# Satellite-derived Cloud Properties in Near Real Time for Weather and Aviation Safety

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# Objectives

- Provide accurate cloud and radiation properties from meteorological satellites for use by the meteorological, climate, energy, transportation, and other communities

  e.g.,

  - *aircraft icing conditions*
  - *surface radiation budget*
  - *NWP assimilation*
  - *fog, ceiling, etc.*

- Make them timely and widespread for real-time applications
  - *nowcasting & assimilation*
  - *near-global at high temporal resolution*
  - *3-D characterization of clouds*

# Data

- Available geostationary satellites provide up to 1-hour monitoring between ~60°S and ~60°N (*currently 3 hourly*)
- Sun-synchronous satellites (POES) provide coverage over polar regions and gaps in geostationary coverage

Satellite imager channels used in common for cloud detection and retrievals.

| Satellite | Sub-satellite Longitude or Equator Crossing Time | Common (visible) resolution, km | Central or radiance equivalent channel wavelength, µm | | | | |
|---|---|---|---|---|---|---|---|
| | | | Visible (VIS) | Shortwave-IR (SIR) | Infrared (IR) | Split-window (SW) | $CO_2$ |
| GOES-11 | 135°W | 4 (1) | 0.651 | 3.91 | 10.7 | 12.0 | N/A |
| GOES-12 | 75°W | 4 (1) | 0.651 | 3.92 | 10.7 | N/A | 13.3 |
| Meteosat | 0° | 3 (1) | 0.640 | 3.92 | 10.8 | 12.0 | 13.4 |
| FY-2C | 105°E | 5 (1.25) | 0.724 | 3.79 | 10.8 | 12.0 | N/A |
| MTSAT-1R | 140°E | 5 (1.25) | 0.724 | 3.79 | 10.8 | 12.0 | N/A |
| *Aqua* | 1330 LT | 1 (0.25) | 0.646 | 3.79 | 10.8 | 12.0 | 13.3 |
| *Terra* | 1030 LT | 1 (0.25) | 0.646 | 3.78 | 10.8 | 12.0 | 13.3 |

- AVHRR on NOAA/Envisat can also be used for POES coverage

# Approach

- Normalize all imagers to well-calibrated" reference POES imager

  *- **Terra** & Aqua MODIS*
  *- TRMM VIRS*

*Minnis et al., JTech, 2002, 2008*

- System to ingest, analyze, and store satellite & auxiliary data

  *- U Wisc McIDAS, NASA, & NOAA NESDIS for data*
  *- apply 4/5-channel algorithms used for CERES*

*Minnis et al., TGRS, 2008, 2010*

- System to disseminate derived products

  *- digital files*
  *- online gif imagery & loops*
  *- North American domain to NCEP*

*http://www-angler.larc.nasa.gov*

# NASA Langley Cloud Products

## Standard, Single-Layer VISST/SIST

| | **Cloud** |
|---|---|
| 0.65, 1.6 µm Reflectances | Mask, Phase |
| 3.7, 6.7, 10.8 µm Temp | Optical Depth, IR emissivity |
| 12 or 13.3 µm Temp | Effective droplet Radius or ice crystal Diameter |
| Broadband Albedo | Liquid/Ice Water Path |
| Broadband OLR | Effective Temp, height, pressure |
| Clear-sky Skin Temperature | Top/ Bottom Pressure |
| Icing Potential** | Top/ Bottom Height |
| Pixel Lat, Lon | |
| Pixel SZA, VZA, RAZ | |

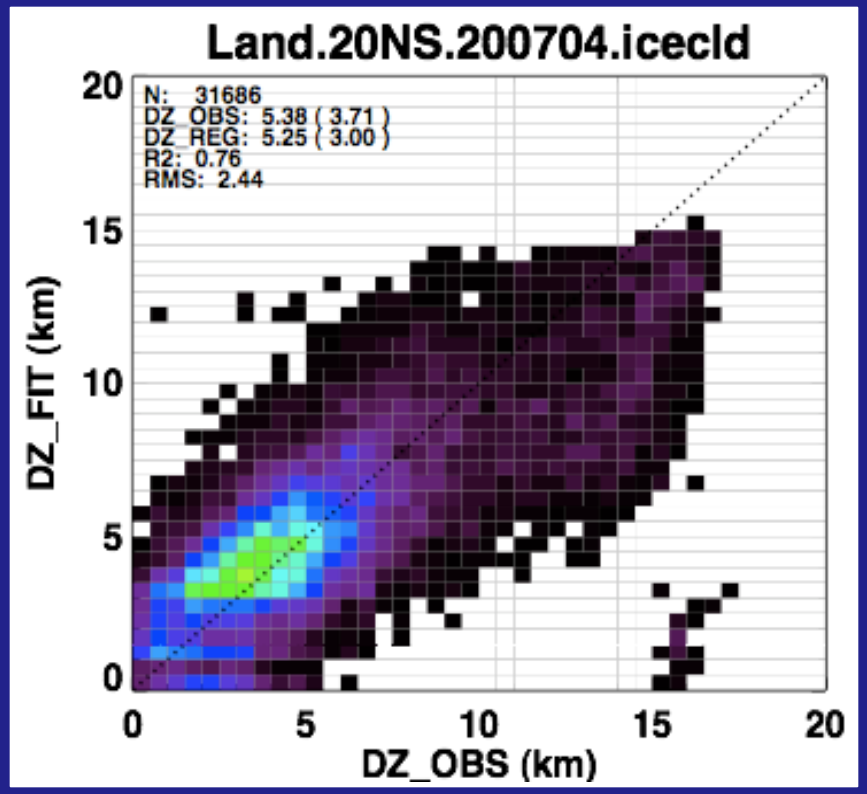
## Multi-Layer, CIRT, $CO_2$ channel only

*Upper & lower cloud*

| | |
|---|---|
| Multilayer ID (single or 2-layer) | |
| effective temperature | optical depth, thickness |
| effective particle size | ice or liquid water path |
| height, top/base height | pressure |

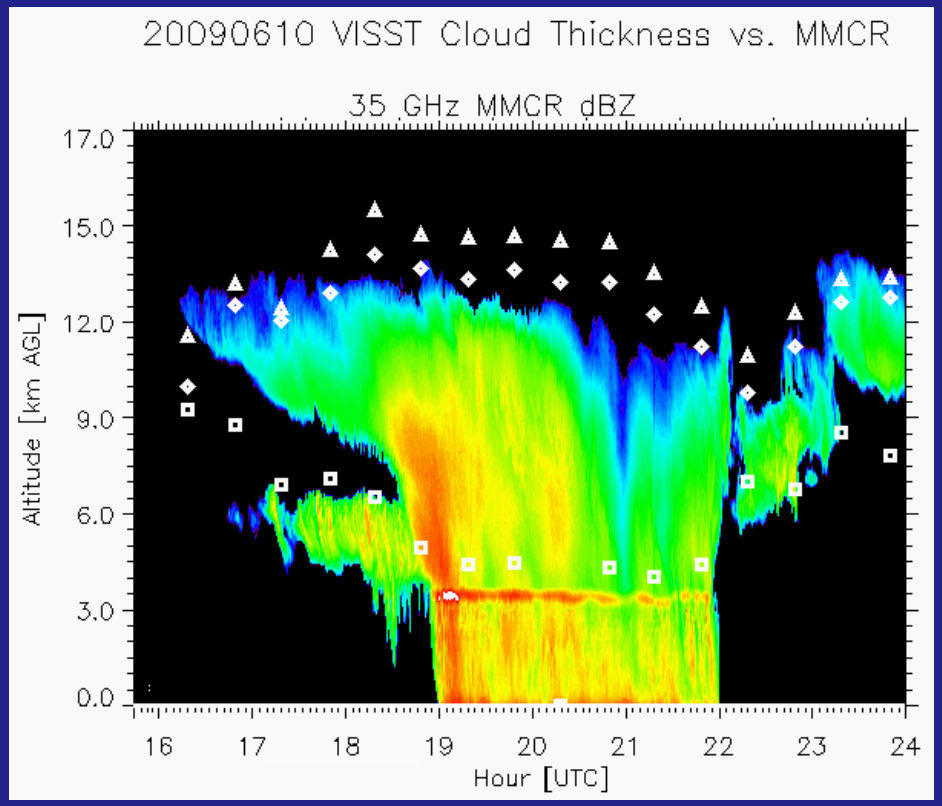
# Cloud Thickness from CloudSat, CALIPSO & GOES

CALIPSO/CloudSat ice cloud thickness (DZ_OBS) vs GOES thickness, April 2007




DZ_FIT based on empirical fit to CALIPSO/CloudSat data from different month

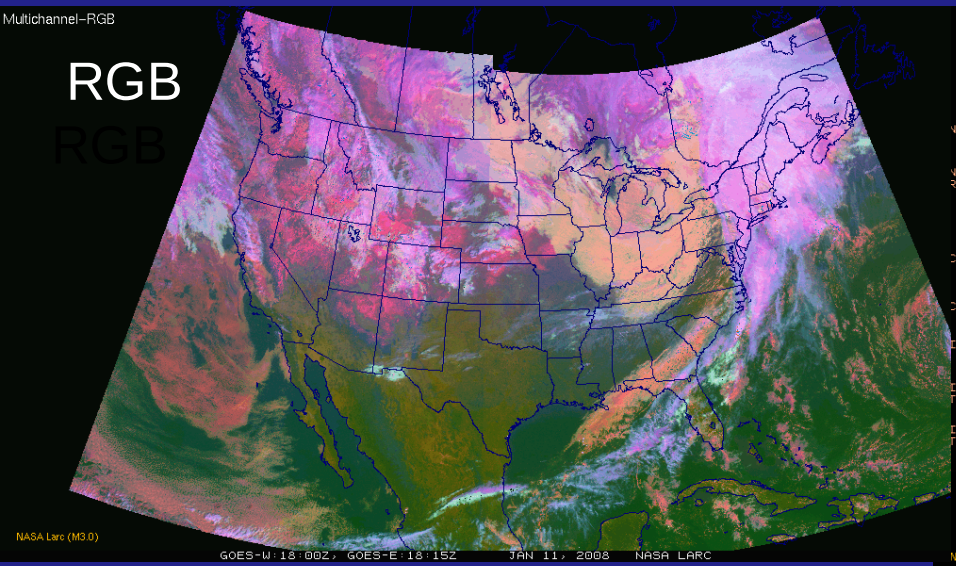
Cloud boundaries from GOES-12 over ARM SGP radar, 10 June 2009

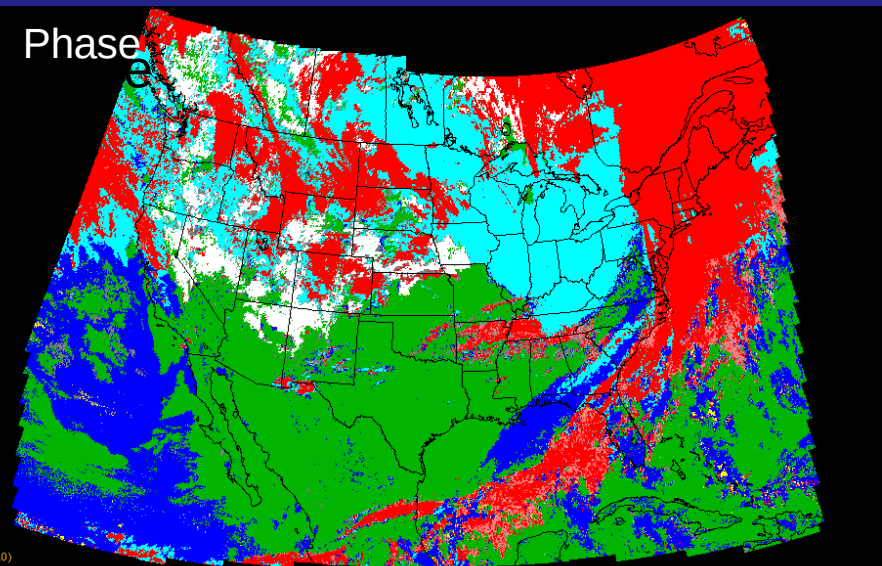


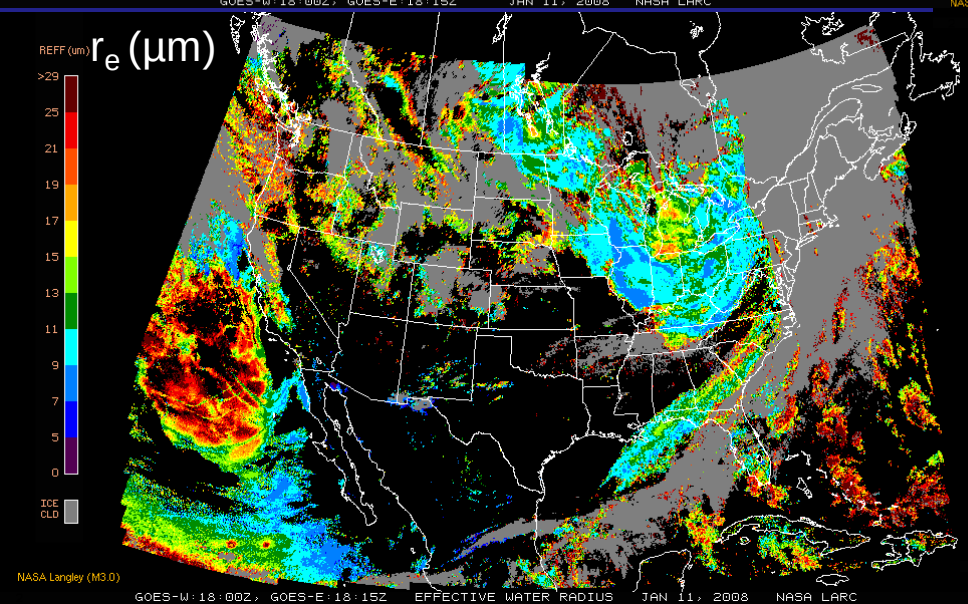

- Triangle – physical top
- diamond – effective top
- square - base

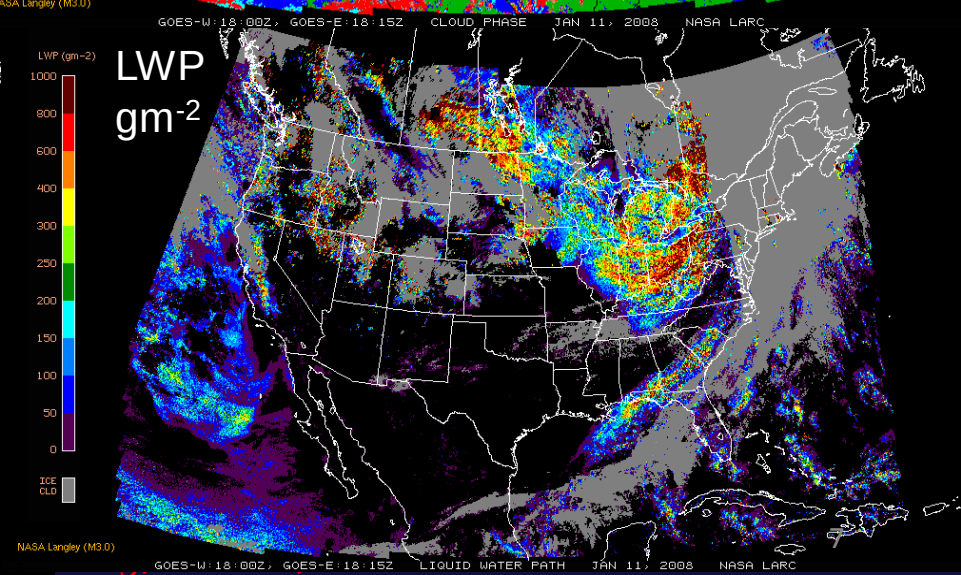
# CONUS Domain Cloud Products
# 1815 UTC, 8 Jan 2008

