Regional Data Assimilation of AIRS Observations at the SPoRT Center

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Joint Center for Satellite Data Assimilation Seminar Series

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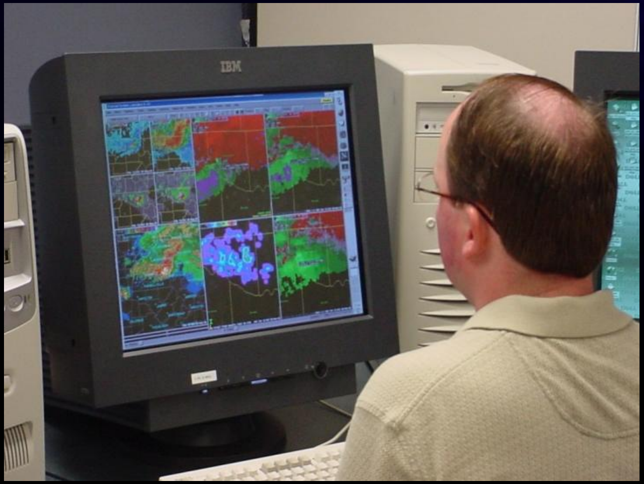
The SPoRT Center
Infusing NASA Technology Into NWS WFOs

Mission of the SPoRT Center: Apply NASA measurement systems and unique Earth science research to improve the accuracy of short-term (0-24 hr) weather prediction at the regional and local scale

- conduct focused research
- evaluate in "testbed" mode
- transition priority products to WFOs



External Partners
NWS (Southern Region, HQs), NESDIS (STAR, NDE), NCEP, JCSDA, JPL, GSFC (GMAO)

End users:
WFOs in Southern Region, other Govt organizations, and numerous private sector weather partners

Keys to success

- ***link data / products to forecast problems***
- ***Integrate capabilities into AWIPS***
- ***Provide training / forecaster interaction & feedback***

Focused Research and its Transition

Exploit use of satellite observations for diagnostic analysis and nowcasting (MODIS, AMSR-E, and AIRS, special GOES products)

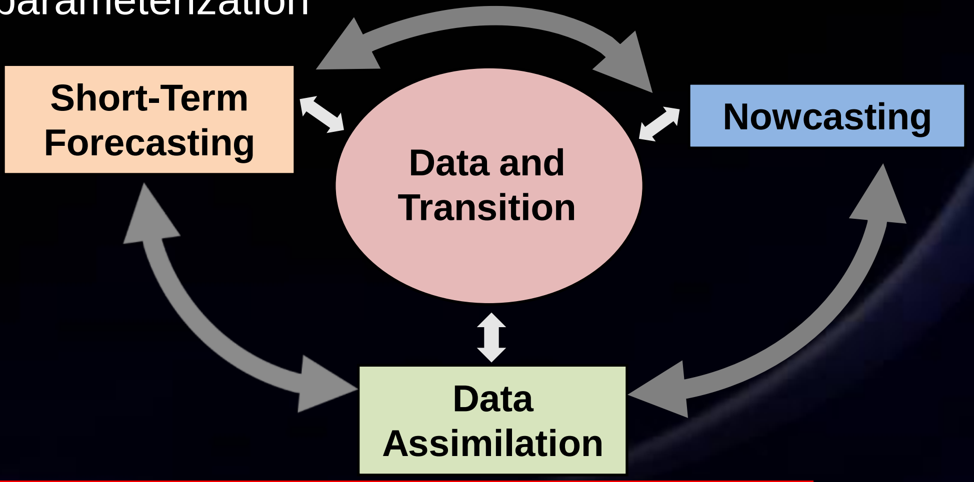
- timing and location of thunderstorms, severe weather, and precipitation
- diagnostic analysis of current conditions, cloud cover, visibility, fog, etc. (esp. at night), morning minimum temperatures (and its local variations)
- coastal weather processes (sea breeze convection / temperatures), off-shore precipitation processes
- weather in data void regions

