Sky Cover:

Shining Light on a Gloomy Problem

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

Objective I

Create an hourly sky cover analysis based on the following requirements:

- The sky cover quantity is an average over an entire hour.
- Satellite and in-situ surface observations of cloud cover are complementary.
- The range of the sky cover quantity is between 0% and 100%.

Goal I

Produce an operations-grade sky cover product for the field

Objective II

Create an optimal sky cover forecast based on the following assumptions:

- The relationship between sky cover and numerical weather prediction cloud/moisture variables is roughly linear.
- The model variables adequately represent the atmosphere at the initial time and at times in the future.

Goal II

Produce an operations-grade sky cover forecast for the field

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 United States Federal Meteorological Handbook (FMH) No. 1 defines sky cover as “the amount of the celestial dome hidden by clouds and/or obscurations”.

Observing the Sky

There are three primary sources 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 observers (typically with aid of instrumentation)

Observing the Sky

There are issues with each observation type:

- Satellites observe the atmosphere from the top, such that high clouds obscure low clouds.
- Near surface clouds and clouds smaller than the satellite FOV may not be properly represented.
- Satellite observations are instantaneous.

Observing the Sky

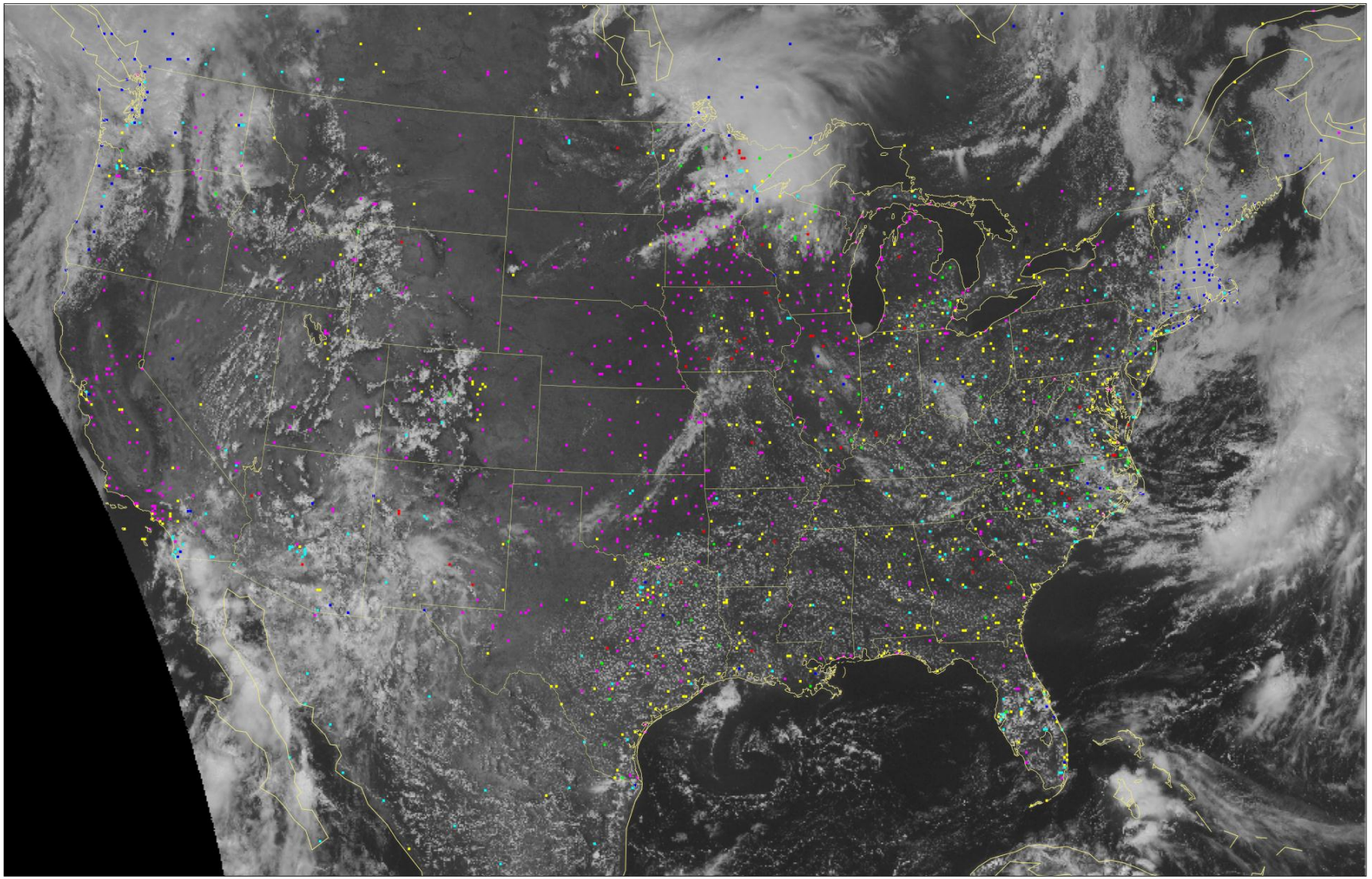
There are issues with each observation type:

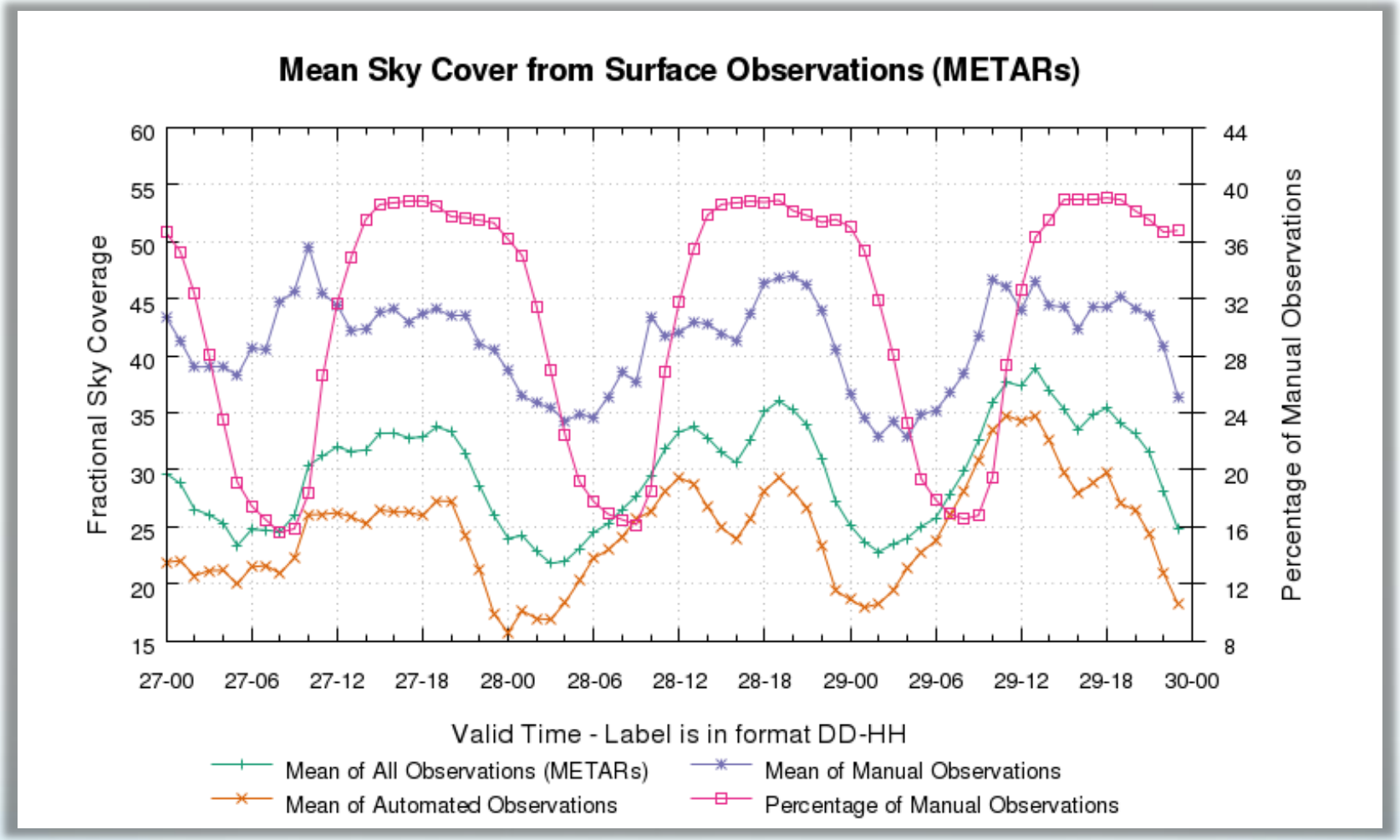
- Ceilometers fail to detect/report high cloud (over 12 kft) and do not observe the celestial dome.
- The human observations require estimation and are not as precise.
  - Sky conditions reported as one of five coverage modes in coded surface observation reports.