Light Blue - Supercooled



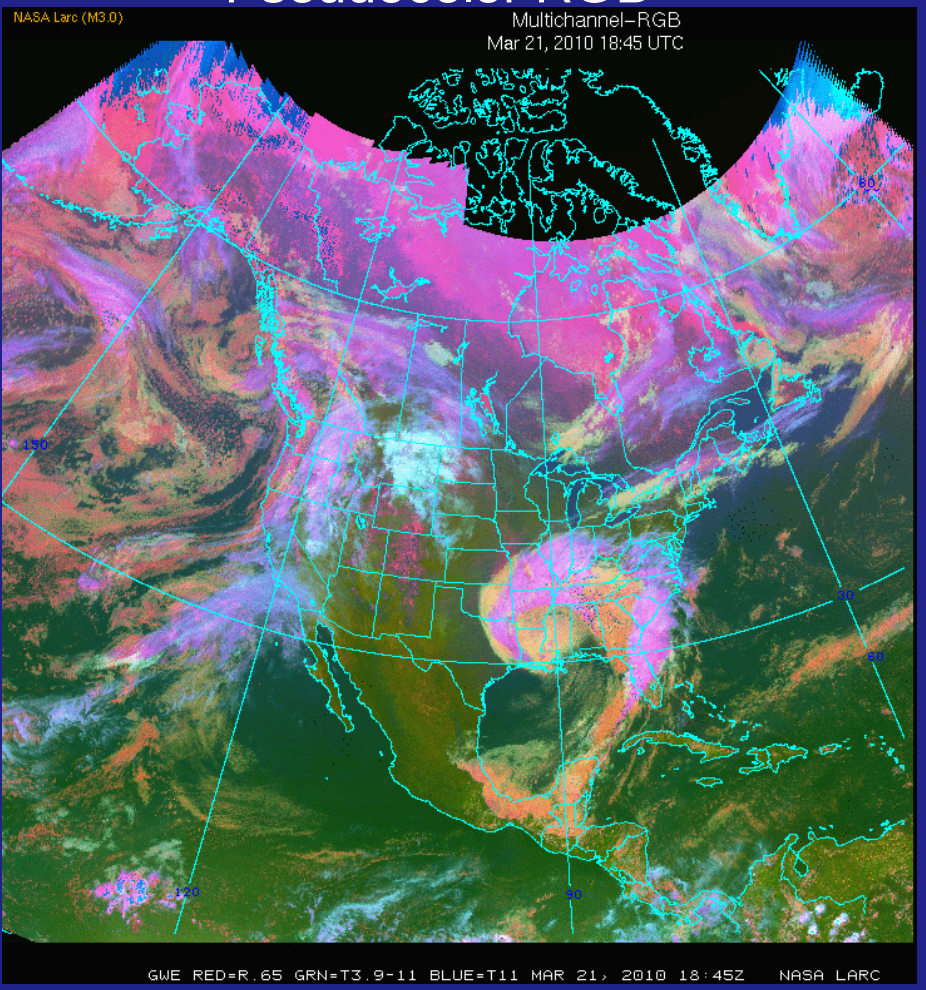



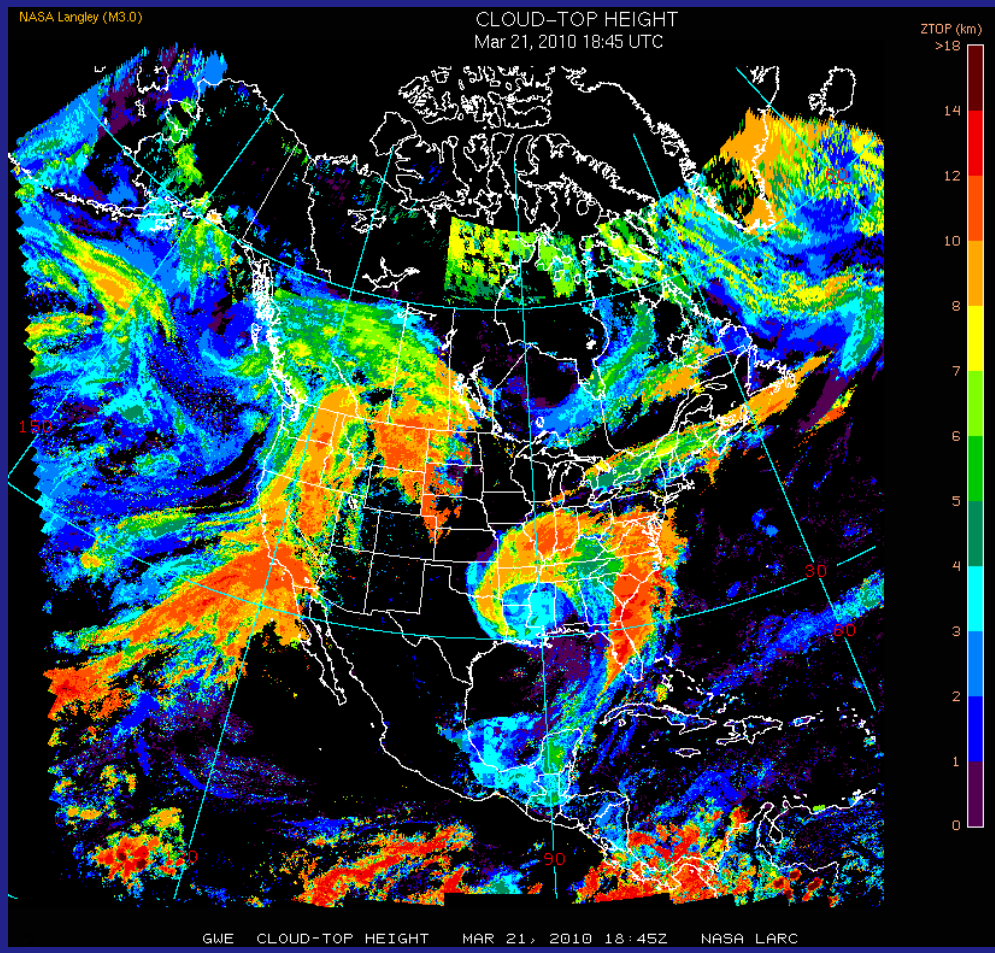



# North American Domain
## 1845 UTC, 21 March 2010

Pseudocolor RGB

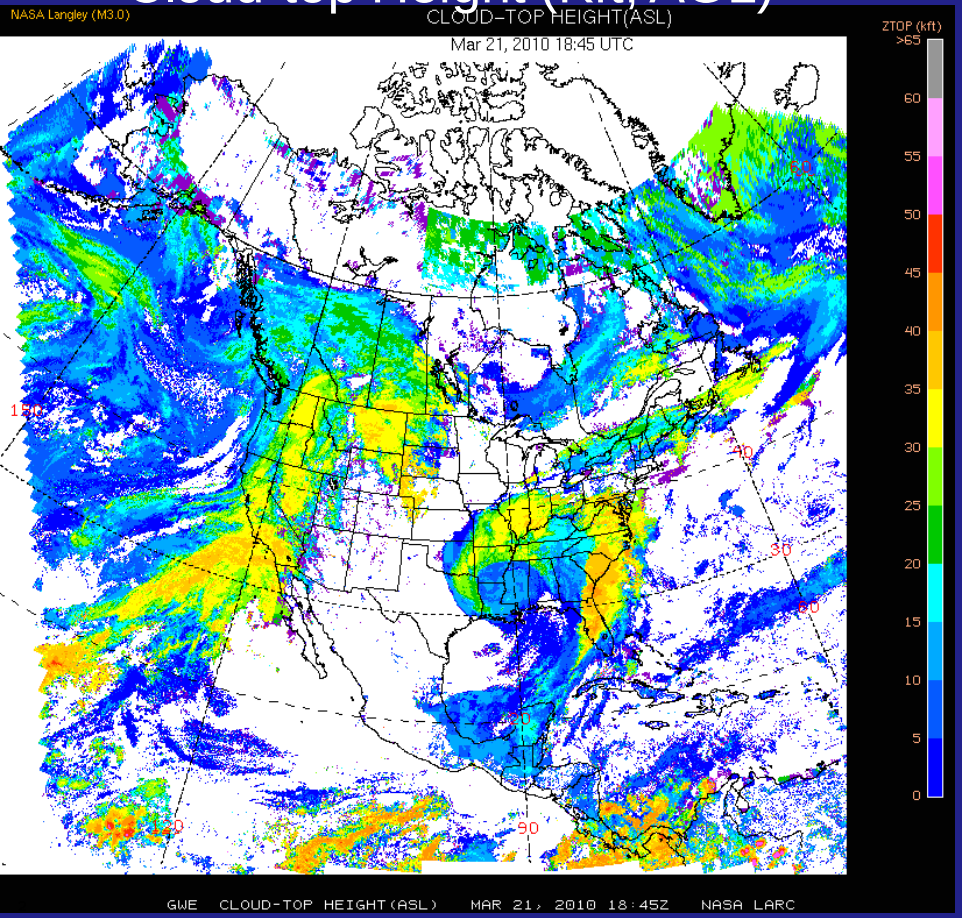



Cloud-top Height (km)

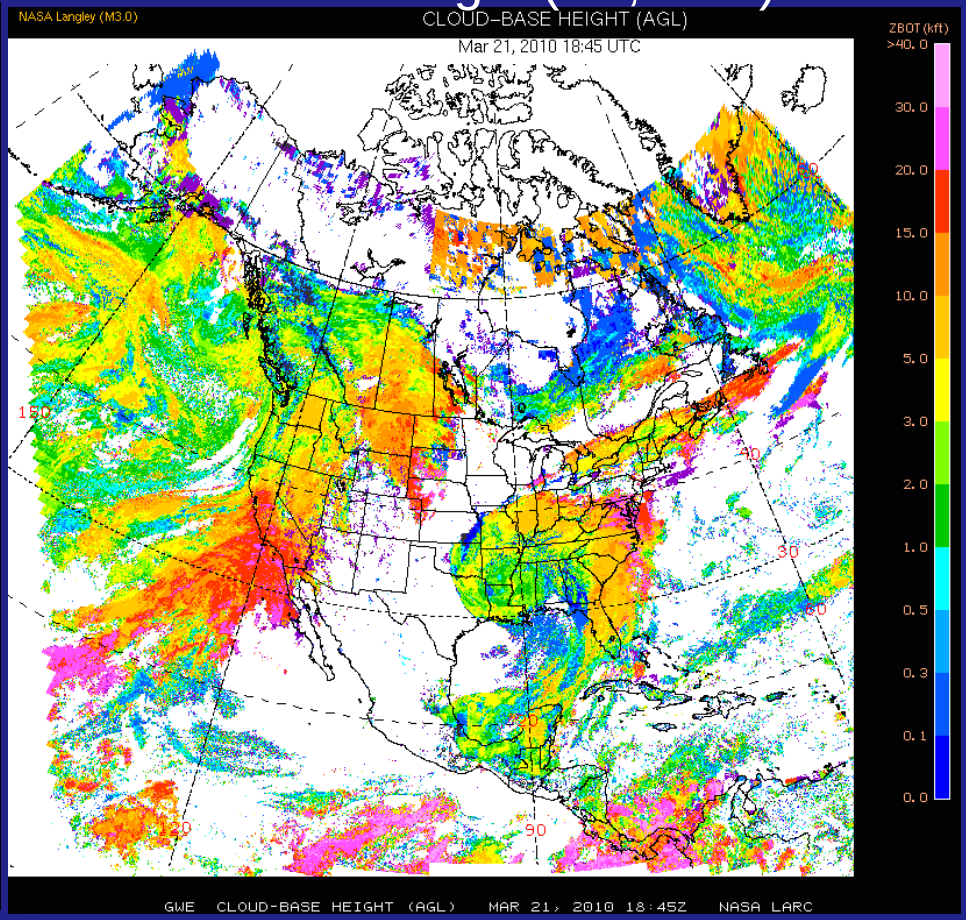


# North American Domain
## 1845 UTC, 21 March 2010

Cloud-top Height (Kft, AGL)



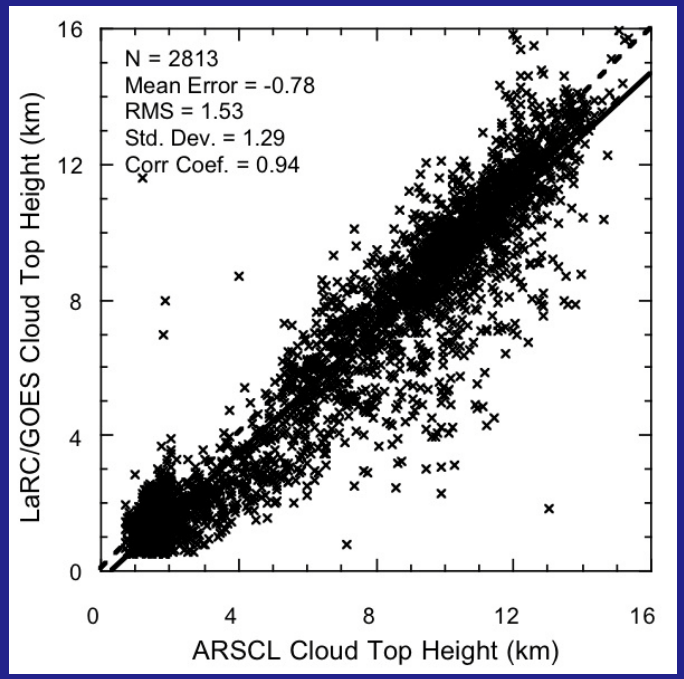

Cloud-base Height (Kft, AGL)



# Other Aspects of Icing & Aviation Safety

- Need estimates of layers containing icing
  - top and base (ceiling) heights
  - profiles of water content & temperature

Single-layer cloud-top heights over ARM SGP, 2000-2004




*Smith et al., GRL, 2008*

Errors in GOES Single-layer $Z_{top}$, ARM SGP, 2000-04

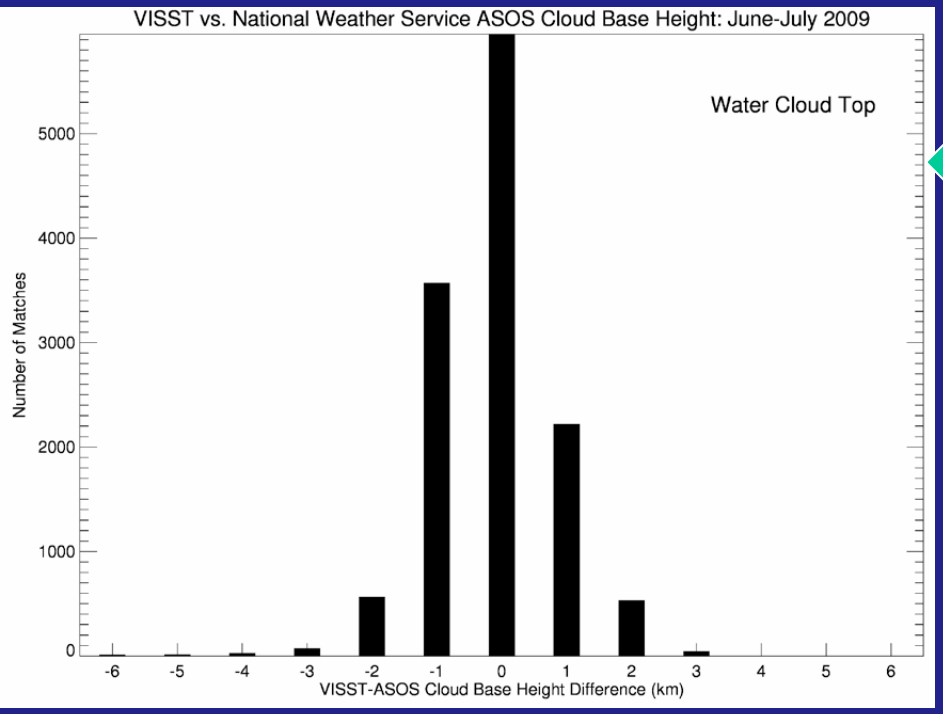
| Algorithm | Bias (km) | σ (km) | R |
|---|---|---|---|
| All clouds | | | |
| LaRC | -0.8 | 1.3 | 0.94 |

- Low cloud-top height rms error only 0.8 km

# Cloud Base Heights

Cloud thickness estimated as function of optical depth, temperature, water-path, Reff & phase: cloud base height = top - thickness

Histogram, GOES-ASOS




VISST Cloud Base vs. National Weather Service Automated Surface Observing System (ASOS) Central USA: June-July 2009

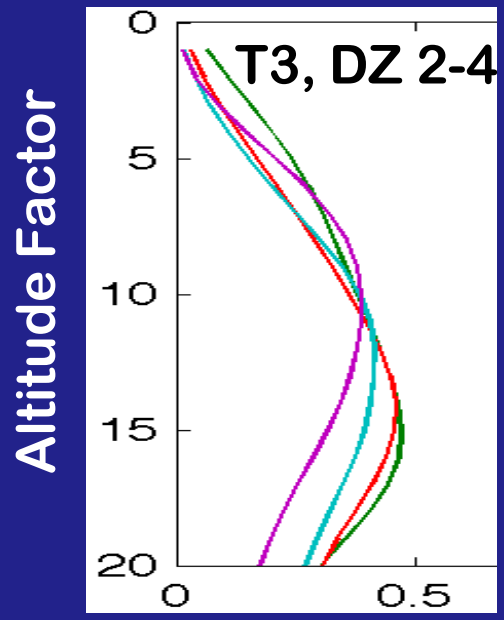
| | RMS Error (km) | Bias (km) | Number of Matches |
|---|---|---|---|
| Water Cloud Base | 0.99 | -0.14 | 13024 |
| Ice Cloud Base | 3.13 | 2.43 | 8947 |

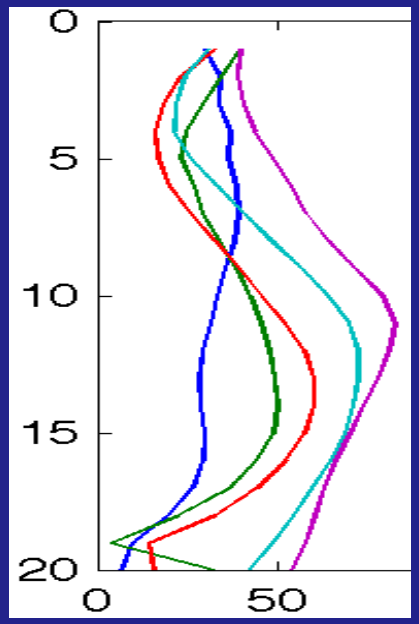
- Base height error only slightly greater than top error for water clouds
- Base height error large for ice clouds (precip clouds included)

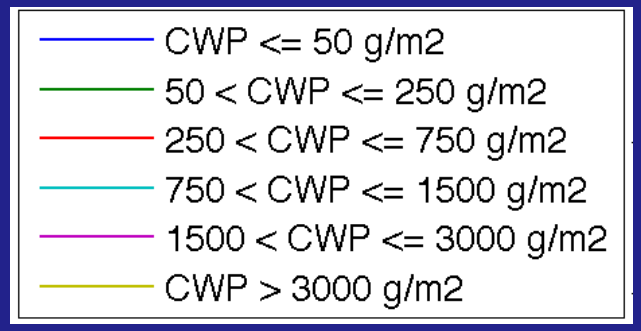
# Developing Method for Profiling Ice/Liq Water Contents

- Develop avg normalized profiles of IWC/LWC from GOES-CloudSat data
  - *Use variety of categories based on cloud water path CWP, $T_{eff}$, DZ*

| Category | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| DZ (km) | 0-1 | 1-2 | 2-4 | 4-7 | 7 + | - |
| T (K) | < 220 | 220-235 | 235-250 | 250-273 | 273 + | - |
| CWP ($gm^{-2}$) | < 50 | 50-250 | 250-750 | 750-1500 | 1500-3000 | 3000 + |