Unique modeling configurations

- coupled WRF / LIS (satellite data to improve surface parameterizations) (Case 5/20)
- use of high resolution SST in regional models WRF, WRF-NMM (EMS) (Jedlovec 6/17)
- Use of CloudSat observations to improve parameterization schemes within WRF

Data assimilation studies

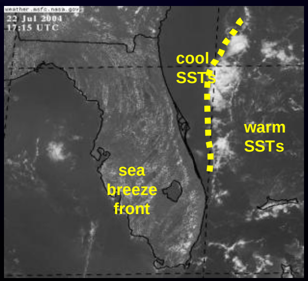
- AIRS radiances in GSI / WRF-NAM (McCarty 2/18)
- AIRS profiles in WRF-Var / WRF-ARW (Zavodsky 2/18)

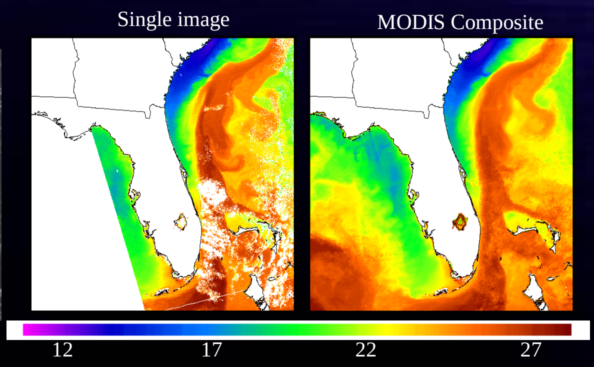


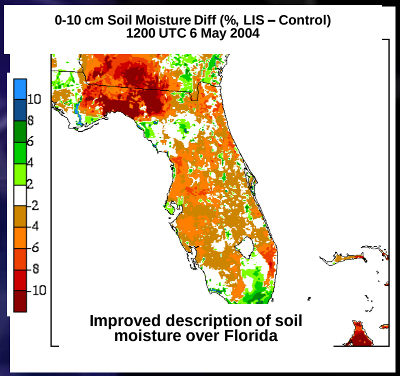
Data Assimilation and Modeling Transitions

Unique datasets

High resolution MODIS / AMSR-E composite replaces RTG SST fields in regional forecast models leading to improved coastal weather forecasts – impact on tropical systems





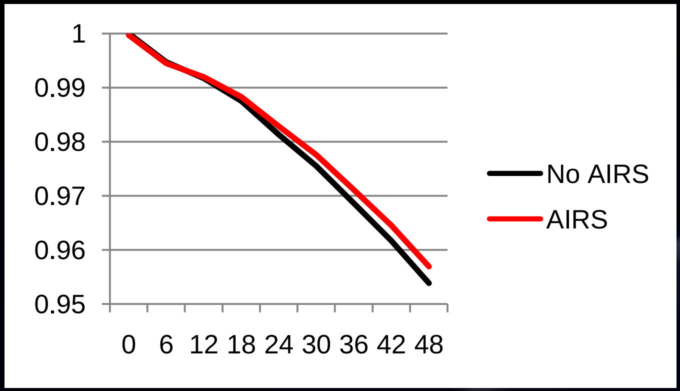


Research model applications

Implement coupled WRF / LIS for better characterization of regional lands surface changes from climatology – snow cover, vegetation changes

Data assimilation approaches

Assimilating AIRS radiances (GSI) and profiles (WRF-Var) into WRF leads to regional forecast model improvements