Sky Cover Comparison

Thu Aug 29 19:00:00 UTC 2013

Surface Sky Observations/METARs (%)




Mean Sky Cover from Surface Observations (METARs)
Fractional Sky Coverage
Percentage of Manual Observations
60
55
50
45
40
35
30
25
20
15
44
40
36
32
28
24
20
16
12
8
27-00
27-06
27-12
27-18
28-00
28-06
28-12
28-18
29-00
29-06
29-12
29-18
30-00
Valid Time - Label is in format DD-HH
Mean of All Observations (METARs)
Mean of Manual Observations
Mean of Automated Observations
Percentage of Manual Observations

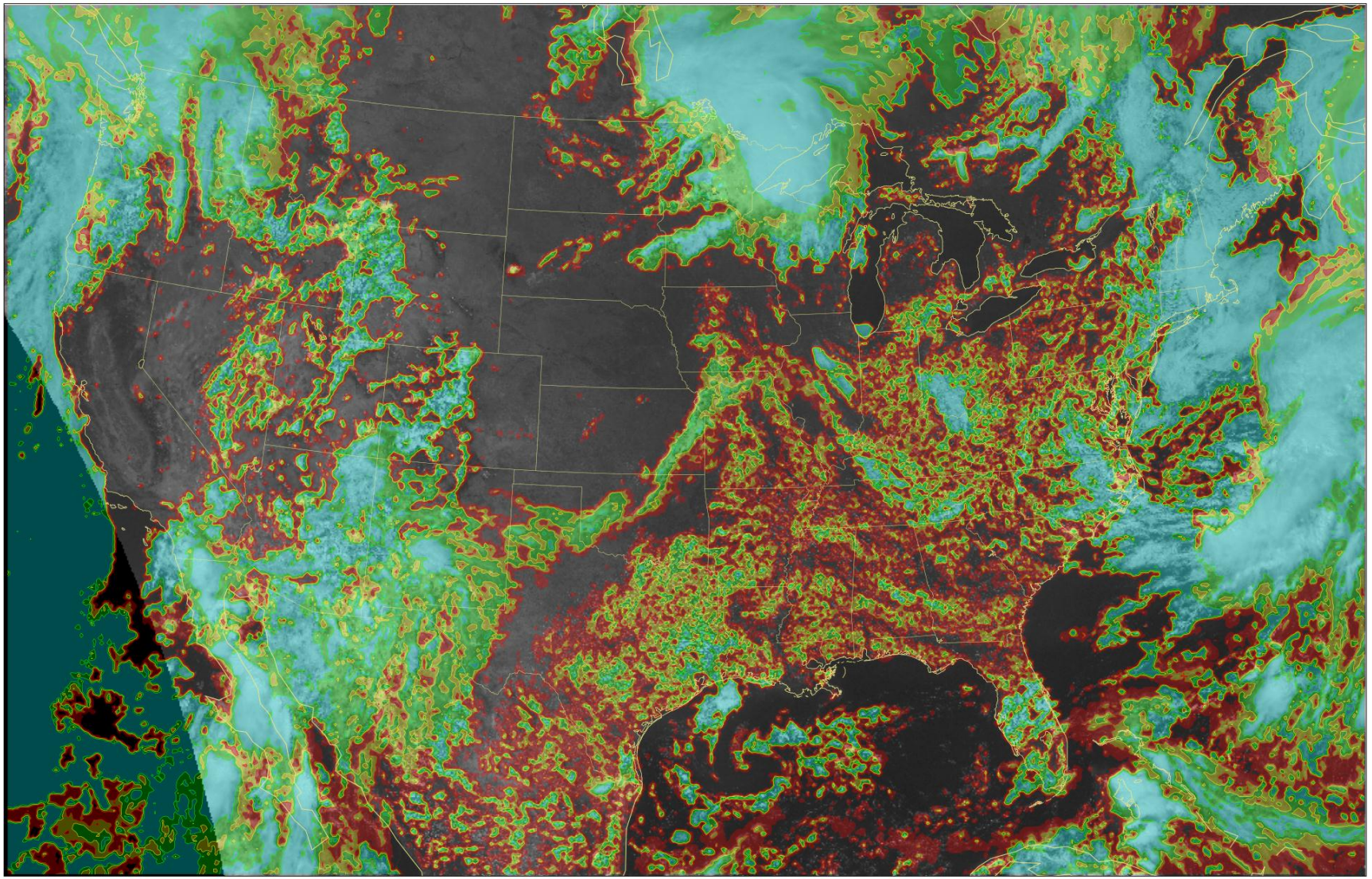
Satellite Sky Cover Product

- Based on ECA obtained from the operational GOES imagers (East and West)
- Corrected when high (low effective emissivity) cloud obscures underlying low cloud
- High effective emissivity cloud is enhanced
- Every scan is spatially averaged to produce an ad hoc celestial dome (pixel-centered 11 x 11 box)
- Temporally averaged over a one-hour window

Sky Cover Comparison

Thu Aug 29 19:00:00 UTC 2013

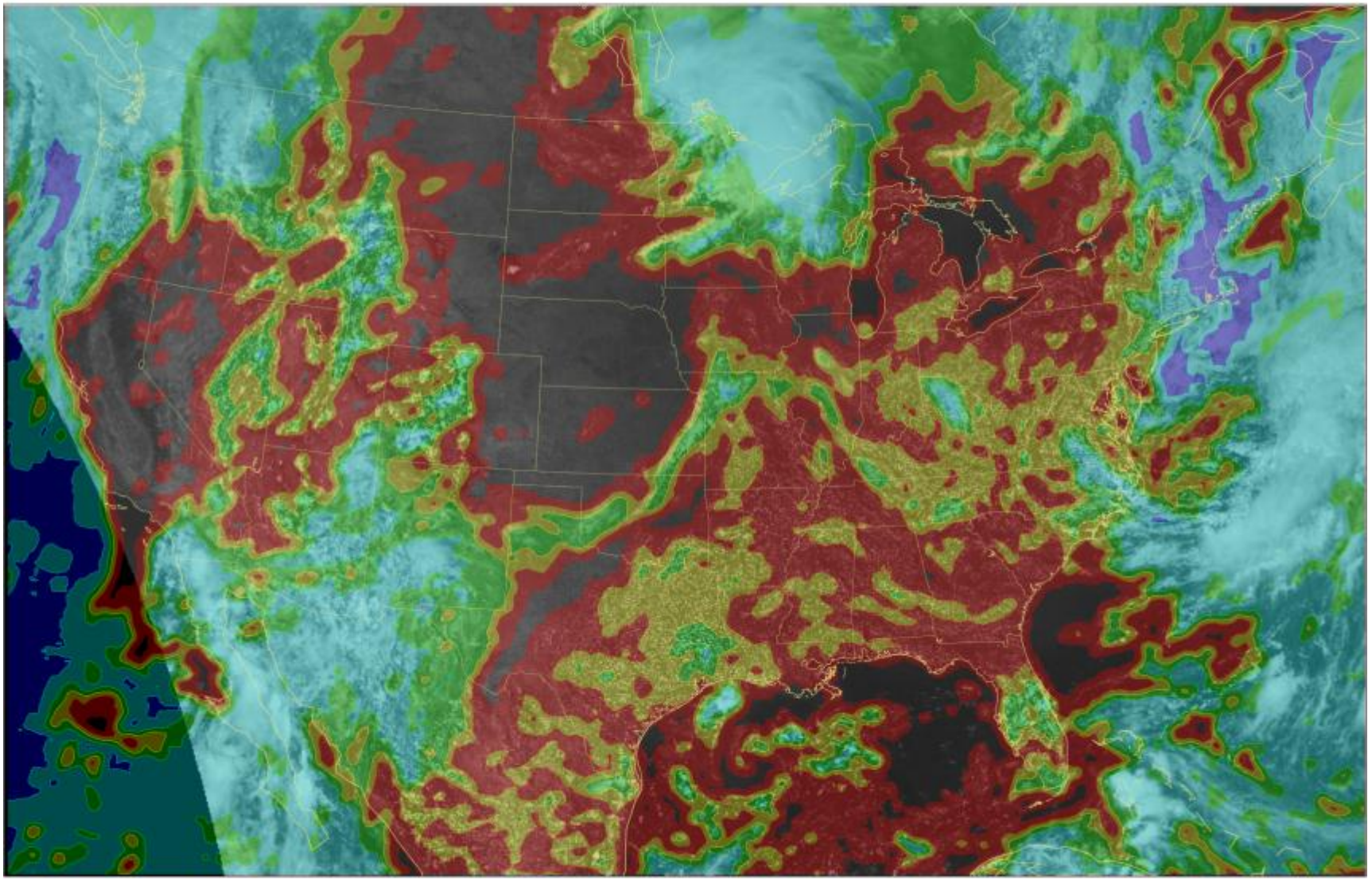
GOES Imager Effective Cloud Amount (%)



Sky Cover Comparison

Thu Aug 29 19:00:00 UTC 2013

GOES Imager Sky Cover Product (%)