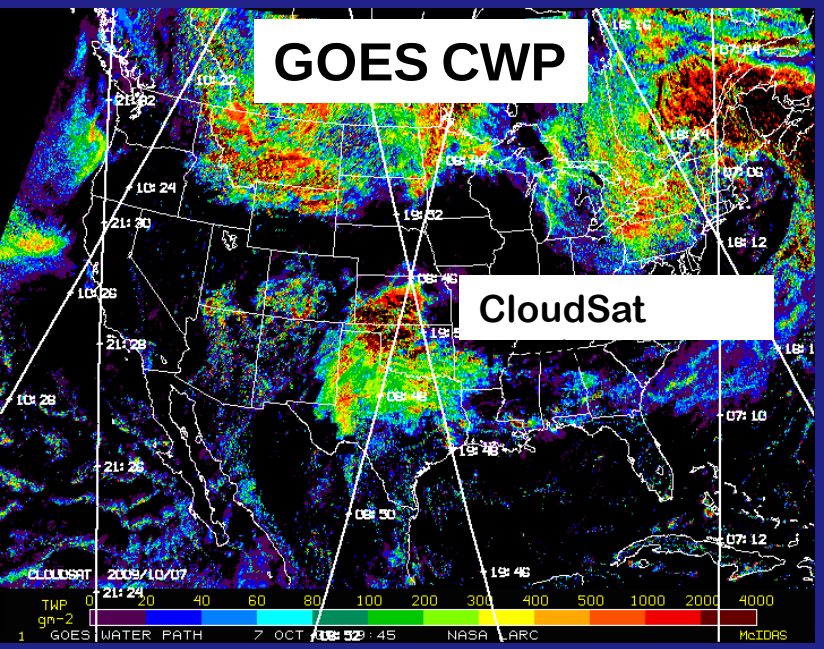


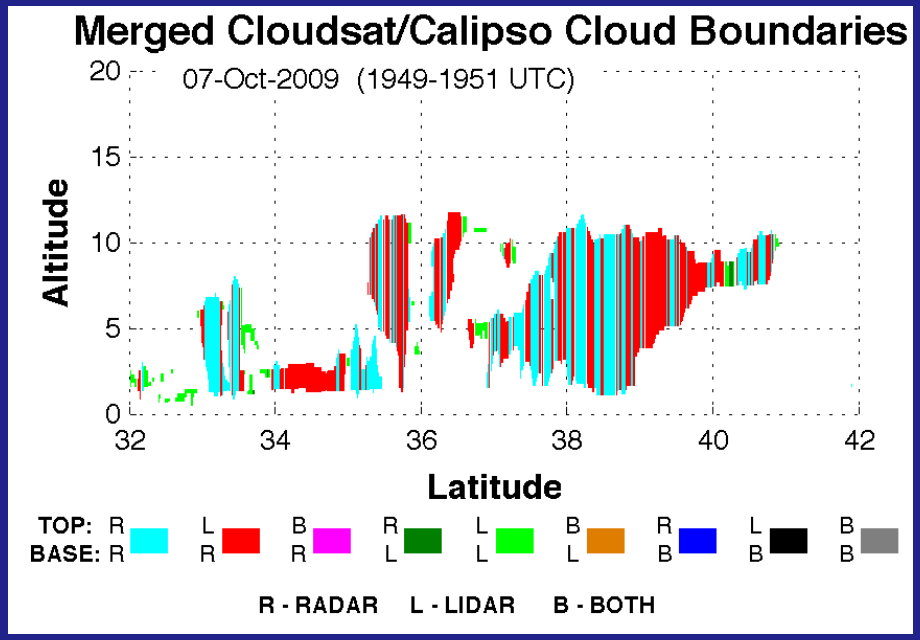



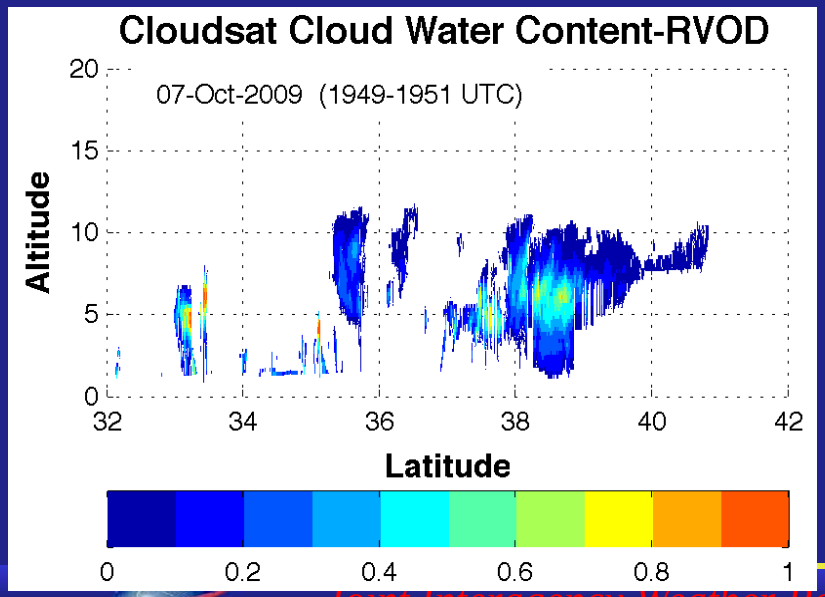



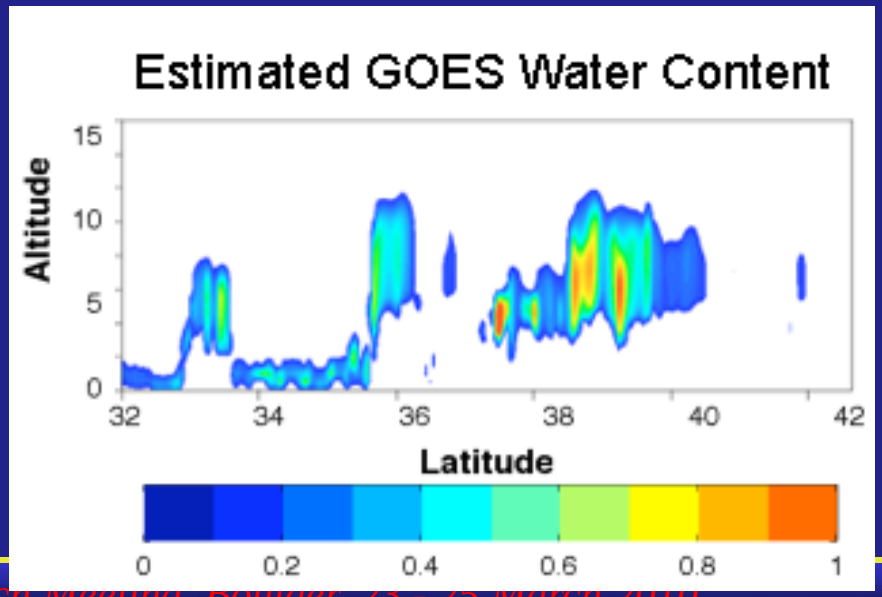

- Reverse process provides profile for a given pixel

# Testing with CloudSat, 20 UTC, 7 Oct. 2009

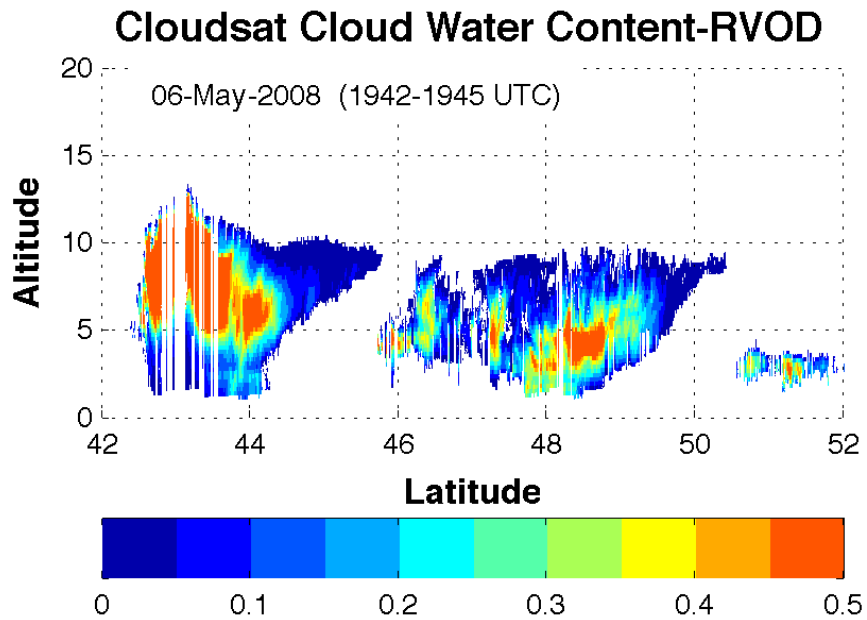


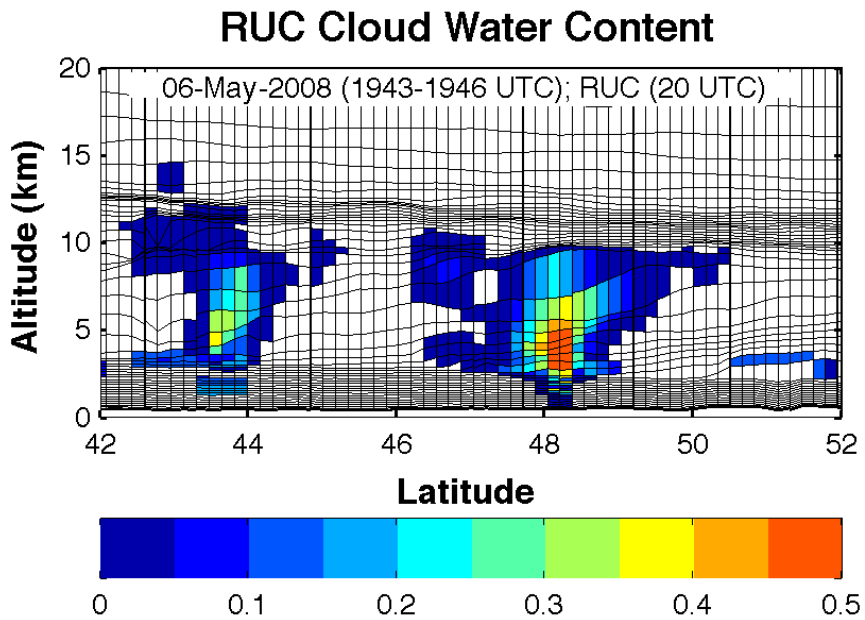



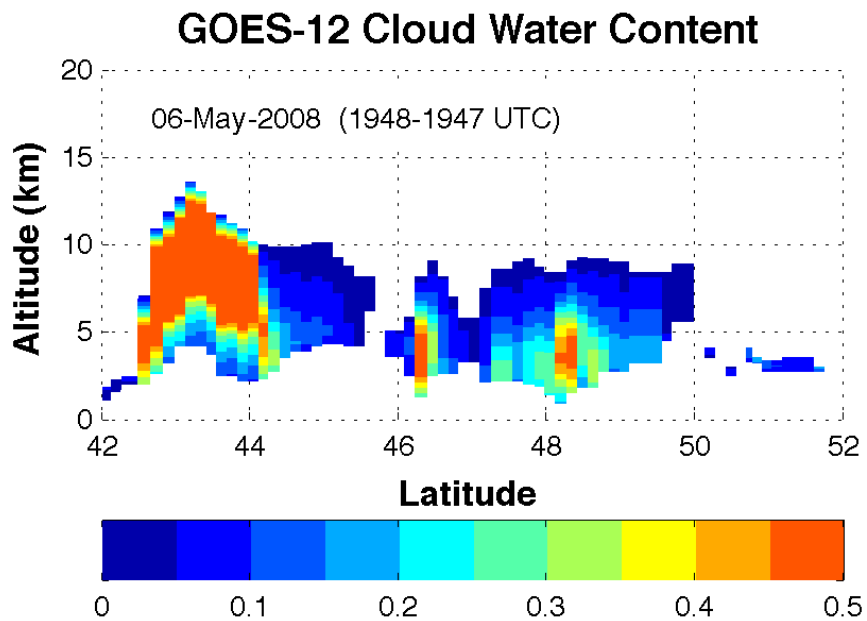



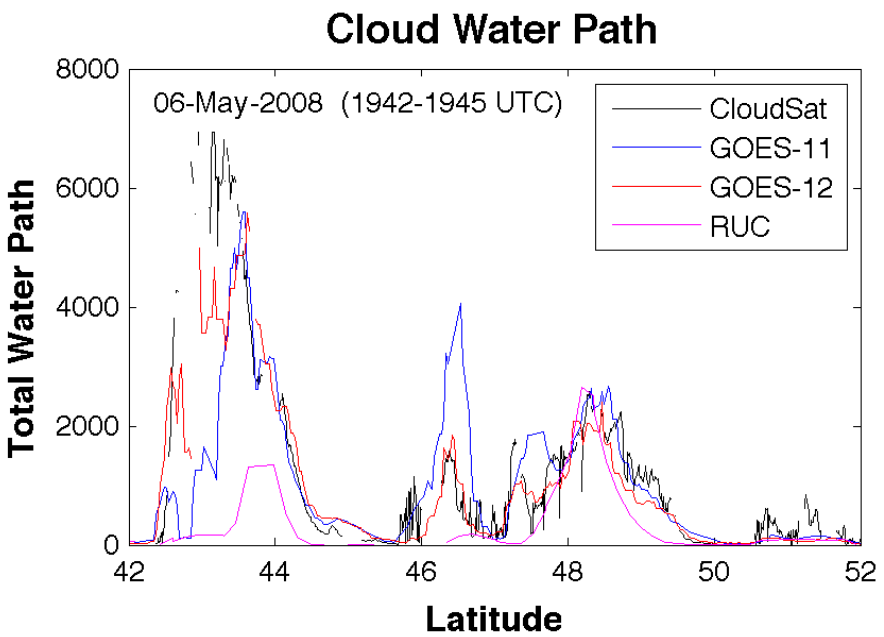



