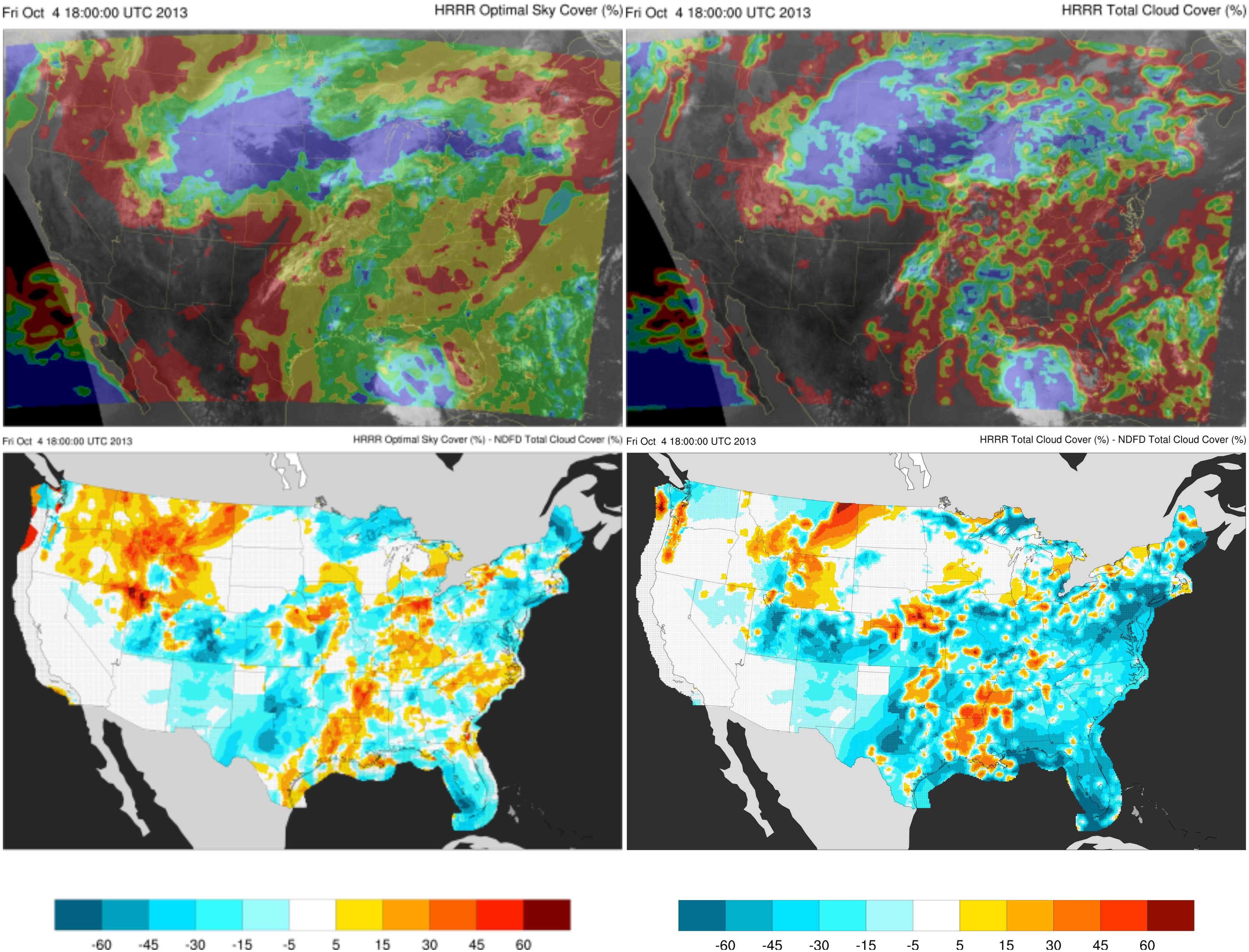
Results

Forecasts valid between 21 September 2013, 0 UTC, and 1 November 2013, 23 UTC

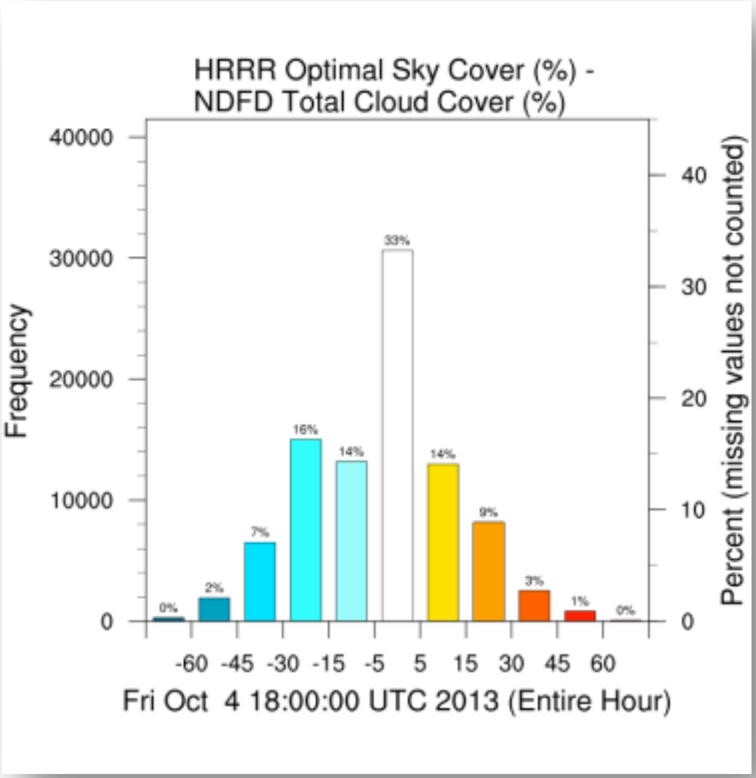
Validated against blended sky cover analysis

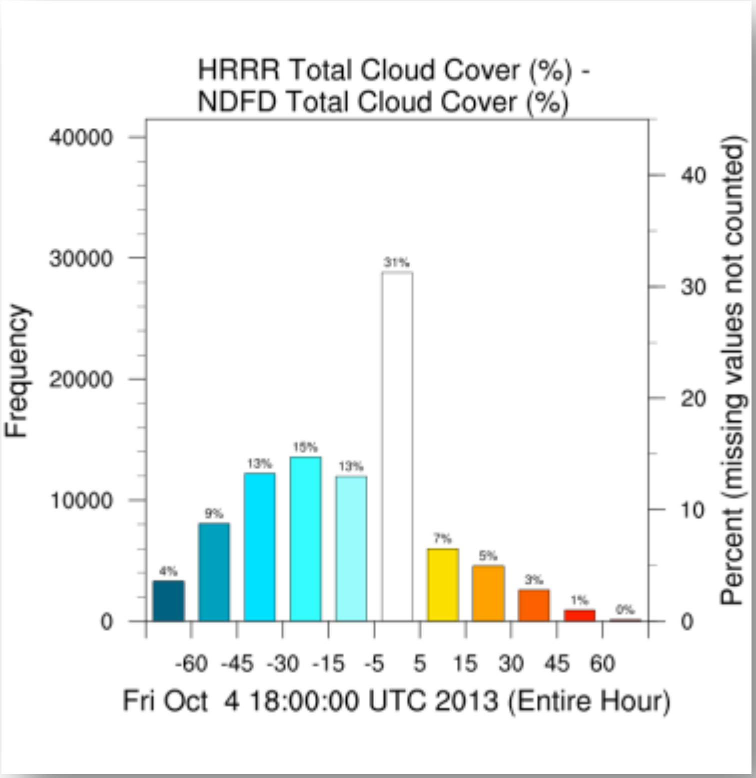
0-hour	**Operational**	**Optimal**	**Improvement**
Cases	823	793	
ME	-13.1%	-7.6%	**5.5%**
MAE	17.3%	17.5%	**-0.2%**
RMSE	27.2%	26.5%	**1.2%**

3-hour	**Operational**	**Optimal**	**Improvement**
Cases	810	784	
ME	-12.4%	-9.6%	**2.8%**
MAE	23.9%	20.3%	**3.6%**
RMSE	35.7%	30.0%	**5.7%**


Fri Oct 4 18:00:00 UTC 2013
HRRR Optimal Sky Cover (%)
Fri Oct 4 18:00:00 UTC 2013
HRRR Total Cloud Cover (%)
Fri Oct 4 18:00:00 UTC 2013
HRRR Optimal Sky Cover (%) - NDFD Total Cloud Cover (%)
Fri Oct 4 18:00:00 UTC 2013
HRRR Total Cloud Cover (%) - NDFD Total Cloud Cover (%)
-60 -45 -30 -15 -5 5 15 30 45 60
-60 -45 -30 -15 -5 5 15 30 45 60

