# IMPROVING CLOUD AND MOISTURE REPRESENTATION

## BY ASSIMILATING GOES SOUNDER PRODUCTS INTO ANALYSES FOR NWP

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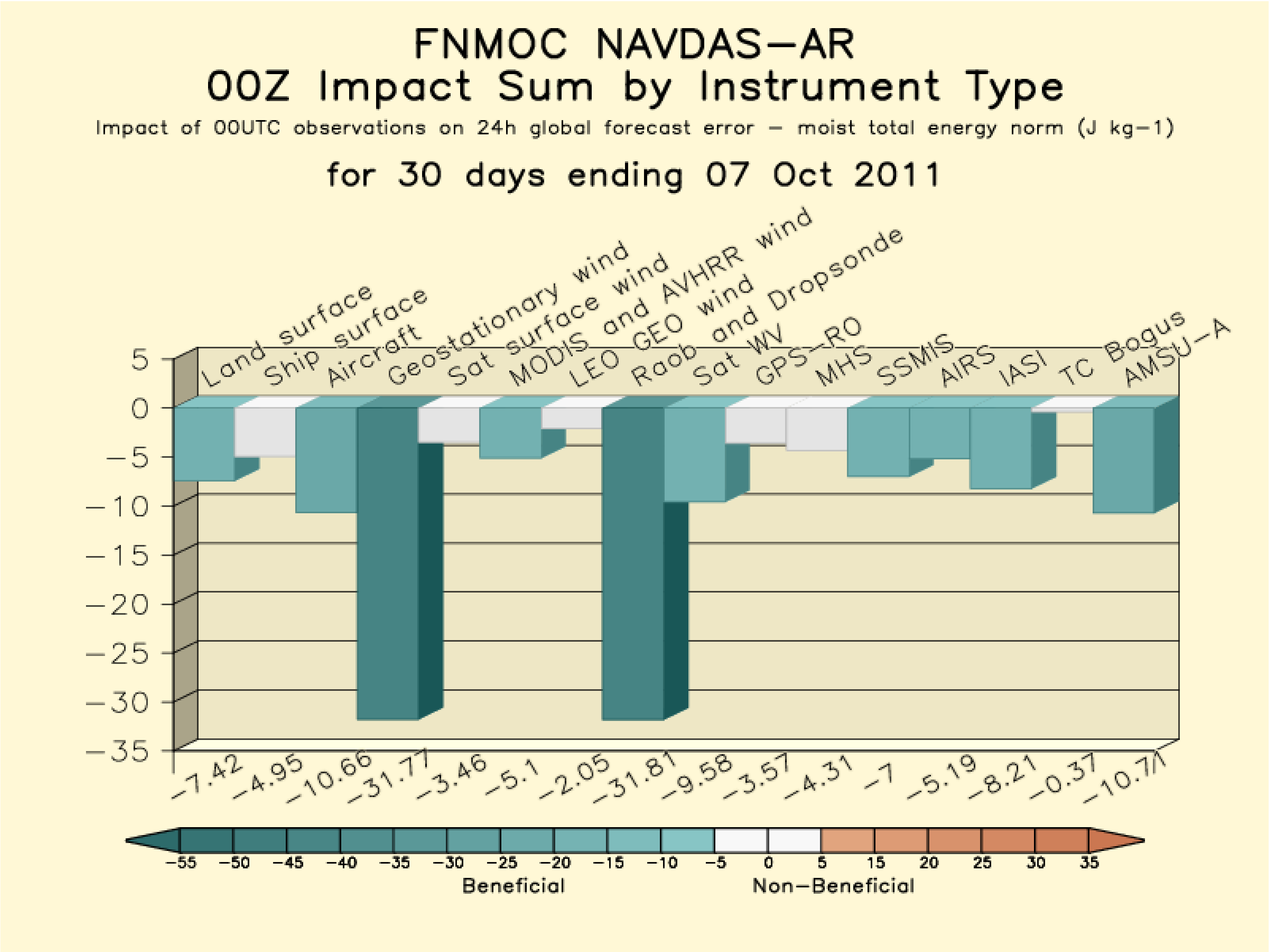
C I M S S

# Basic Premise of NWP

## An Initial Value Problem

- The following constrain the accuracy of numerical weather prediction (NWP) solutions:
  - Parameterizations and approximations within the model
  - Atmospheric features occurring on scales smaller than resolved by the model
  - *Limited observations to populate the initial analysis (especially in the "upper air" and over oceans)*
  - *Quality, precision, and accuracy of the observations*
  - Boundary conditions and domain size




**For Fleet Numerical Meteorology and Oceanography Center NOGAPS model**

http://www.nrlmry.navy.mil/obsens/

# Research Questions

- What contribution can GOES Sounder cloud and moisture retrievals provide to improving the moisture analysis for regional NWP models with a horizontal grid length of approximately 20 km?
  - Grid length considered for parameterizations and retrieval density
  - NWS Milwaukee model configuration/domain used
- How do these retrievals manifest into a better solution over the first 12 to 24 hours of the simulation?
- How can cloud fraction be formulated from retrievals to better match the expectations of operational users?

# Information Extracted from Satellites for Numerical Weather Prediction

## Radiances
- Direct assimilation (3Dvar)
- Requires model errors, observation errors
- Scale dependence
- Surface type restrictions

## Retrieved parameters
- Dependent variable assimilation (1,3Dvar)
- Requires model errors, retrieval errors
- Physical accuracy, non-linearity
- Bypass surface type restrictions

## Motion
- Cloud track, water vapor track
- Height assignment errors
- Radiance tracking (4Dvar)

**The CIMSS Regional Assimilation System (CRAS) is used to assess the impact of space-based observations on numerical forecast accuracy.**

CRAS is unique in that, since 1996, it's development was guided by validating forecasts using information from GOES.

**Output online: http://cimss.ssec.wisc.edu/cras/**

Slide credit: Robert Aune, NOAA/NESDIS

# CIMSS Regional Assimilation System (CRAS)

The 12-hour spin-up currently uses:

- **3-layer precipitable water (mm) from the GOES-13/15 sounders**
- **Cloud-top pressure (hPa) and effective cloud amount (%) from the GOES-13/15 sounders**
- 4-layer thickness (m) from the GOES-13/15 sounders
- Cloud-top pressure (hPa) from MODIS
- Gridded hourly precipitation amounts from NCEP
- Cloud-track and water vapor winds (m/s) from the GOES-13/15 imagers
- Cloud-top pressure (hPa) and effective cloud amount (%) from the GOES-13 imager
- Surface temperature (C), dew points (C) and winds (m/s)
- Sea surface temperature (C) and sea ice coverage (%) from NCEP rtg analysis

# US Operational Forecast Models

## Limited use of GOES Sounder observations

- The North American Model (NAM) and Global Forecast System (GFS) **do** use brightness temperatures from the GOES Sounders (GOES-W/15 and GOES-E/13) over ocean as part of their radiance assimilation system.

- However, they **do not** use retrievals, and they **do not** use GOES Sounder observations over land.

- The Rapid Update Cycle (RUC) **does** use precipitable water (PW) *retrievals* over ocean from GOES-15 only.

# CLOUD AND MOISTURE ASSIMILATION

Methodology and Examples

# Assimilating GOES Sounder in CRAS

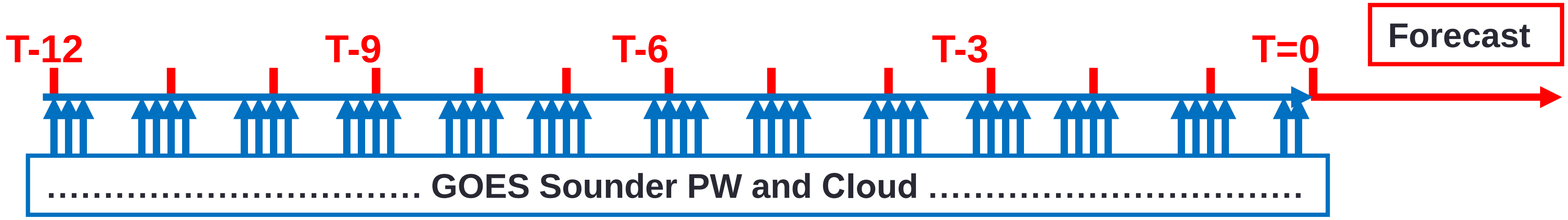
Cloud-top pressure and effective cloud amount are used adjust cloud water mixing ratio in the model. Cloud checks are performed for low, high, and multi-layer clouds.

| Background | GOES | Operation |
|---|---|---|
| Clear | Clear | Do nothing (check RH) |
| Cloudy | Cloudy | Adjust cloud, RH, match top (up to two layers) |
| Cloudy | Clear | Clear cloud, adjust RH |
| Clear | Cloudy | Build new cloud, adjust RH |

Water Vapor Adjustments using GOES 3-Layer Precipitable Water Retrievals (Li).

1) Mean background mixing ratio profile is computed.
2) Perturbations are removed.
3) Mean profile is adjusted to match GOES 3-layer PW using 1D var (strong constraint).
4) Perturbations are added to adjusted profile.
5) RH profile checked for "clearness".

A 12-hour spin-up forecast is used to initialize water vapor and clouds.




Slide credit: Robert Aune, NOAA/NESDIS

# Assimilating 3-Layer Precipitable Water from GOES

**CRAS water vapor adjustments using GOES 3-layer precipitable water retrievals are performed for clear fields-of-view only. This slide describes the procedure.**

$r_M$ = GOES total precipitable water

$r_B$ = Background total precipitable water

$w(\sigma)_B$ = background mixing ratio

$w'(\sigma)_B$ = background mixing ratio perturbation

$w_0$ = surface mixing ratio

$w_S(T)$ = saturation mixing ratio

$w(\sigma)_F$ = final mixing ratio

Let,

$$\bar{r}_M = \frac{1}{n}\sum_{n} r_M \,, \quad \text{n = number of GOES obs in grid cell}$$

Precipitable water is defined as: $r = \frac{p_0}{g}\int_\sigma w(\sigma)d\sigma$

Define a mean mixing ratio profile: $\hat{w}(\sigma) = w_0\sigma^{\lambda} - w'_B(\sigma)$ such that

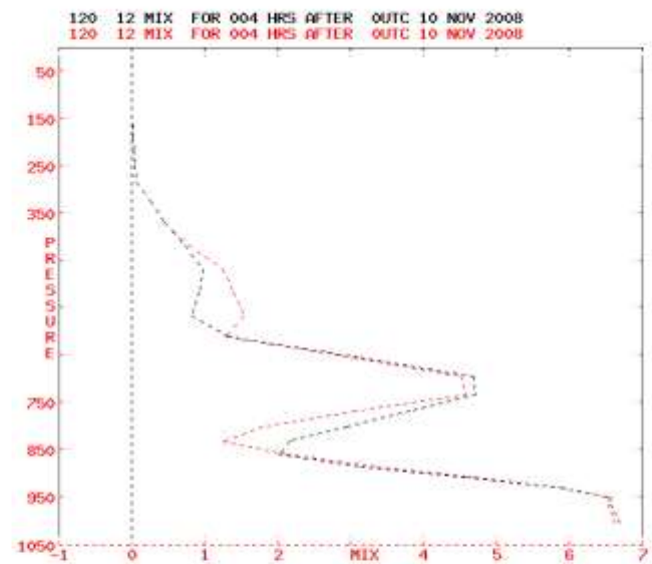
$$\frac{p_0}{g}\int_\sigma w'_B(\sigma)d\sigma \quad \text{is a minimum and } 1.0 < \lambda < 3.5 \quad \text{following Smith, 1966.}$$

Solve for $\lambda = \lambda'$ such that:

$$\bar{r}_M = \frac{p_0}{g}\int_\sigma \hat{w}_0\sigma^{\lambda'} + w'_B(\sigma)d\sigma \text{ with: } [\hat{w}_0\sigma^{\lambda'} + w'_B(\sigma)] < w_S(T)$$

The final adjusted mixing ratio is:

$$w_F(\sigma) = \hat{w}_0\sigma^{\lambda'} + w'_B(\sigma)$$




Mixing ratio profile before (red) and after (black) assimilating total precipitable water from the GOES sounder

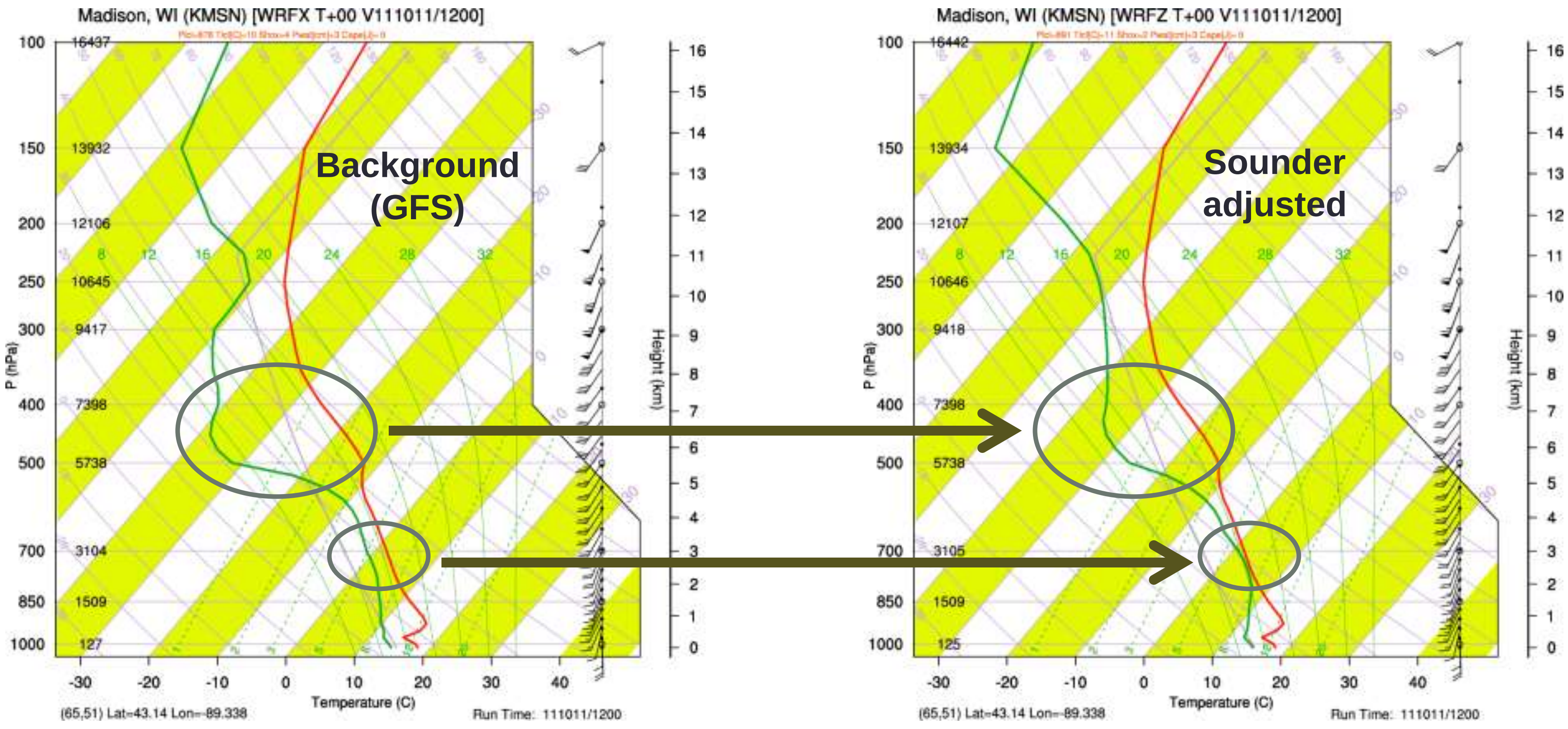
* Smith, W.L., 1966: Note on the relationship between total precipitable water and surface dew point. J. Appl. Meteor., 5, 726-727.

Slide credit: Robert Aune, NOAA/NESDIS

# GOES-13 Sounder Moisture Correction

## Madison, WI; 11 October 2011, 12 UTC

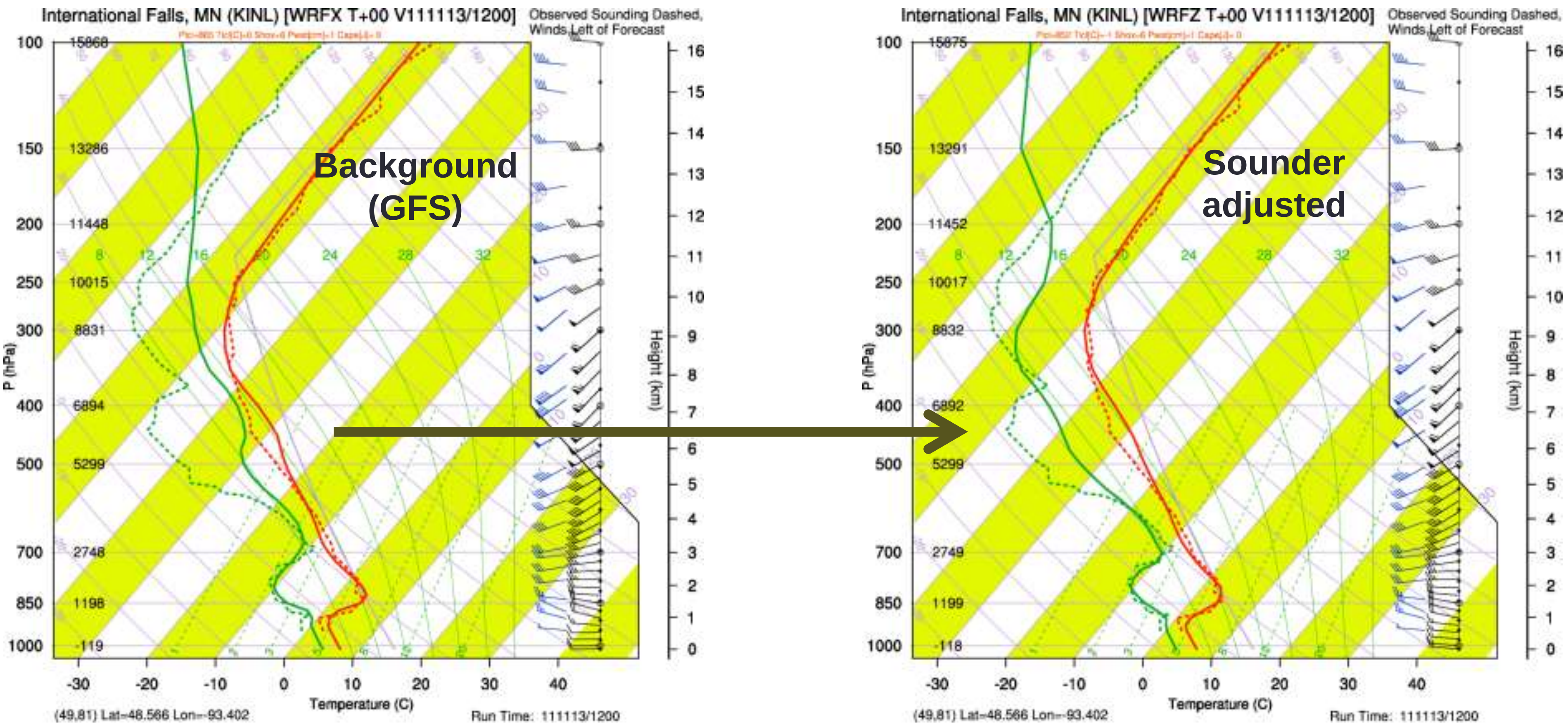
This example shows how moisture is added to the background analysis ahead of approaching precipitation while the distribution is maintained.



# GOES-13 Sounder Moisture Correction

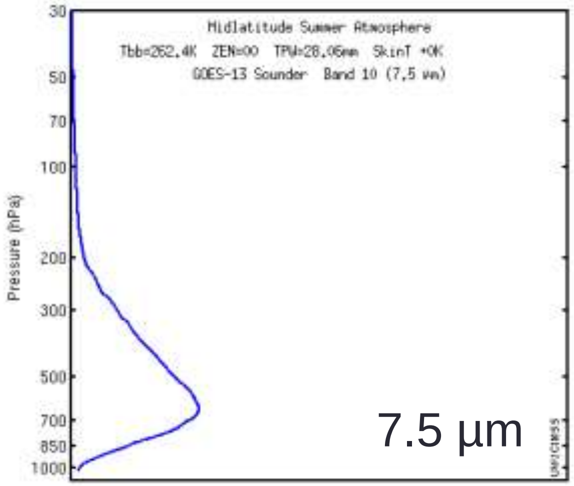
## International Falls, MN; 13 November 2011, 12 UTC

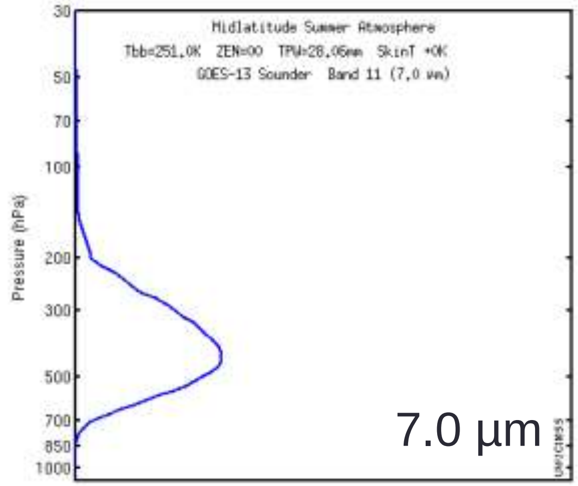
This example shows the improvement to the background (left) by the GOES Sounder retrieval (right), compared to a radiosonde (dashed).

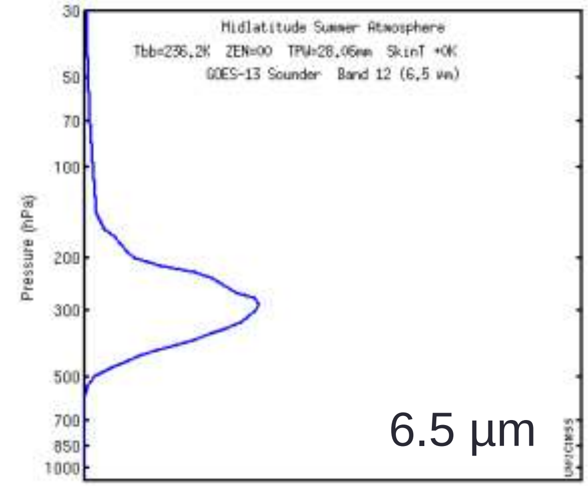


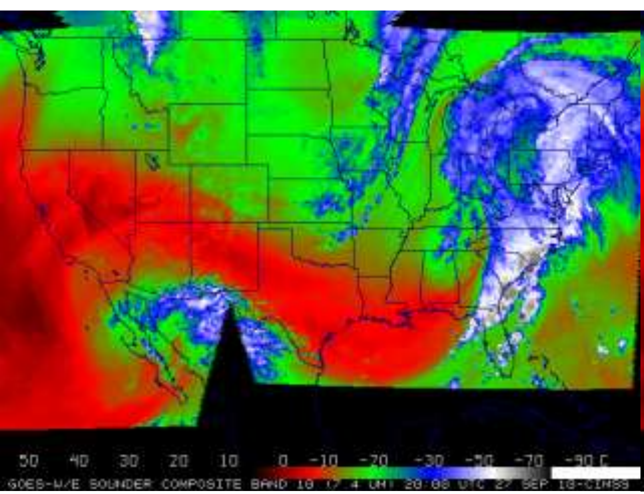
# Current GOES-13 Sounder Weighting Functions

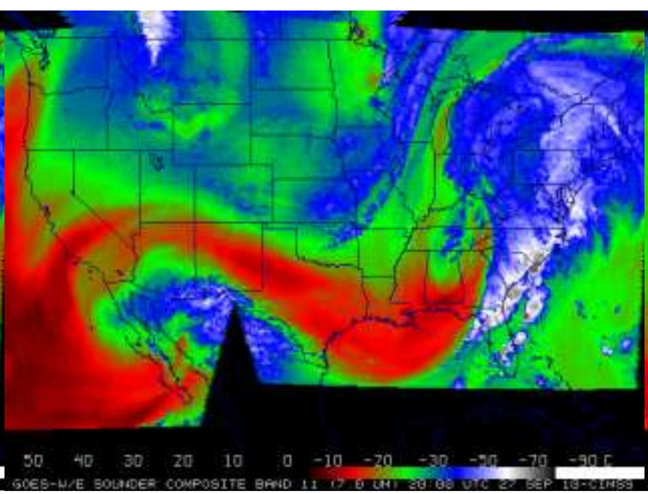
Geostationary satellites can provide information of mid-level water vapor.