# Testing with CloudSat, 19 UTC, 6 May 2008

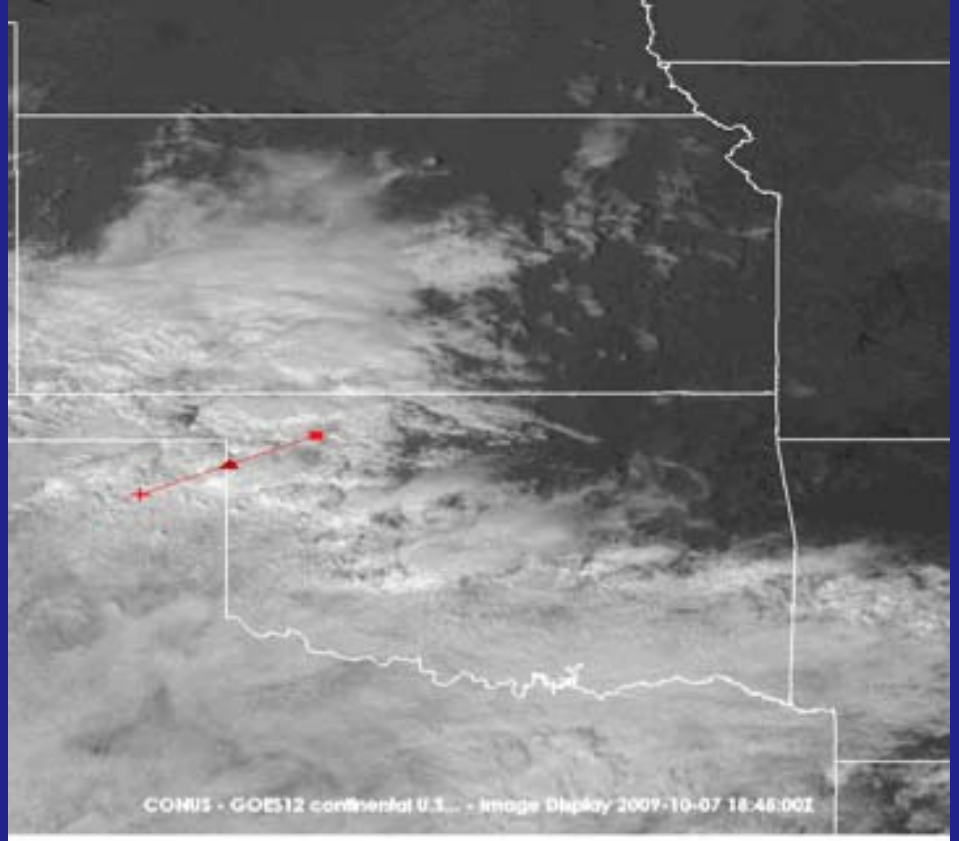


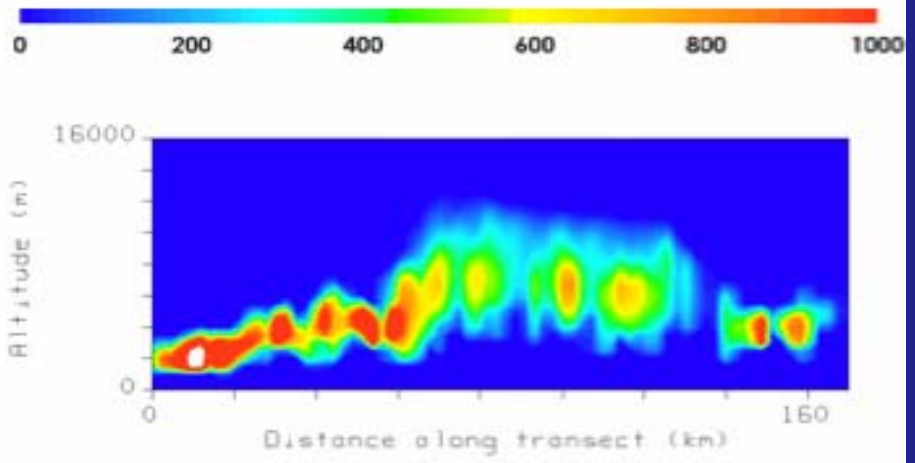



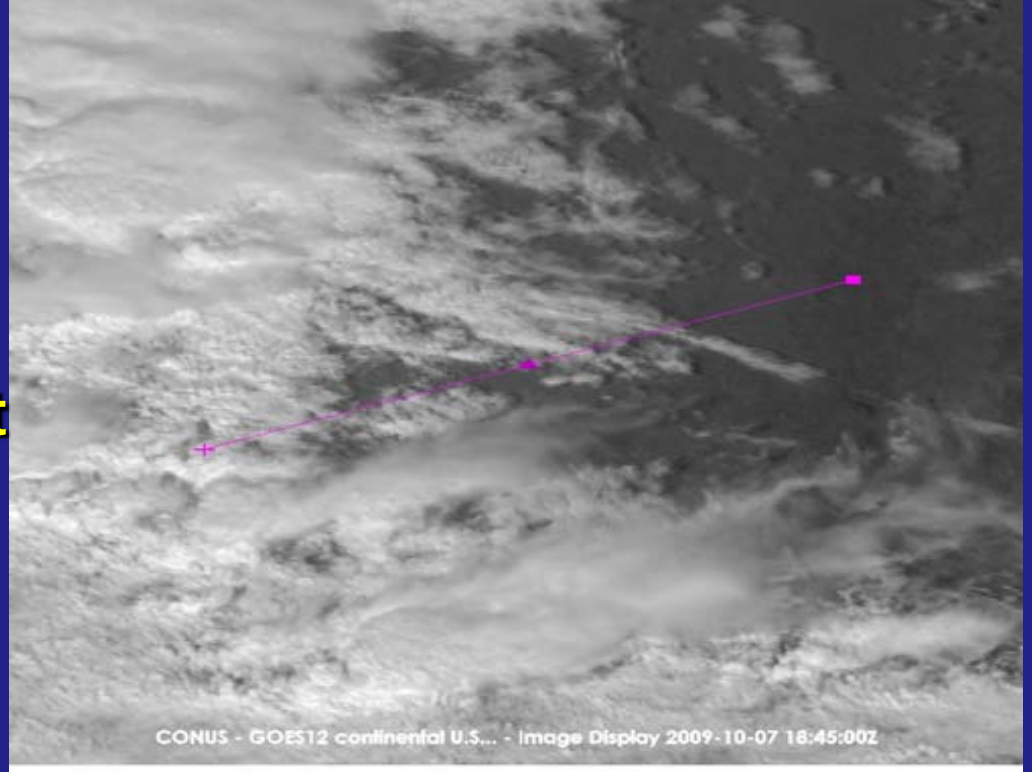



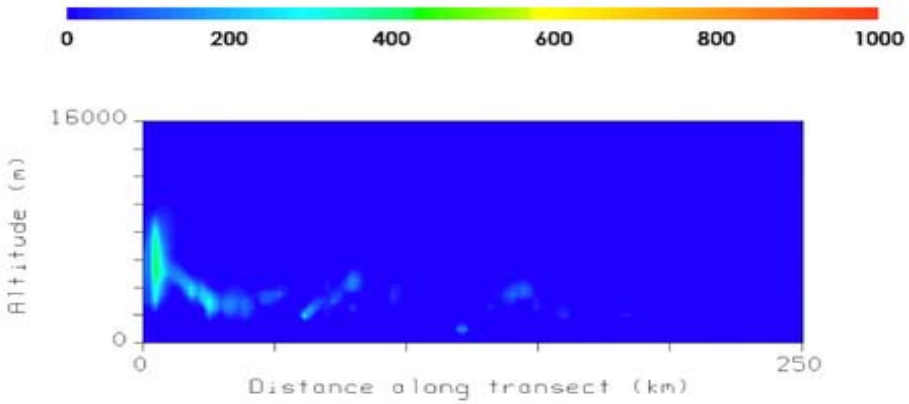
**Following water content profiles for selected cloud transect**
**7 October, 2009**
**1845 – 2245 UTC**



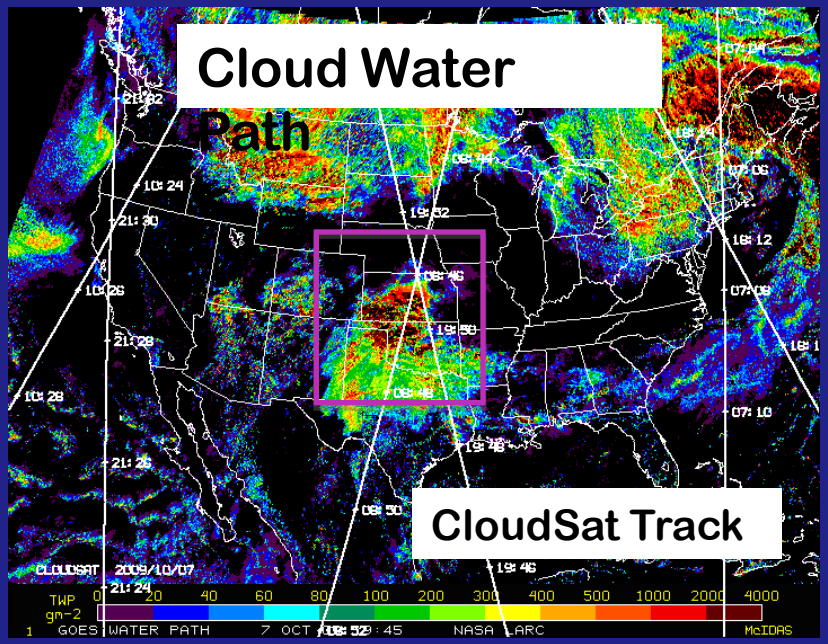



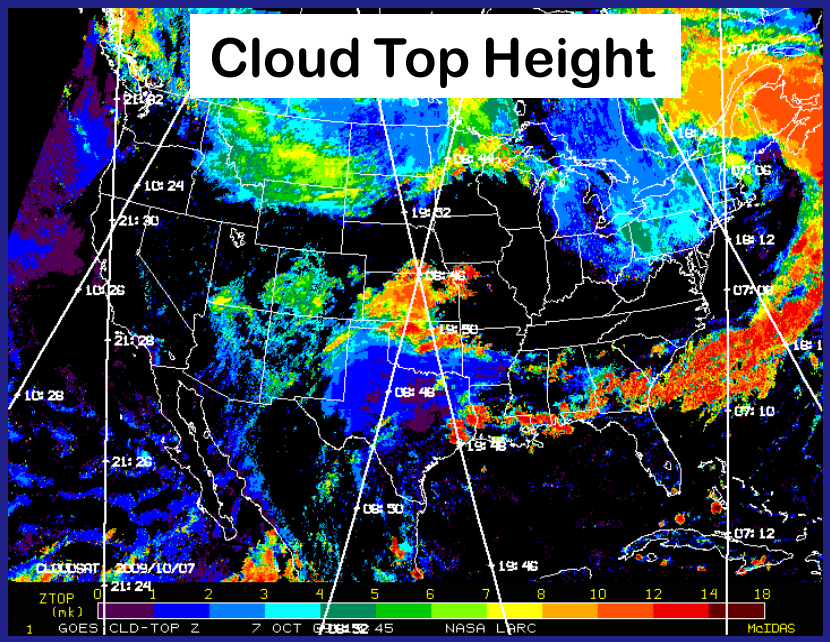
**Following water content profiles for selected fixed transect**
**7 October, 2009**
**1845 – 2245 UTC**