1 25 50 75 99

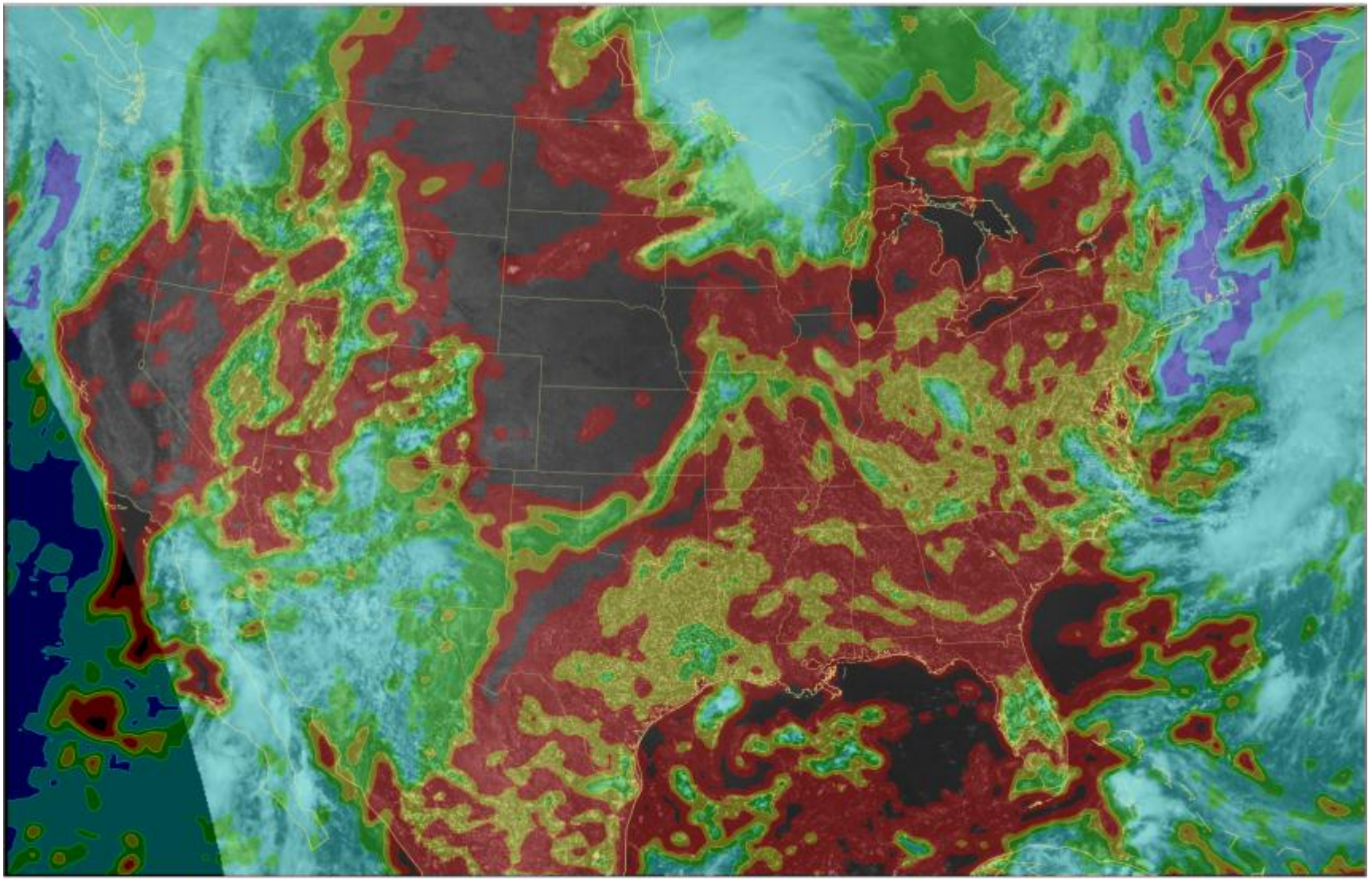
Blended Sky Cover Analysis

- If the surface station observation reports clear (less than 5% celestial dome coverage), the satellite sky cover product value is used.
- If the surface station observation reports some cloud (5% or better coverage of the celestial dome), the surface observation is used when the value is greater than that from the satellite.
- In other situations where both observations are available, a weighted average is performed.

Sky Cover Comparison

Thu Aug 29 19:00:00 UTC 2013

GOES Imager Sky Cover Product (%)

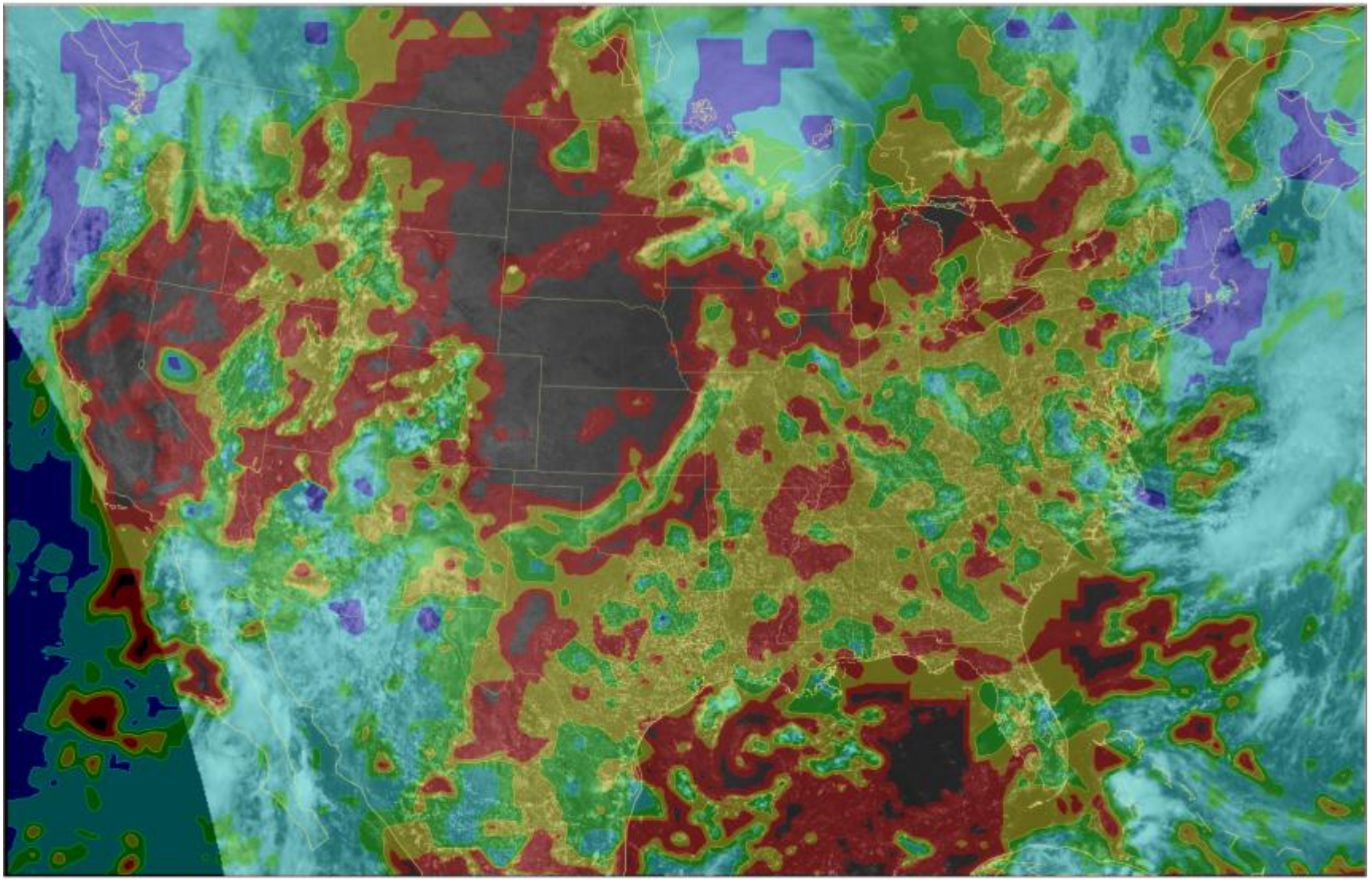


1 25 50 75 99

Sky Cover Comparison

Thu Aug 29 19:00:00 UTC 2013

Satellite/Surface Blended Sky Cover (%)



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)