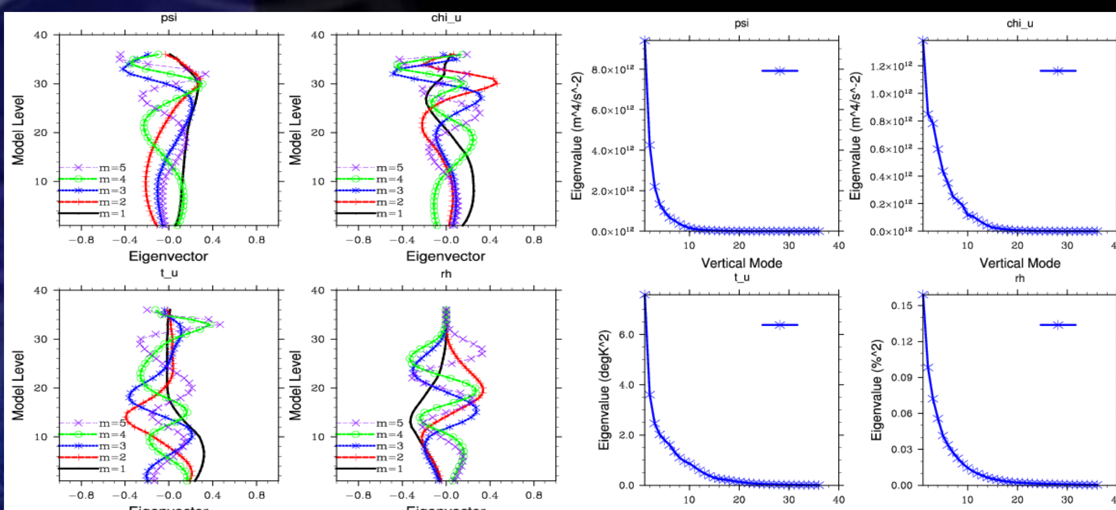


Brief History of AIRS Profile Assimilation at SPoRT

LAPS to initialize WRF but found it incorrectly handled moisture profiles

Transitioned work to ADAS

- Previous experience with this system and easy to alter code to accept new observation types
- Analyses had long computation time
- Forecast improvement at later hours but degradation at earlier hours, which didn't make sense
- ADAS does not dynamically adjust momentum fields leading to spin-up issues when inserted into WRF
- Decided to switch to variational scheme to overcome some of these issues



Tuned WRF-Var system to assimilate AIRS L2 T and q profiles

- generated **B** matrix using control WRF forecasts and "gen_be" software (NMC method)
- altered source code to add AIRS profile data sets as separate land and water sounding data types with separate error characteristics

Use of AIRS Profiles

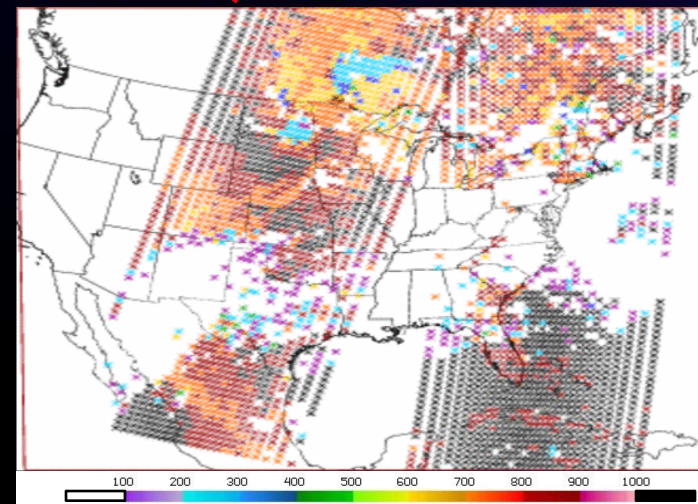
L2 Version 5 temperature and moisture profiles