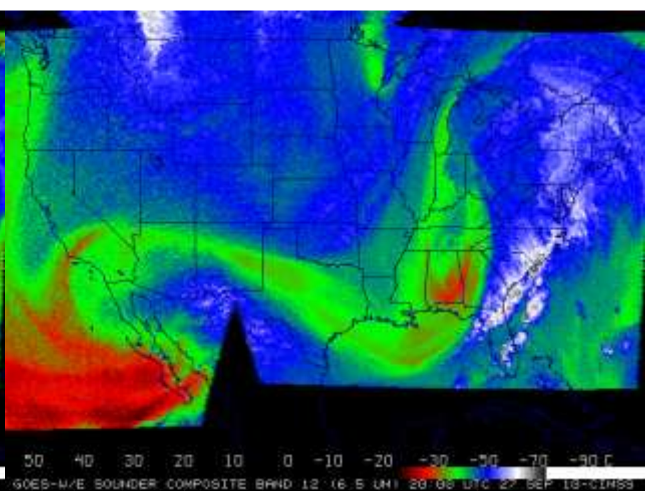


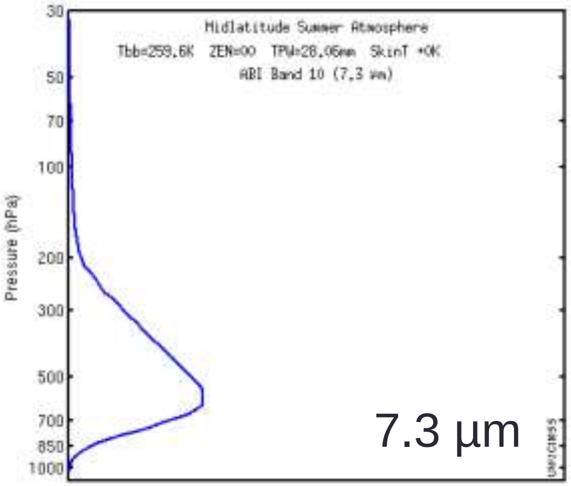


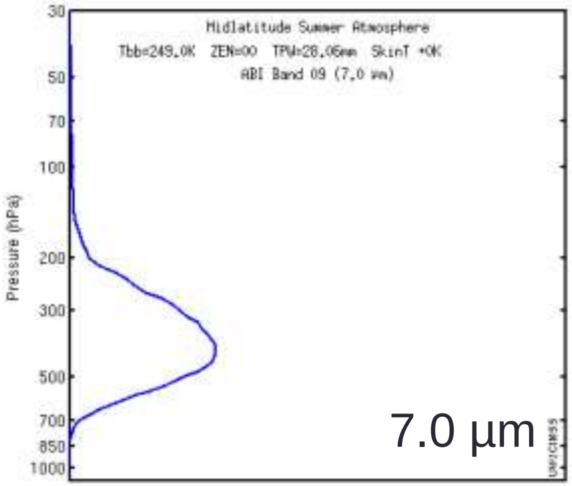


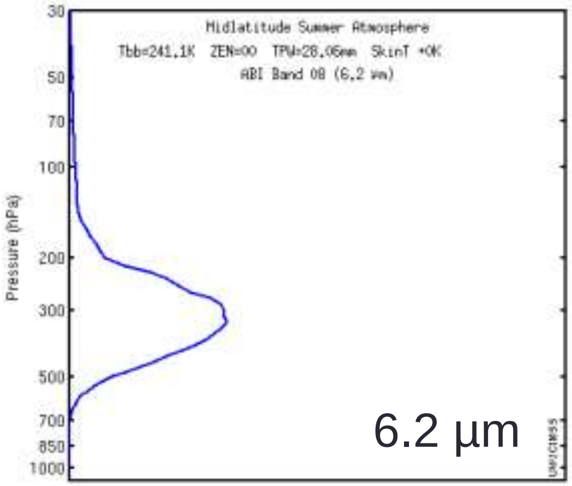
**Plots courtesy of Mat Gunshor, CIMSS**

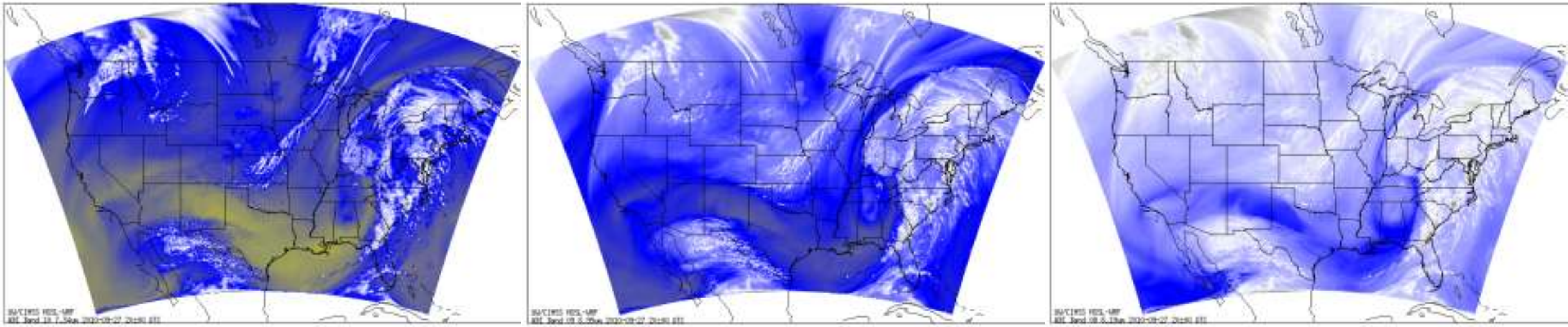
# GOES-R ABI Weighting Functions

This capability will continue in the GOES-R era, but still no surface moisture resolution.



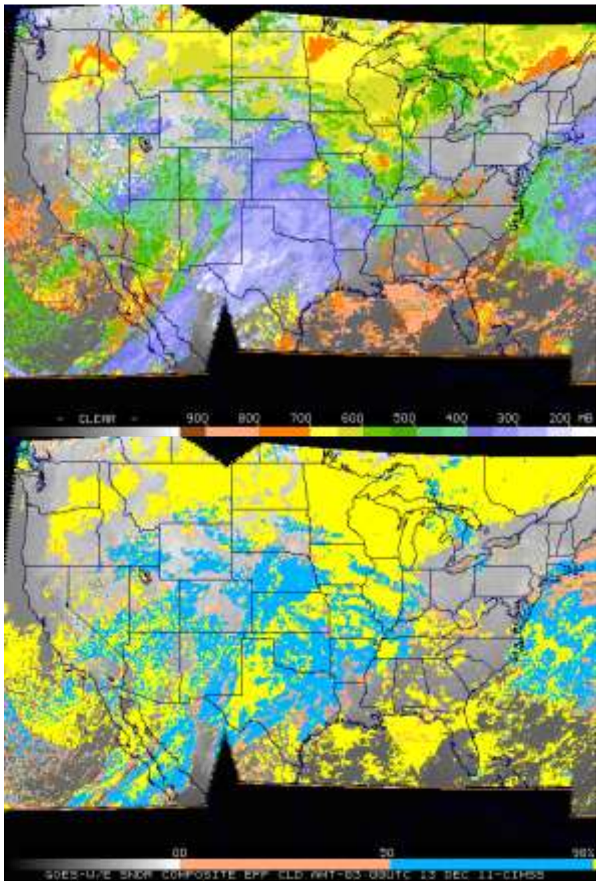



Simulated imagery

**Images courtesy of Justin Sieglaff, CIMSS**

# Assimilating Clouds from GOES

Retrievals of cloud-top pressure (CTP) and effective cloud amount (ECA) from GOES are used to adjust cloud water mixing ratio in the CRAS spin-up forecast. (Similar to Bayler et.al., 2000, Mon. Wea. Rev. 128, 3911-3920.)




## Cloud Modification Options

| Background | GOES | Operation |
|---|---|---|
| Clear | Clear | Check RH |
| Cloudy | Clear | Clear cloud, adjust RH |
| Clear/Cloudy | Cloudy | Build cloud, adjust RH, match top |

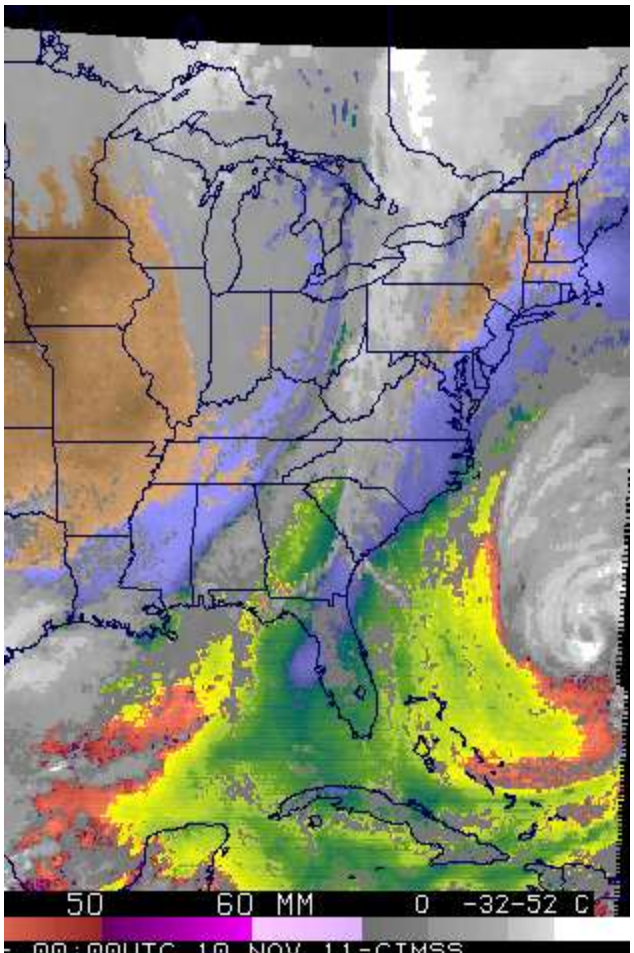
## Procedure

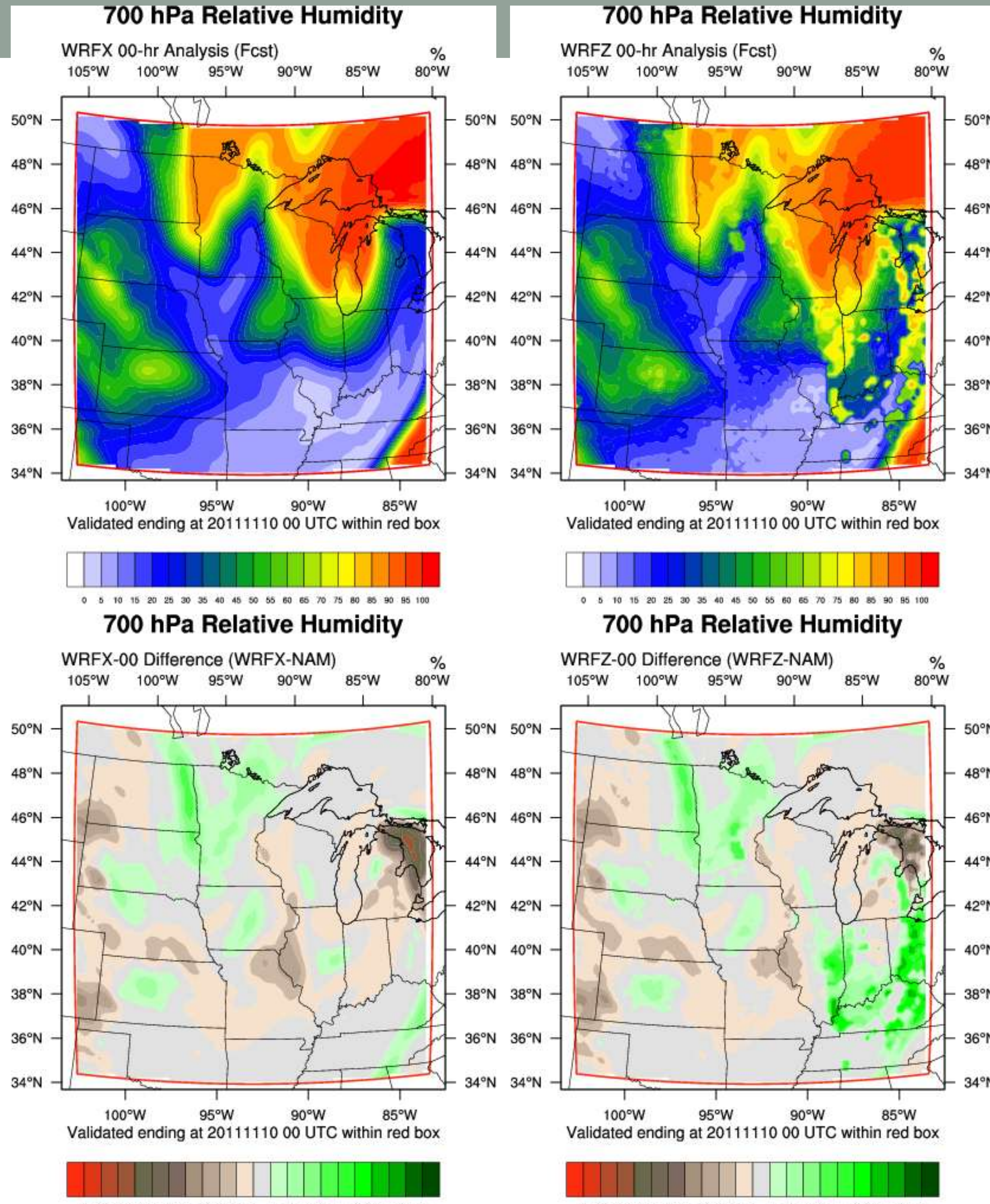
Given:
$CTP_M(n)$ = GOES cloud-top pressure vector at grid cell, n = count
$ECA_M(n)$ = GOES effective cloud amount vector at grid cell, n = count
$q_c(k)$ = cloud mixing ratio at model level k
$q^*_c(T)$ = Max cloud mixing ratio (Auto-conversion)
$n(k)$ = # GOES retrievals per model grid cell

1. Bin 5km $CTP_M(n)$ onto a model grid cell
2. Sort grid cell $CTP_M$ and $ECA_M$ onto model pressure levels
3. If $RH(k) > RH_{evap}(k) - 20\%$, proceed
4. Clear cloud above $CTP_M$ , $q_C(k)$ | ($CTP_M$ , top) = 0
5. For layers above 600 hPa: $q_c(k) = [\ \Sigma_n\ ECA_M(k)\ ]\ /\ n(k) \times q^*_c(T)$
6. For layers below 600 hPa: $q_c(k) = n_{cld}(k)\ /\ n(k) \times q^*_c(T)$

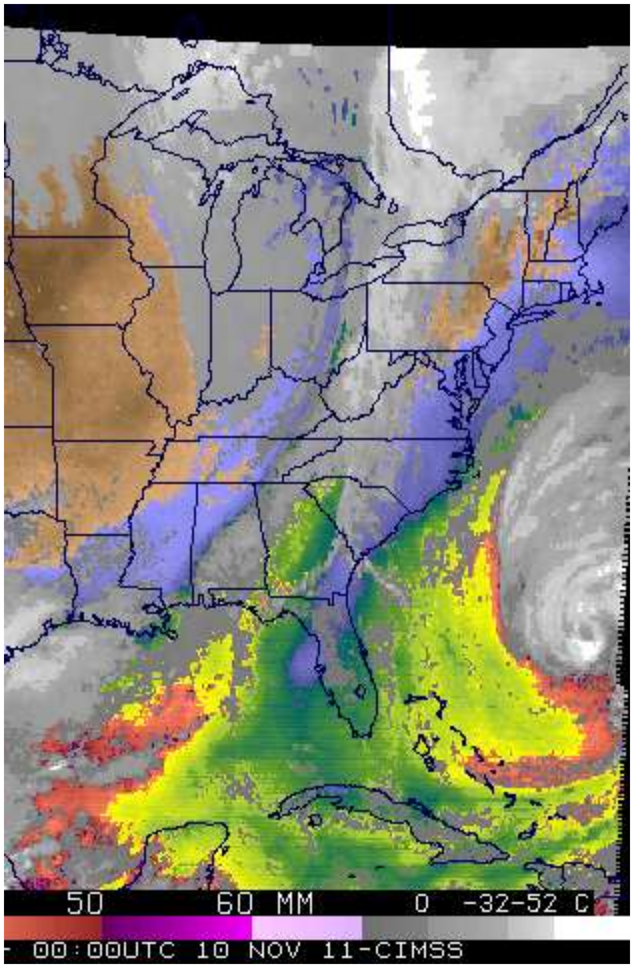
Slide credit: Robert Aune, NOAA/NESDIS

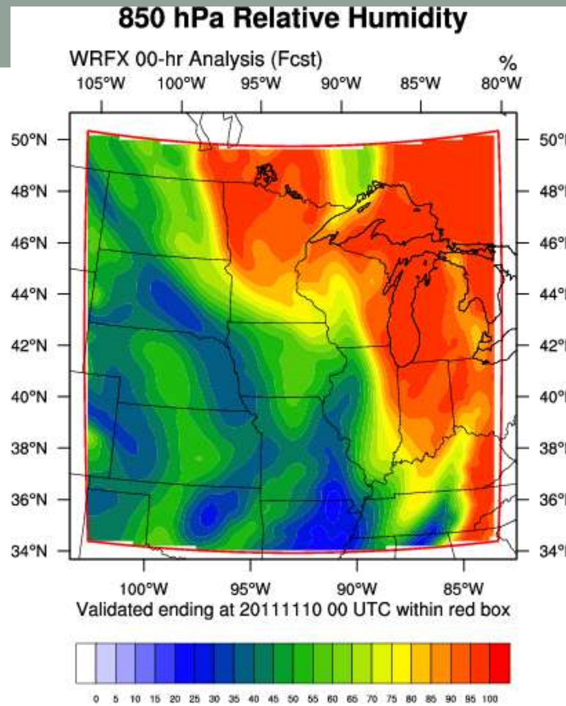
# 700 hPa Relative Humidity Adjustments from Cloud Assimilation

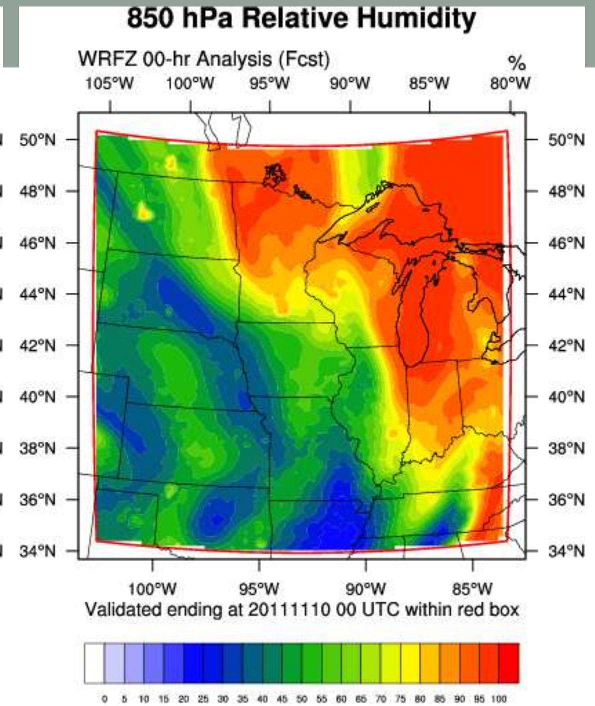


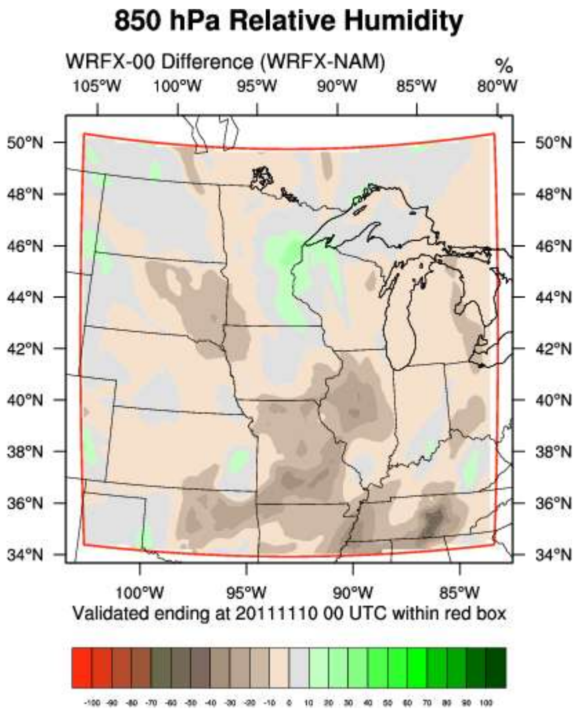



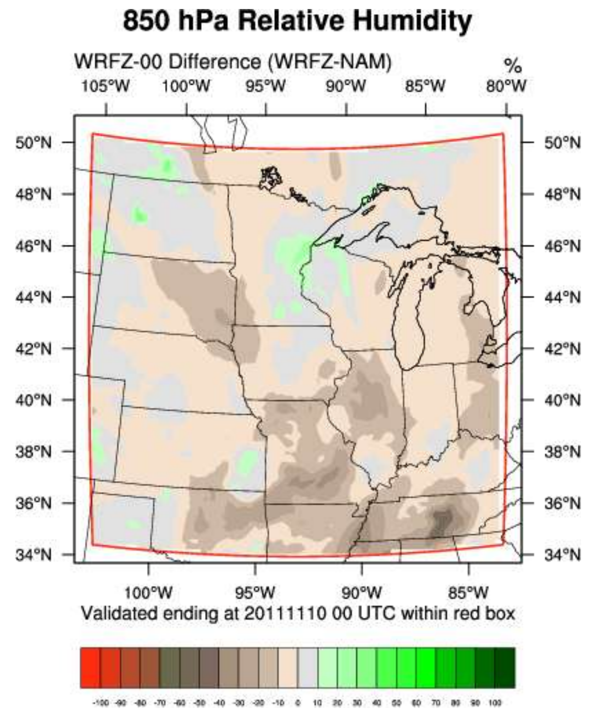
# 850 hPa Relative Humidity Adjustments from Cloud Assimilation



# RESPONSE OF KAIN-FRITSCH CONVECTIVE SCHEME TO DIFFERENT MOISTURE CONCENTRATIONS

Part A

# Kain-Fritsch (KF) Convective Scheme

- The WRF simulations in this experiment all utilize the Kain-Fritsch convective parameterization, which
  - is a mass flux scheme
  - requires an adjusted response based on the grid scaling
- The closure for the KF scheme is convective available potential energy (CAPE).
  - This is an important source for
    - latent heat release
    - accumulated convective precipitation

# Kain-Fritsch (KF) Convective Scheme

- It has been shown in Kain and Fritsch (1990) that the normalized vertical mass flux varies significantly
  - by a factor of two in the upper troposphere for changes of relative humidity between 50% and 90%.
- This sensitivity is critical because, for cold temperatures, the amount of water vapor mixing ratio required to adjust the relative humidity is not particularly substantial.