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Goal II

Produce an operations-grade sky cover forecast for the field

Forecasting Sky Cover

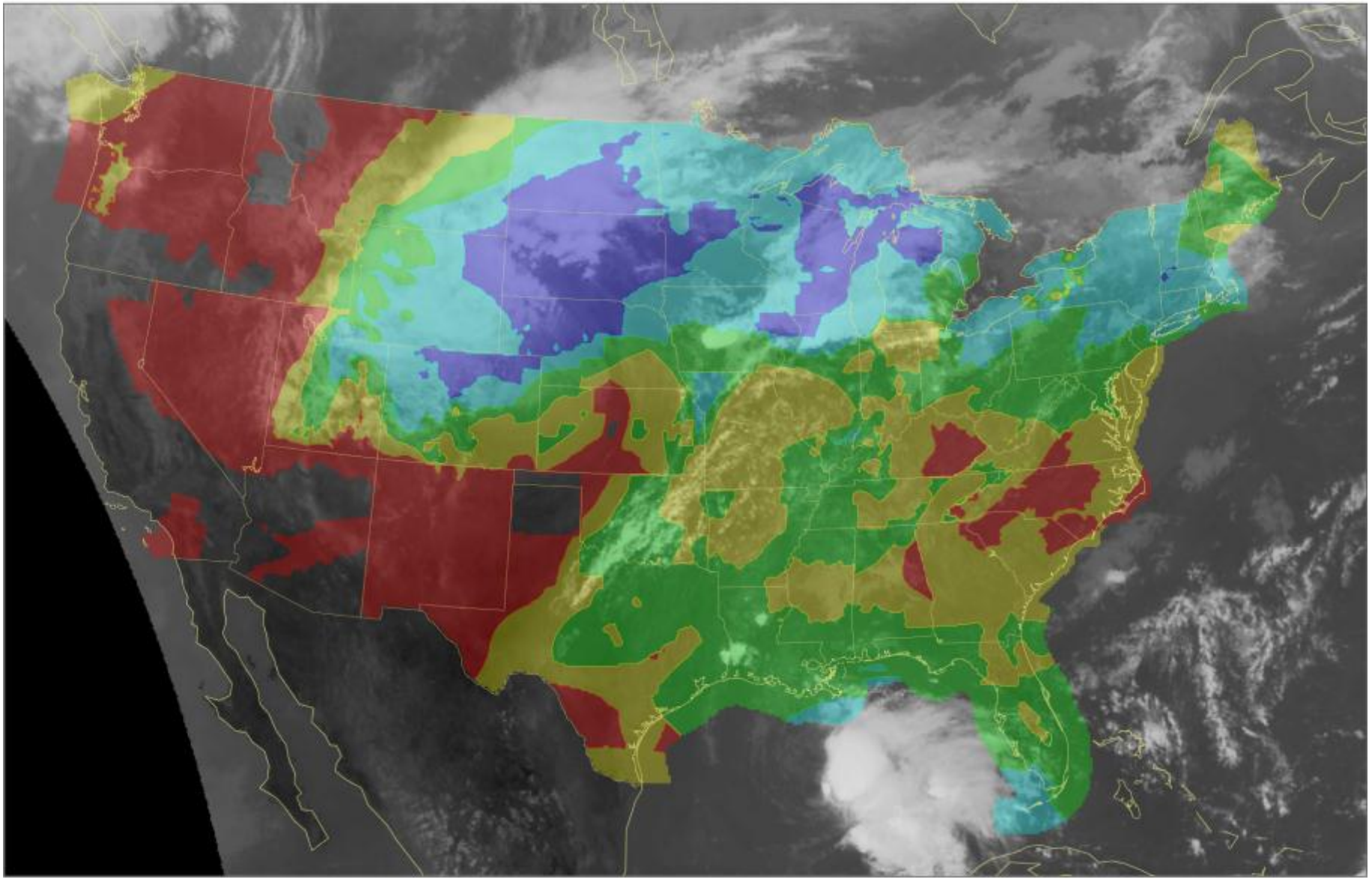
The National Weather Service (NWS) National Digital Forecast Database (NDFD) contains an operational sky cover forecast field. Issues with the national one-hour forecast include:

- 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.

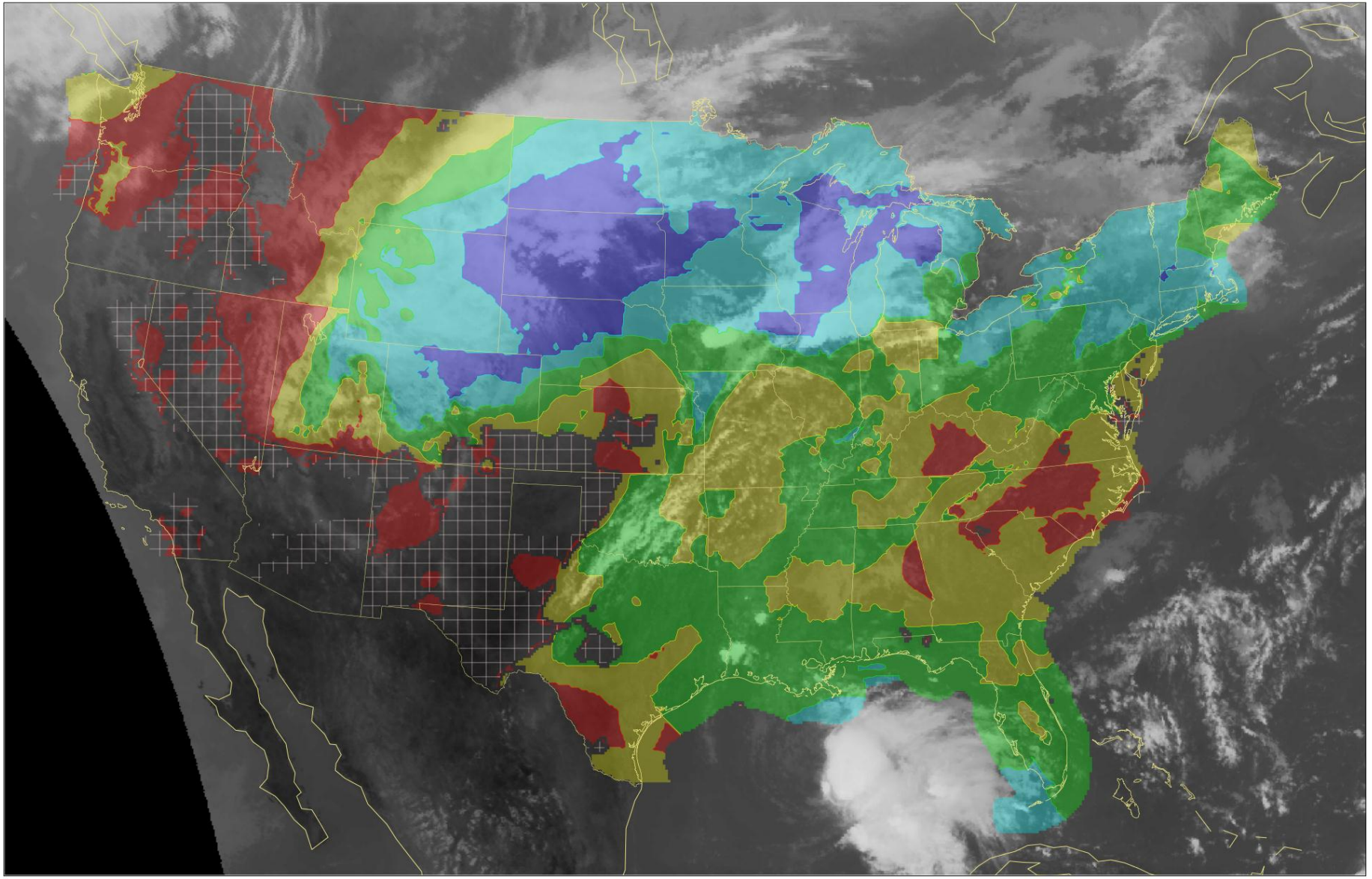
Fri Oct 4 18:00:00 UTC 2013

NDFD Total Cloud Cover (%)



Fri Oct 4 18:00:00 UTC 2013

NDFD Total Cloud Cover (%)