Case Study


HRRR Optimal Sky Cover (%) -
NDFD Total Cloud Cover (%)
40000
30000
20000
10000
0
Frequency
40
30
20
10
0
Percent (missing values not counted)
0%
2%
7%
16%
14%
33%
14%
9%
3%
1%
0%
-60 -45 -30 -15 -5 5 15 30 45 60
Fri Oct 4 18:00:00 UTC 2013 (Entire Hour)


HRRR Total Cloud Cover (%) -
NDFD Total Cloud Cover (%)
40000
30000
20000
10000
0
Frequency
40
30
20
10
0
Percent (missing values not counted)
4%
9%
13%
15%
13%
31%
7%
5%
3%
1%
0%
-60 -45 -30 -15 -5 5 15 30 45 60
Fri Oct 4 18:00:00 UTC 2013 (Entire Hour)

Results

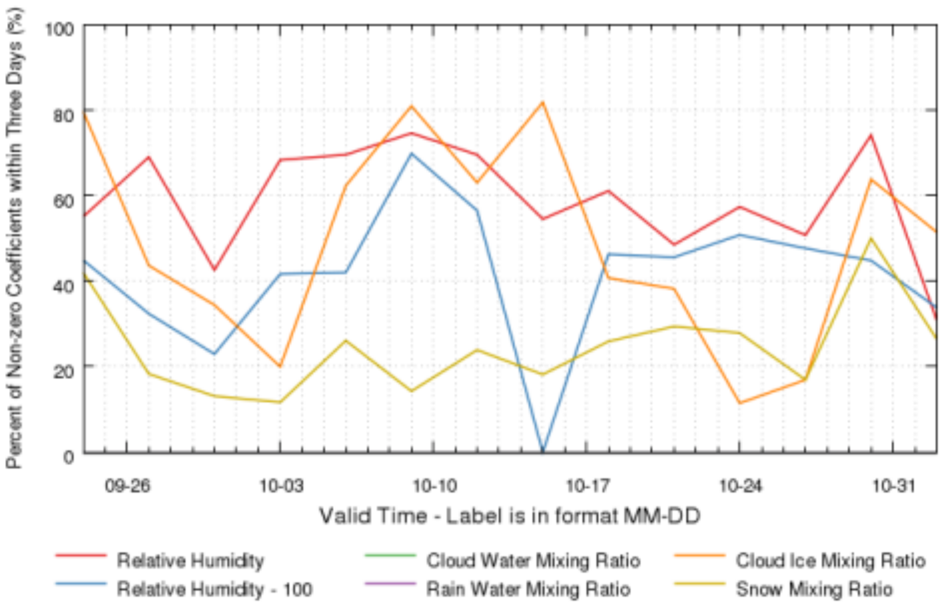
Forecasts valid between 21 September 2013, 0 UTC, and 1 November 2013, 23 UTC

Validated against NWS NDFD one-hour sky cover forecast

0-hour	**Operational**	**Optimal**	**Improvement**
Cases	281	270	
ME	-11.9%	-6.4%	**5.5%**
MAE	20.6%	16.1%	**4.5%**
RMSE	28.4%	22.4%	**4.0%**

3-hour	**Operational**	**Optimal**	**Improvement**
Cases	274	784	
ME	-11.0%	-8.4%	**2.6%**
MAE	24.1%	17.1%	**7.0%**
RMSE	32.7%	23.8%	**8.9%**