# Experiment I Design

**Objective**: Understand NWP response to different moisture concentrations.

**Approximate change in mixing ratio from GFS initial conditions**

## Six simulations:

| Simulation | Approximate change in mixing ratio from GFS initial conditions |
|---|---|
| GFS Initial Conditions | |
| CRAS Initial Conditions | |
| GFS Initial Conditions with 90% of Original RH | $\Delta w_{EA}$ = 0.23 g/kg |
| GFS Initial Conditions with 90% of Original Relative Humidity at and below 800 hPa | $\Delta w_{LYR}$ = 1.25 g/kg |
| GFS Initial Conditions with 90% of Original Relative Humidity between 400 and 750 hPa | $\Delta w_{LYR}$ = 0.30 g/kg |
| GFS Initial Conditions with 90% of Original Relative Humidity between 100 and 350 hPa | $\Delta w_{LYR}$ = 0.01 g/kg |

Each simulation shared the same:

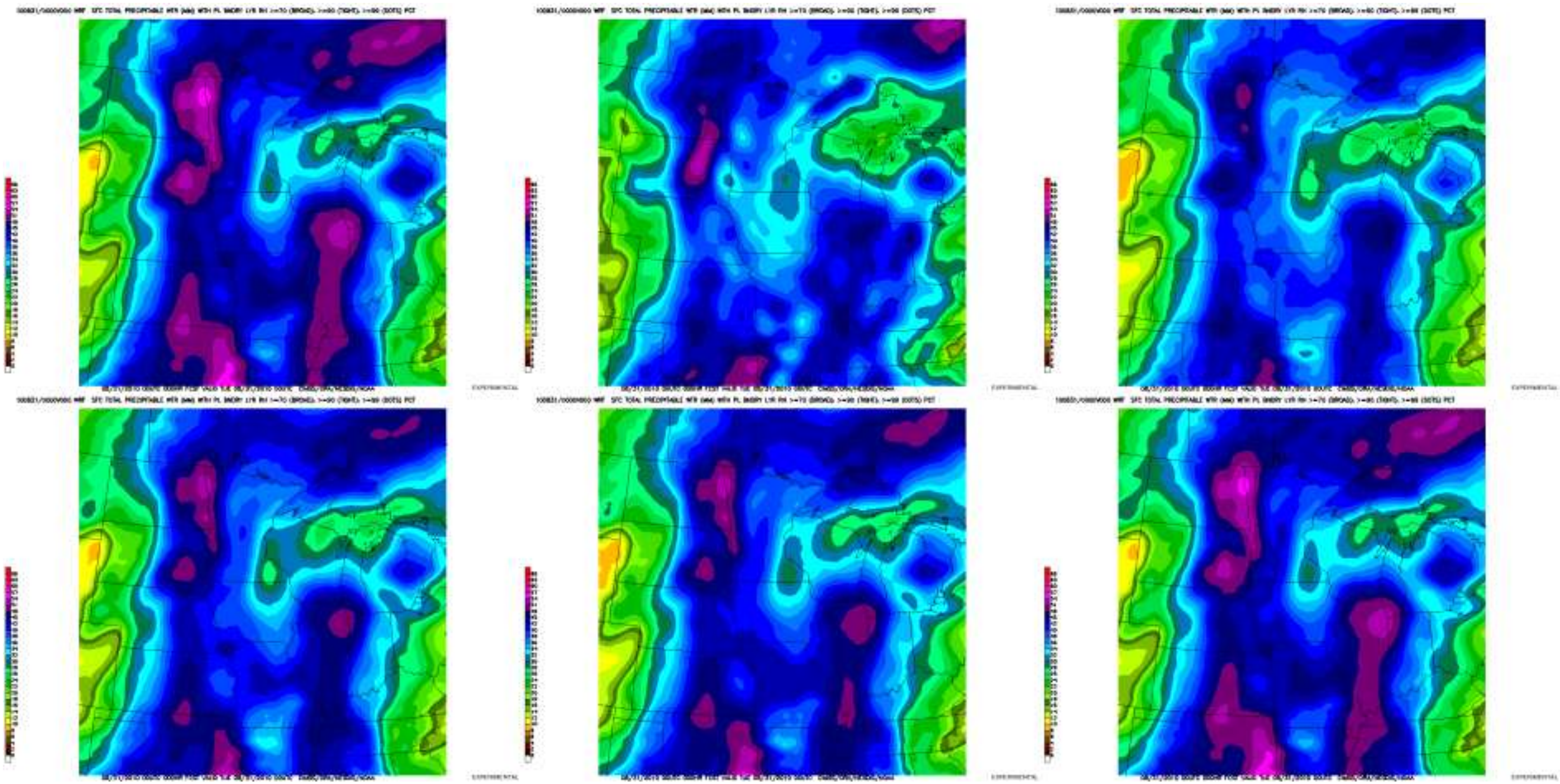
- Adaptive time step
- 20 km spacing on 100 x 100 square grid consisting of 45 vertical levels
- 100 hPa top of model
- Model start at 31 August 2010 at 00:00 UTC
- 36-hour length with a boundary update every three hours

| | |
|---|---|
| **Dynamics** | Non-Hydrostatic |
| **Cumulus Scheme** | Kain-Fritsch |
| **Microphysics Scheme** | WSM Single-Moment 5-Class |
| **PBL Scheme** | Yonsei University |
| **Land Surface Scheme** | 5-Layer Thermal Diffusion LSM |
| **Surface Layer Physics** | Monin-Obukhov with heat and moisture surface fluxes |
| **Long Wave Radiation** | RRTM |
| **Short Wave Radiation** | Dudhia Scheme |
| **Time-Integration Scheme** | Runge-Kutta 3$^{rd}$ Order |
| **Damping** | Rayleigh |

# Comparison of Total Precipitable Water (Entire Atmosphere)

Initialized: 31 August 2010, 00 UTC
Interval: 3 hourly    Duration: 36 hours

GFS Initial Conditions | CRAS Initial Conditions | GFS Initial Conditions with 90% of Original RH

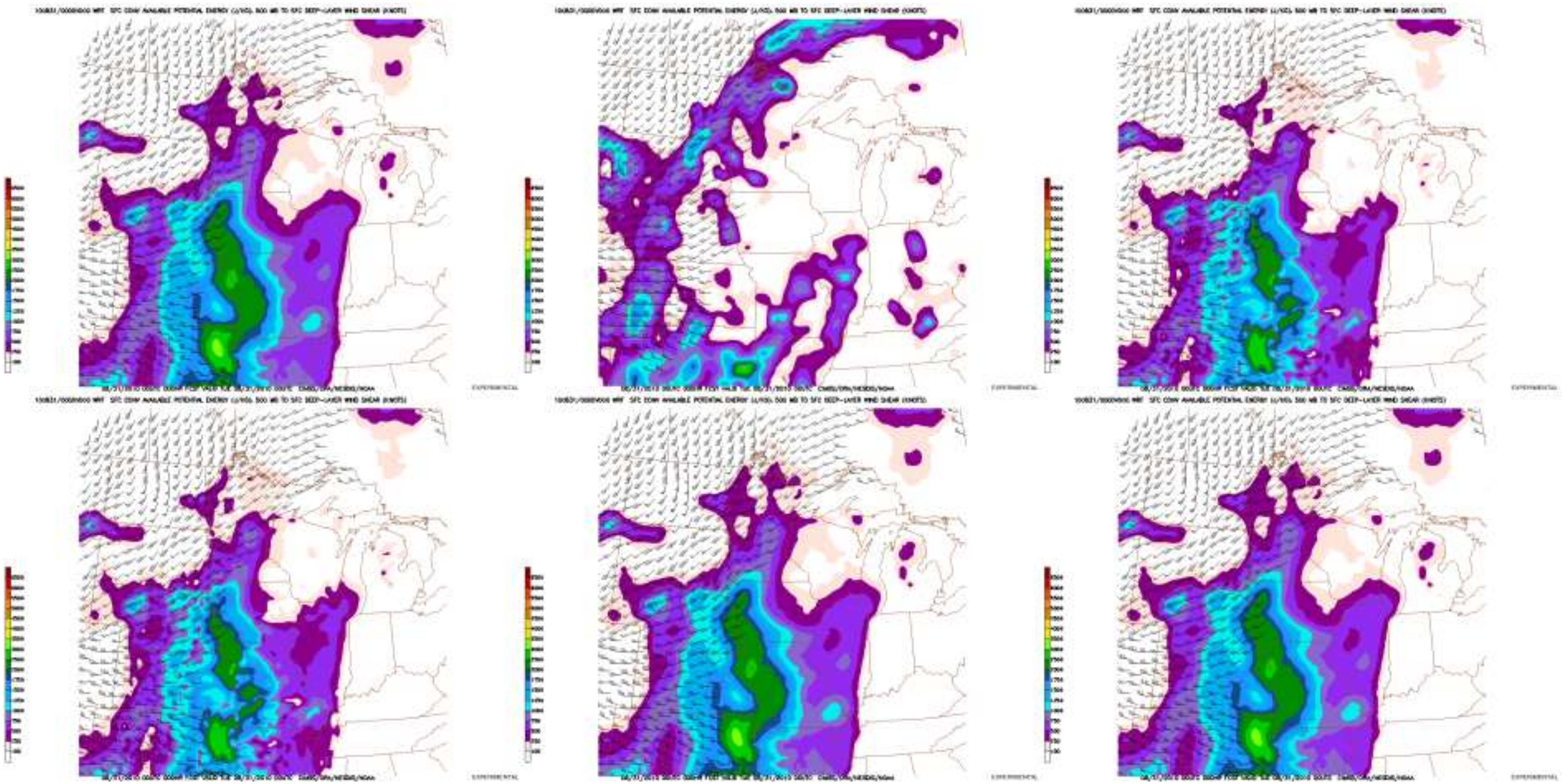


GFS Initial Conditions with 90% of Original Relative Humidity at and below 800 hPa | GFS Initial Conditions with 90% of Original Relative Humidity between 400 and 750 hPa | GFS Initial Conditions with 90% of Original Relative Humidity between 100 and 350 hPa

# Comparison of SBCAPE, Deep-Layer Wind Shear

Initialized: 31 August 2010, 00 UTC
Interval: 3 hourly Duration: 36 hours

GFS Initial Conditions | CRAS Initial Conditions | GFS Initial Conditions with 90% of Original RH

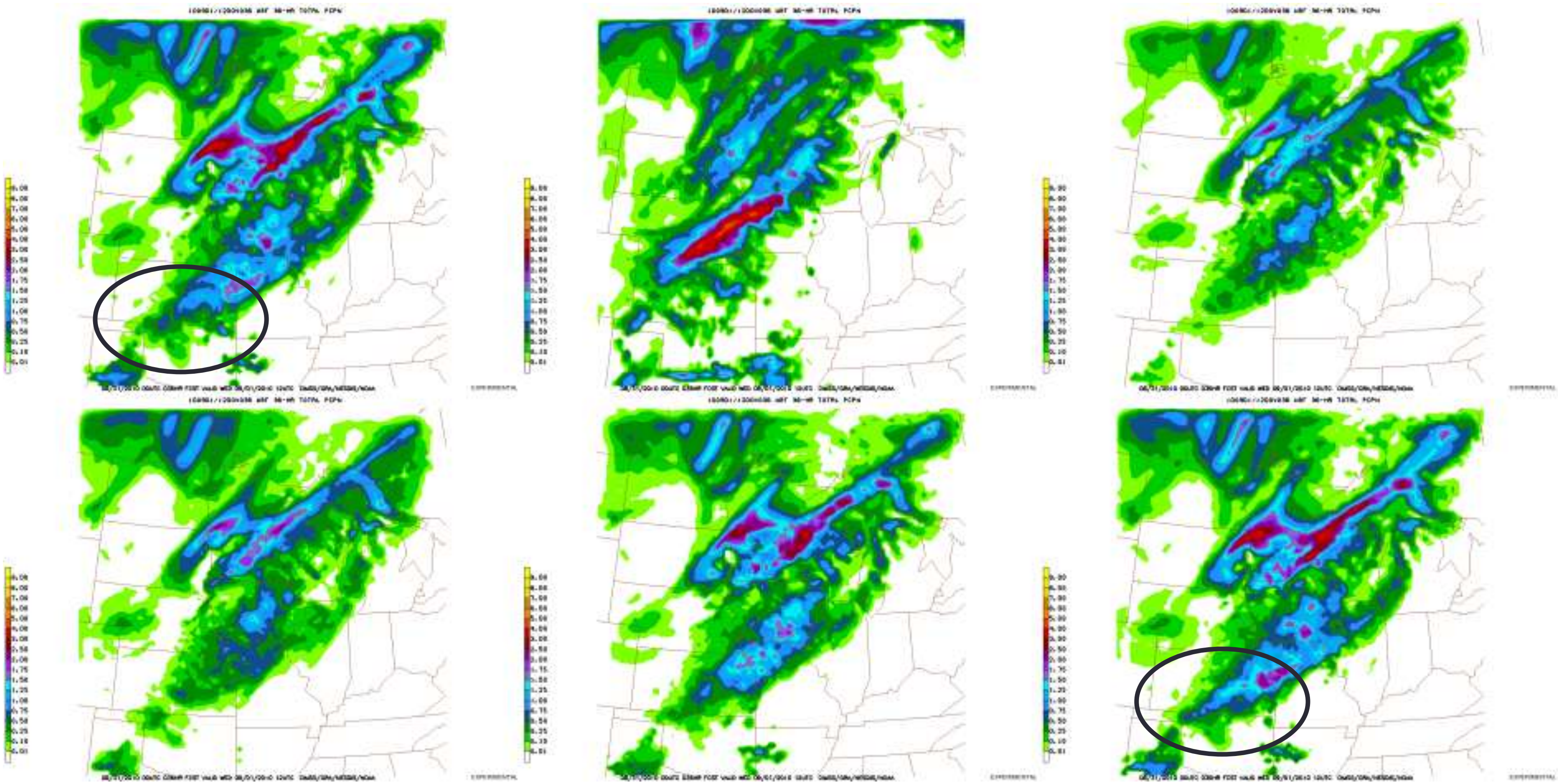


GFS Initial Conditions with 90% of Original Relative Humidity at and below 800 hPa | GFS Initial Conditions with 90% of Original Relative Humidity between 400 and 750 hPa | GFS Initial Conditions with 90% of Original Relative Humidity between 100 and 350 hPa

# Comparison of 36-hour Accumulated Precipitation

Initialized: 31 August 2010, 00 UTC
Forecast valid: 1 September 2010, 12 UTC

GFS Initial Conditions | CRAS Initial Conditions | GFS Initial Conditions with 90% of Original RH



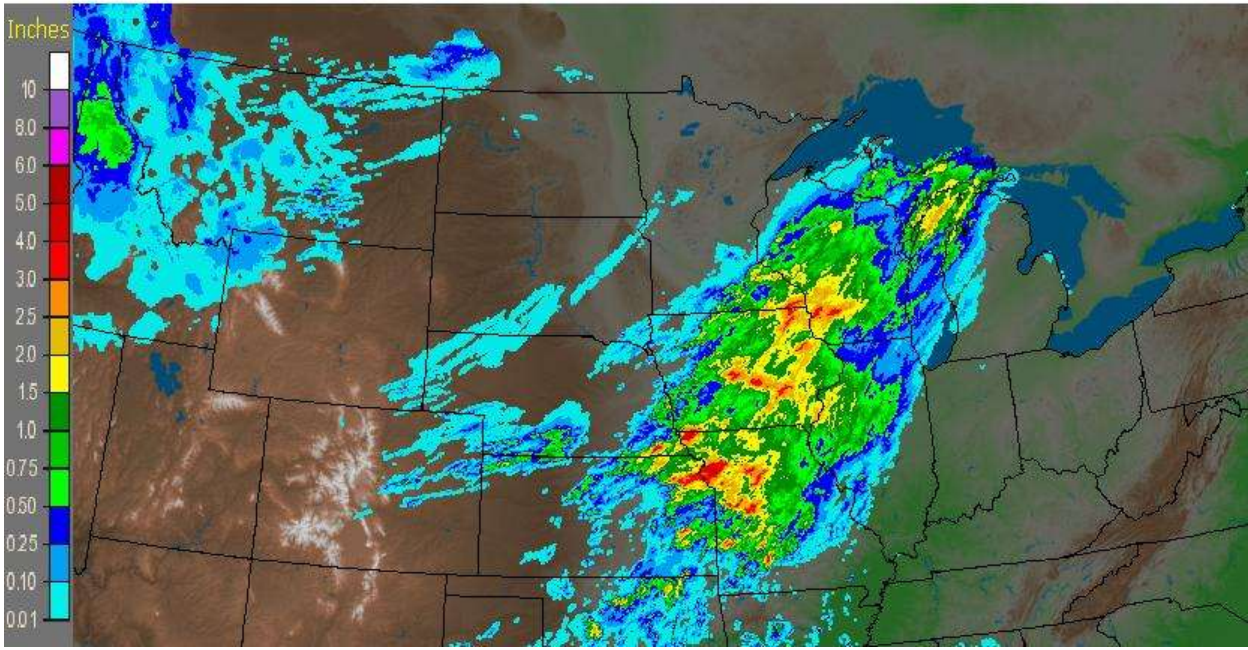
GFS Initial Conditions with 90% of Original Relative Humidity at and below 800 hPa | GFS Initial Conditions with 90% of Original Relative Humidity between 400 and 750 hPa | GFS Initial Conditions with 90% of Original Relative Humidity between 100 and 350 hPa

# Precipitation

- Precipitation output from NWP models is traditionally spatially distributed and lacking in sharp, reliable definition, even in some high resolution models
- Precipitation often falls as the result of convective parameterizations which keep the model numerically stable, or for the wrong reasons (not due to local moisture convergence)

NWS Central Region: 9/1/2010 1-Day Observed Precipitation
Valid at 9/1/2010 1200 UTC- Created 9/3/10 21:38 UTC

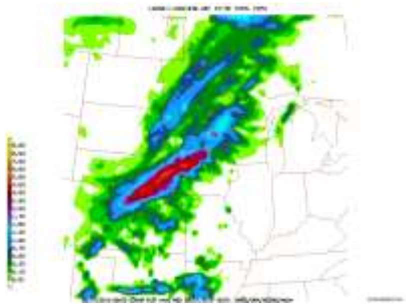
Source: NWS/AHPS




24-hour accum precip prior to 1200 UTC on 1 Sept

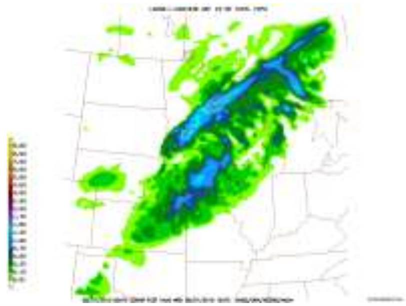
GFS Initial Conditions

24-hour accum precip prior to 1200 UTC on 1 Sept



CRAS Initial Conditions

24-hour accum precip prior to 1200 UTC on 1 Sept



GFS Initial Conditions with 90% of Original RH

# PERFORMANCE OF MOISTURE REPRESENTATION IN CURRENT OPERATIONAL MODELS AND WRF RUNS WITH GOES-13 SOUNDER RETRIEVALS IN ANALYSES

Part B

# Experiment II Design

**Objective**: Quantify NWP response to GOES-13 Sounder-adjusted moisture concentrations.

Three Advanced Research Weather Research and Forecast (WRF-ARW) simulations are run twice daily (00/12Z):

- **WRFX** – Initial conditions and boundary conditions from previous (06/18Z) GFS run
- **WRFY** – Initial conditions and boundary conditions from initial hour CRAS20MKX run
- **WRFZ** – Initial conditions of previous (06/18Z) GFS run modified with GOES-13 Sounder retrievals and GFS boundary conditions

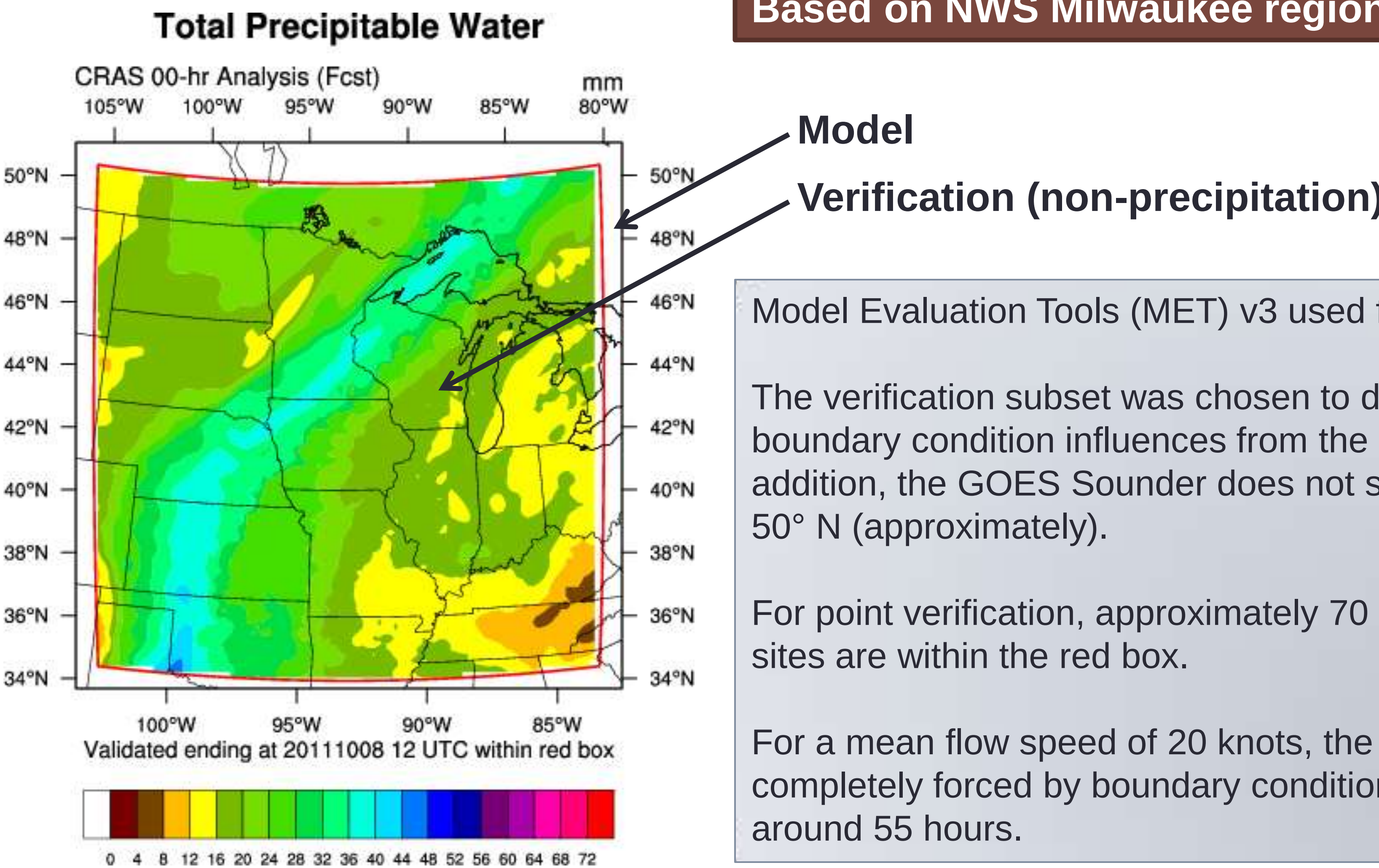
Each 36-hour simulation used:

- an adaptive time step,
- 20 km horizontal spacing on 100 x 100 square grid consisting of 45 vertical levels, with
- 50 hPa at the top of the model.

| | |
|---|---|
| **Dynamics** | Non-Hydrostatic with Gravity Wave Drag |
| **Cumulus Scheme** | Kain-Fritsch |
| **Microphysics Scheme** | WSM Single-Moment 5-Class |
| **PBL Scheme** | Yonsei University |
| **Land Surface Scheme** | Noah 4-Layer LSM |
| **Surface Layer Physics** | Monin-Obukhov with heat and moisture surface fluxes |
| **Long Wave Radiation** | RRTM |
| **Short Wave Radiation** | Dudhia Scheme |
| **Time-Integration Scheme** | Runge-Kutta 3$^{rd}$ Order |
| **Damping** | Rayleigh |

# Experiment Domain

## Model and Verification




**Based on NWS Milwaukee regional domain**

Model Evaluation Tools (MET) v3 used for statistics.

The verification subset was chosen to discount any boundary condition influences from the results. In addition, the GOES Sounder does not scan above 50° N (approximately).

For point verification, approximately 70 GPS-TPW sites are within the red box.

For a mean flow speed of 20 knots, the domain is completely forced by boundary conditions after around 55 hours.