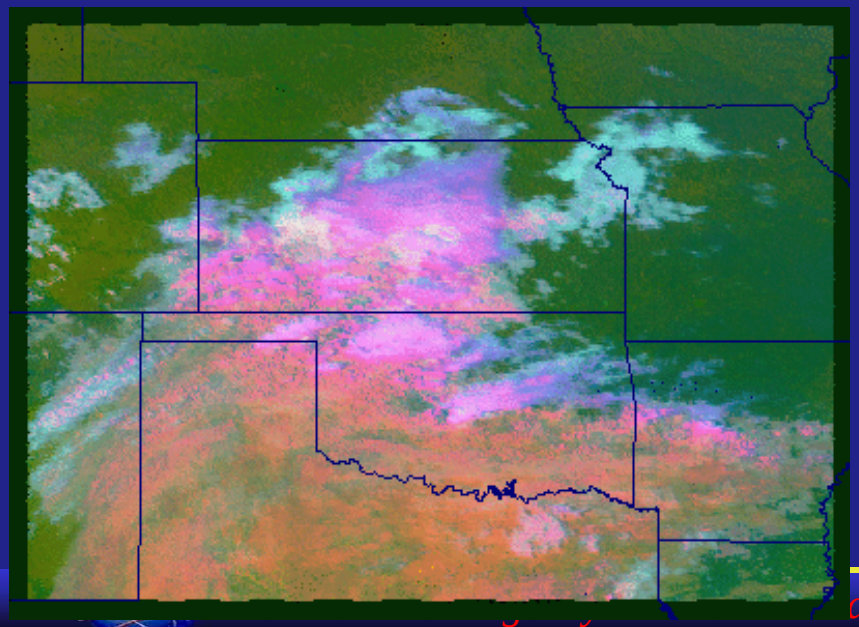


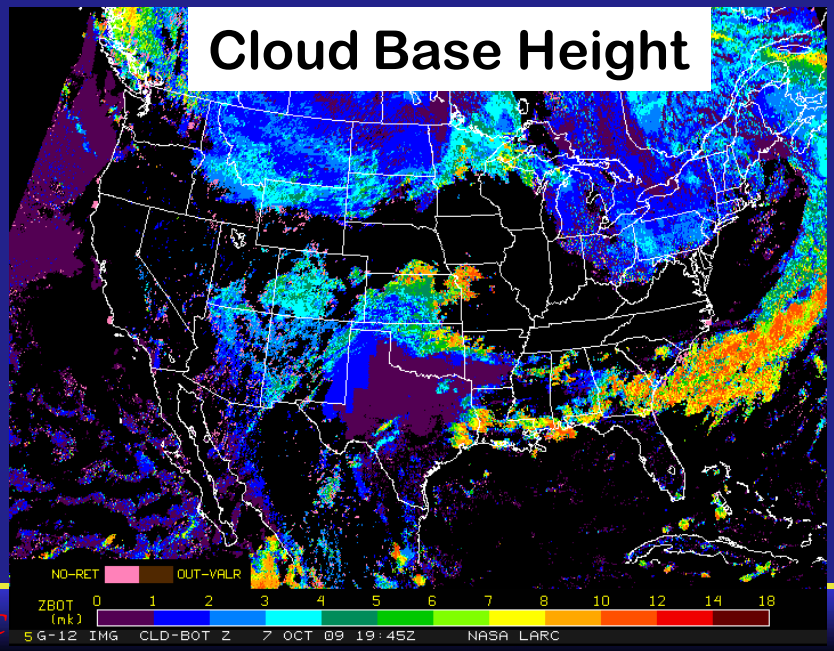



# GOES-12 Cloud Property Retrievals, 1945 UTC, 7 Oct 2009

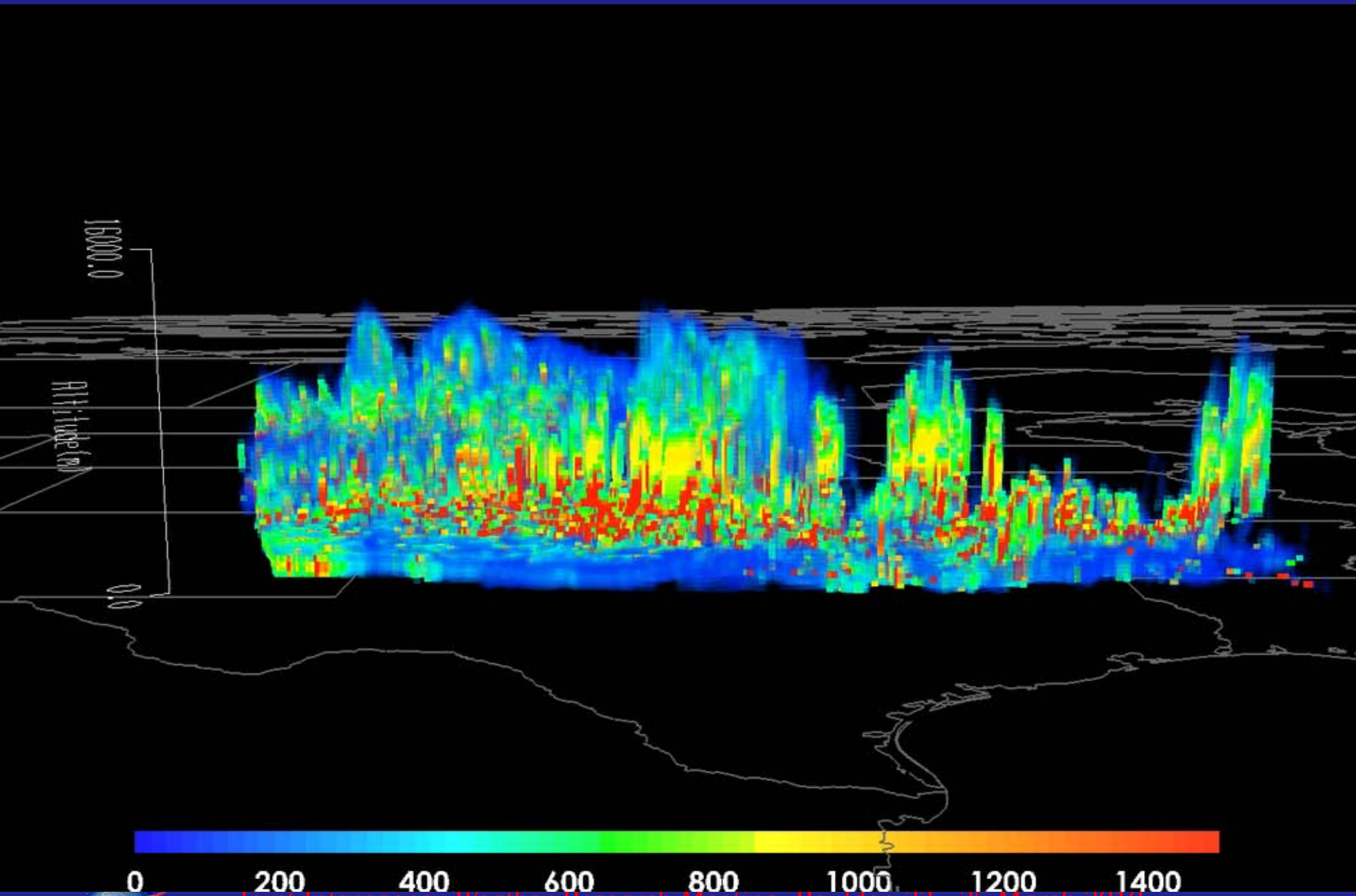


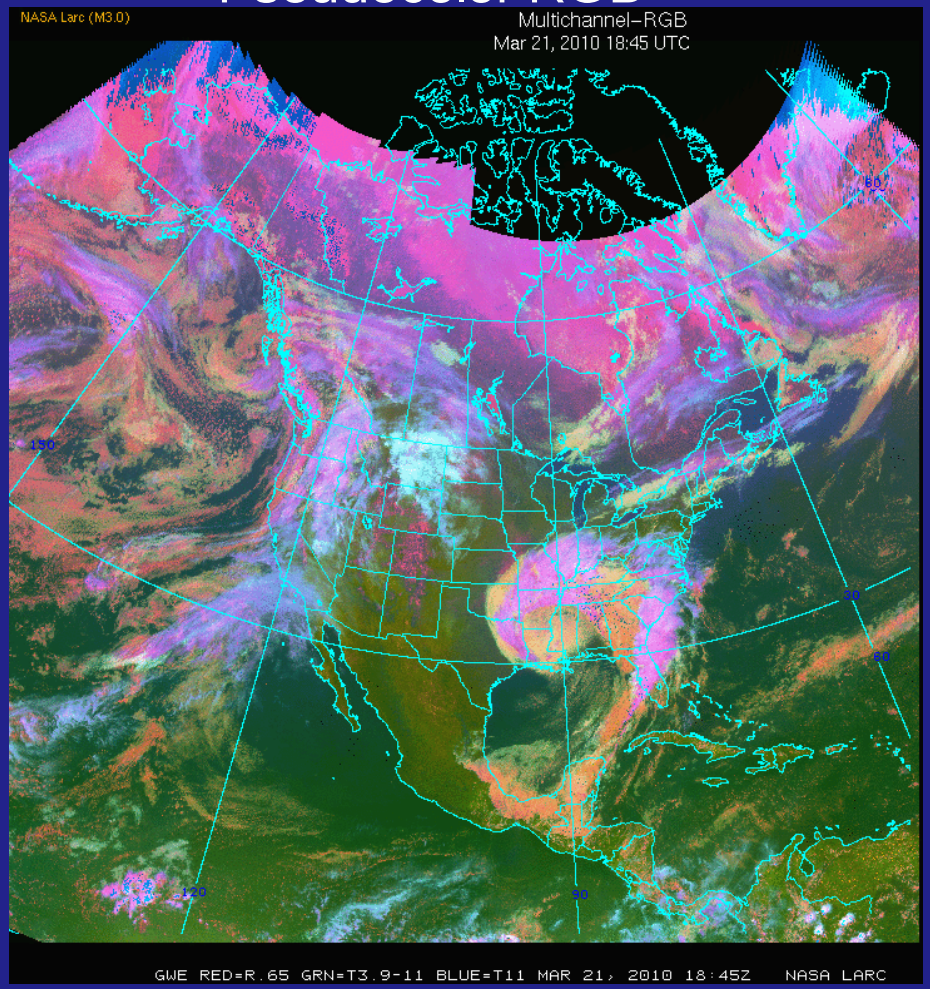


# GOES-12 4-D Cloud Water Content Profiles, ($gm^{-2}$), 7 Oct 2009

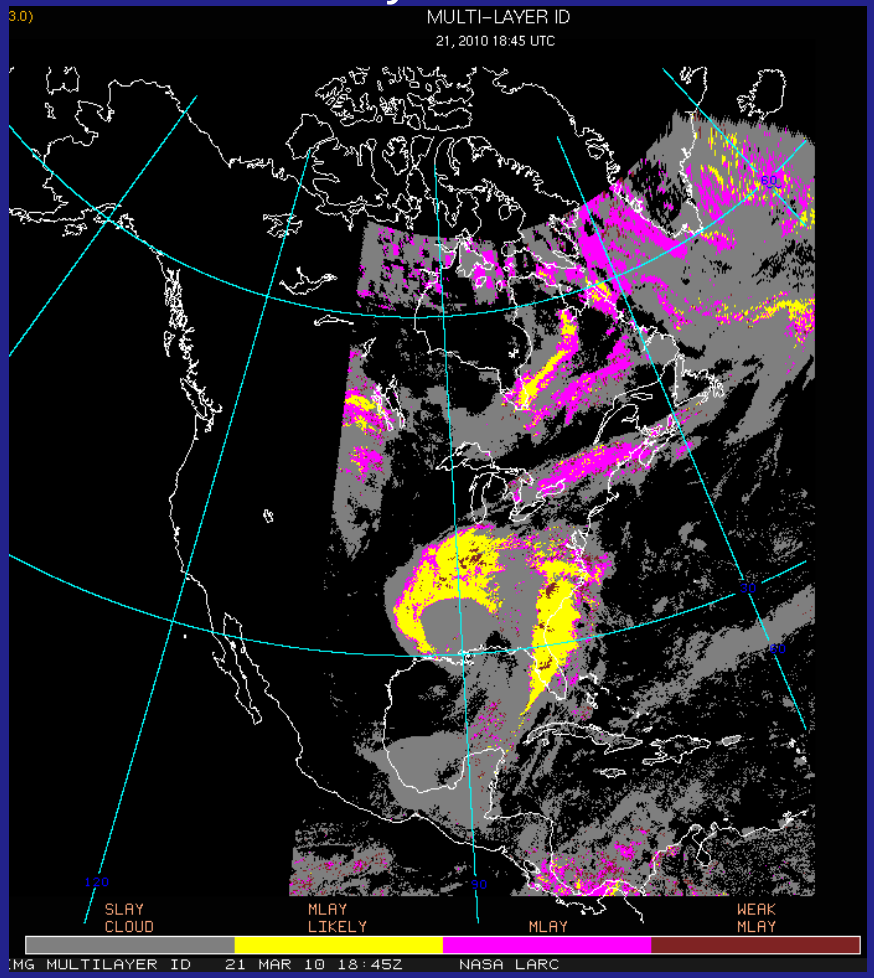


# North American Domain
## 1845 UTC, 21 March 2010 Multilayer Cloud Detection

Pseudocolor RGB



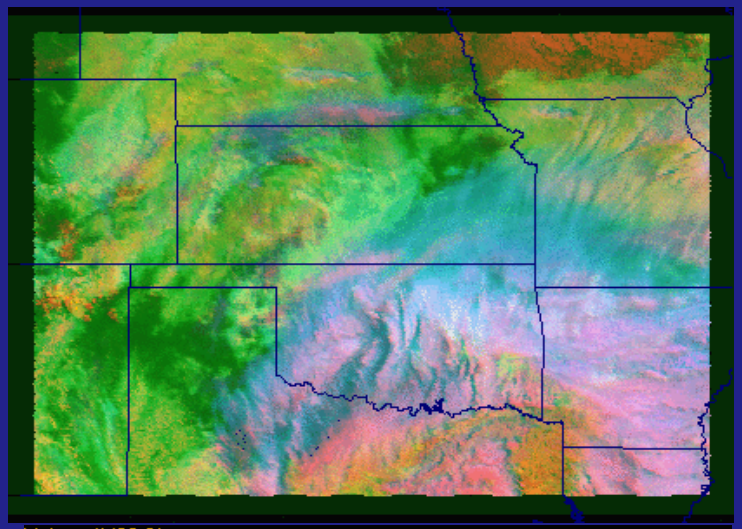

Multi-layer Cloud ID

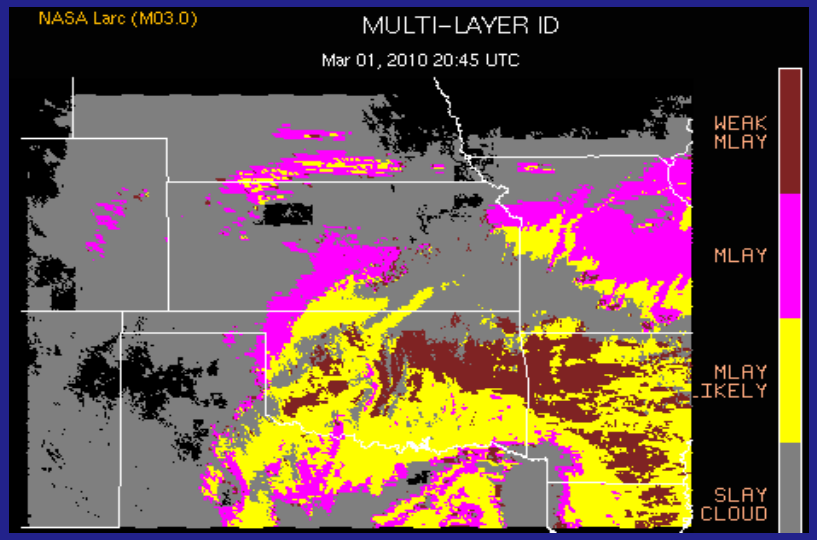


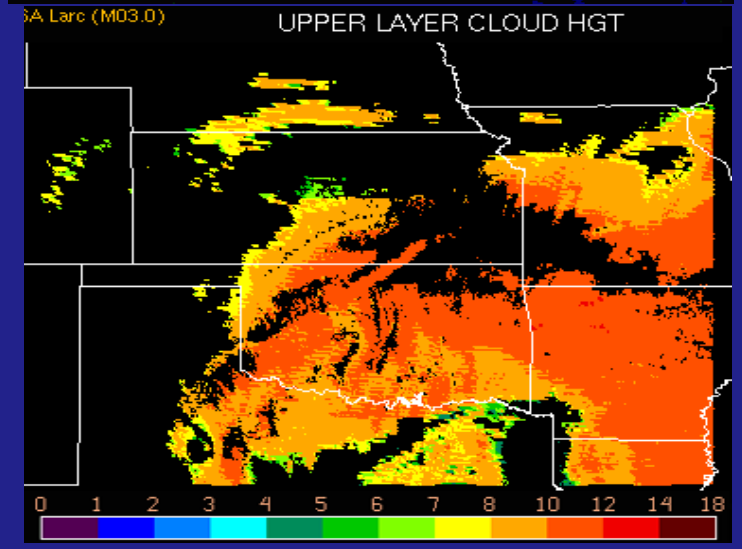

*Detecting & retrieving multilayered clouds improves characterization of 3-D fields*

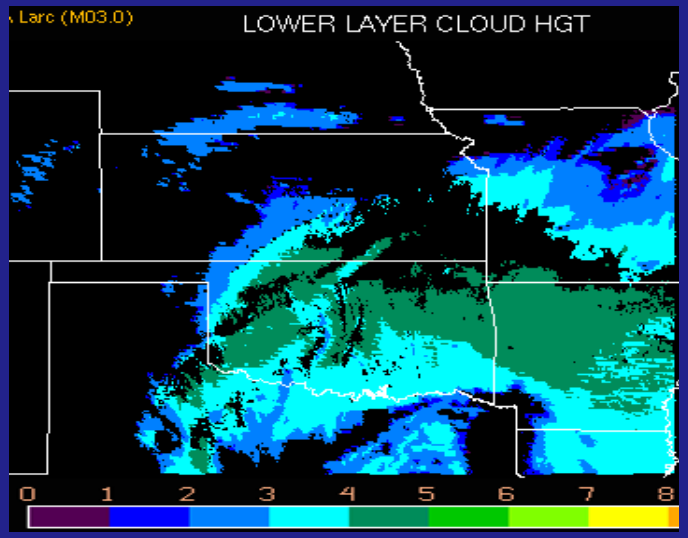
# Multilayer Clouds Over Southern Great Plains

GOES-12, 1 Mar 2010, 2045 UTC Multilayer Cloud Heights (km) over SGP Domain

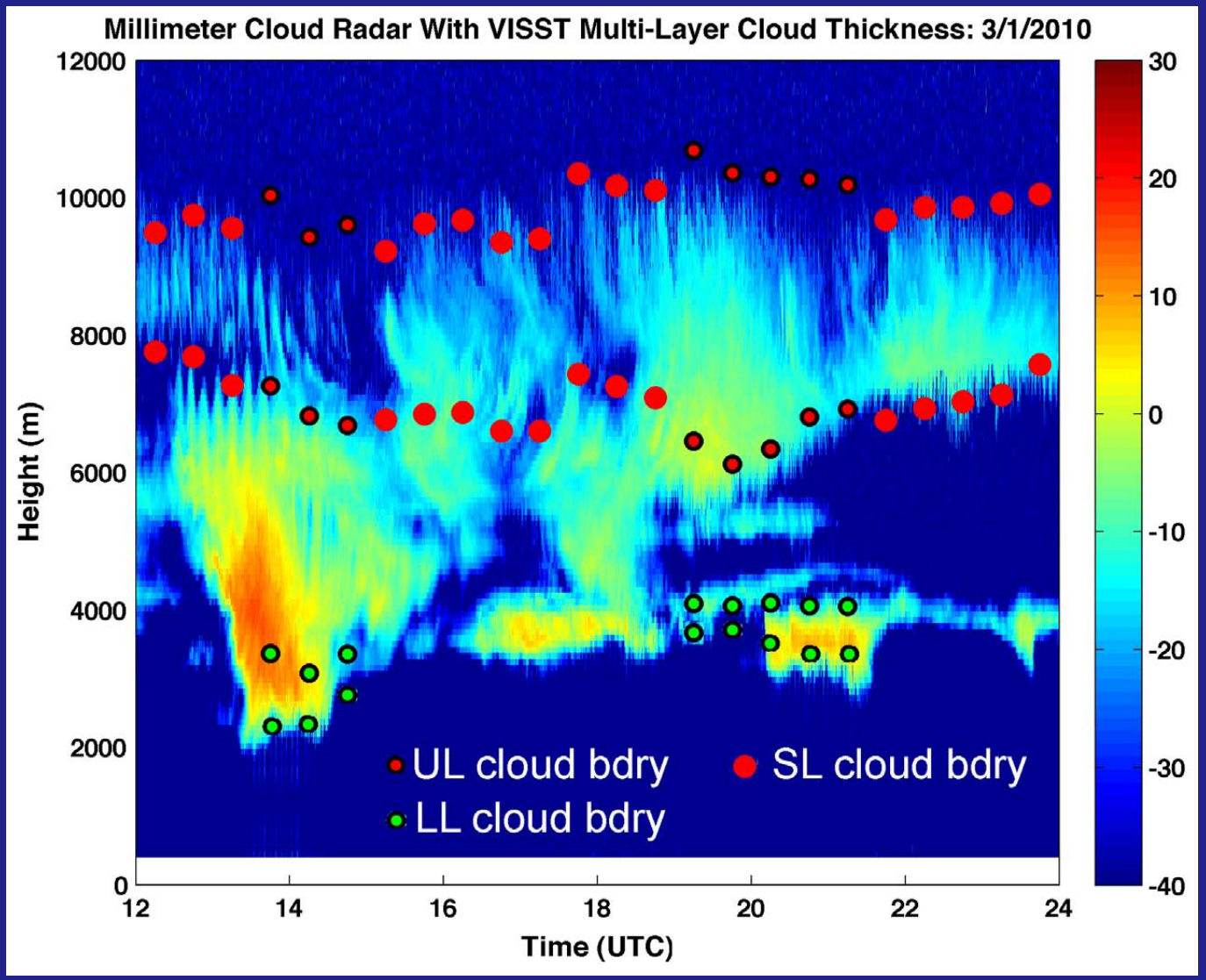




# Comparing with ARM Cloud Radar, Lamont, OK
# 1 March 2010

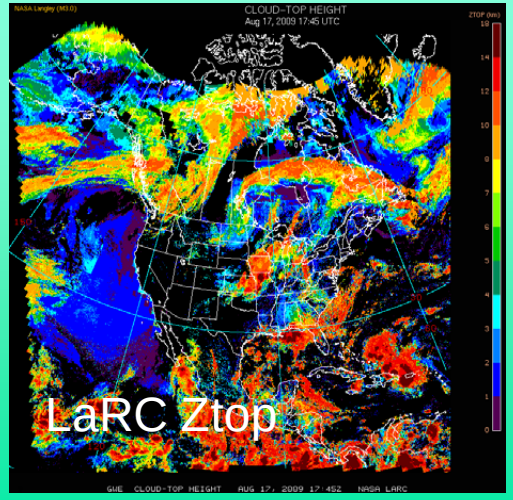


# Using the LaRC Cloud Products in the NOAA Rapid Update Cycle (RUC) Numerical Weather Prediction Model for Aviation Safety