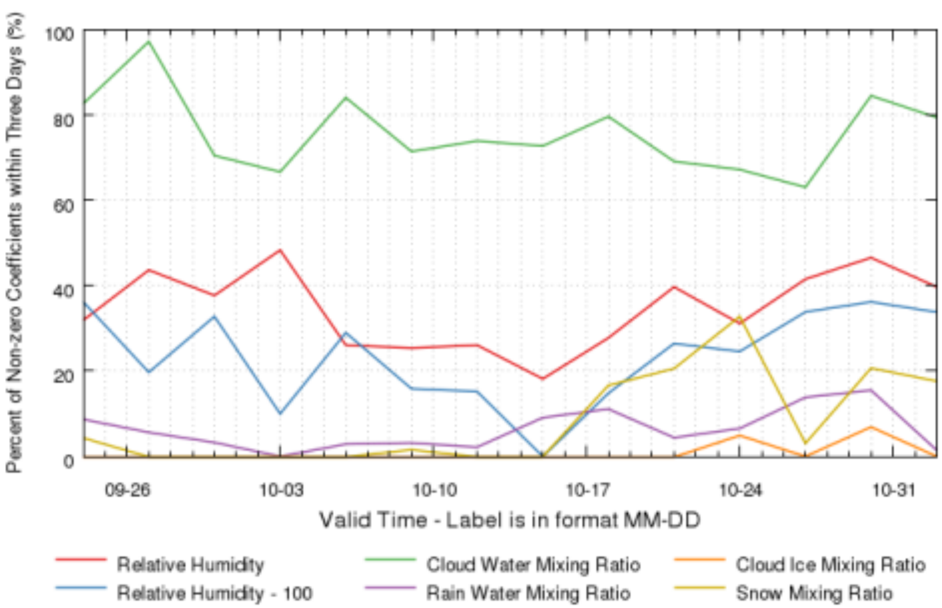
300 hPa Constituents of HRRR Optimal Sky Cover Analysis (Duration)



300 hPa Quantity	Mean
Relative Humidity	58.9%
Relative Humidity - 100	43.6%
Cloud Water Mixing Ratio	0.0%
Rain Water Mixing Ratio	0.0%
Cloud Ice Mixing Ratio	47.2%
Snow Mixing Ratio	25.0%

Means valid 1 UTC, 21 September 2013, through 23 UTC, 1 November 2013

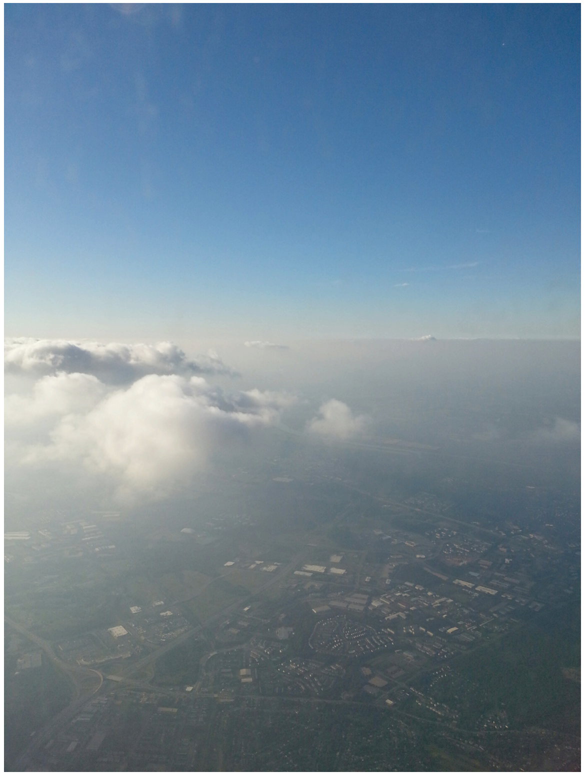
900 hPa Constituents of HRRR Optimal Sky Cover Analysis (Duration)