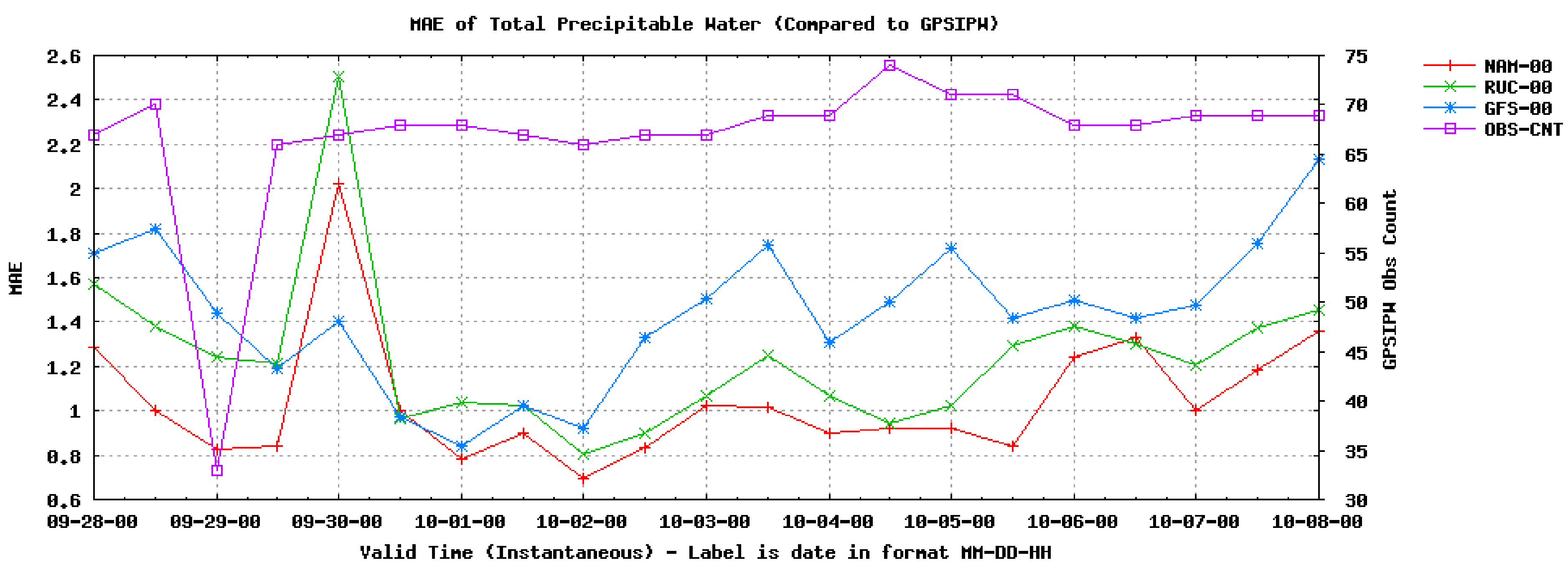
# Total PW Mean Absolute Error

## Analyses verified against GPS-TPW

| Model | Mean MAE |
|---|---|
| NAM | 1.04 |
| RUC | 1.24 |
| GFS | 1.43 |

The NAM and RUC assimilate GPS-TPW measurements, while the GFS does not.

Verified output every 12 hours between September 28, 2011, 00 UTC, and October 8, 2011, 00 UTC, for a total sample of 21 times



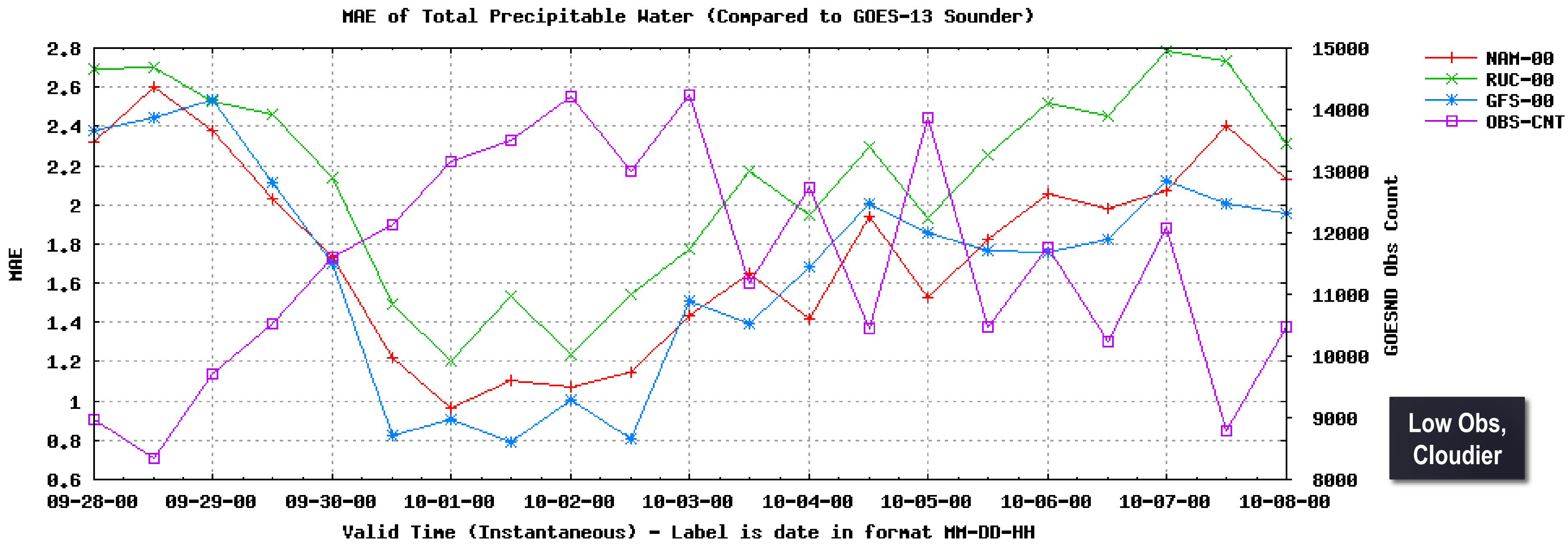
# Total PW Mean Absolute Error

## Analyses verified against GOES-13 Sounder (Ma retrievals)

| Model | Mean MAE |
|---|---|
| GFS | 1.69 |
| NAM | 1.76 |
| RUC | 2.13 |

The GFS is used as the first guess for the GOES-13 Sounder retrievals, but not the GFS run it is verified against.

Verified output every 12 hours between September 28, 2011, 00 UTC, and October 8, 2011, 00 UTC, for a total sample of 21 times



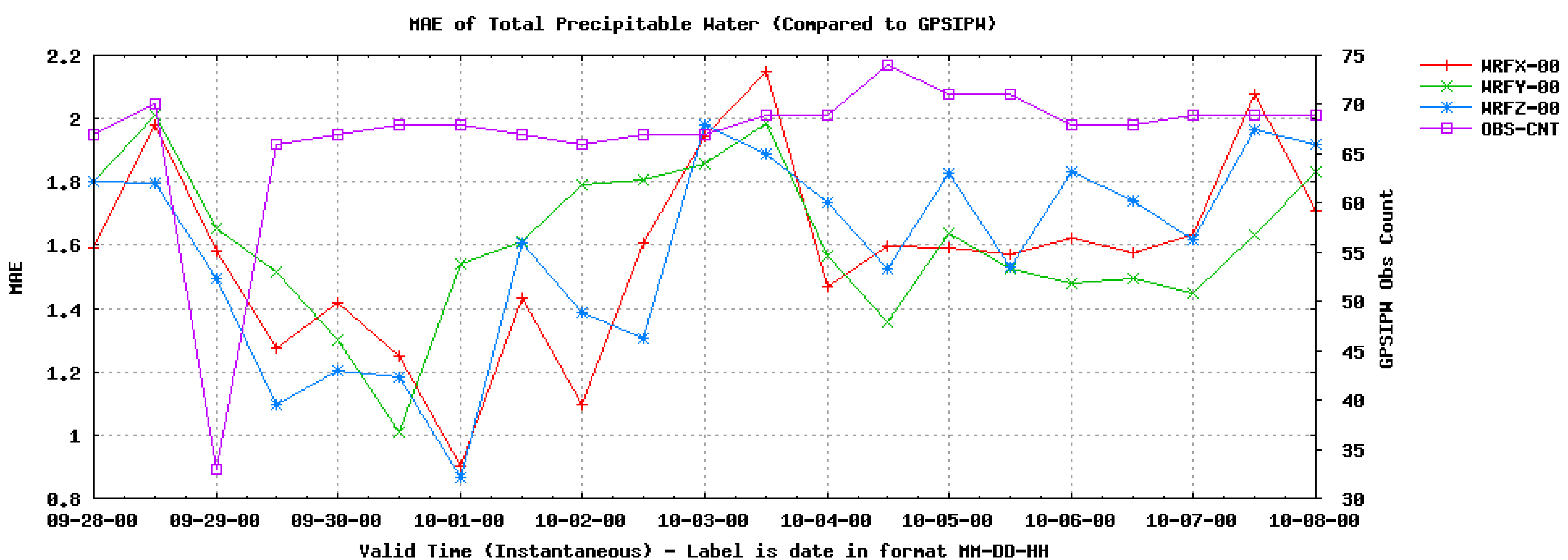
# Total PW Mean Absolute Error

## Analyses verified against GPS-TPW

| Model | Mean MAE |
|---|---|
| WRFX | 1.58 |
| WRFZ | 1.59 |
| WRFY | 1.61 |

**Inconclusive results are due to the poor spatial heterogeneity of GPS sites across the domain compared to the magnitude of correction.**

Verified output every 12 hours between September 28, 2011, 00 UTC, and October 8, 2011, 00 UTC, for a total sample of 21 times



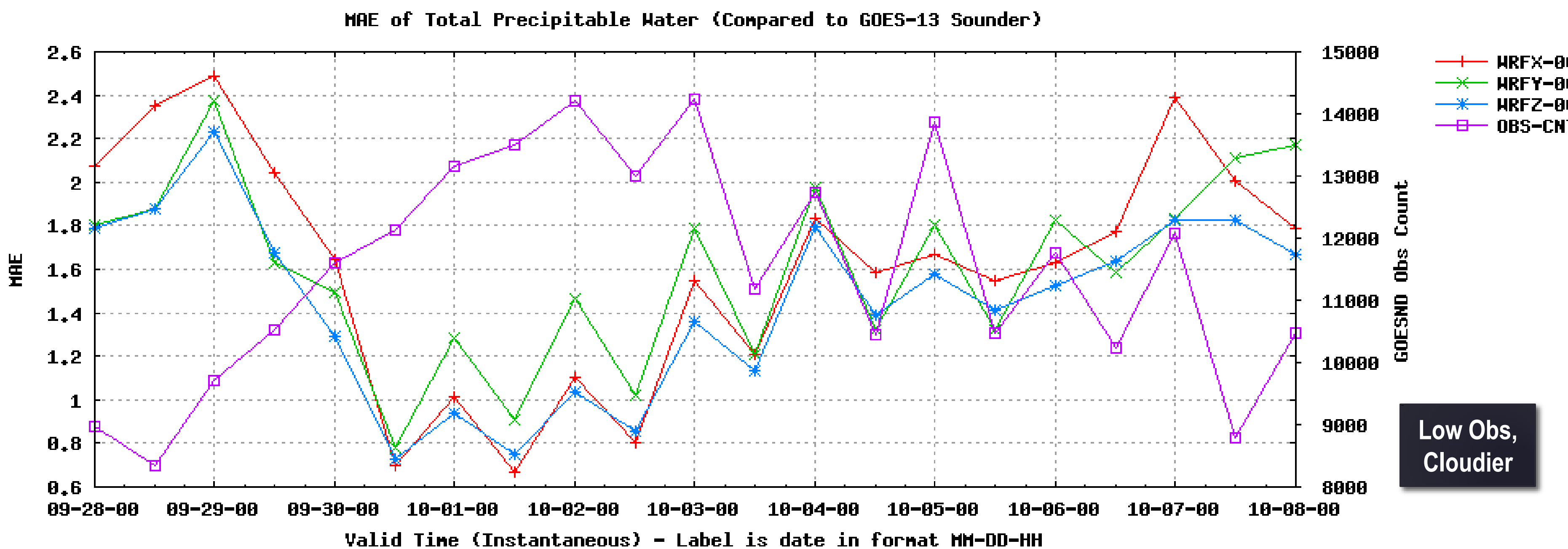
# Total PW Mean Absolute Error

## Analyses verified against GOES-13 Sounder (Ma retrievals)

| Model | Mean MAE |
|---|---|
| WRFZ | 1.44 |
| WRFY | 1.59 |
| WRFX | 1.61 |

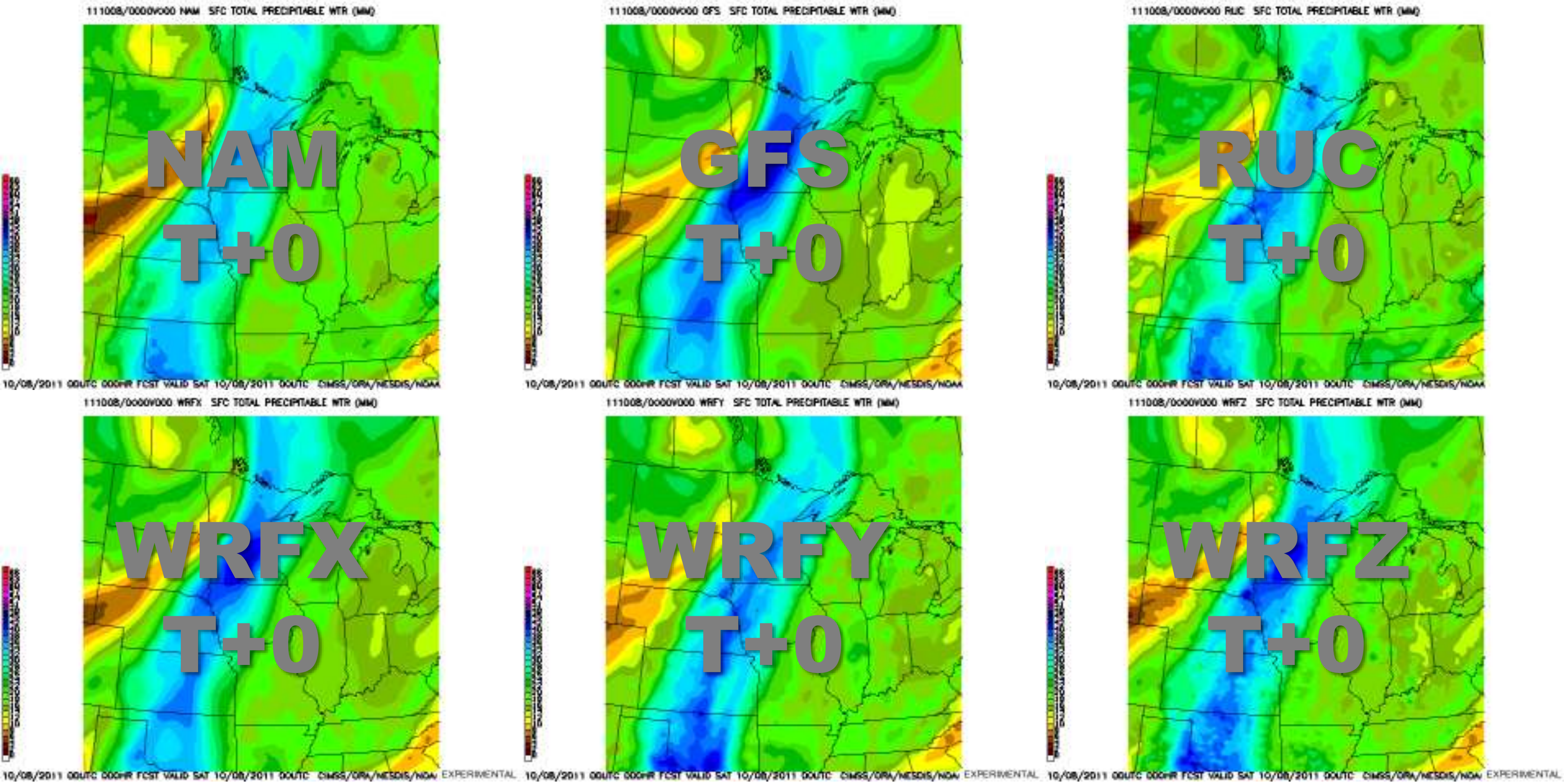
The WRFY and WRFZ contain Sounder retrievals which improve the MAE in clear fields of view.

Verified output every 12 hours between September 28, 2011, 00 UTC, and October 8, 2011, 00 UTC, for a total sample of 21 times



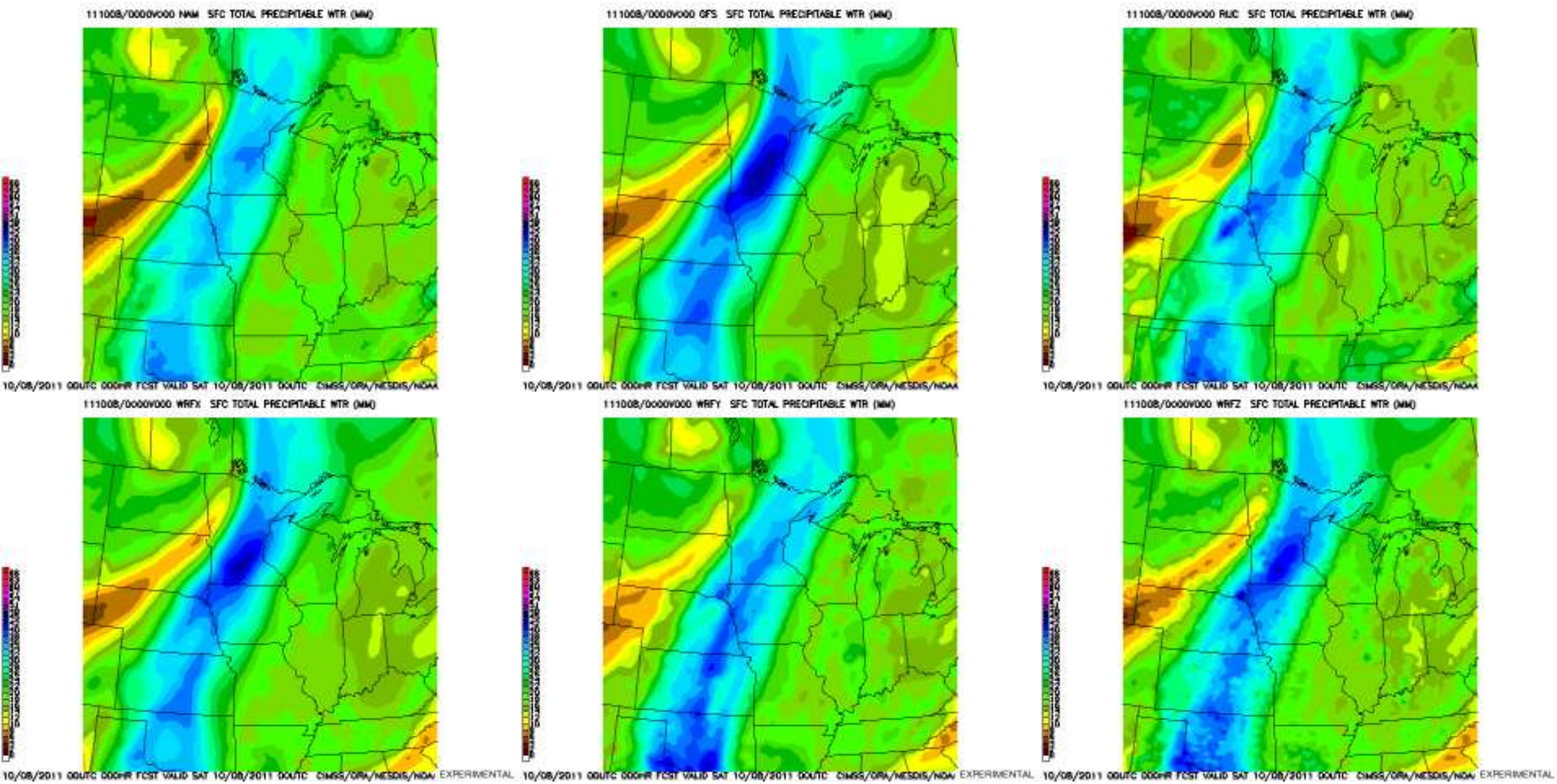
# Total Precipitable Water

## Analyses for 8 October 2011, 00 UTC



# Total Precipitable Water

## Analyses for 8 October 2011, 00 UTC



# Total PW Mean Absolute Error

## Forecasts verified against GPS-TPW

### 12-hour

| Model | Mean MAE |
|---|---|
| WRFZ | 1.72 ☑ |
| WRFX | 1.77 |
| WRFY | 1.81 |

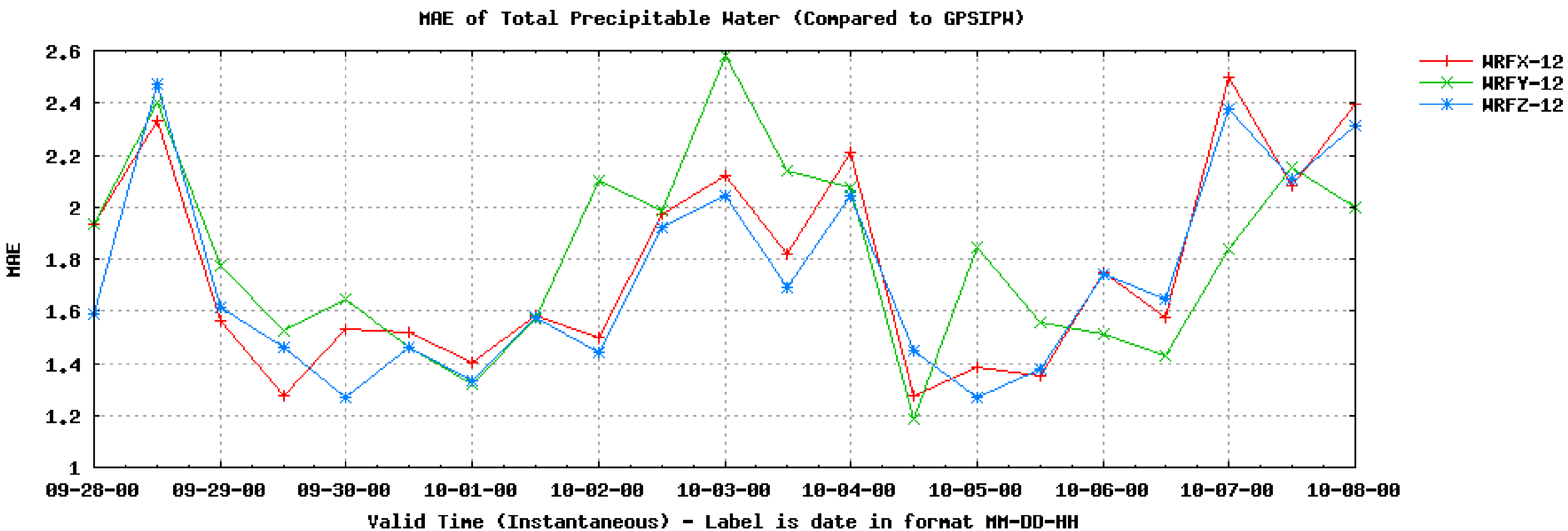
**Verified output every 12 hours between September 28, 2011, 00 UTC, and October 8, 2011, 00 UTC, for a total sample of 21 times**