**Observations**
Surface: T, RH, precip, radar, METARs,…
Aircraft: PiREPs

**Common Satellite Observations**
SST, cloud winds, T(z)

**Satellite Cloud Observations**

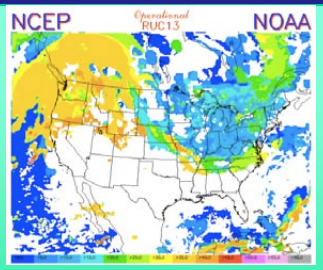



**Forecast fields** ($x_1'$, $x_2'$, ….) at $t_{0-1}$

**Assimilate data** ($x_1$, $x_2$,…) at $t_0$ into model using physics parameterizations

**Analysis fields** ($x_1'$, $x_2'$, ….) at $t_0$ initialize forecast

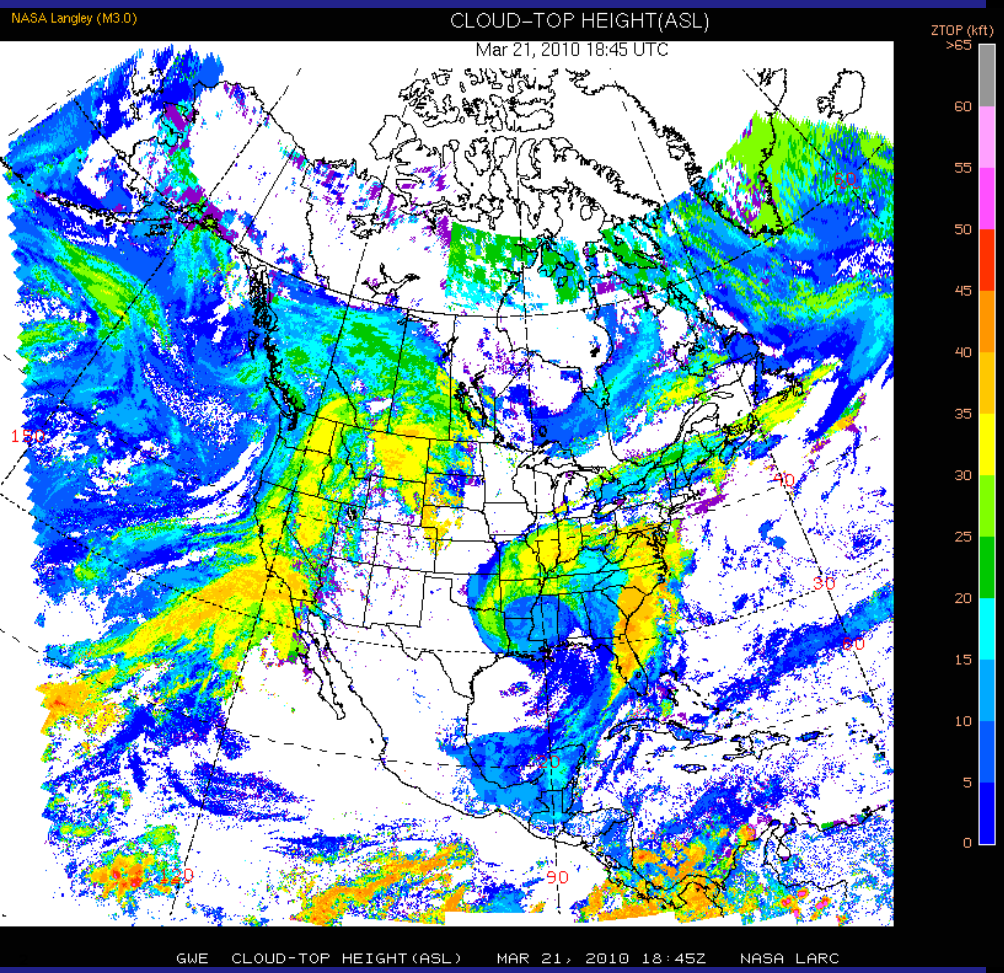
**Run forecast model**



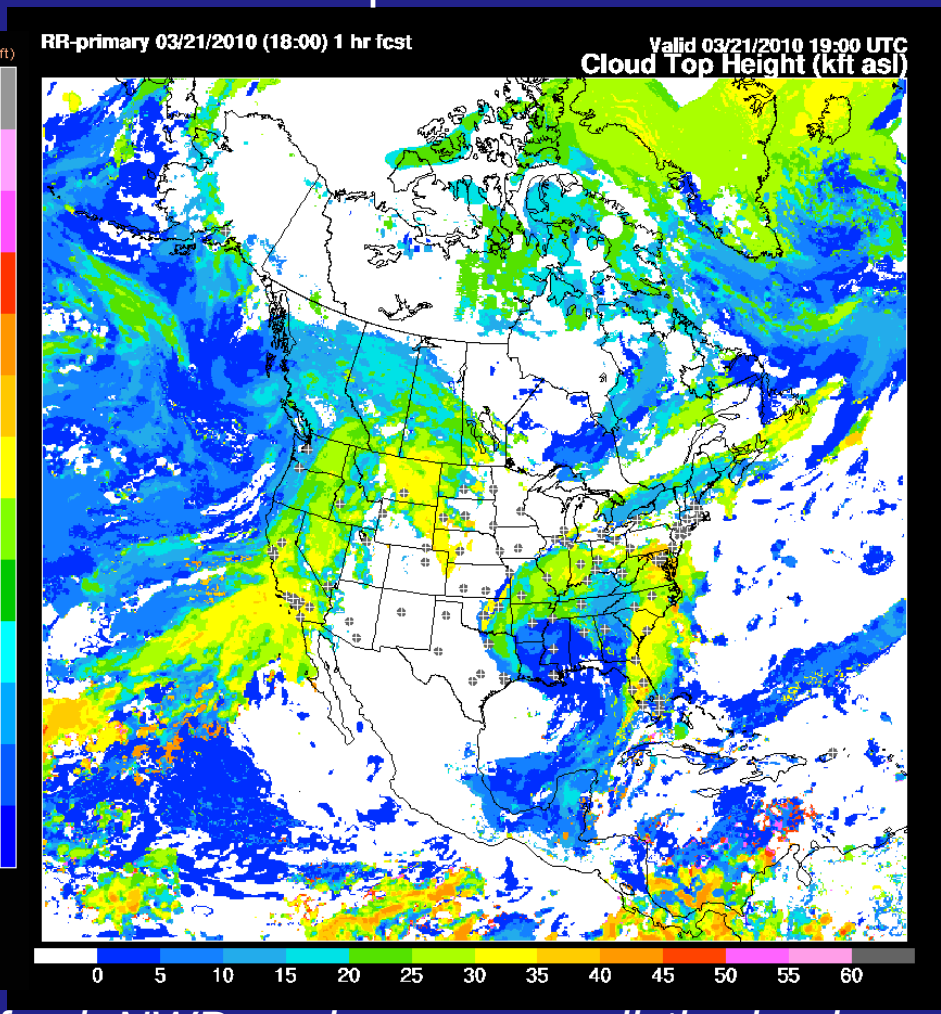

**Forecast fields** ($x_1'$, $x_2'$, ….) at $t_1$

# North American Domain
## 1845 UTC, 21 March 2010 Cloud-top Heights (Kft, AGL)

GOES



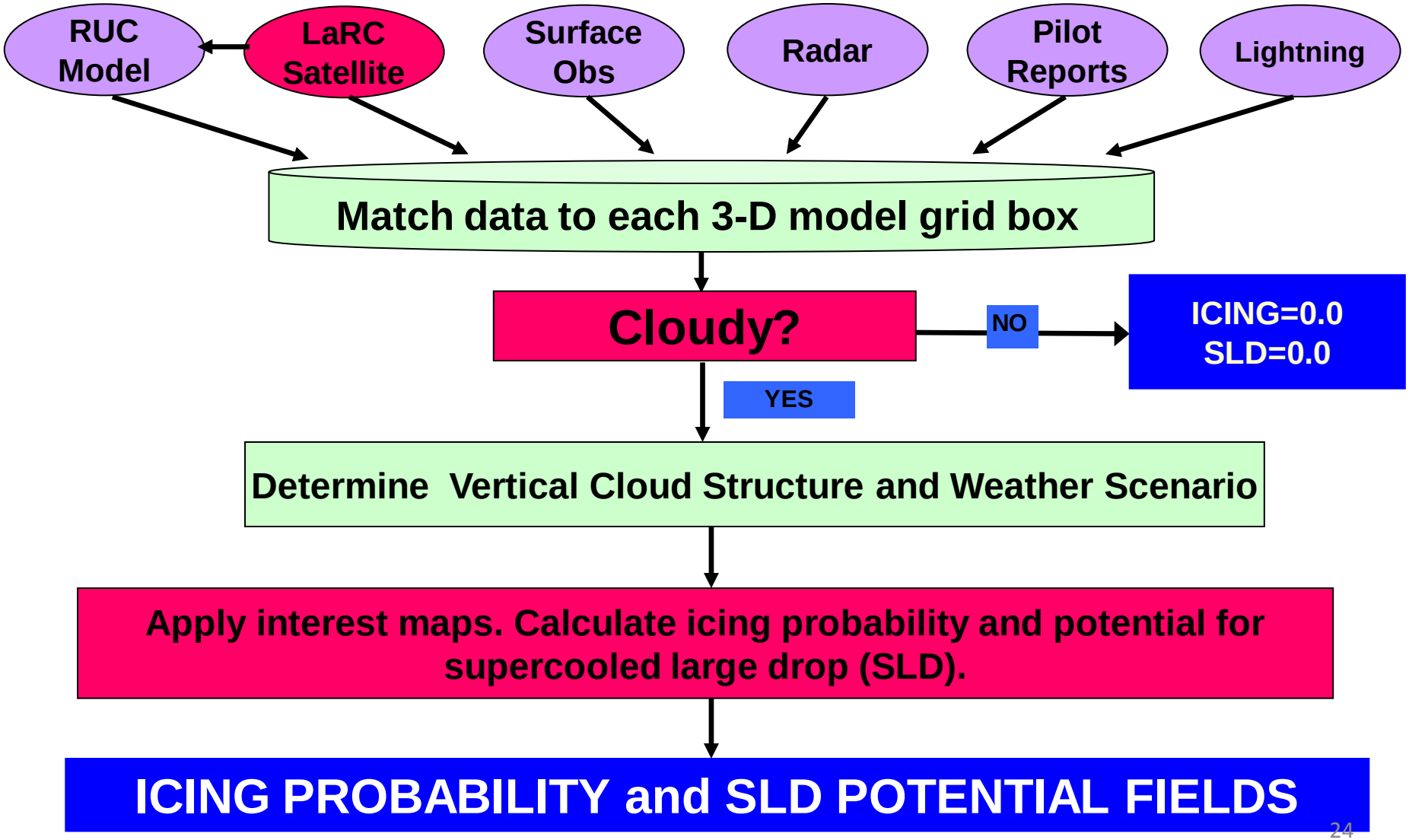

Rapid Refresh




*Cloud data assimilated into NOAA Rapid Refresh NWP produce more realistic clouds*

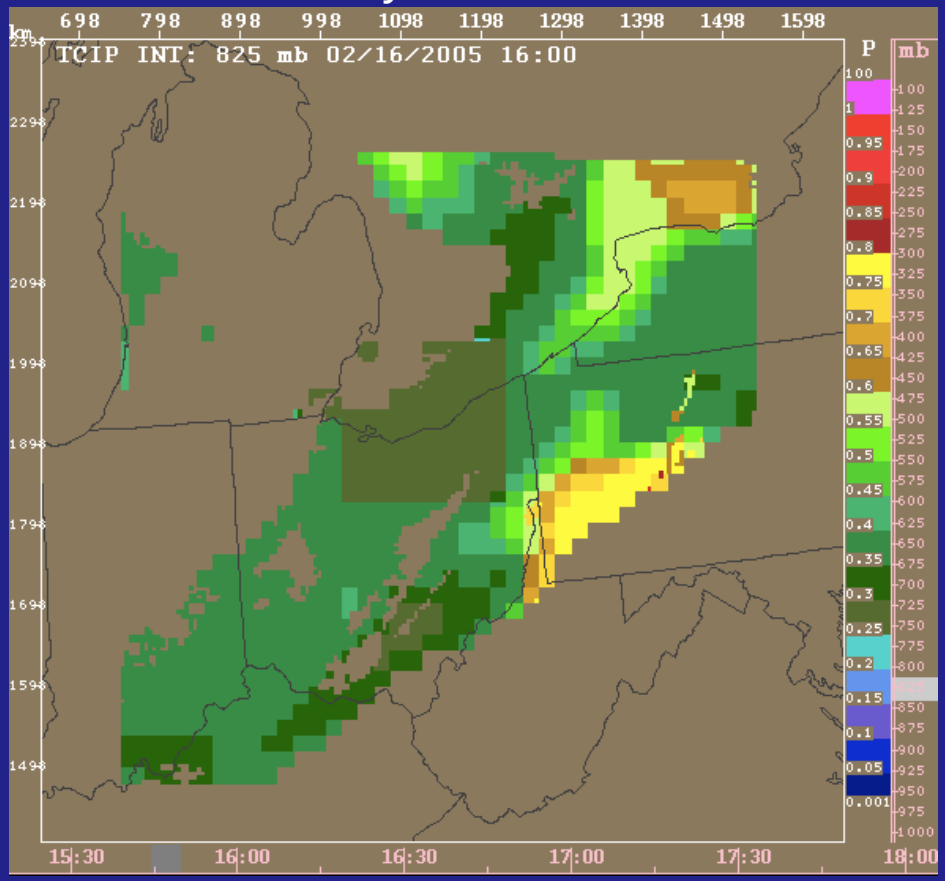
# Assimilation – Aircraft Icing

## CONUS: FAA-NCAR Current Icing Potential (CIP) Product

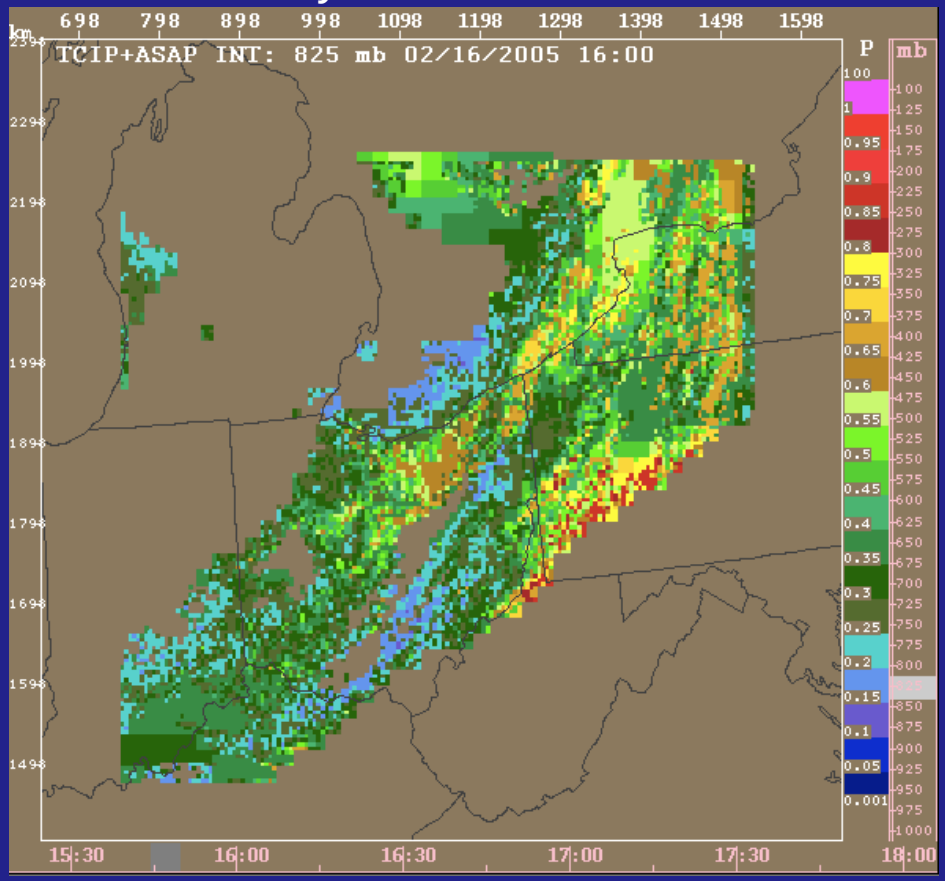


# Improved Icing Severity Indices

CIP Severity w/o LaRC Products




Severity w/ LaRC Products

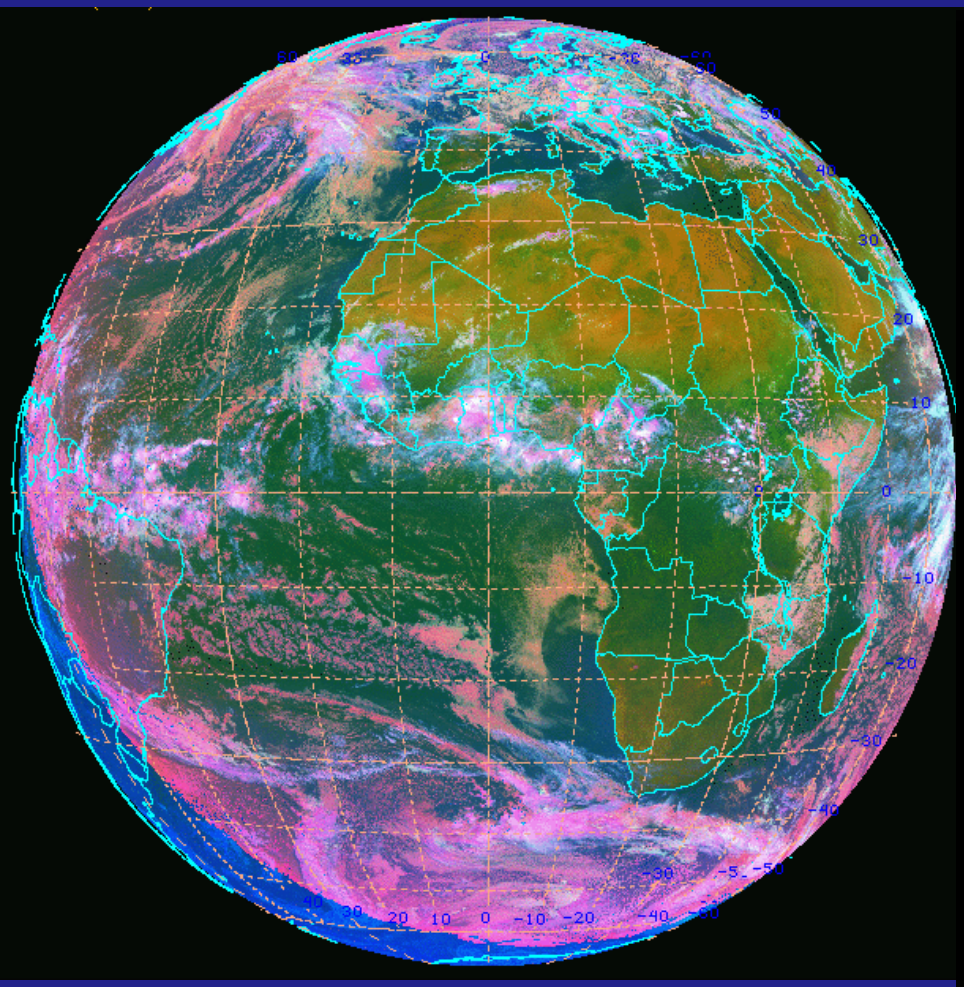



- Better definition of the field gives more options to pilots!
- Results validated against research aircraft flights from NASA GRC

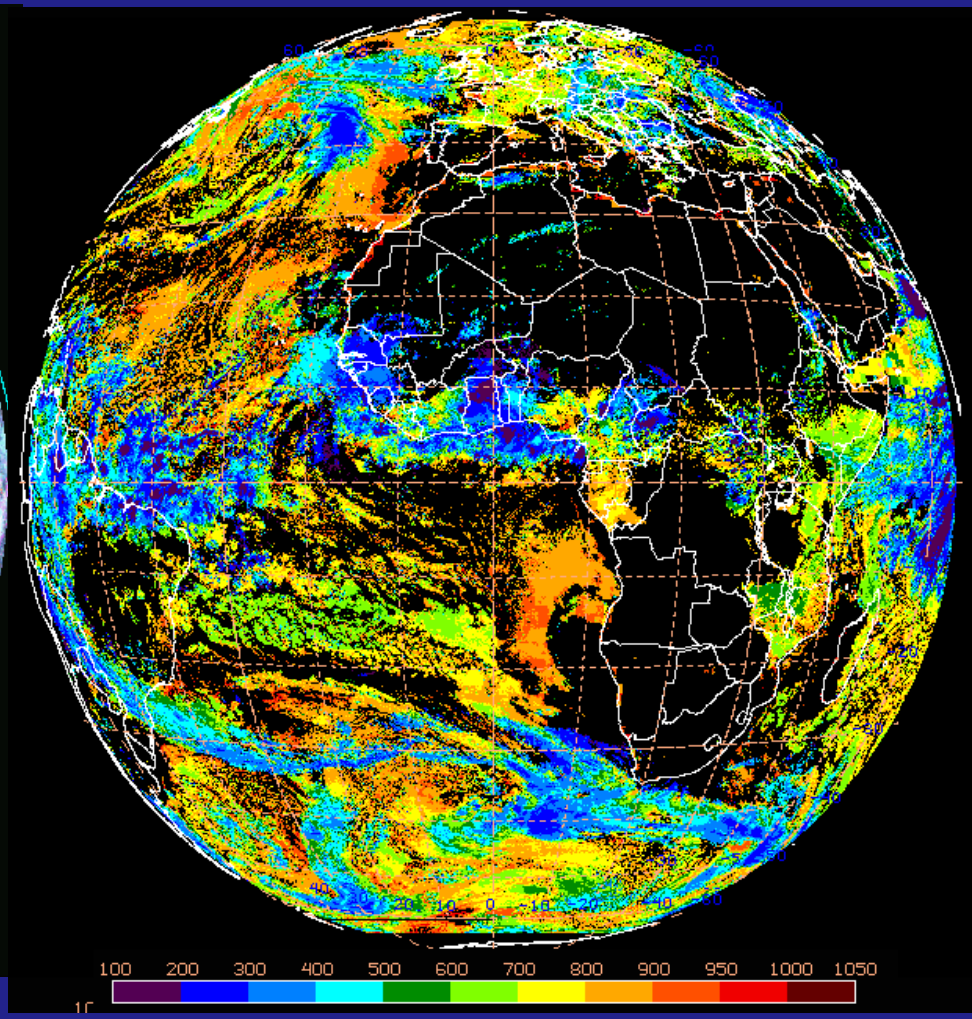
# Global LaRC Cloud Products

Meteosat-9 SEVIRI Cloud Height, 1030 UTC, 13 June 2008

RGB



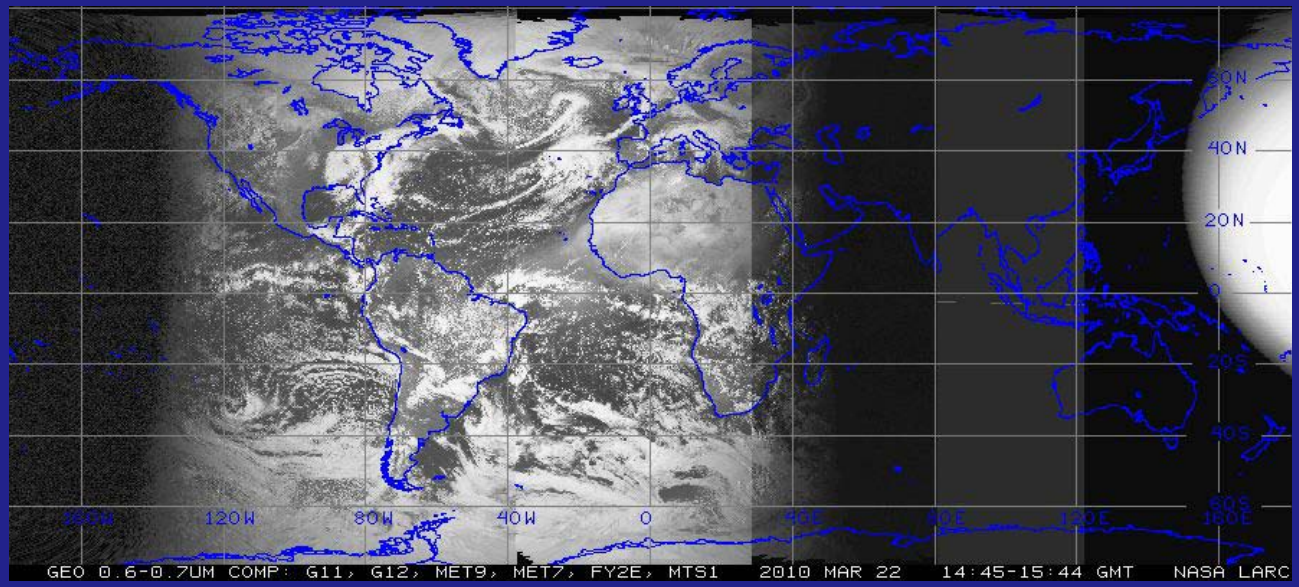
Cloud Effective Pressure (hPa)