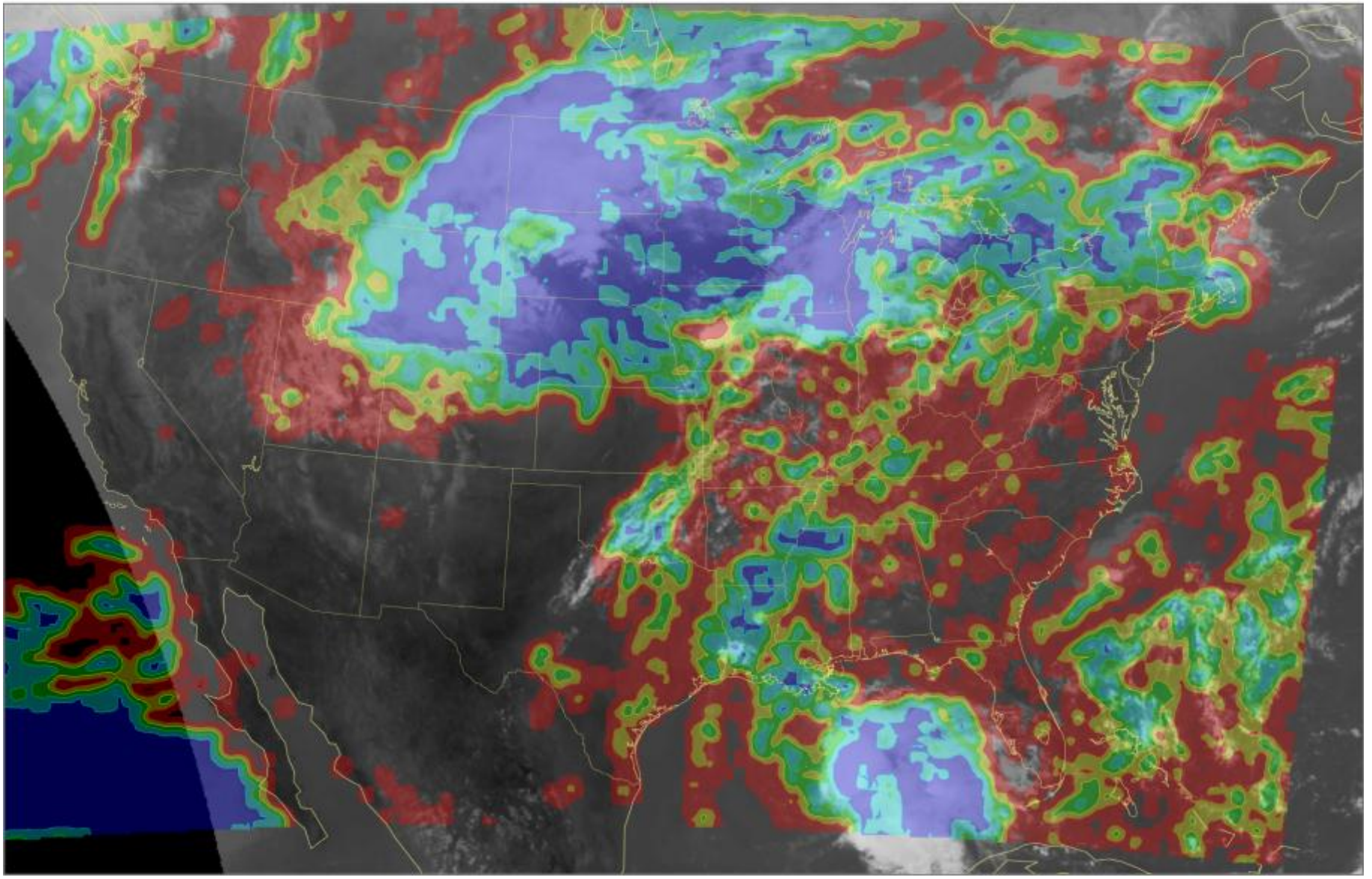


HRRR

- High-Resolution Rapid Refresh (http://ruc.noaa.gov/hrrr/)
- Horizontal resolution of 3 km, 50 vertical levels
- Cloud-resolving model, no convective parameterization
- Literature available for WRF framework which is the 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 (%)



Optimizing Sky Cover

- Input fields (subset of points)
  - Truth: Adjusted blended sky cover analysis
  - Components
- Design model (formats: linear, mixed integer, others)
  - Objective using free variable, subject to constraints
  - 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:

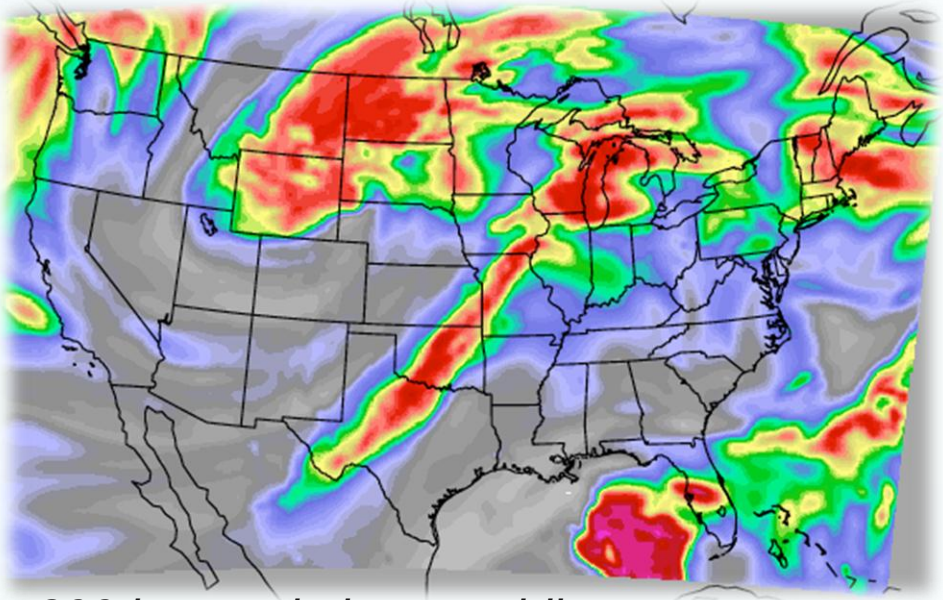
- Relative Humidity (all levels)
- Cloud Water Mixing Ratio, Cloud Ice Mixing Ratio, Rain Water Mixing Ratio, Snow Mixing Ratio (all levels)
- Absolute Vorticity (200 hPa only), partitioned into positive and negative components

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

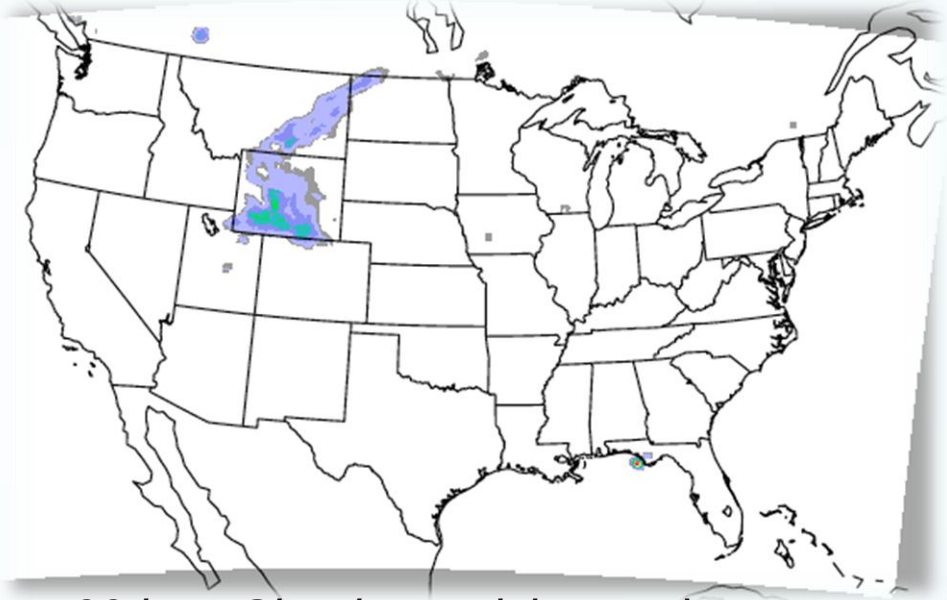
Optimizing Sky Cover

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

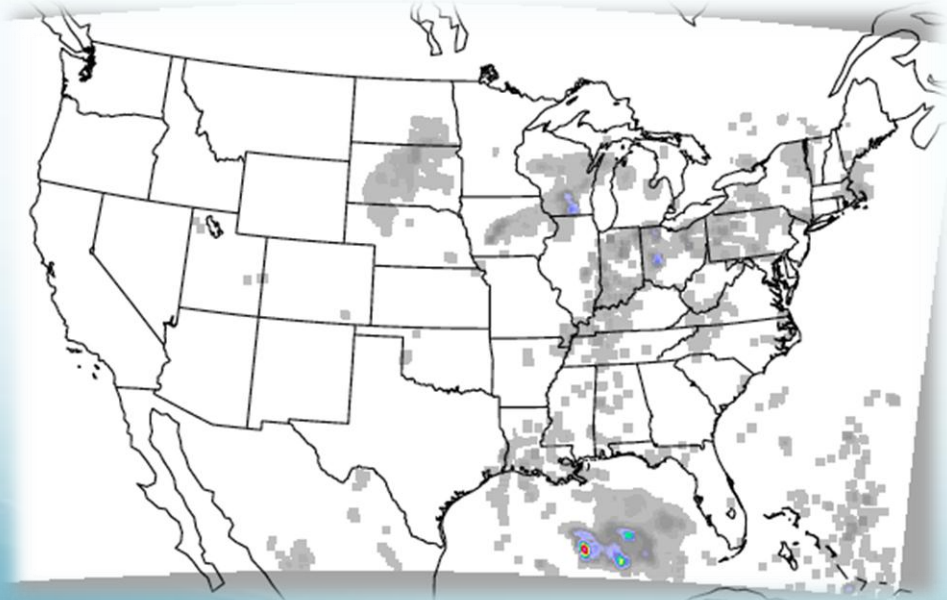
- Terms:
  - Coefficient allowed for 200 hPa positive and negative absolute vorticity ($m_{200}AV_{200}$)
  - Coefficient allowed for relative humidity quantities (m_xRH_x)
  - Threshold allowed for applying coefficient to 1000 hPa relative humidity field ($m_{1000}RH_{1000}$ if $RH_{1000} > RH_T$)
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