### 24-hour

| Model | Mean MAE |
|---|---|
| WRFZ | 2.01 ☑ |
| WRFX | 2.01 |
| WRFY | 2.23 |

### 36-hour

| Model | Mean MAE |
|---|---|
| WRFX | 2.30 ☑ |
| WRFZ | 2.31 |
| WRFY | 2.79 |



# Total PW Mean Absolute Error

## Forecasts verified against NAM analysis

**12-hour**

| Model | Mean MAE |
|---|---|
| WRFZ | 1.93 ☑ |
| WRFX | 1.97 |
| WRFY | 2.09 |

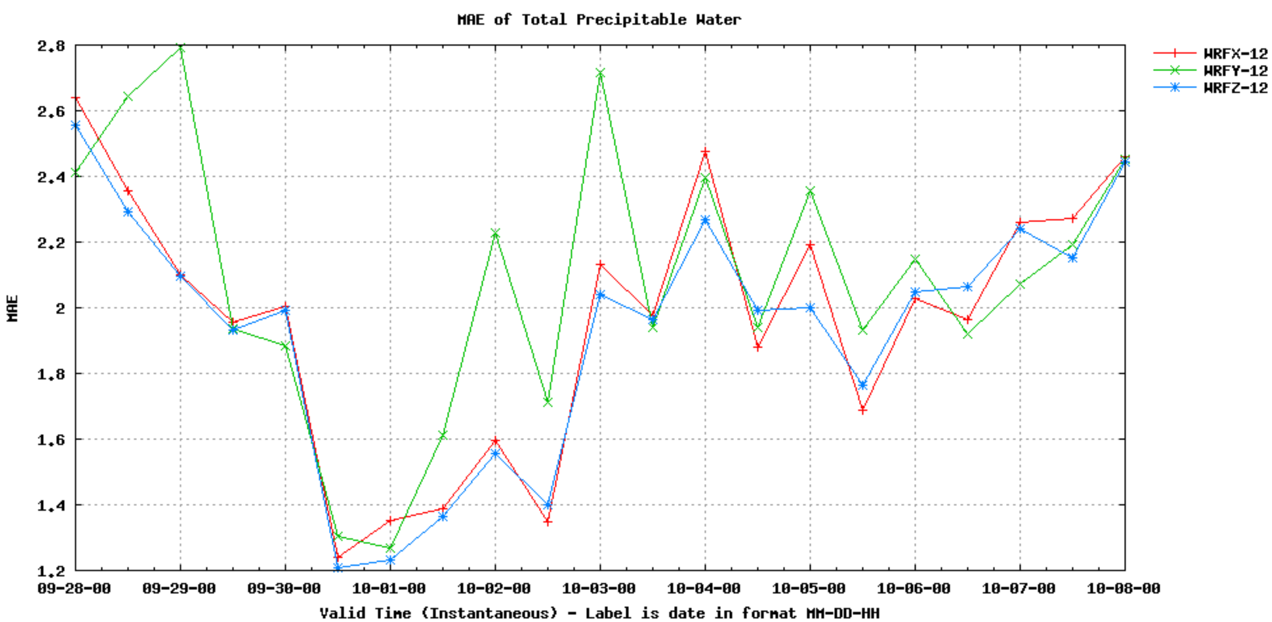
**Verified output every 12 hours between September 28, 2011, 00 UTC, and October 8, 2011, 00 UTC, for a total sample of 21 times**

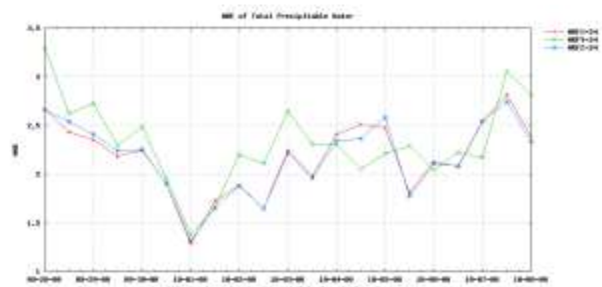
**24-hour**

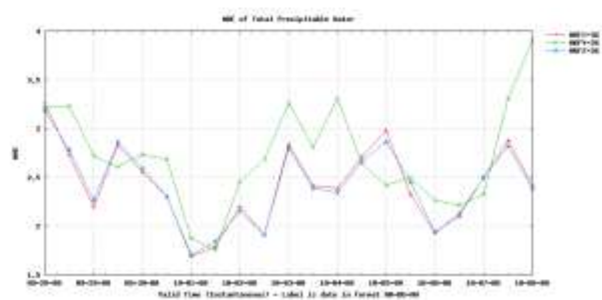
| Model | Mean MAE |
|---|---|
| WRFZ | 2.17 ☑ |
| WRFX | 2.17 |
| WRFY | 2.32 |

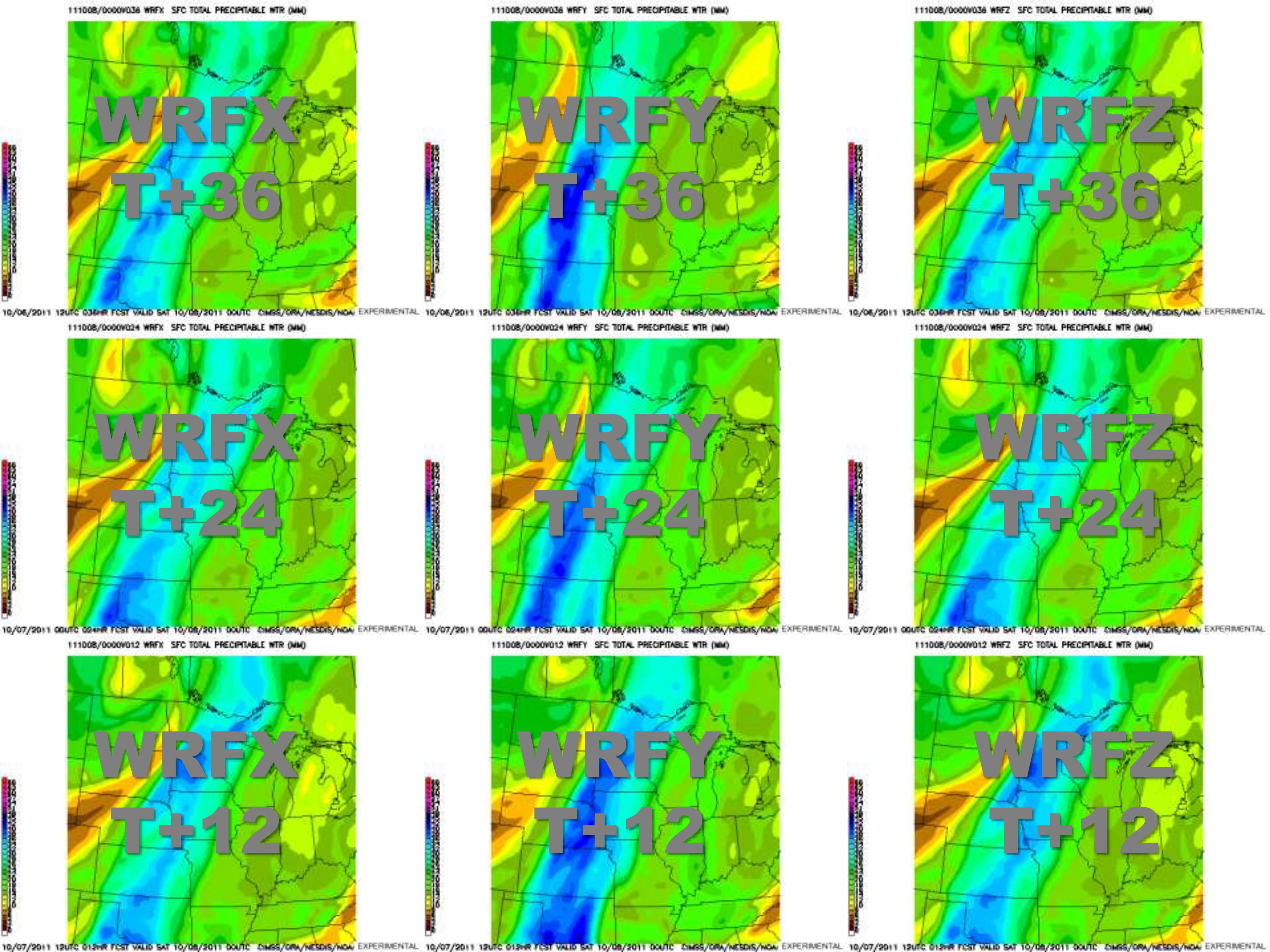
**36-hour**

| Model | Mean MAE |
|---|---|
| WRFZ | 2.42 ☑ |
| WRFX | 2.43 |
| WRFY | 2.71 |






111008/0000V036 WRFX SFC TOTAL PRECIPITABLE WTR (MM)
WRFX
T+36
10/06/2011 12UTC 036HR FCST VALID SAT 10/08/2011 00UTC CIMSS/ORA/NESDIS/NOAA EXPERIMENTAL
111008/0000V036 WRFY SFC TOTAL PRECIPITABLE WTR (MM)
WRFY
T+36
10/06/2011 12UTC 036HR FCST VALID SAT 10/08/2011 00UTC CIMSS/ORA/NESDIS/NOAA EXPERIMENTAL
111008/0000V036 WRFZ SFC TOTAL PRECIPITABLE WTR (MM)
WRFZ
T+36
10/06/2011 12UTC 036HR FCST VALID SAT 10/08/2011 00UTC CIMSS/ORA/NESDIS/NOAA EXPERIMENTAL
111008/0000V024 WRFX SFC TOTAL PRECIPITABLE WTR (MM)
WRFX
T+24
10/07/2011 00UTC 024HR FCST VALID SAT 10/08/2011 00UTC CIMSS/ORA/NESDIS/NOAA EXPERIMENTAL
111008/0000V024 WRFY SFC TOTAL PRECIPITABLE WTR (MM)
WRFY
T+24
10/07/2011 00UTC 024HR FCST VALID SAT 10/08/2011 00UTC CIMSS/ORA/NESDIS/NOAA EXPERIMENTAL
111008/0000V024 WRFZ SFC TOTAL PRECIPITABLE WTR (MM)
WRFZ
T+24
10/07/2011 00UTC 024HR FCST VALID SAT 10/08/2011 00UTC CIMSS/ORA/NESDIS/NOAA EXPERIMENTAL
111008/0000V012 WRFX SFC TOTAL PRECIPITABLE WTR (MM)
WRFX
T+12
10/07/2011 12UTC 012HR FCST VALID SAT 10/08/2011 00UTC CIMSS/ORA/NESDIS/NOAA EXPERIMENTAL
111008/0000V012 WRFY SFC TOTAL PRECIPITABLE WTR (MM)
WRFY
T+12
10/07/2011 12UTC 012HR FCST VALID SAT 10/08/2011 00UTC CIMSS/ORA/NESDIS/NOAA EXPERIMENTAL
111008/0000V012 WRFZ SFC TOTAL PRECIPITABLE WTR (MM)
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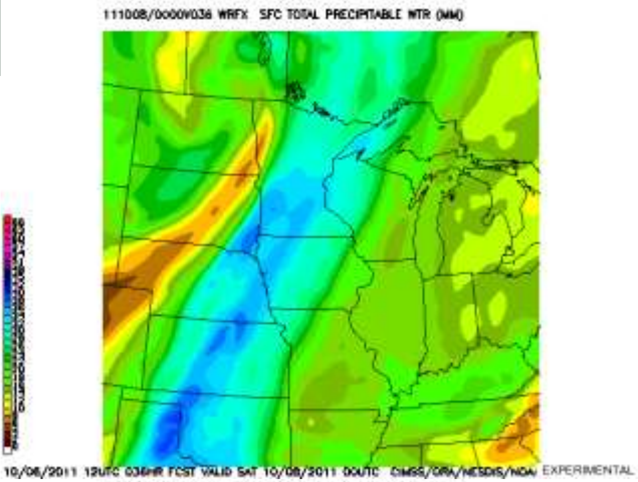
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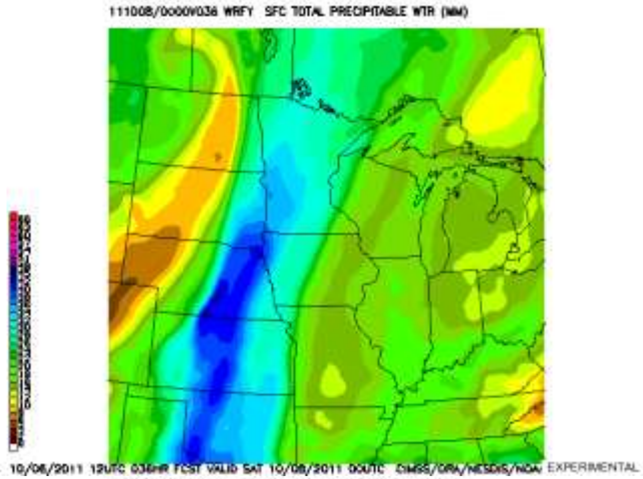
EXPERIMENTAL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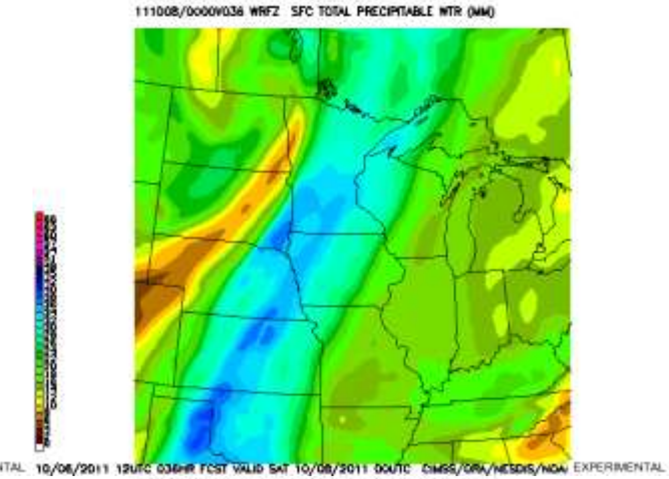
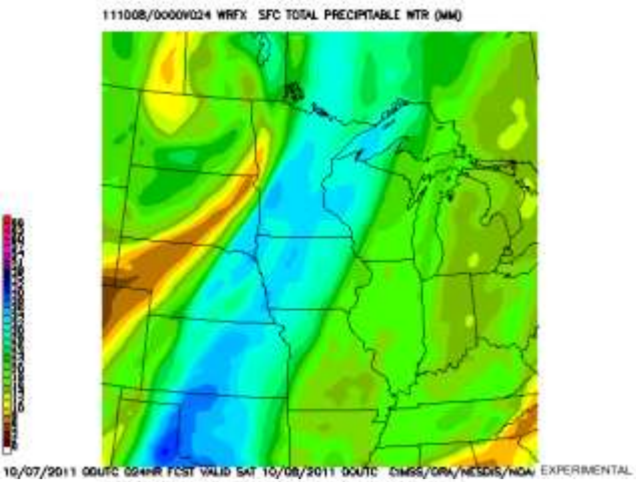
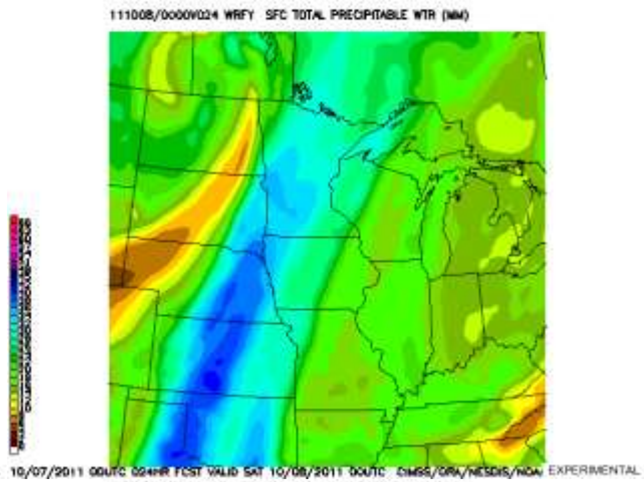
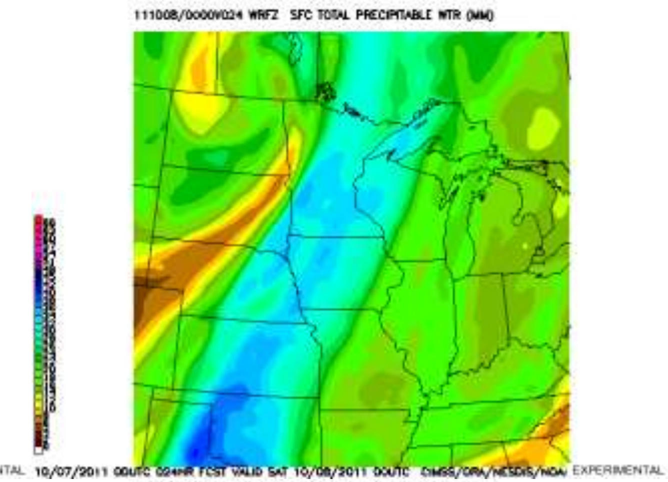
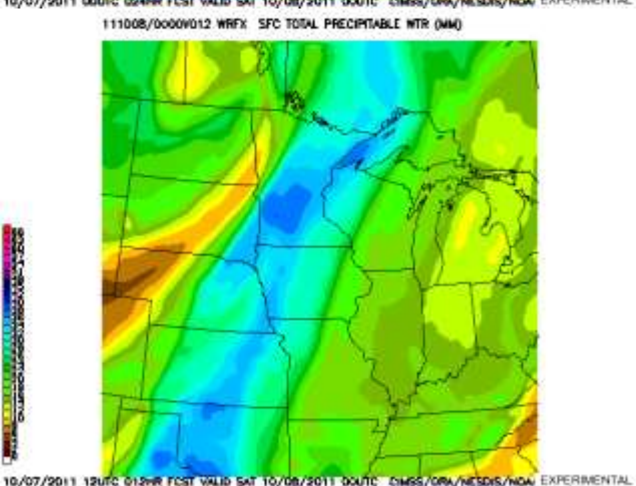
EXPERIMENTAL

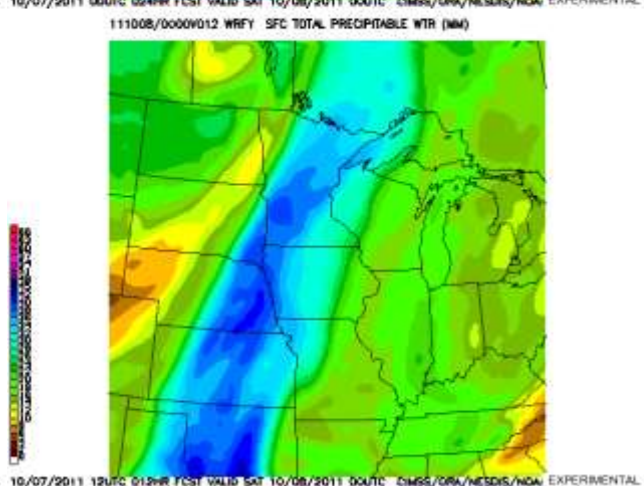

111008/0000V036 WRFZ SFC TOTAL PRECIPITABLE WTR (MM)
10/06/2011 12UTC 036HR FCST VALID SAT 10/08/2011 00UTC CIMSS/ORA/NESDIS/NOAA
EXPERIMENTAL

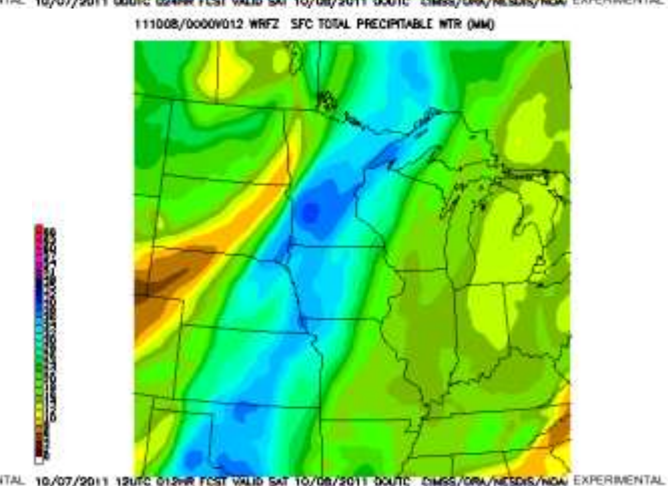

111008/0000V024 WRFX SFC TOTAL PRECIPITABLE WTR (MM)
10/07/2011 00UTC 024HR FCST VALID SAT 10/08/2011 00UTC CIMSS/ORA/NESDIS/NOAA
EXPERIMENTAL


111008/0000V024 WRFY SFC TOTAL PRECIPITABLE WTR (MM)
10/07/2011 00UTC 024HR FCST VALID SAT 10/08/2011 00UTC CIMSS/ORA/NESDIS/NOAA
EXPERIMENTAL


111008/0000V024 WRFZ SFC TOTAL PRECIPITABLE WTR (MM)
10/07/2011 00UTC 024HR FCST VALID SAT 10/08/2011 00UTC CIMSS/ORA/NESDIS/NOAA
EXPERIMENTAL


111008/0000V012 WRFX SFC TOTAL PRECIPITABLE WTR (MM)
10/07/2011 12UTC 012HR FCST VALID SAT 10/08/2011 00UTC CIMSS/ORA/NESDIS/NOAA
EXPERIMENTAL


111008/0000V012 WRFY SFC TOTAL PRECIPITABLE WTR (MM)
10/07/2011 12UTC 012HR FCST VALID SAT 10/08/2011 00UTC CIMSS/ORA/NESDIS/NOAA
EXPERIMENTAL

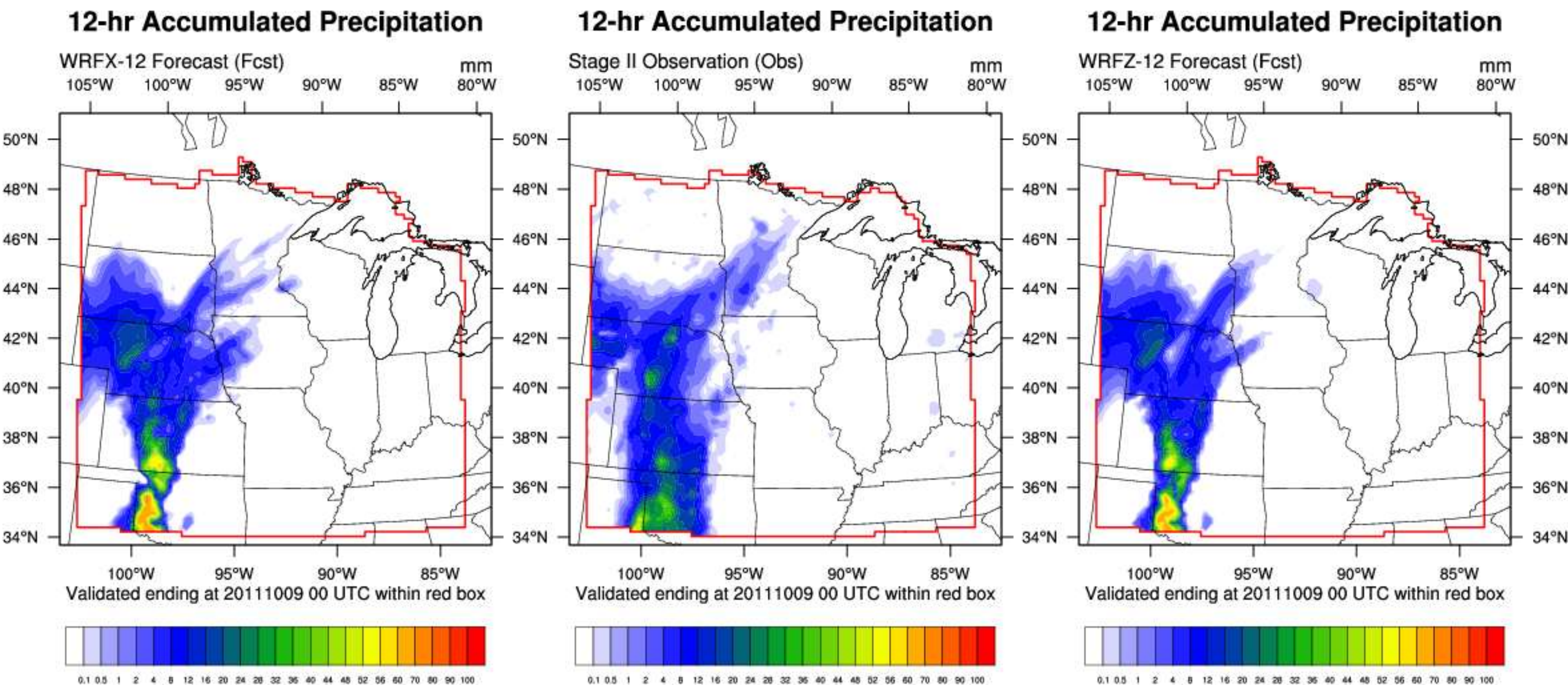

111008/0000V012 WRFZ SFC TOTAL PRECIPITABLE WTR (MM)
10/07/2011 12UTC 012HR FCST VALID SAT 10/08/2011 00UTC CIMSS/ORA/NESDIS/NOAA
EXPERIMENTAL

# Precipitation:  WRFX vs. WRFZ

## 12-hr Accumulation ending 9 October 2011, 00 UTC

WRFX produced more precipitation than observed over south central Kansas.