- Full-disk processed every 3 hours along with 4 other GEOsats

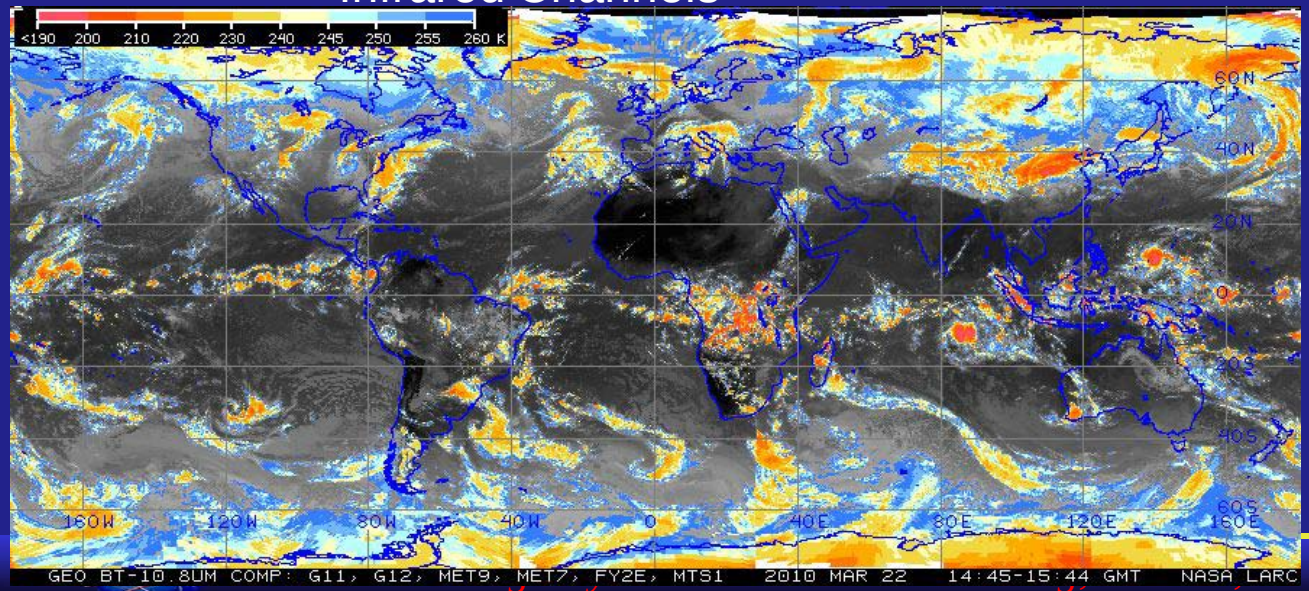
# Global GEOSat Retrievals, 15 UTC, 23 March 2010

Visible Channels




- Combines
  - ** GOES-11 & 12*
  - ** Meteosat-9*
  - ** MTSAT*
  - ** FY-2D*

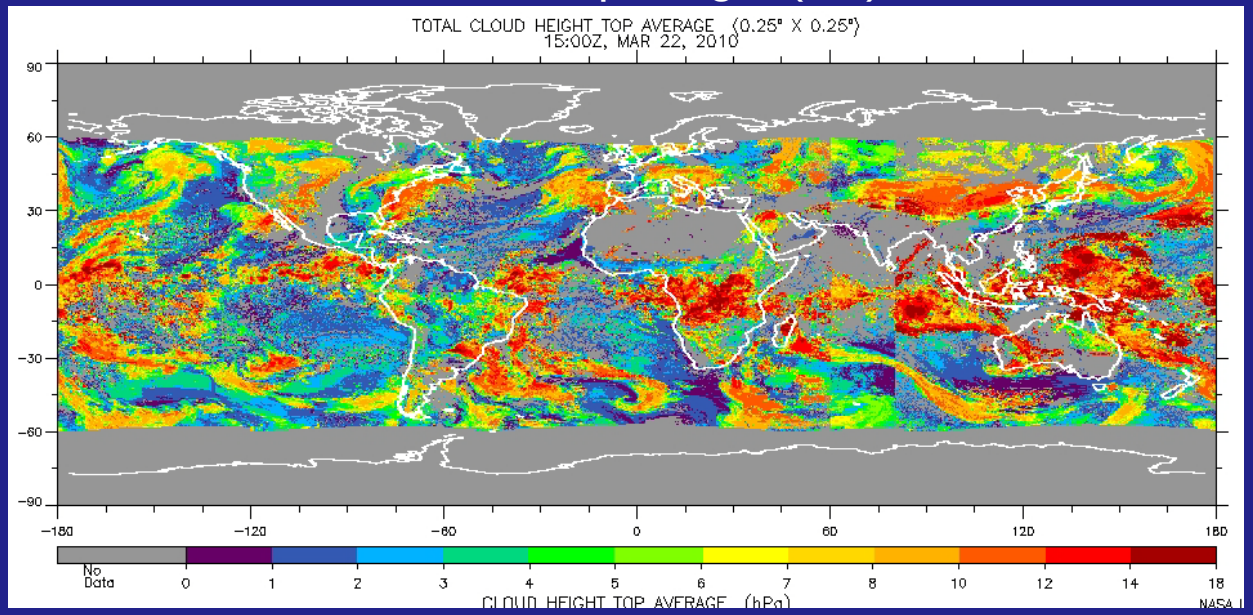
Infrared Channels



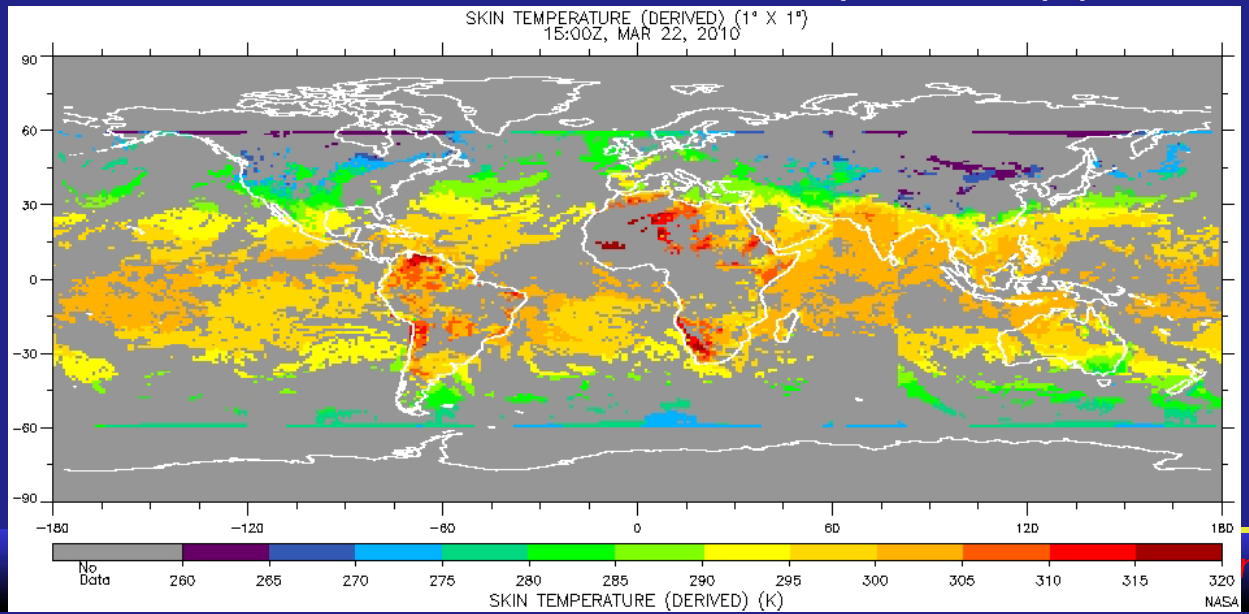

- Quality of some satellite imagery (e.g., FY-2D and MTSAT) is problematic

# Global GEOSat Retrievals, 15 UTC, 23 March 2010

Cloud-top Height (km)



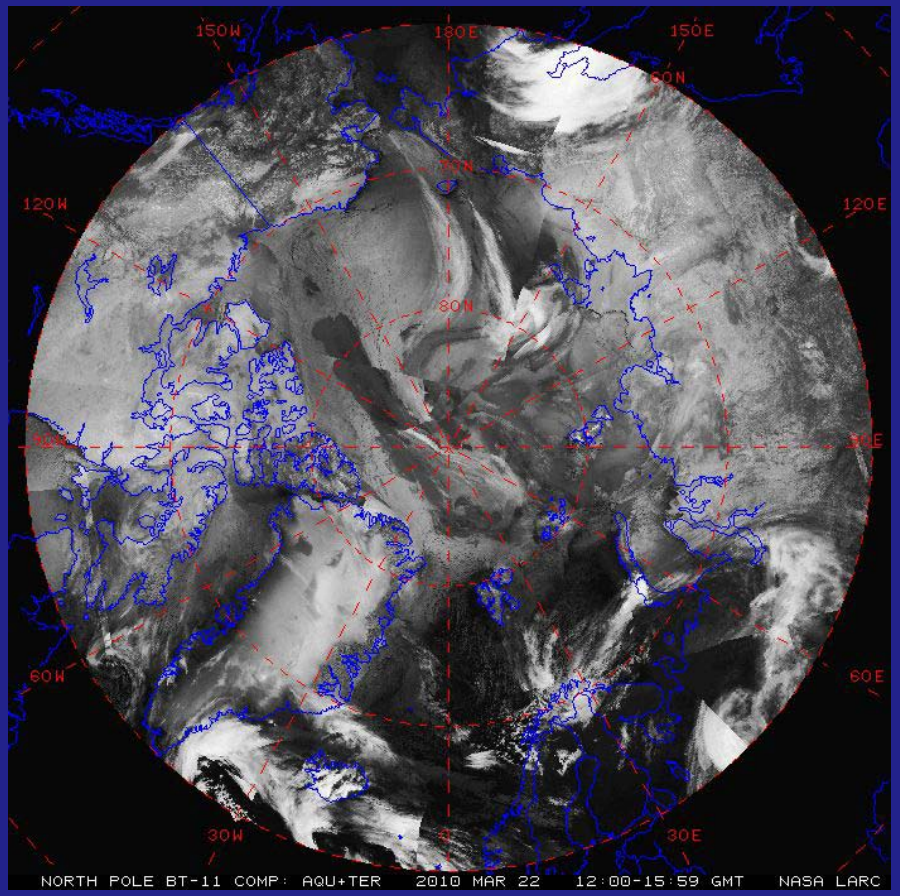

Clear Area Surface Skin Temperature (K)



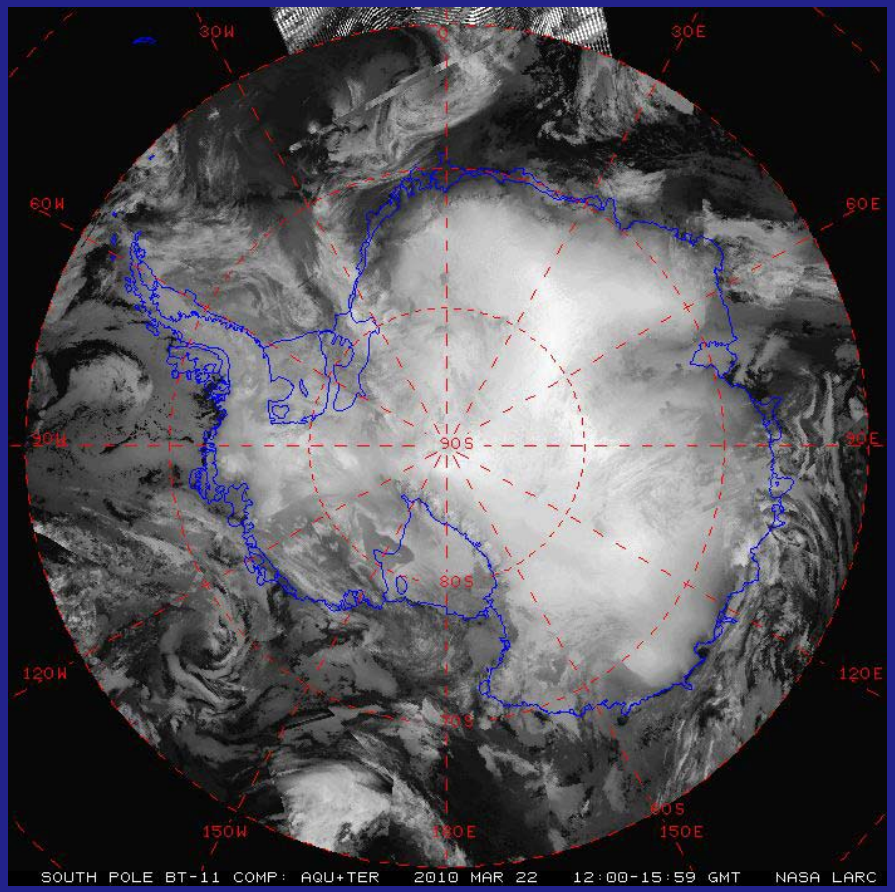

- Nighttime information is limited because of lack of visible channel
  - e.g., optical depth
- FY-2D lack of quality obvious in both parameters
- Results currently produced every 3 hours, 1 hour possible

# Covering the Poles, 15 UTC, 23 March 2010
# MODIS IR Composites

Northern Hemisphere



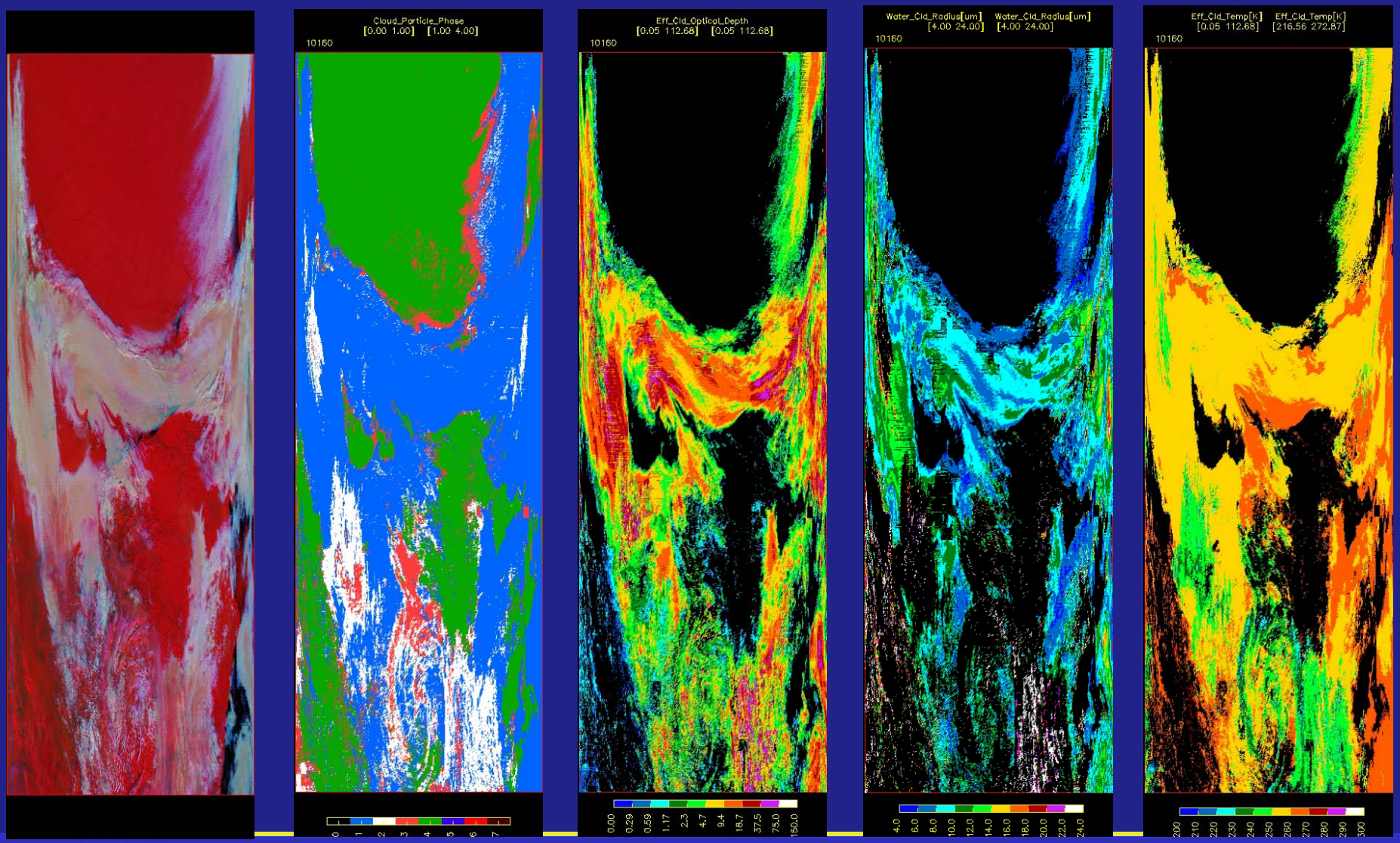

Southern Hemisphere




"Operational" MODIS retrieval code under development

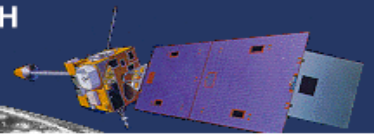
# Covering the Poles, 00 UTC, 1 May 2007
# Terra MODIS Retrievals: Arctic Ocean, Siberia, Alaska

RGB | Phase | opt depth | droplet $r_{eff}$ (μm) | $T_{eff}$ (K)



# NASA LANGLEY CLOUD AND RADIATION RESEARCH

*(Minnis Group)*



User Warning, Please read !