Assimilate the 28-vertical-level standard product

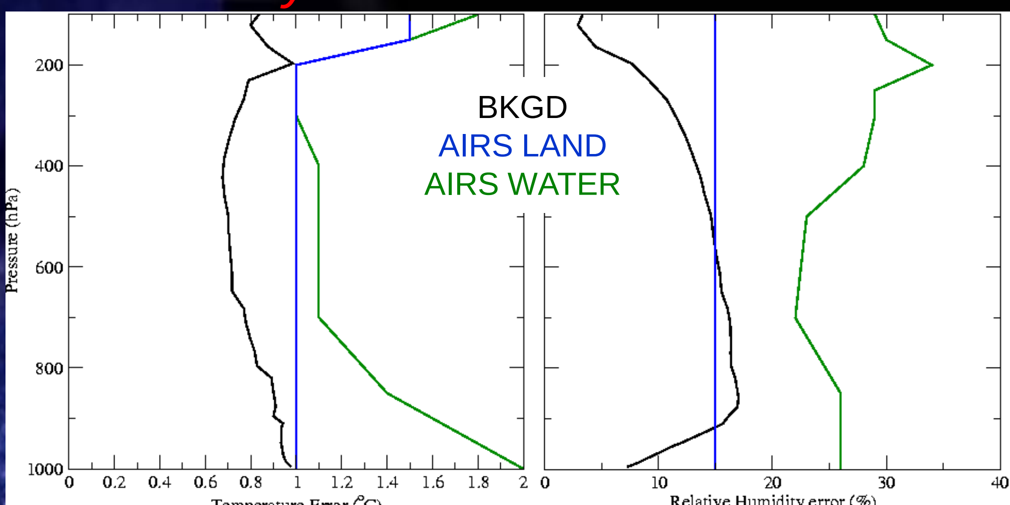
- problematic vertical correlations in 100-level support product

Data are quality controlled using P_{best} value in each profile to ensure only highest quality data