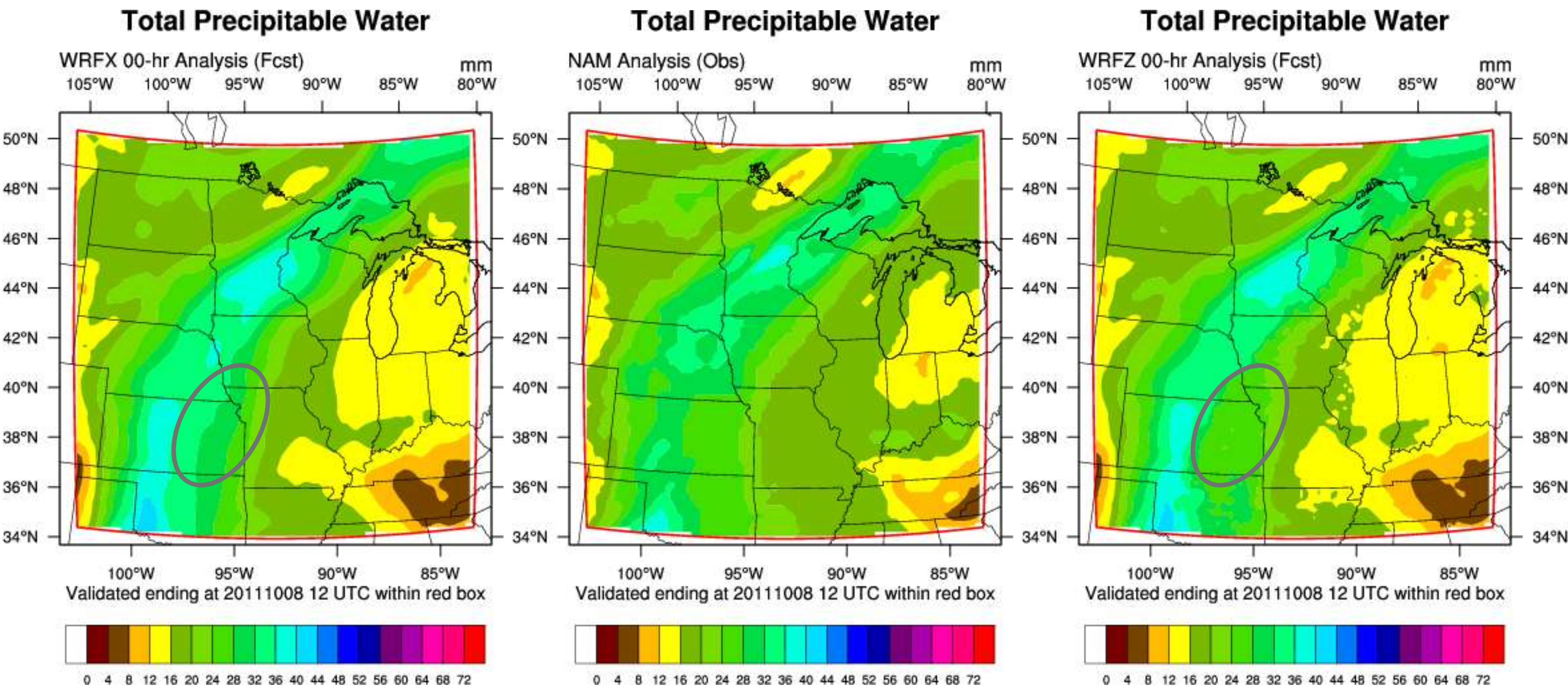
| Model | MAE (ST2) |
|---|---|
| **WRFZ** | 1.48 ☑ |
| WRFX | 1.65 |



# PW Analysis: WRFX vs. WRFZ

## Valid 8 October 2011, 12 UTC

WRFX started with PW up to 8 mm too moist over eastern Kansas, whereas the WRFZ exhibited less bias.

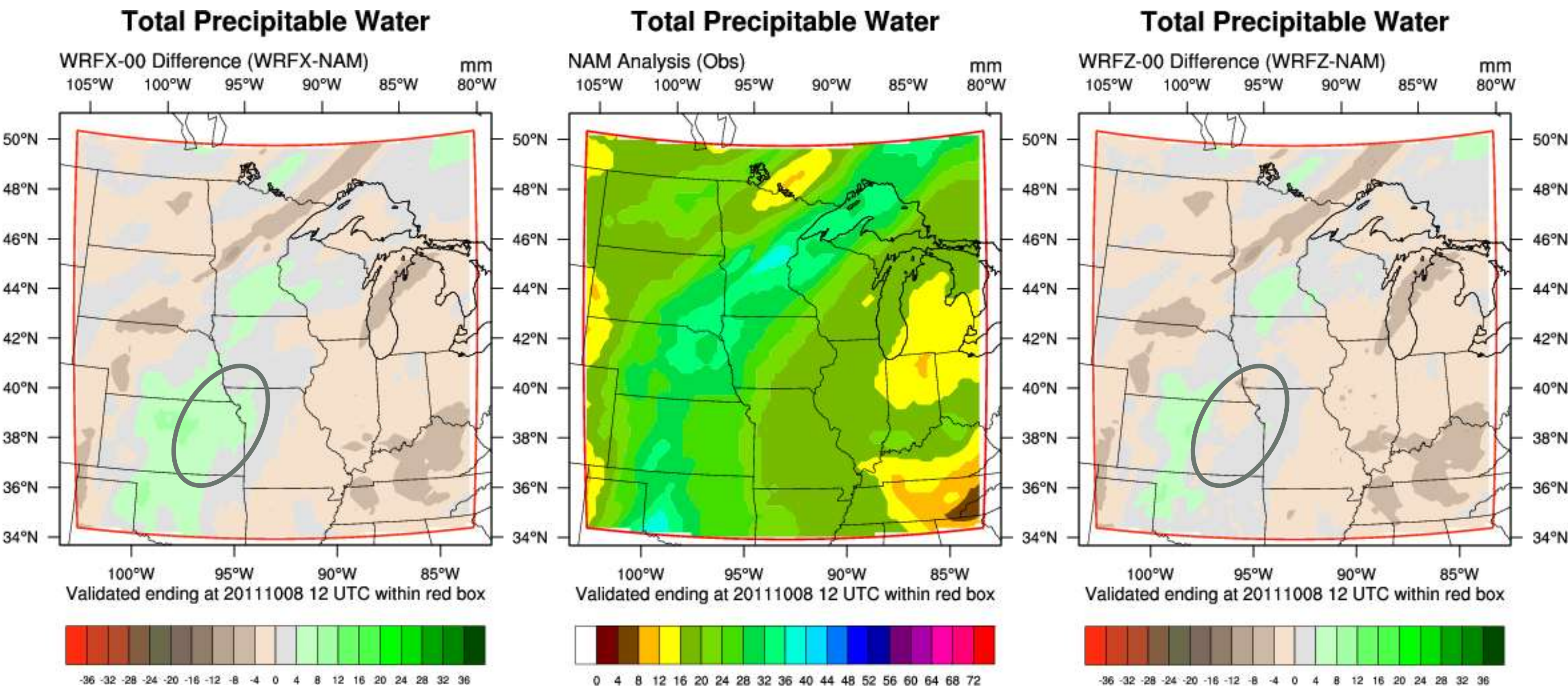


# PW Analysis:  WRFX vs. WRFZ

## Valid 8 October 2011, 12 UTC

| Model | MAE (GPS) |
|---|---|
| **WRFZ** | 1.58 ☑ |
| WRFX | 1.87 |

WRFX started with PW up to 8 mm too moist over eastern Kansas, whereas the WRFZ exhibited less bias.



# Summary of Presented Results

## Runs from 28 September to 8 October 2011

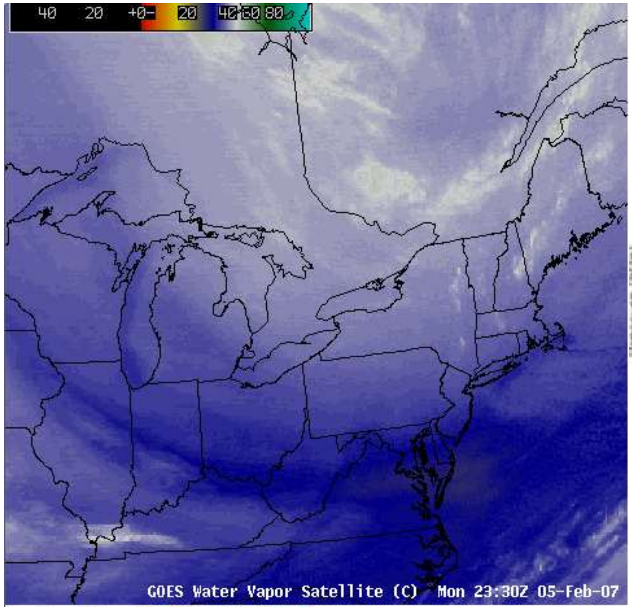
- Comparing WRFX and WRFZ, two sources of precipitable water verification confirm forecasts are statistically better, albeit slightly, 12 hours after initialization *if GOES-13 Sounder input is included*.
  - This may produce better precipitation verification, but not in regimes favoring light precipitation or limited areal extent.
- No substantial impact of added observations at 24 or 36 hours in the late September, early October flow regime.
- Lesser performance of WRFY suggests that CRAS dynamics and physics are influencing the solution negatively.

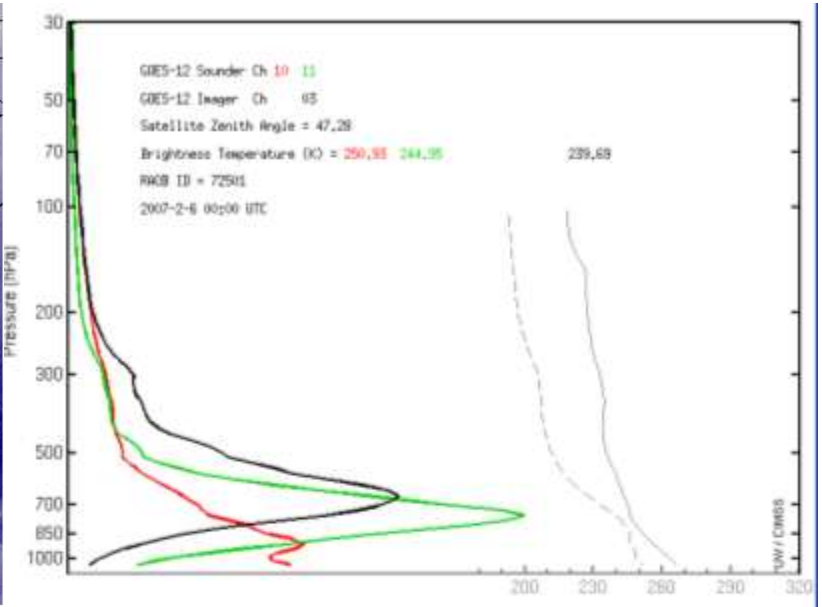
# Predictions for Winter Performance

## Statistics online at http://cimss.ssec.wisc.edu/cras/

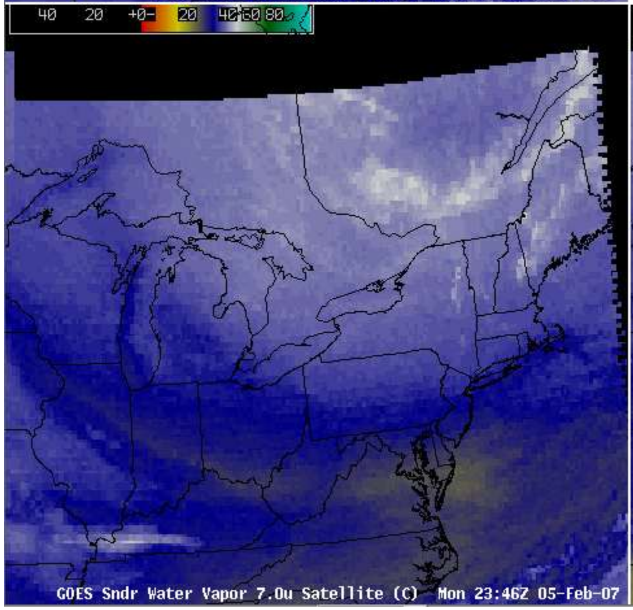
- More clouds means likely less Sounder observations of precipitable water.
- Faster flow conditions will advect observations off the domain fairly early in the simulations.
- In clear conditions, a drier upper troposphere will favor observed moisture contributions from lower in the atmosphere.
- Dynamic weather systems resulting in well-forced precipitation may show impact of precipitable water assimilation on precipitation amounts better than weakly-forced, high-moisture convective precipitation regimes.

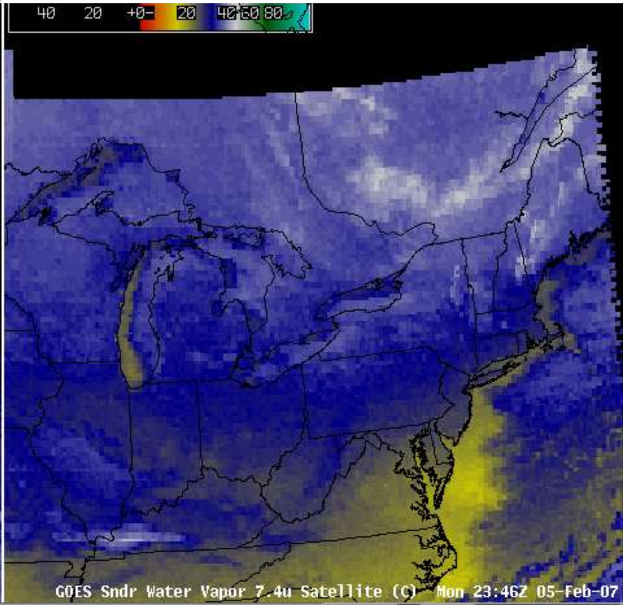
# Example from CIMSS Satellite Blog:  Wintertime Water Vapor




Calculated weighting functions based on February 6, 2007, 00 UTC, radiosonde taken at Upton, NY.




Water vapor near the surface is detected by the GOES-12 Imager and Sounder due to very limited emission (low water vapor) in the upper troposphere.

http://cimss.ssec.wisc.edu/goes/blog/

# CRAS TOTAL SKY COVER ALGORITHM AND PERFORMANCE COMPARED TO WRF CLOUD FRACTION

Part C

## CRAS Total Sky Cover Algorithm

# Motivation

- Sky cover composites from the National Digital Forecast Database (NDFD) lack sufficient integrity from weak office-to-office consistency, and are relatively smooth definition within individual forecast areas.

- Since sky conditions alone are never hazardous, and NDFD text output translates a percent into categorical terms (cloudy, partly cloudy, etc.), forecasters generally place more attention on the other forecast elements.

CRAS Total Sky Cover Algorithm

# WRF Cloud Fraction Formulation

- Xu and Randall (1996) developed the cloud fraction computation for the WRF based on the notion that grid-averaged condensate mixing ratio, consisting of cloud water and cloud ice, is a better diagnostic for stratiform cloudiness than grid-averaged relative humidity.

- This formulation indicates that the cloud amount varies exponentially according to the grid-averaged condensate mixing ratio.
  - The rate of variation is a function of the grid-averaged relative humidity.

CRAS Total Sky Cover Algorithm

# WRF Cloud Fraction Formulation

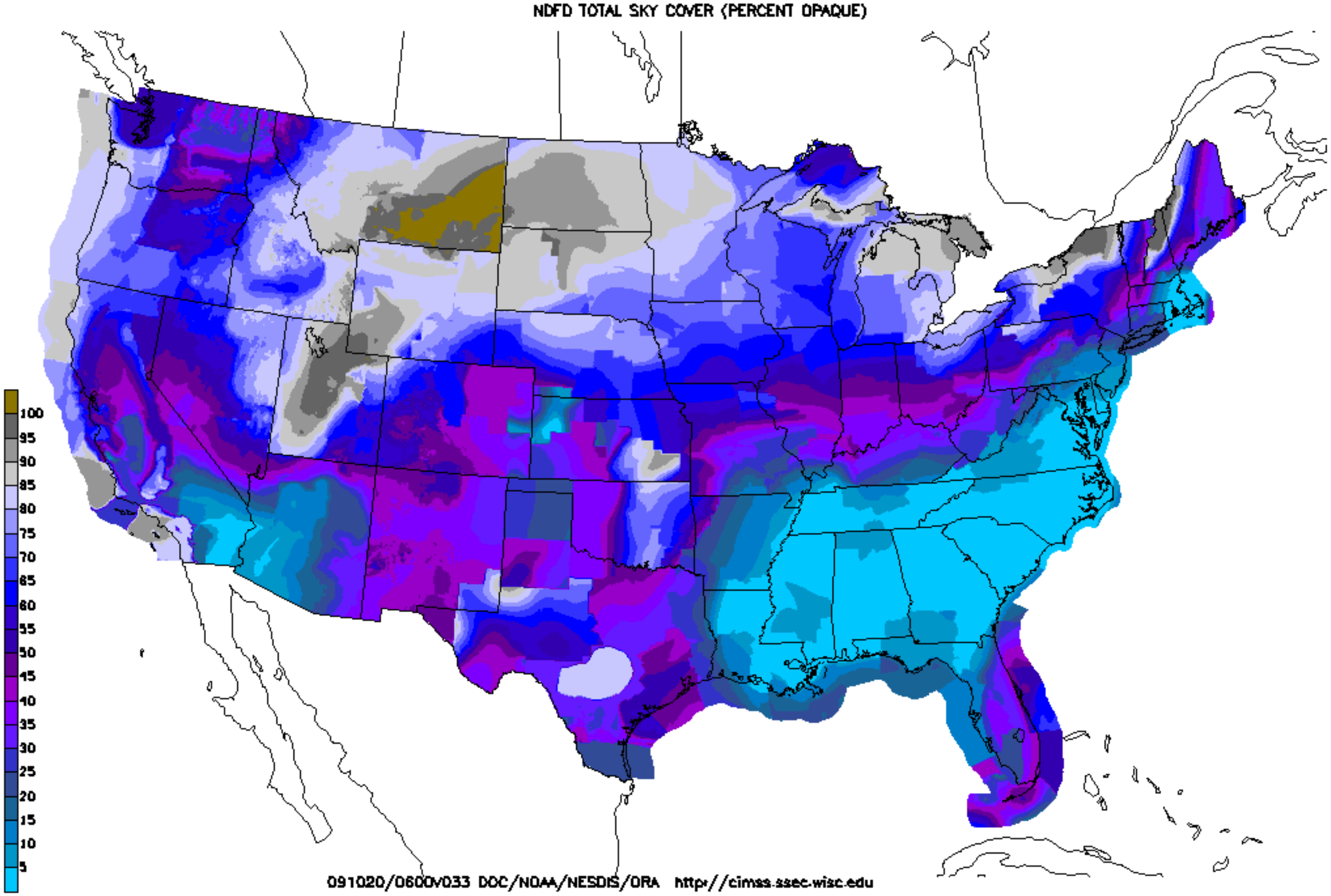
- The result is a coupling between the cloud fraction, $C_{fraction}$, condensate mixing ratio, and relative humidity, *RH*:

$$C_{fraction} = \begin{cases} RH^{k}\left[1 - \exp\left(\dfrac{-\beta_0 \overline{q_l}}{[(1-RH)q_{vs}]^{\tau}}\right)\right], & \text{if RH} < 1 \\ 1, & \text{if RH} \geq 1 \end{cases}$$

- $\overline{q_l}$ is the large-scale liquid water mixing ratio
- $q_{vs}$ is the saturation water vapor mixing ratio
- The values of $k$, $\beta_0$, and $\tau$ were determined empirically to be 0.25, 100, and 0.49, respectively

CRAS Total Sky Cover Algorithm

# Motivation




Example operational output

CRAS Total Sky Cover Algorithm

# Definition

- The NWS/NOAA 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).

## CRAS Total Sky Cover Algorithm

# Cloudy?

**Cirrostratus (Cs) covering the whole sky**

http://www.srh.weather.gov/srh/jetstream/synoptic/h7.htm

CRAS Total Sky Cover Algorithm

# Methodology Outline

- Compute a cloud concentration profile.
- Average the profile for the upper and lower troposphere based on the number of cloud layers.
- Determine the local sky cover.
- Combine adjacent grid points to form an upper and lower celestial dome, then combine the two domes, giving the lower celestial dome preference.

CRAS Total Sky Cover Algorithm

# Methodology

- For every grid point at each vertical level, if cloud mixing ratio is greater than or equal to 0.01 g/kg, then a ratio is computed of this mixing ratio to the auto-conversion limit (based solely on the temperature at that grid point).

- The resulting ratio, generally between 0 and 1, is the fraction of cloud water to the maximum cloud water possible at the point without precipitation.

- A ratio greater than one means the cloud at that point (on the level) is precipitating.

CRAS Total Sky Cover Algorithm

# Auto-Conversion Limit

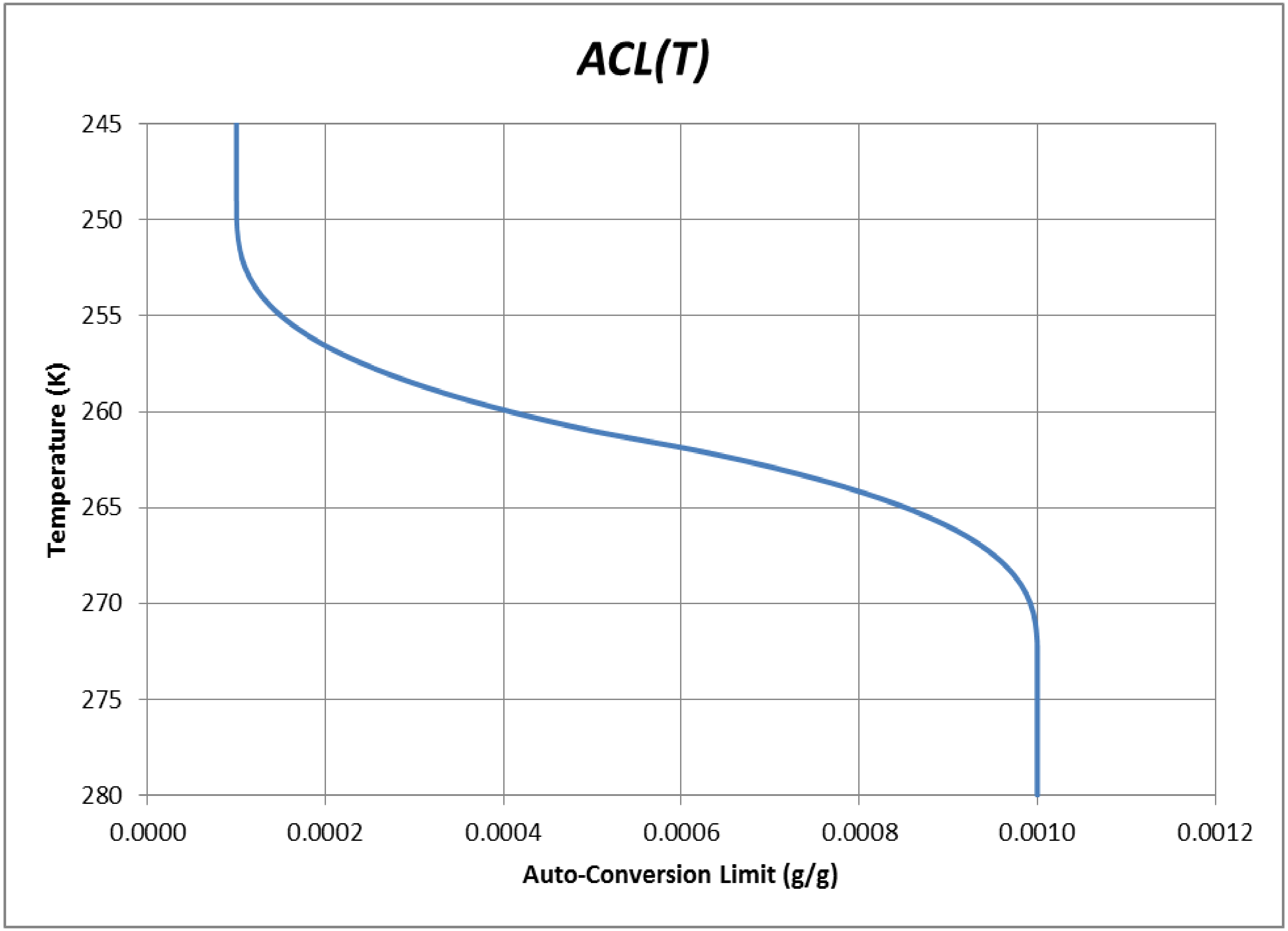
- Let *ACL* be the auto-conversion limit in g/g, and *T* the temperature in K. The limit is approximated based solely on temperature in four piecewise functions:
  - $\mathrm{T} \geq 273$: $ACL = 0.001$
  - $261 \leq T < 273$: $ACL = 0.001 - 0.005((273-\mathrm{T})/12)^3$
  - $249 \leq T < 261$: $ACL = 0.0001 + 0.004((T-249)/12)^3$
  - $T < 249$: $ACL = 0.0001$

- The *ACL(T)* is greatest and constant for warm clouds (liquid).