*Site Map:*

Minnis Group Homepage

*Satellite Calibration:*

Langley Satellite Calibration

*Viewers/Tools:*

NOAA AVHRR Viewer

MODIS Viewer

MID-Atlantic NEXRAD

ARM-SGP NEXRAD

Angles Viewer

Plot RUC Sounding

Gridded VISST Products

Satellite Overpass Predictor

*Field Experiments:*

AMF-China New!!

TC4 2007

PACDEX 2007

COPS 2007

FRAM 2007

CCVEX 2006

TWP-ICE 2006

MASRAD Pt. Reyes

MIDCIX 2004

MPACE 2004

INTEX-NA

ATReC 2003

THORPEX

CRYSTAL

ARM SGP

## Satellite Imagery And Cloud Products Page

**Real-time and Historical Cloud Product Loops:** The cloud products are derived with VISST/SIST algorithm. Select a domain from the table below to access the real-time (blue cells) and archived products.

| New!! FULL-DISK CLOUD PRODUCTS (Real Time) New!! | | | | |
|---|---|---|---|---|
| GOES-WEST | GOES-EAST | METEOSAT | FY2C | MTSAT-1R |

| CLOUD PRODUCTS | | | | |
|---|---|---|---|---|
| GOES WEST | GOES EAST | METEOSAT | MTSAT-1R | NOAA 15/16/17 and TERRA/AQUA |
| West CONUS non-java JV Applet | East CONUS non-java JV Applet | WEST EUROPE JV Applet | NAURU JV Applet | ARM-NSA JV Applet |
| MERGED CONUS non-java JV Applet | | EUROPE JV Applet | MANUS JV Applet | ARM-SGP JV Applet |
| ARM-SGP JV Applet | ARM-SGP JV Applet | ARM-NIAMEY JV Applet | DARWIN JV Applet | COVE JV Applet |
| ARM-NSA | COVE | | TWP | ATReC/AIRS |
| Monterey | ATReC/AIRS | | AMF-China | TWP |
| TC4 | CRYSTAL | | | |
| | OHIO | | | |

**Real-time and Historical Satellite Imagery Loops:** The links from the table below provide access to the real-time (blue cells) and historical image loops for various satellites.

| SATELLITE IMAGERY | | | | |
|---|---|---|---|---|
| Mid-West US (SGP) | Northeast US | Mid-Atlantic US | Southeast US | CONUS |
| E. Pacific G-12 | Pacific/West | TWP DARWIN MTSAT | TWP DARWIN FY2C | TWP DARWIN MTSAT & FY2C |
| ATReC GOES-12 | Florida | TWP GOES-9 | GMS-5 TWP | PACS EPIC |
| MASRAD | AVHRR CONUS | MODIS CONUS | AVHRR NSA | |

| FULL-DISK SATELLITE IMAGERY | | | | |
|---|---|---|---|---|
| GOES-W FD | GOES-E FD | MET-9/0E FD | MET-7/57E FD | FY2C/105E FD |
| MTSAT/140E FD | | | | |

| COMPOSITE SATELLITE IMAGERY | | |
|---|---|---|
| Global Geostationary | North Pole MODIS | South Pole MODIS |

http://www-angler.larc.nasa.gov

# Summary and Conclusions

- Cloud properties are valuable on their own for nowcasting
  - can be used to detect potential icing conditions
    - *see W. Smith talk*
  - provide approximate 3-D view of clouds
  - estimates of cloud base heights (ceiling)
  - most useful in remote areas with no other information
    - *available for all GEOSats, soon in polar regions*

- Cloud properties have increased value when assimilated
  - *NOAA Rapid Update Cycle (RUC & Rapid Refresh) NWP model used for aviation*
    - *see Benjamin/Weygandt talks*
  - *NCAR/FAA Current/Future Icing Potential (CIP/FIP) Products*
    - *see Haggerty talk*

# Future Work

- Complete move to operational system
  - *backup system for 24/7 operations*
- Replace FY-2D for improved Asian coverage
  - *MODIS & AVHRR, FY-2E, Korean COMS?*
- Develop new techniques to deal with terminator & snow backgrounds
  - *CO2 / IR / SIR combinations? regional memory?*
- Enhance thickness & WC profiles using different categories & other spectral channels (e.g., 1.6, 2.1 µm)
- Continue improvement of $CO_2$ and other ML techniques
- Minimize use of defaults at night
  - *test theoretical optical depth limits for various emission channels*
- Study HIWC signals

For references: http://www-pm.larc.nasa.gov/
data: http://www-angler.larc.nasa.gov/

# Data Product Formats

- Pixel-level Product: Binary data retrieved at instrument nominal resolution.

- Gridded Product: 0.5º or 1.0º average separated by cloud height / phase.
  - *includes surface radiative fluxes & skin temperature*

- Surface Site, Aircraft, & CALIPSO/ICESat Matched Products

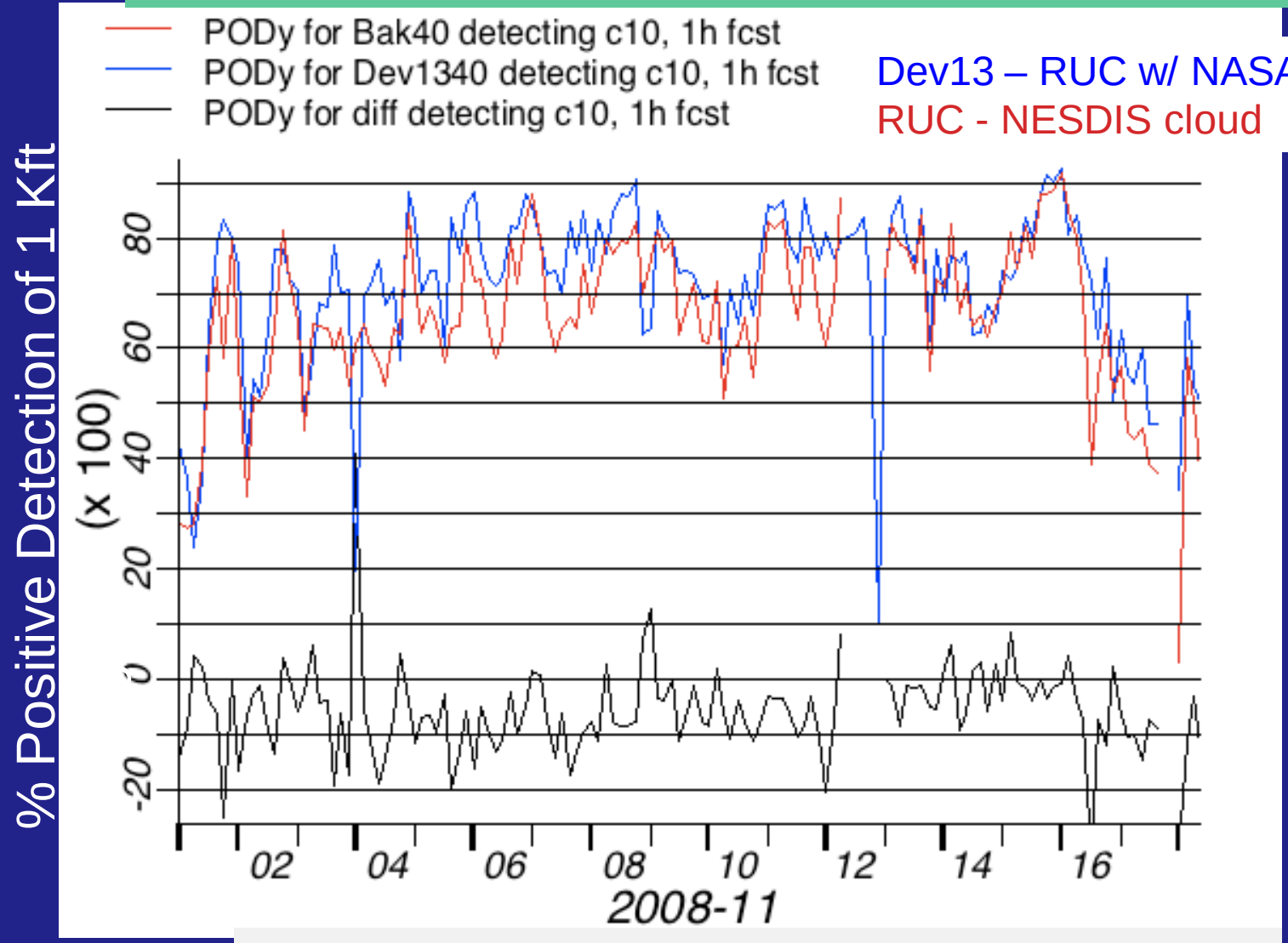
Means within 10 or 20-km radius centered of selected (ARM & Euro) surface sites; single or weighted 4 pixels average along aircraft/satellite flight path.

- Current lag times
  - 0.5 to 1.5 hrs depending on domain
  - Meteosat results under 24-h delay per ESA

- Spatial/temporal resolution
  - GOES domains, 0.5 hr; others 1.0 hr, nominal 3-5 or sampled 6-8 km
  - Full disk, 3 hr, 9-10 km sampled

# Improving RUC Forecasts With LaRC Products

## IFR 1000' ceiling - 1h forecasts - PODy - November 2008



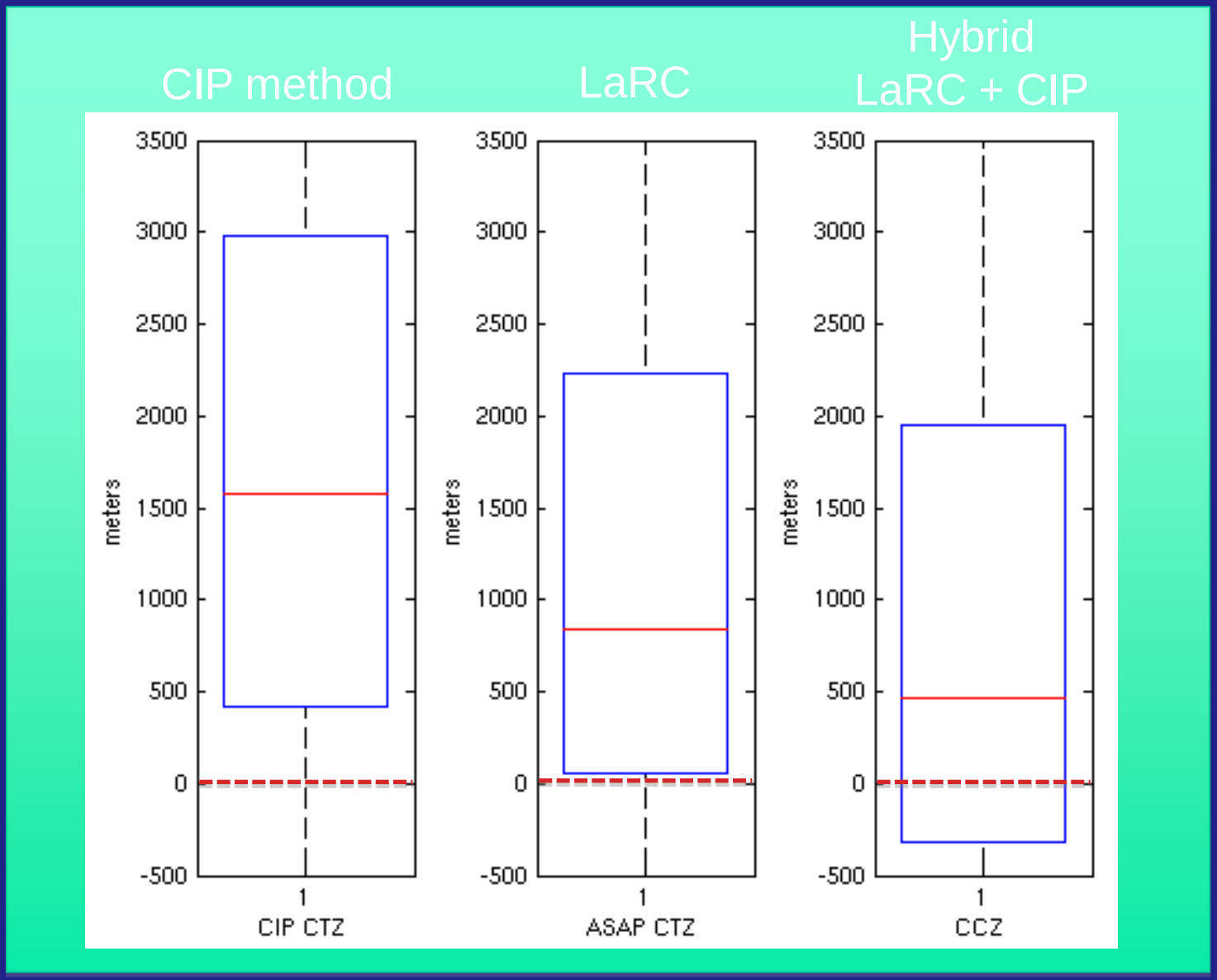

- Dev13 forecasts correctly predict ceilings below 1000' ~9% more often than operational RUC

# CIP Assimilation – Aircraft Icing Product

## Assimilation process uses fuzzy logic

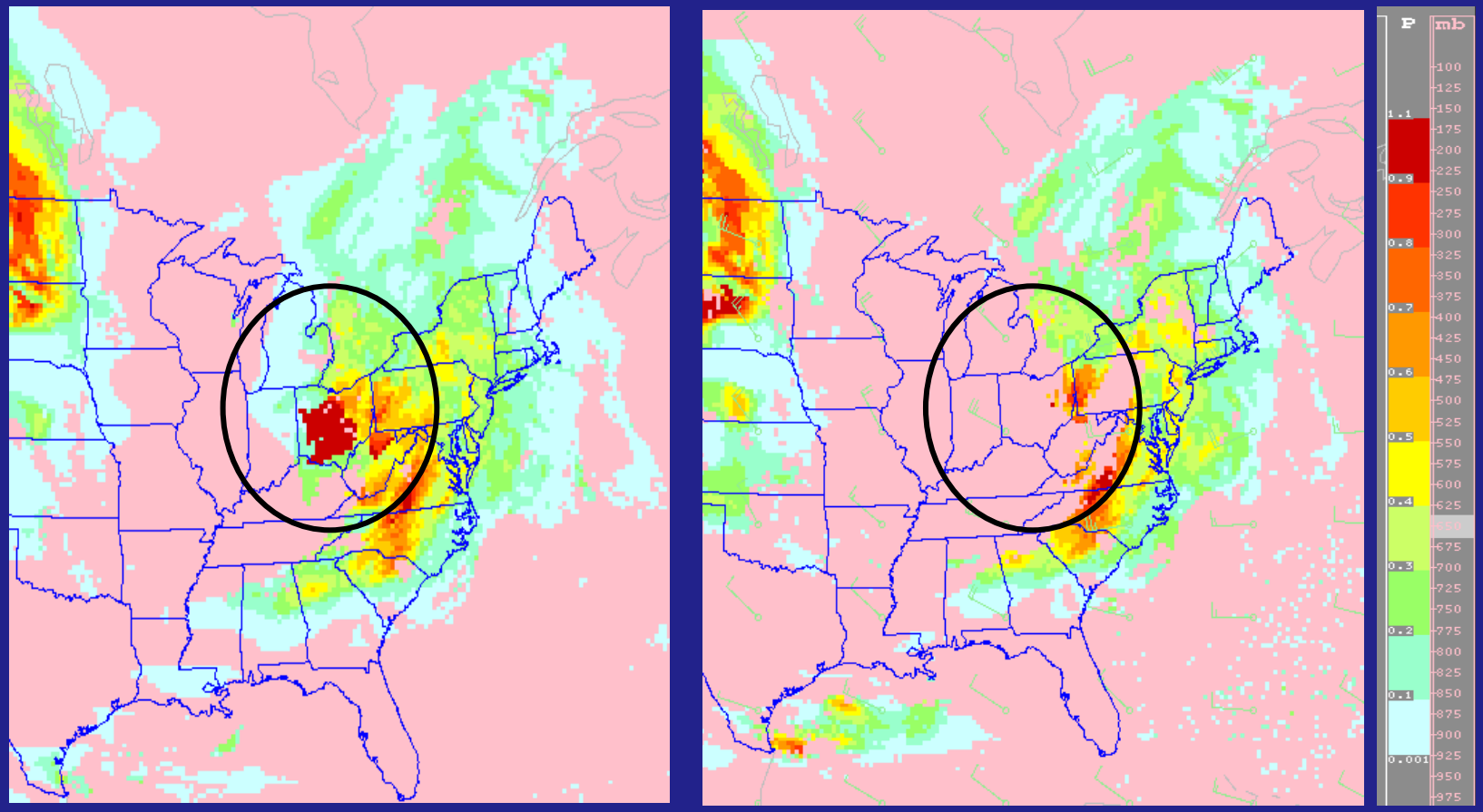
| Satellite Product | CIP Function |
|---|---|
| Hydrometeor phase | → Cloud Screening |
| Cloud Effective temperature | → Cloud-top Temperature Area of Interest |
| Cloud Effective temperature<br>Cloud Effective height | → Cloud-Top Height |
| Liquid water path<br>Droplet Effective Radius | → Icing Intensity |

# Errors in Cloud Top Height Estimates
## (Compared to TOP from PiREPS)




Inclusion of satellite heights improves icing top estimates

# Icing Probability at 8 kft -- 19 January 2005




CIP Method

Hybrid Method

- LaRC products reduce volume of air classified as icing