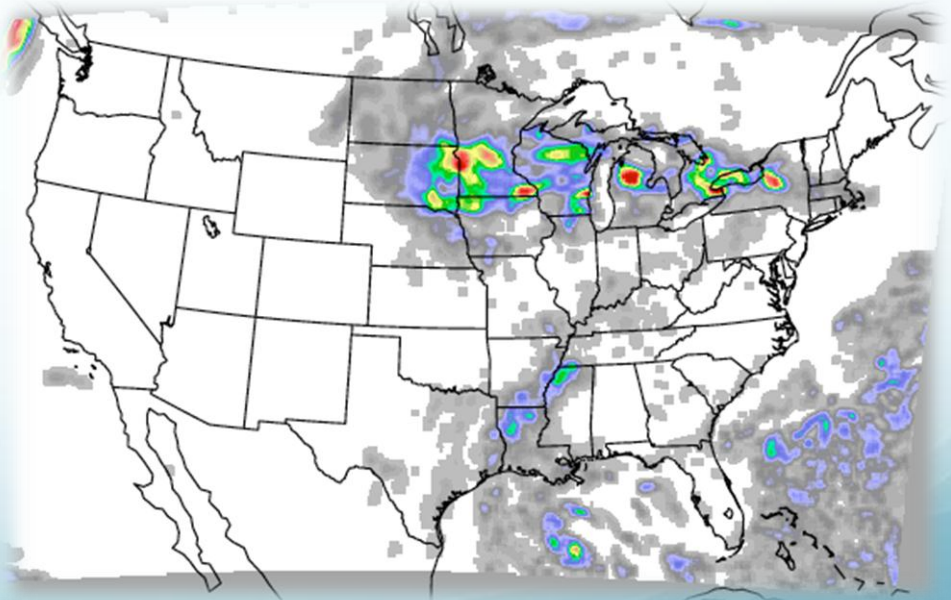
300 hPa Relative Humidity



500 hPa Cloud Ice Mixing Ratio



700 hPa Rain Water Mixing Ratio



900 hPa Cloud Water Mixing Ratio

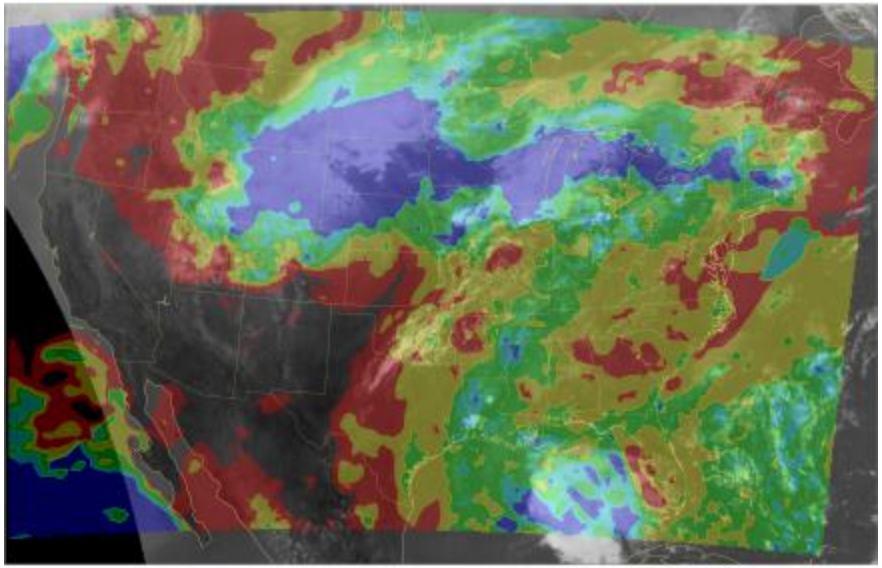
All images are HRRR model analysis output valid at 18 UTC on 4 October 2013.

Optimizing Sky Cover

- Constraints:
  - Enforce physical relationships
    - Range of acceptable values (0 to 100)
    - Extent of relative humidity and absolute vorticity correlating to cloud
  - Enforce thresholds (mixed integer)
  - Maintain similar mean value and approximate value distribution of output field to similarly match the truth field
  - Guide optimizer
    - Away from scalar adjustments, toward coefficient adjustments (maintain spatial gradients)

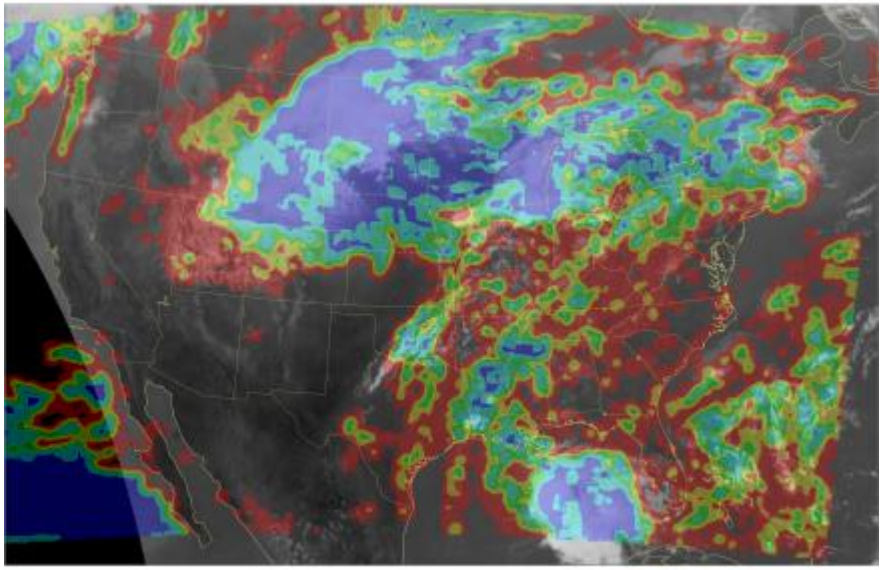
Fri Oct 4 18:00:00 UTC 2013

HRRR Optimal Sky Cover (%)



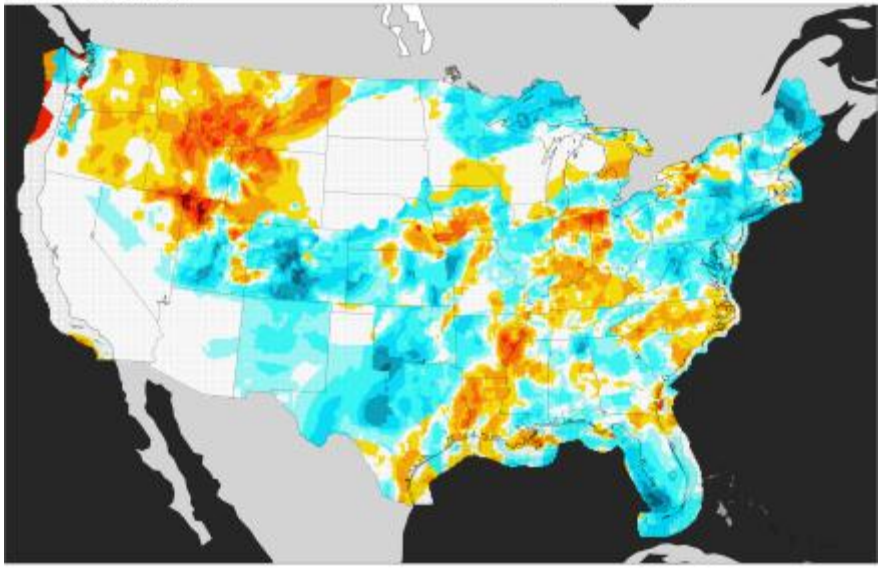
Fri Oct 4 18:00:00 UTC 2013

HRRR Total Cloud Cover (%)



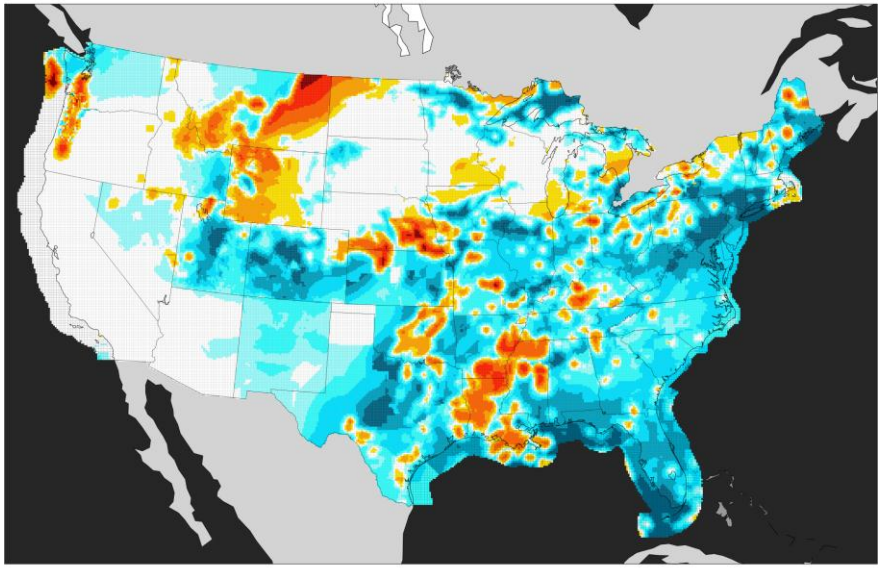
Fri Oct 4 18:00:00 UTC 2013

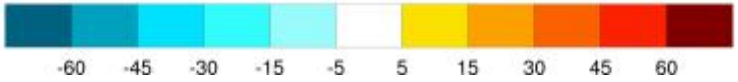
HRRR Optimal Sky Cover (%) - NDFD Total Cloud Cover (%)