- The slope of *ACL(T)* is steepest at 261 K, the temperature at which there is maximum ice growth, and the typical average cloud transition from liquid to ice.

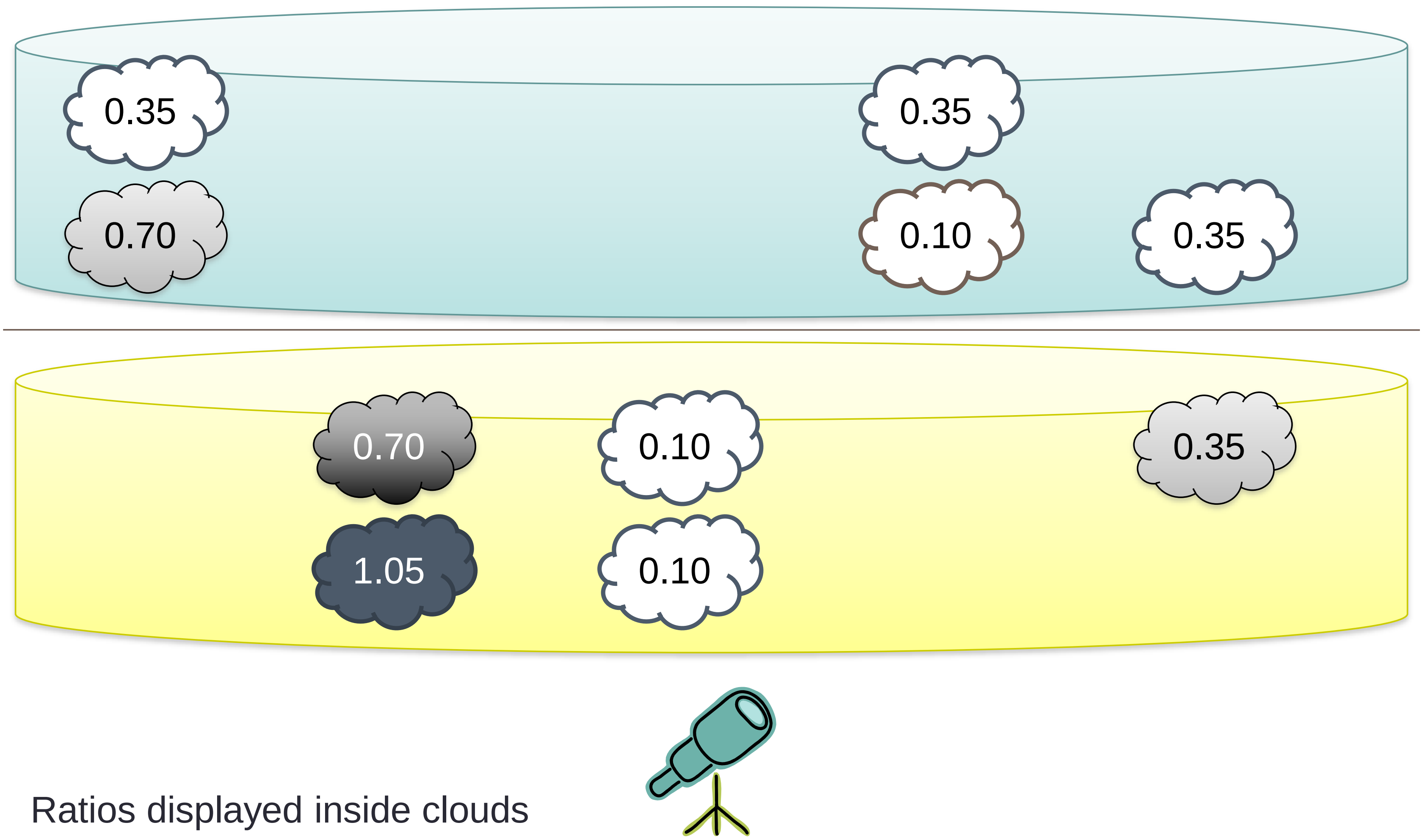
CRAS Total Sky Cover Algorithm

# Auto-Conversion Limit



CRAS Total Sky Cover Algorithm

# Example Atmosphere




Ratios displayed inside clouds

CRAS Total Sky Cover Algorithm

# Methodology

- Essentially, the fraction of mixing ratio to ACL is a first guess at how much each test point is attenuating sunlight due to cloud.

- If the sigma level of the test point is greater than 0.5 (roughly 500 hPa), then the ratio is half of the original value.
  - This ad hoc approach prevents ice cloud from producing overcast conditions. Since the upper half of the troposphere is largely cold and dry, the fraction of mixing ratio to ACL is not an ideal approximation.

- The next step is to vertically average the ratios at each grid point. One average is done for all test points at or above $\sigma$=0.5, another is done for those below.

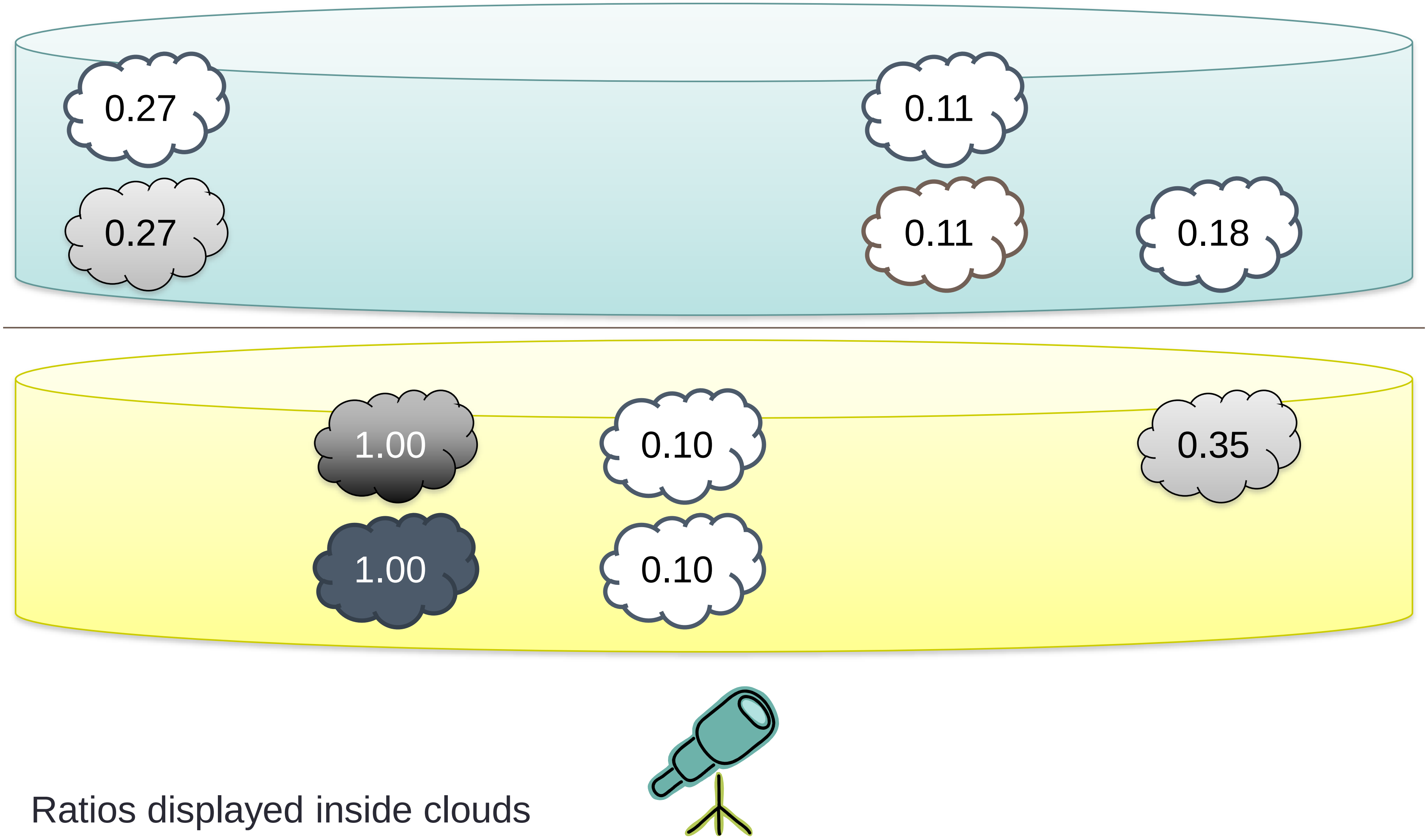
CRAS Total Sky Cover Algorithm

# Methodology

- If any of the layers averaged below $\sigma=0.5$ has a cloud mixing ratio greater than the auto-conversion limit, then the cloud cover ratio is 1 (100%).
  - We assume overcast conditions in areas of precipitation.
- For the layers averaged at or above $\sigma=0.5$, if the vertical average is greater than 0.5 (50%), then the cloud cover is lowered to 0.5 (for the upper troposphere component).
  - Ice cloud reflectivity typically greater than for water cloud.
- The next step is to combine the two ratio averages into a sky cover.

CRAS Total Sky Cover Algorithm

# Example Atmosphere




Ratios displayed inside clouds

## CRAS Total Sky Cover Algorithm

# Methodology

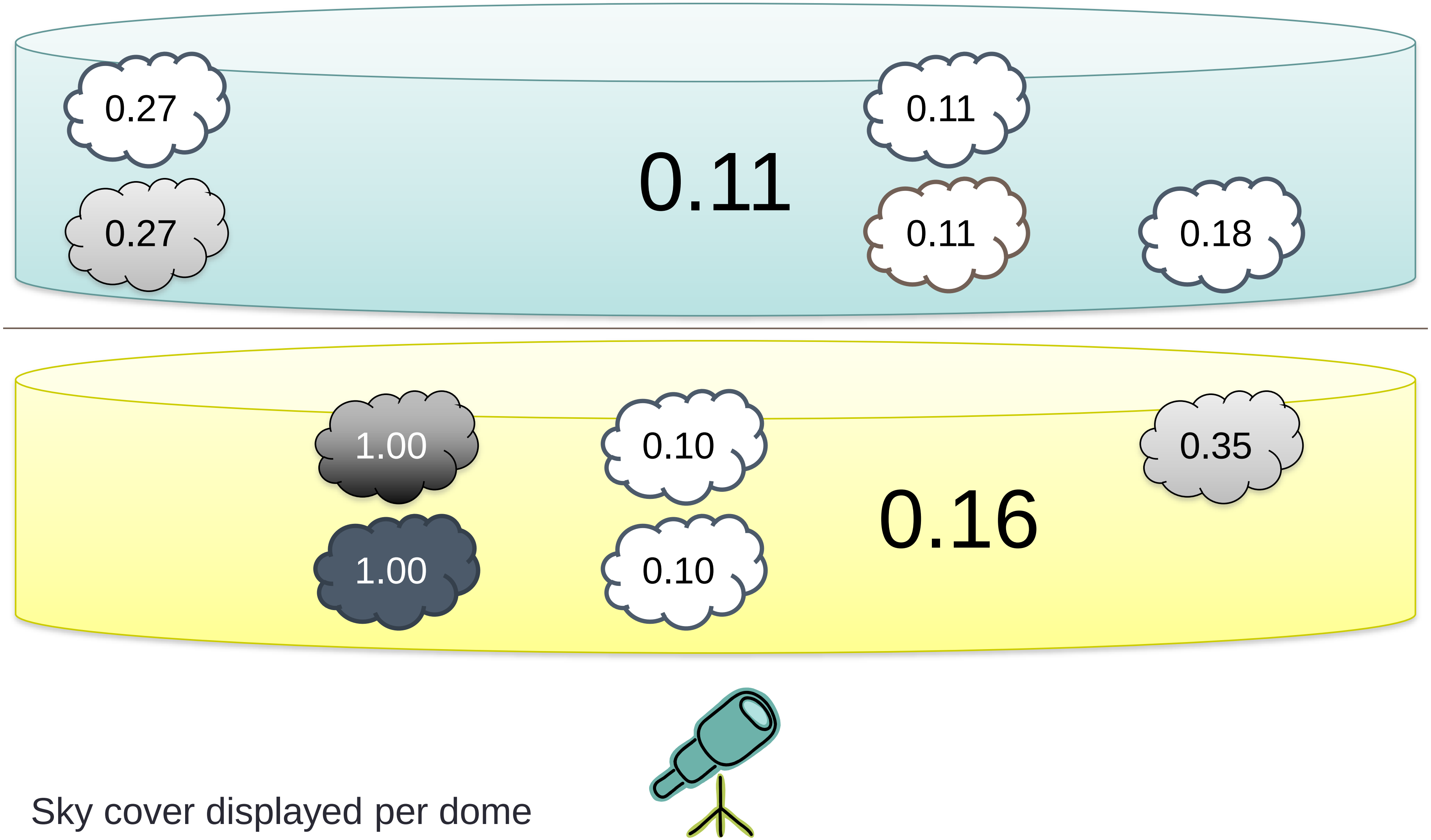
- To create the upper celestial dome for ice cloud for every grid point, the ratio average for each adjacent grid point contributes to 20% of the total. The final 20% contribution comes from the ratio average of the grid point itself.

- To create the lower celestial dome for water cloud for every grid point, the ratio average for each adjacent grid point contributes to 10% of the total. The final 60% contribution comes from the ratio average of the grid point itself.

- This approach was implemented because the upper celestial dome is spatially larger to the observer than the lower celestial dome.

CRAS Total Sky Cover Algorithm

# Example Atmosphere




Sky cover displayed per dome

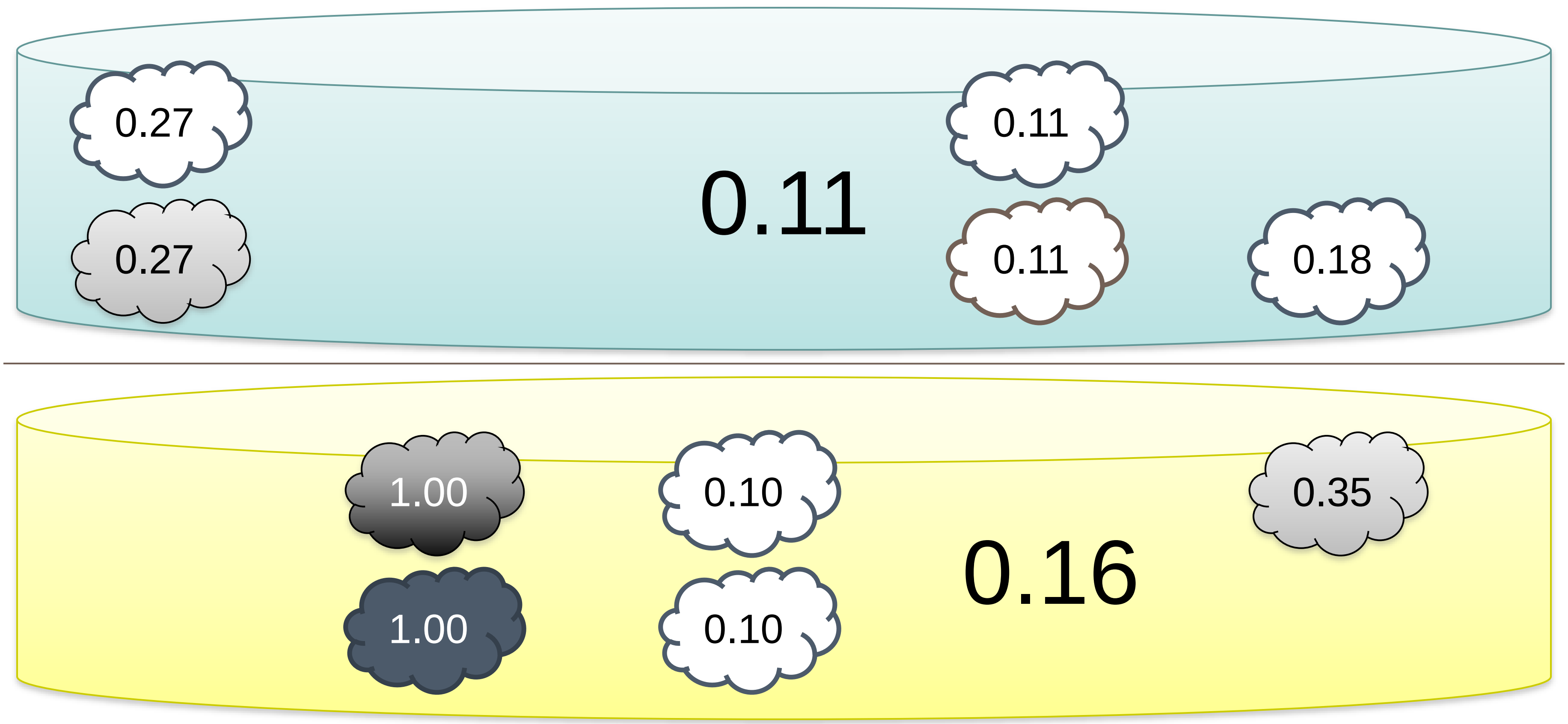
# Methodology

- Finally, to produce sky cover output (SC, in %) at each vertical column in model resolution, the result from the lower celestial dome computation (LCD, in %) is added to the upper celestial dome computation (UCD, in %) over the lower dome area left uncovered by the water cloud (1-LCD, in %).
  - Upper cloud will not contribute to a sky cover fraction if it is obstructed by lower cloud.

- Thus, $SC = LCD + (1\text{-}LCD)(UCD)$

- If the resulting sky cover is less than 5%, we will assume 0%, due to the limited predictability.