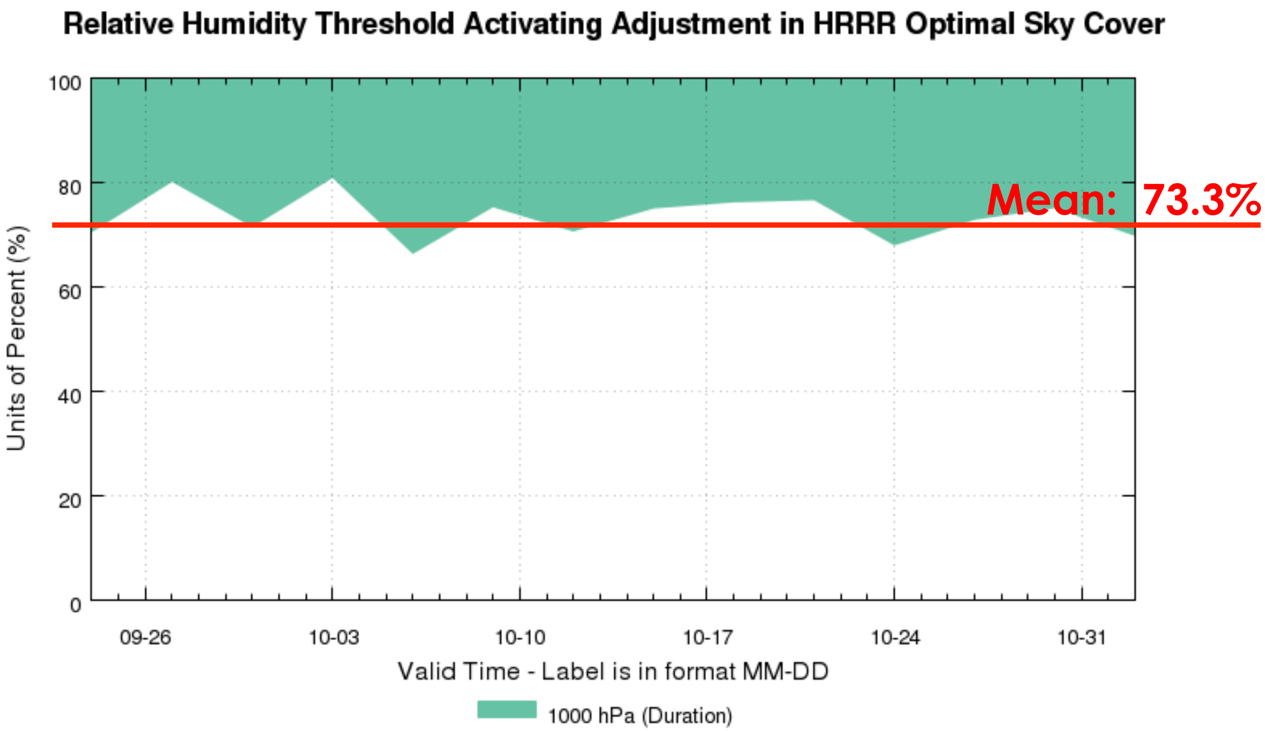


900 hPa Quantity	Mean
Relative Humidity	35.8%
Relative Humidity - 100	25.4%
Cloud Water Mixing Ratio	76.3%
Rain Water Mixing Ratio	6.1%
Cloud Ice Mixing Ratio	0.8%
Snow Mixing Ratio	8.9%

Results

Above the threshold, there is a non-zero coefficient or scalar which applies to the 1000 hPa relative humidity value in *all* optimizer solutions during the period.





Results

- Results are from 21 September 2013 through 1 November 2013 over and near the contiguous United States.
- 950 hPa cloud water mixing ratio is the most frequently selected field in the solved affine relationship.
  - Cloud water mixing ratio from one or more levels in the lower troposphere is frequently correlated with sky cover.
- Higher in the troposphere, there is less reliance on cloud water mixing ratio and more reliance on relative humidity.
- Snow mixing ratio and rain mixing ratio are not commonly included in optimized formulations.
  - Indicates limited HRRR model skill on placement of convective precipitation processes

Tasks Accomplished

- It devises a blended sky cover analysis that incorporates the advantageous properties of surface observations of sky cover and geostationary satellite cloud products.
- It defines a framework for optimizing the blended analysis based on the current near-term human-produced forecasts from the National Digital Forecast Database (NDFD).
- It constructs an affine expression of High-Resolution Rapid Refresh (HRRR) relative humidity, mixing ratio, and vorticity analysis fields with adjustable coefficients and scalars that is optimized to decrease the absolute error compared to the "truth" analysis.

Primary Conclusions

- The combination of surface observations and the satellite sky cover product improves the detection of nocturnal low cloud and general high cloud compared to a single source.
- Relative humidity and cloud water mixing ratio are closely correlated with sky cover, particularly in the lowest levels of the troposphere.
- The linear optimization approach produces an optimal sky cover product with decreased mean error, mean absolute error, and root-mean-square error when validated against the NDFD one-hour forecast, compared to the current operational HRRR output.

Possible Future Directions

- Improve satellite sky cover product with visible transmission (daytime) to lessen overestimate with emissivity approaches
- Focus on NWP to improve analysis and forecast of sky cover:
  - Incorporate terrain information and additional in-situ surface observation fields into blended analysis to confine cloud decks to edges of terrain features
  - Integrate observational decision matrix into variational scheme
  - Produce cloud products from simulated imagery output from NWP model with integrated radiative transfer model
  - Output sky cover from operational models
- Work with NWS to produce a sky cover analysis of record and validate NWP output and human forecasts of sky cover

Questions? Comments?