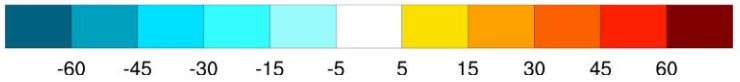


Fri Oct 4 18:00:00 UTC 2013

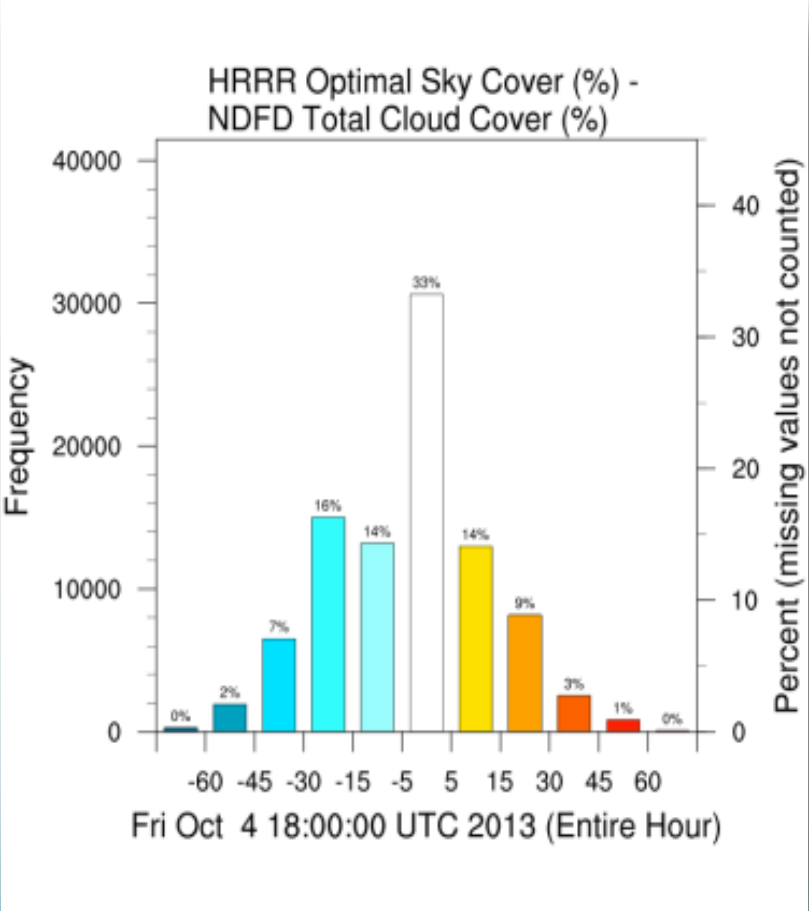
HRRR Total Cloud Cover (%) - NDFD Total Cloud Cover (%)

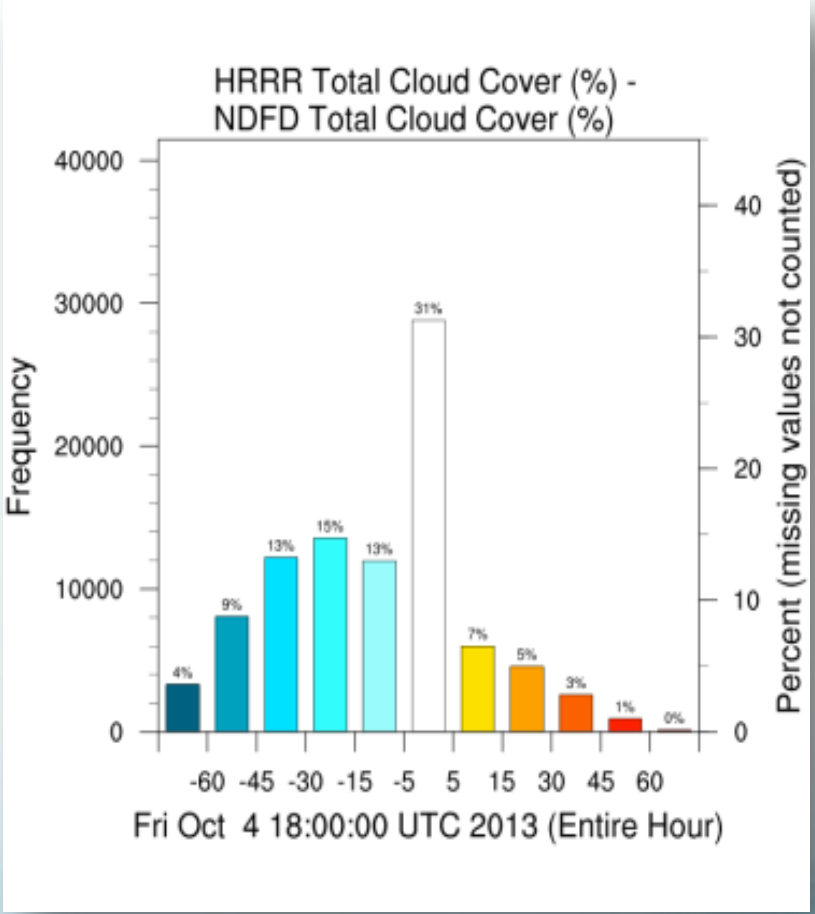






Case Study


HRRR Optimal Sky Cover (%) -
NDFD Total Cloud Cover (%)
Frequency
Percent (missing values not counted)
40000
30000
20000
10000
0
40
30
20
10
0
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 (%)
Frequency
Percent (missing values not counted)
40000
30000
20000
10000
0
40
30
20
10
0
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)

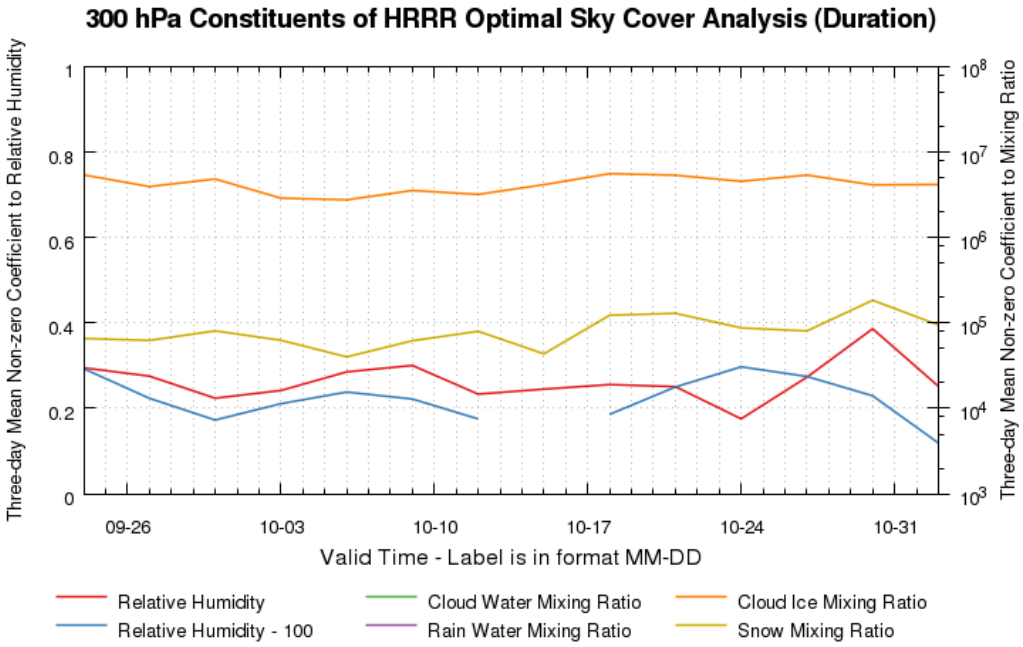
Results

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

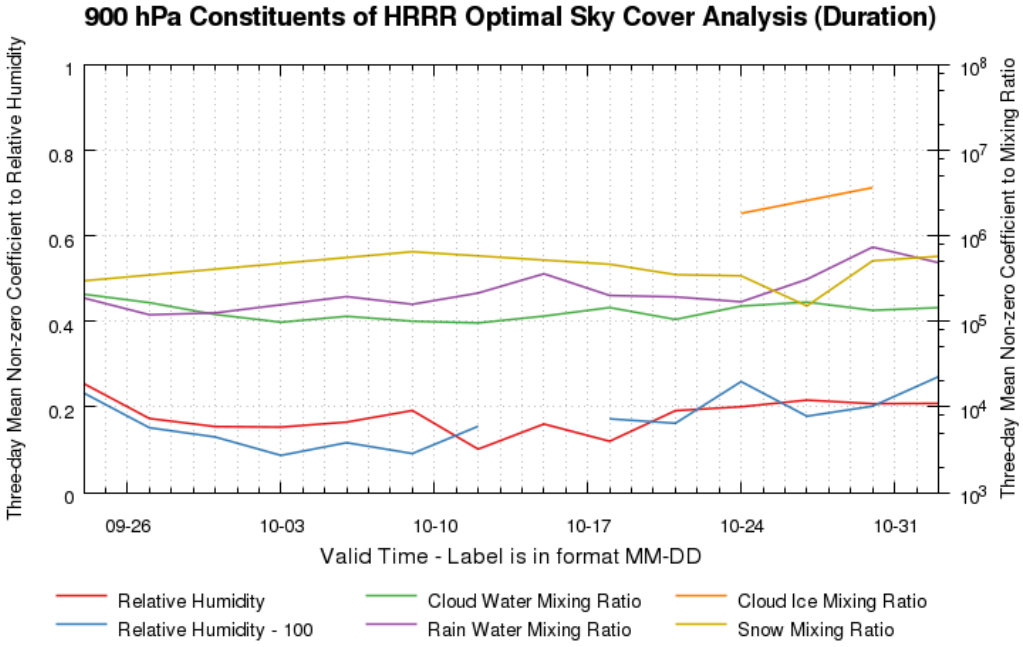
Validated against NWS NDFD one-hour sky cover forecast