# Example Atmosphere

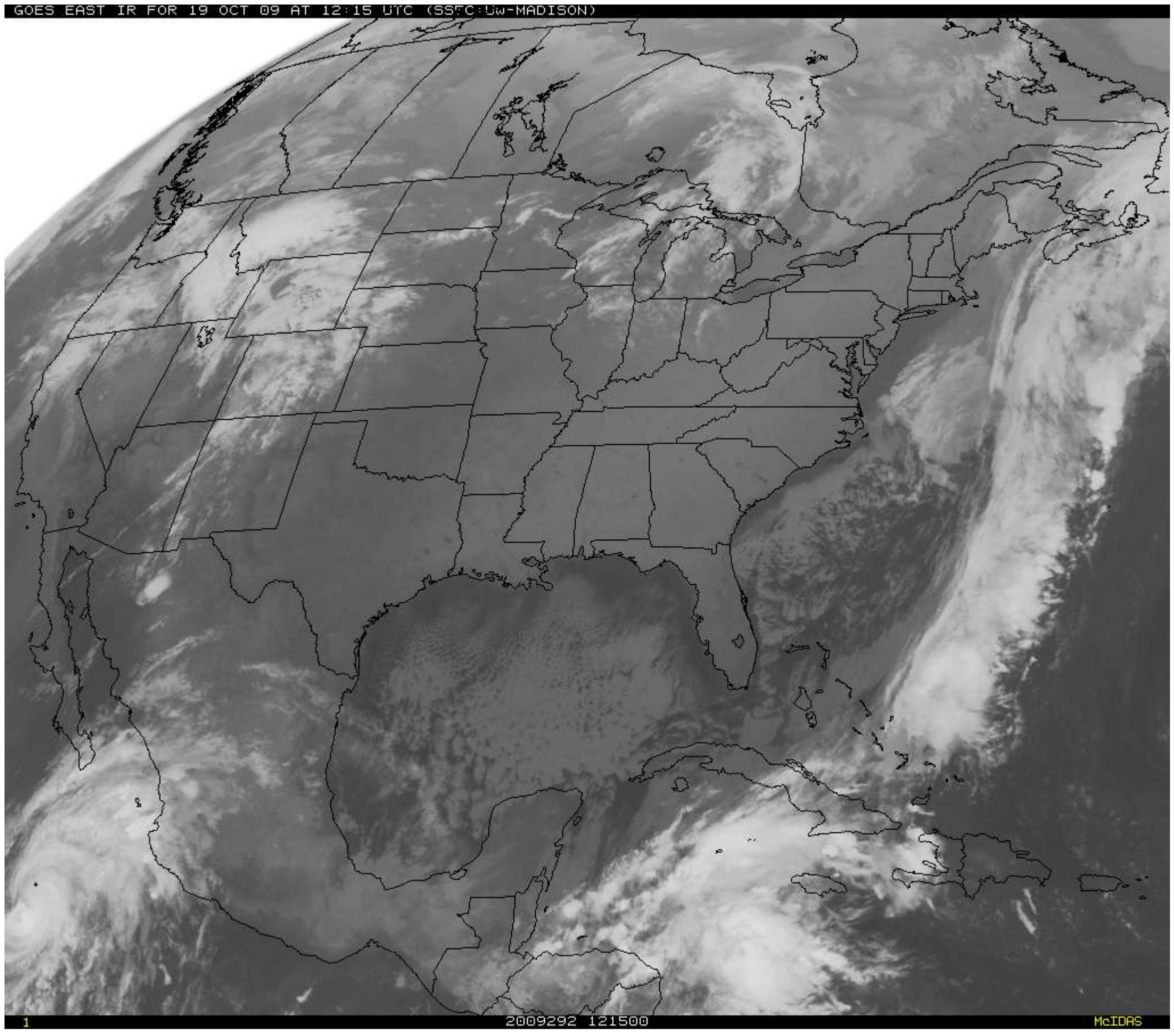




Sky cover displayed per dome

## CRAS Total Sky Cover Algorithm

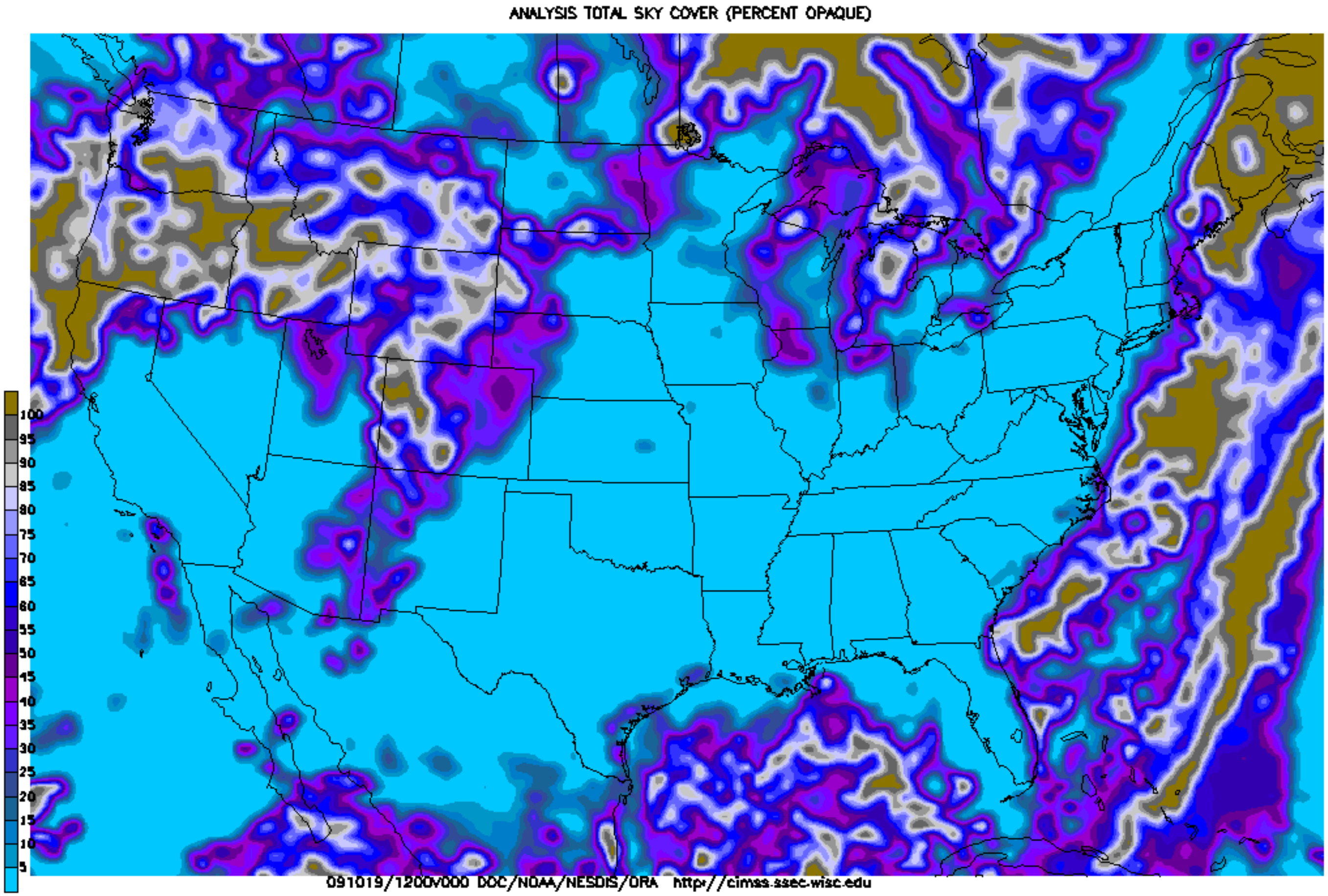
# GOES-East IR Window




12:15 UTC 19 October 2009

## CRAS Total Sky Cover Algorithm

# CRAS Sky Cover Analysis

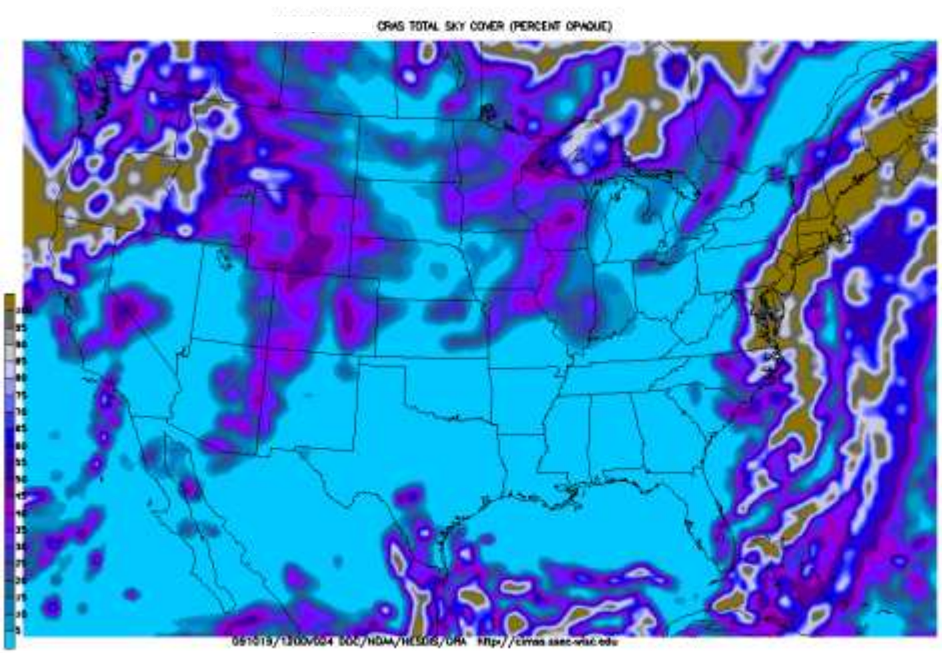



12:00 UTC 19 October 2009

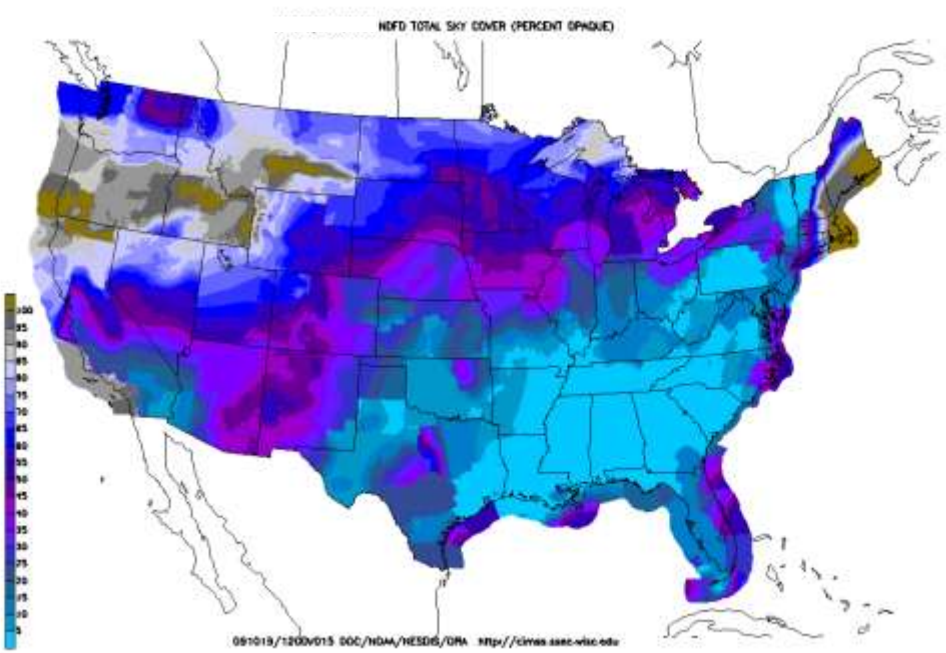
CRAS Total Sky Cover Algorithm

# Forecast Comparison

**CRAS 45 km Sky Cover 24-hour Forecast**



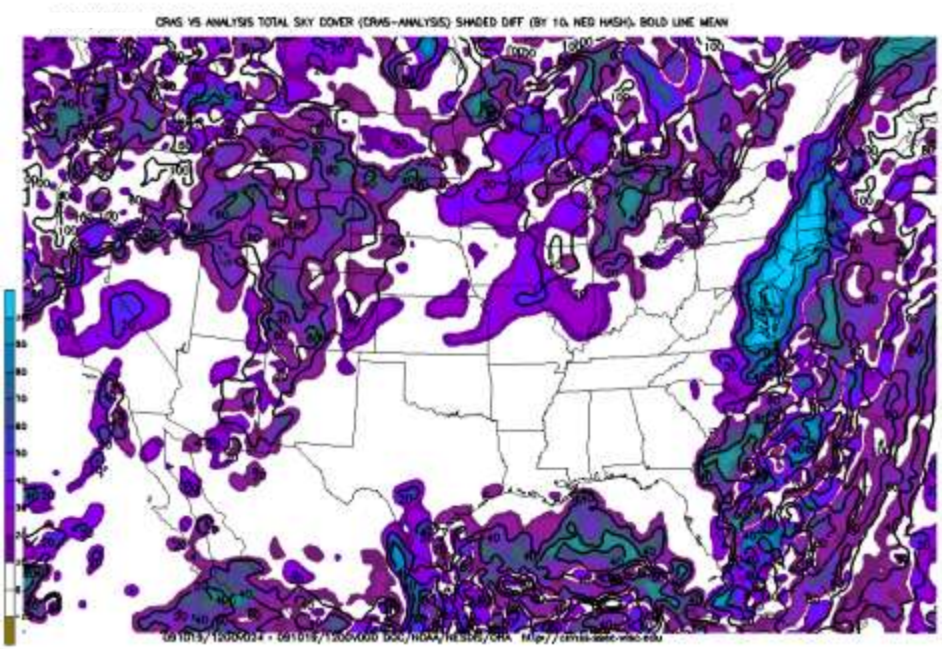

**NDFD Official Sky Cover 15-hour Forecast**



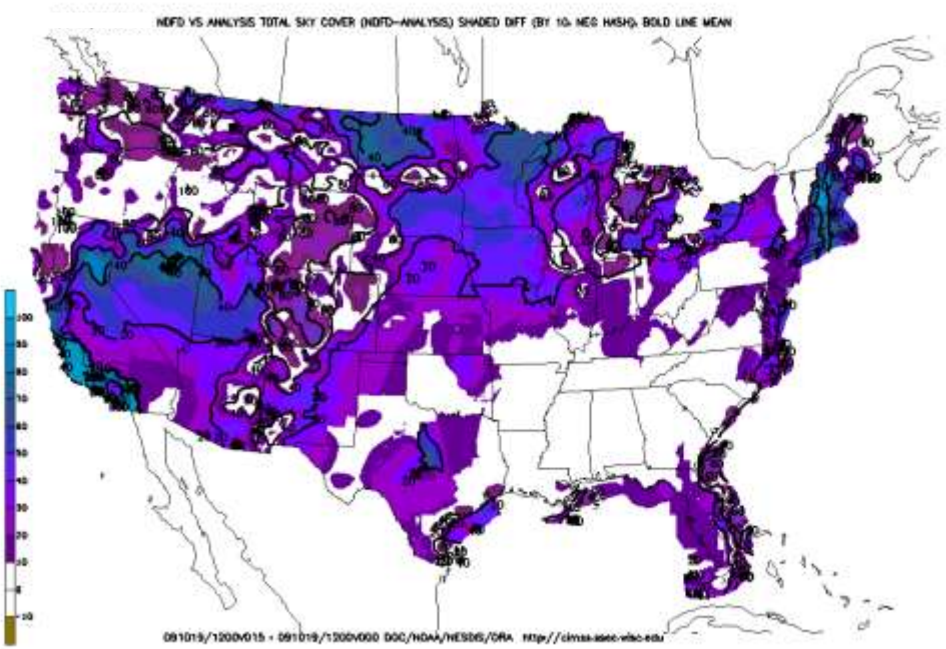

12:00 UTC 19 October 2009

# CRAS Total Sky Cover Algorithm
# **Comparison to Analysis**

**CRAS 45 km Sky Cover 24-hour Forecast**




**NDFD Official Sky Cover 15-hour Forecast**

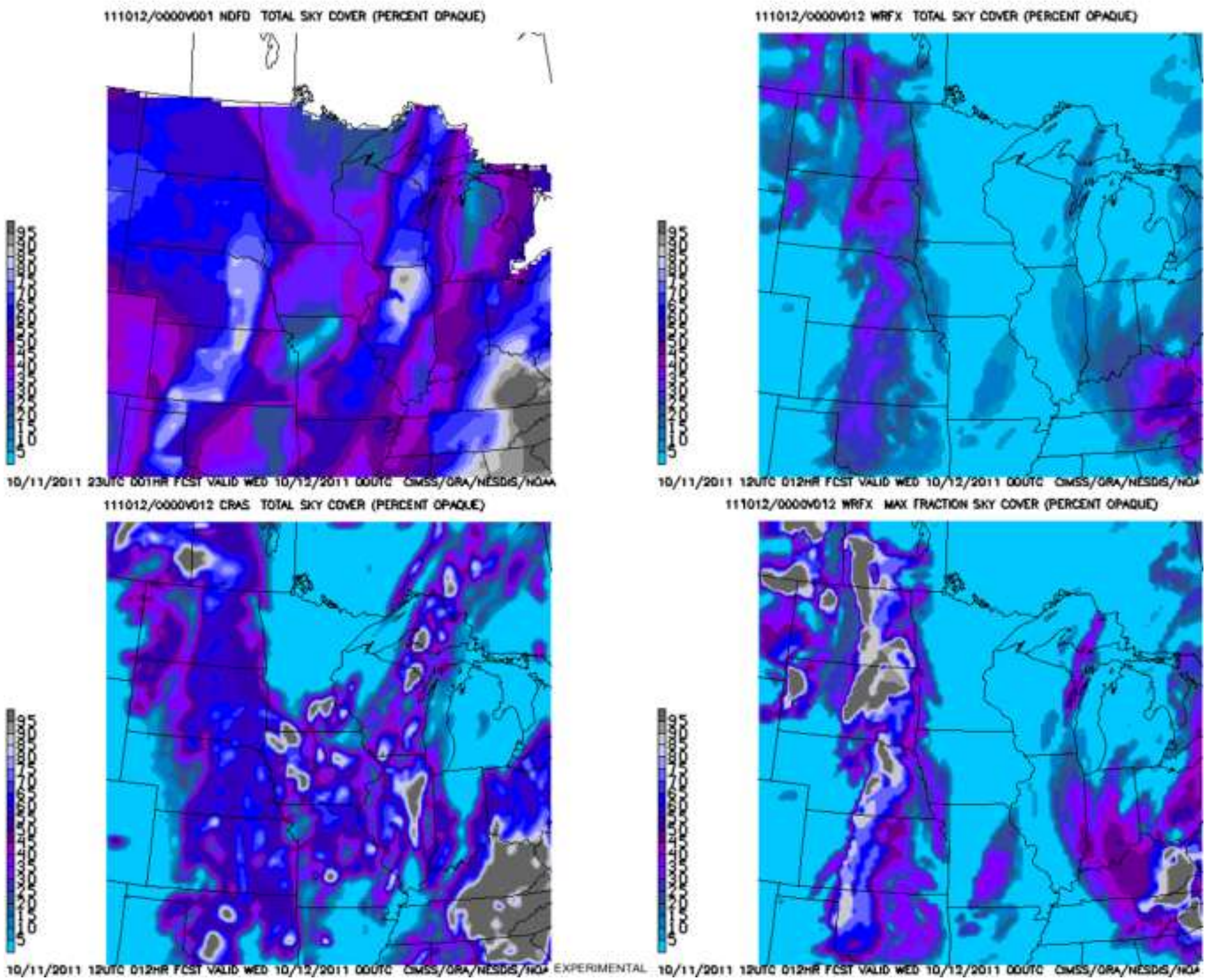



12:00 UTC 19 October 2009

# CRAS Total Sky Cover Algorithm

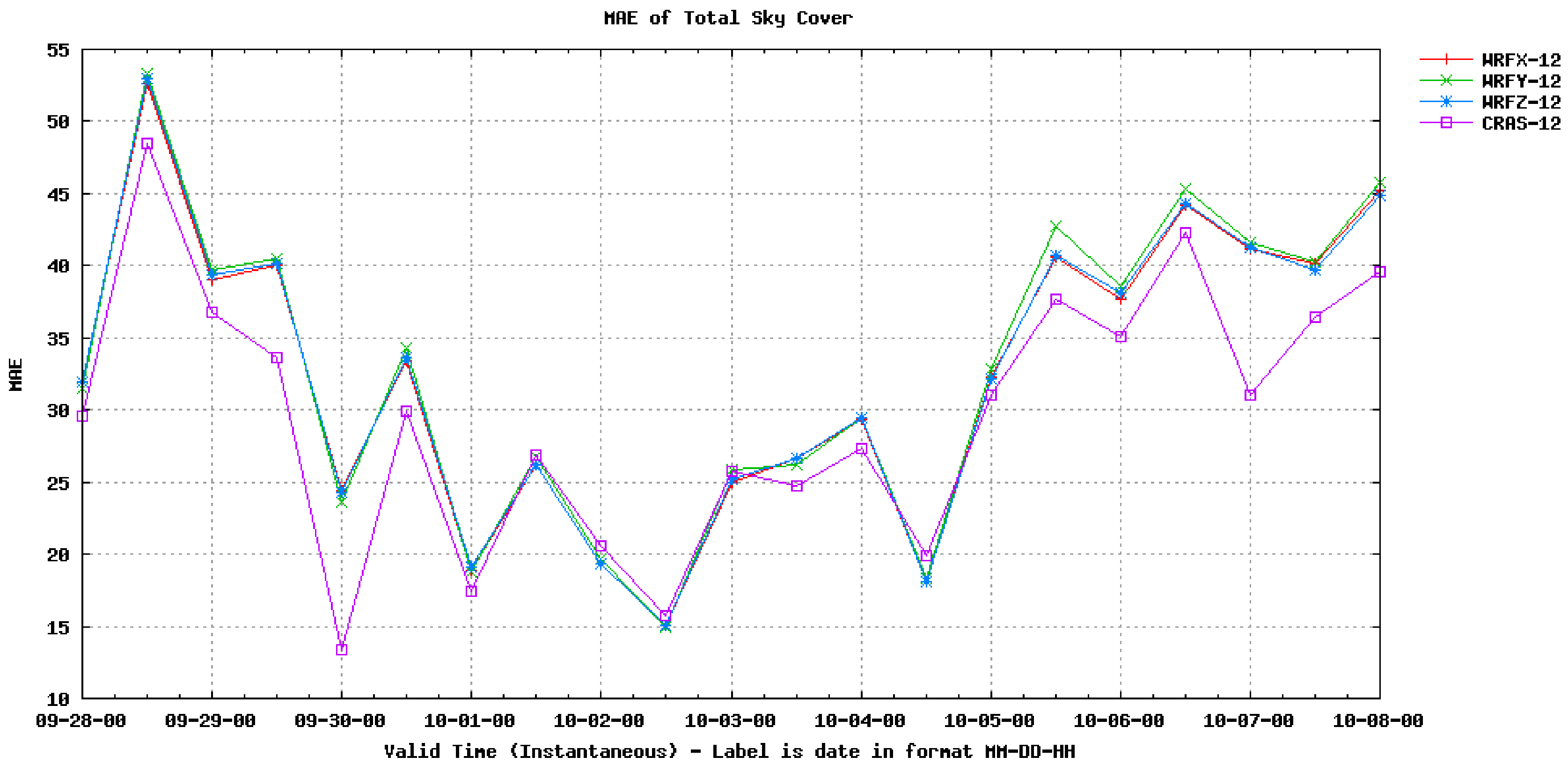
# WRF vs. CRAS Comparisons

- Default WRF cloud fraction takes the average of three primary layers (low, mid, and high). Maximum cloud fraction can be computed if those three layers are averaged (they can be output).
- 12-hr Cloud Cover Forecast MAE compared to the 1-hr NDFD is approximately 20% for CRAS, 25% for WRF with maximum cloud adjustment, and 30% for default WRF.
- NDFD may overestimate clouds when actually clear.
- These sample images, compared 12-hr forecasts to the NDFD, are valid at 12 October 2011, 00 UTC.



## CRAS Total Sky Cover Algorithm

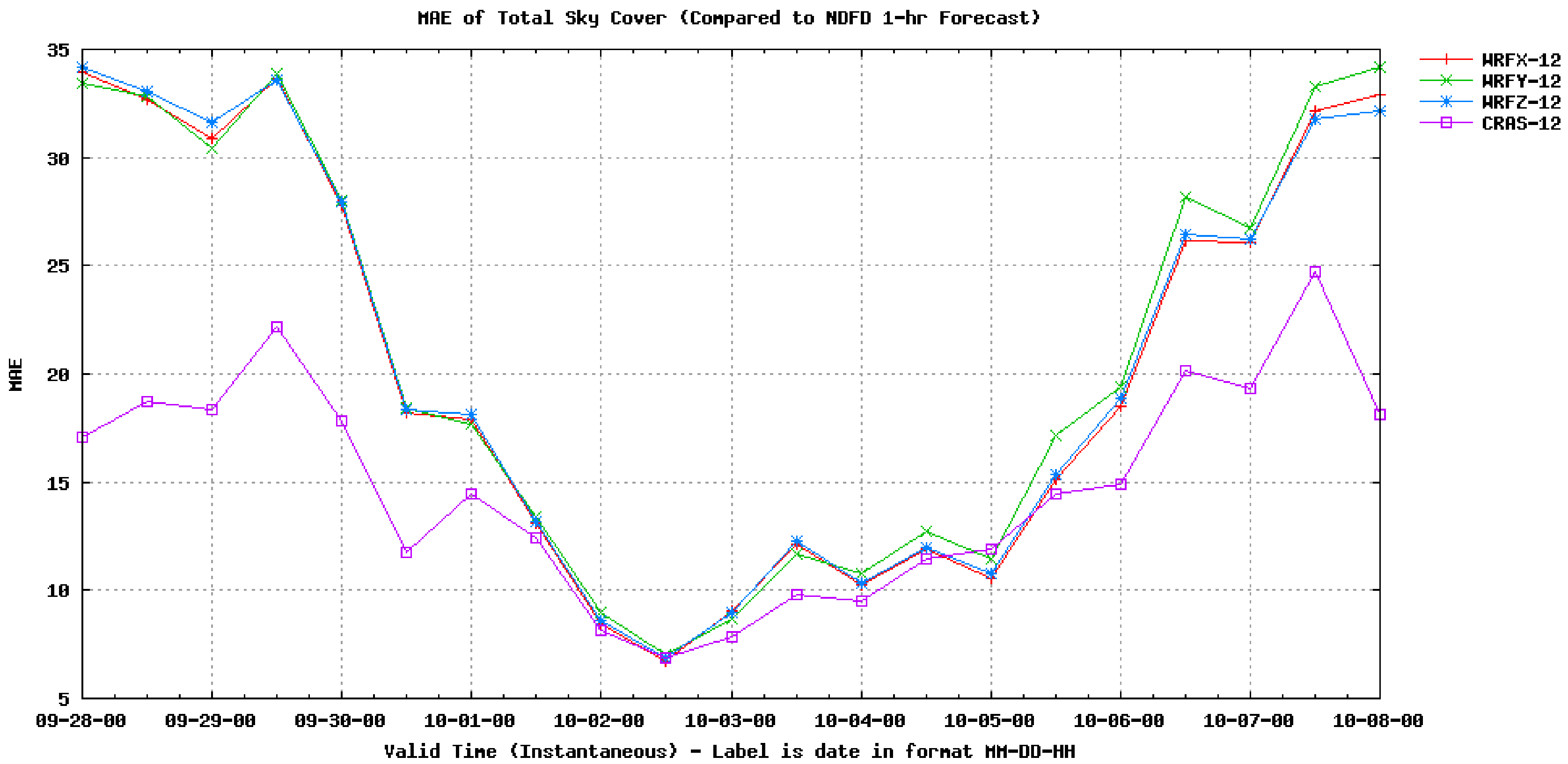
# WRF vs. CRAS Performance




Mean absolute error for total sky cover (%) over the period from 00 UTC 28 September 2011 to 00 UTC 8 October 2011. Error is calculated based on the NAM analysis.

CRAS Total Sky Cover Algorithm

# WRF vs. CRAS Performance




Mean absolute error for total sky cover (%) over the period from 00 UTC 28 September 2011 to 00 UTC 8 October 2011. Error is calculated based on the NDFD 1-hour forecast.

# FINAL THOUGHTS ON RESULTS AND FUTURE DIRECTIONS

Conclusions

# Final Thoughts

- Improvement not as large as hypothesized
  - Number of data sets assimilated into operational models continues to grow, so finding improvement without new instrumentation difficult
- Moisture retrievals slightly beneficial to regional NWP within first 12 hours of forecast in best cases, but largely inconsequential over experiment period
  - Bulk of moisture exists in lower troposphere during the summer and fall months, where GOES Sounder is “blind”
  - Bias of GOES Sounder retrievals is not consistently less than background, when compared to GPS-TPW
  - A 1D-var assimilation scheme on a high spatial resolution grid is likely to weight individual retrievals more, increasing absolute error by decreasing the spatial average
  - Need to investigate techniques which conserve and redistribute moisture on medium horizontal scales $O(10^2)$ km, preserving gradients

# Final Thoughts

- Unable to certify that assimilation scheme and CRAS are functioning efficiently/optimally
  - Comparatively poor performance of WRFY suggests that shortcomings in CRAS dynamics/physics dominating benefit of upstream moisture observations
  - Assimilation technique applied here requires several interpolations between retrieval and WRF analysis since interface is not direct
- Cloud-top pressure occasionally too high in background profiles with substantial inversions
  - New technique necessary to place low cloud based on likely vertical position; trust modeled atmosphere over product?
- WRF cloud fraction performs contrary to NWS expectations
  - Improved cloud cover formulation necessary for short-term NWP models which break from large-scale climate model paradigm

# Final Thoughts

- Satellite observations play a fundamental role in NWP solutions.
- Leveraging the GOES Sounder is one way to improve the accuracy of the WRF-ARW forecast within the first 12 to 24 hours, especially away from oceans, where TPW retrieval assimilation does not occur in operational models.
- Subtle changes to the moisture field can impact NWP performance.
- Graphical output and real-time statistics from experiment are available online.

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