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 Quantity	Mean
Relative Humidity	0.270
Relative Humidity - 100	0.228
Cloud Water Mixing Ratio	NA
Rain Water Mixing Ratio	NA
Cloud Ice Mixing Ratio	4.21×10^{6}
Snow Mixing Ratio	9.61×10^{4}

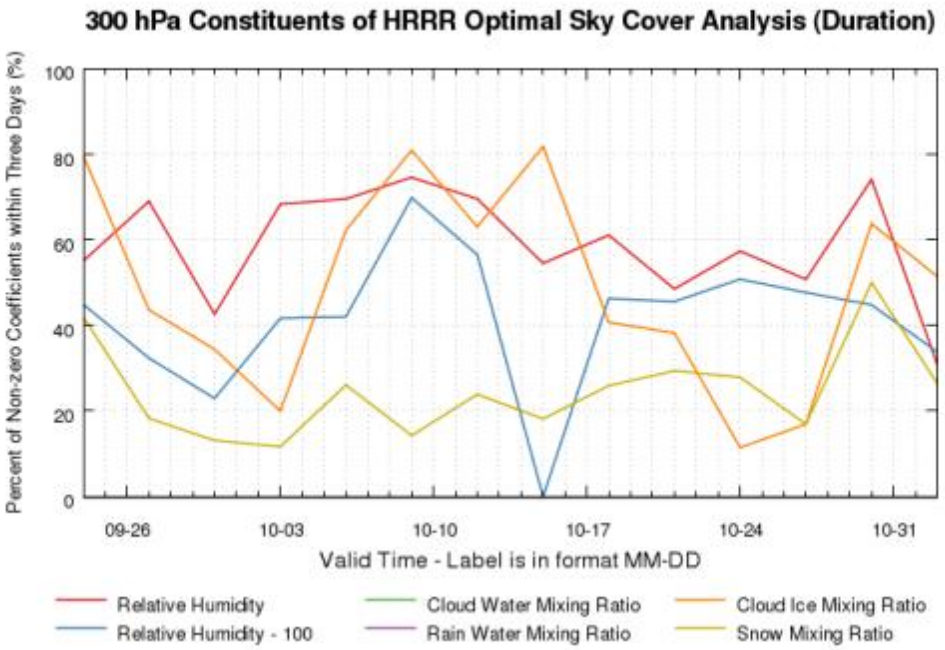


Means valid 1 UTC, 21 September 2013, through 23 UTC, 1 November 2013

900 hPa Quantity	Mean
Relative Humidity	0.184
Relative Humidity - 100	0.182
Cloud Water Mixing Ratio	1.38×10^{5}
Rain Water Mixing Ratio	3.11×10^{5}
Cloud Ice Mixing Ratio	2.88×10^{6}
Snow Mixing Ratio	4.23×10^{5}

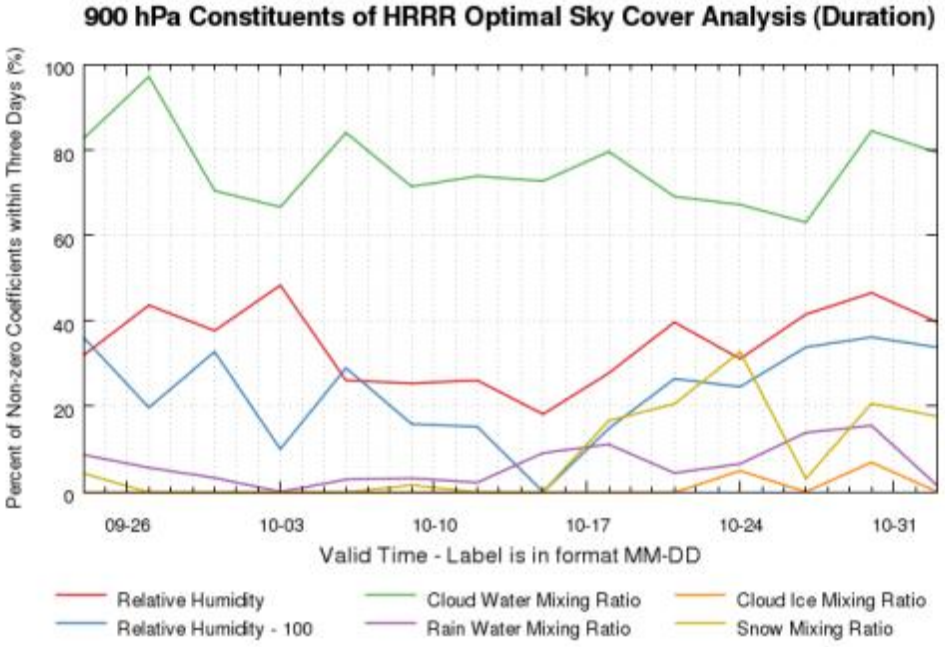
Results

Results



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%

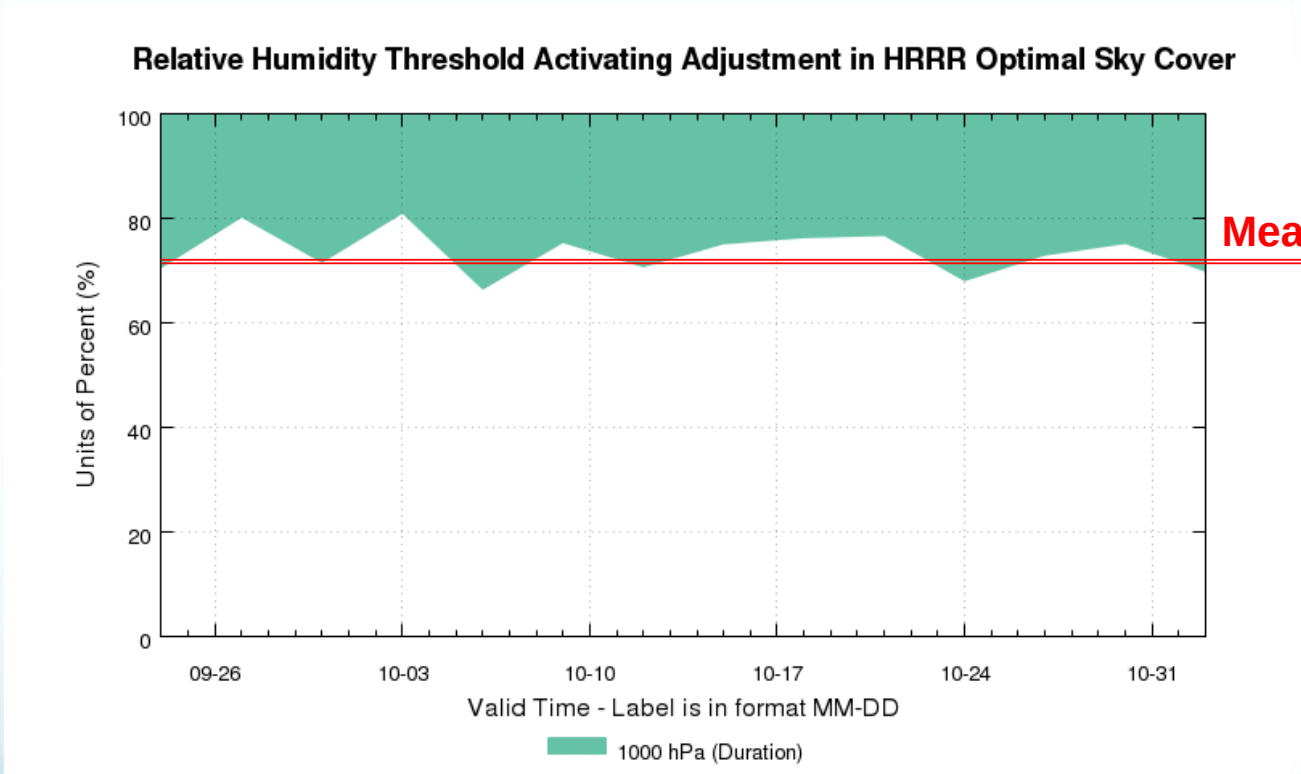
Means valid 1 UTC, 21 September 2013, through 23 UTC, 1 November 2013



900 hPa 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

Summary

- An hourly blended sky cover analysis was produced using multiple sources of sky cover observations.
- The adjusted sky cover analysis was used to build better numerical weather prediction model output of sky cover, using a mixed integer optimization methodology.
- The optimized numerical model output compared to the NDFD one-hour forecast consistently has less mean absolute error than the original/current output.
- Future work will focus on interacting with the NWS to produce a sky cover analysis of record and validate short-term numerical model forecasts of sky cover.

Questions? Comments?

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