AIRS QI's for 19 Jan 2007



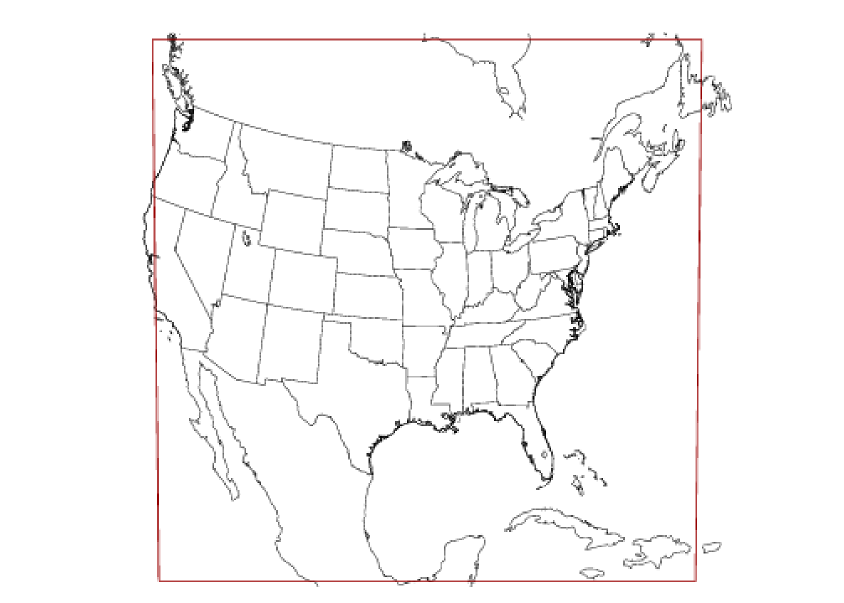
Analysis Error Characteristics



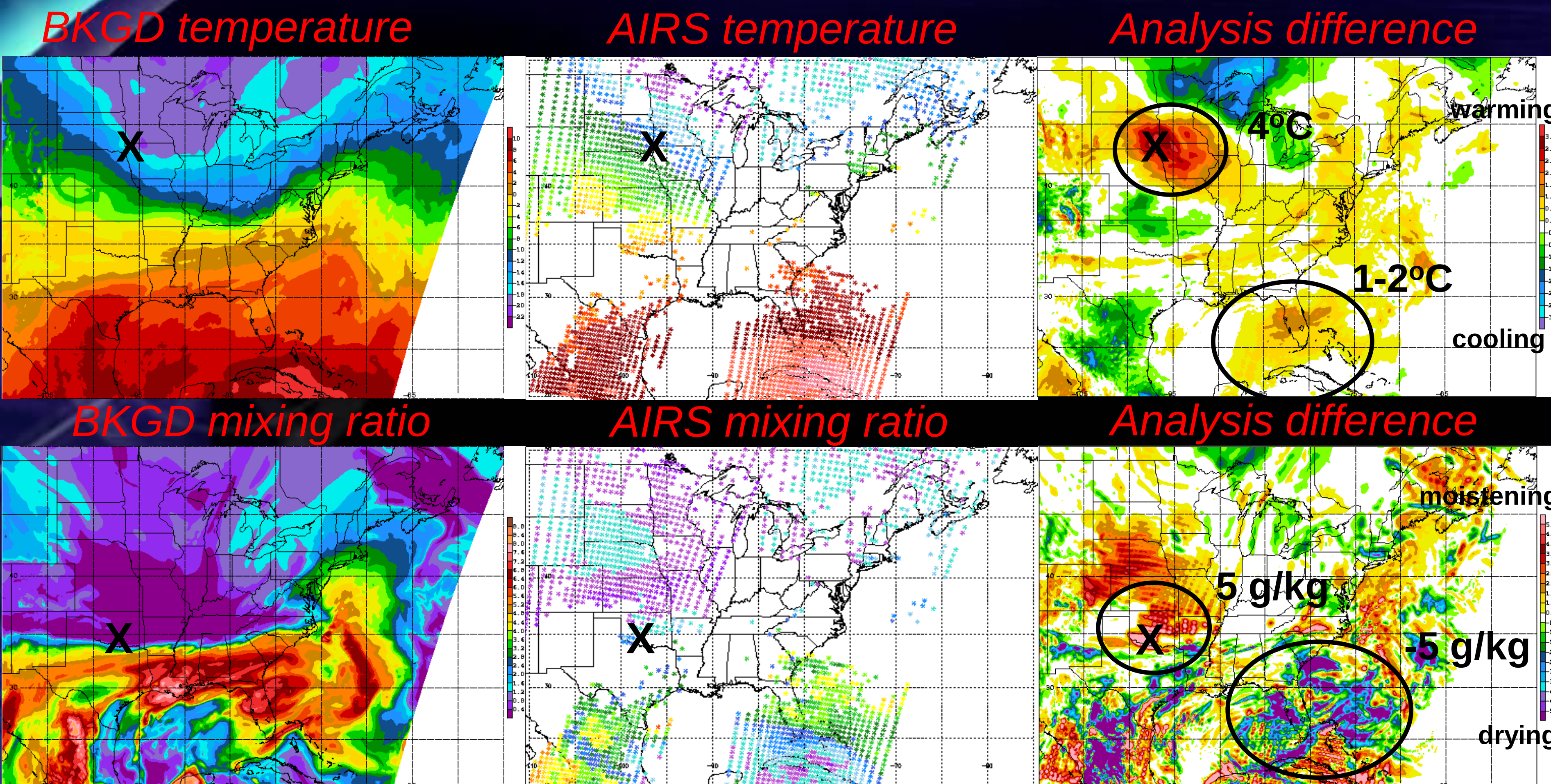
- Assimilate land and water soundings as separate observation types with separate error characteristics
  - instrument specs over water
  - Tobin et al. (2004) errors over land

Analysis/Model Setup

- WRF-ARW initialized with 40-km NAM at 0000 UTC each day
- WRF forecast run to average time of eastern and central AM AIRS overpasses for each particular day (between 0700 and 0900 UTC)
- 12-km analysis and model grid
- Performed two sets of experiments:
  - CNTL: no data assimilation
  - AIRS: only assimilate AM overpass, highest-quality AIRS profiles
- 48-hr forecasts each day for case study period 17 Jan - 22 Feb 2007

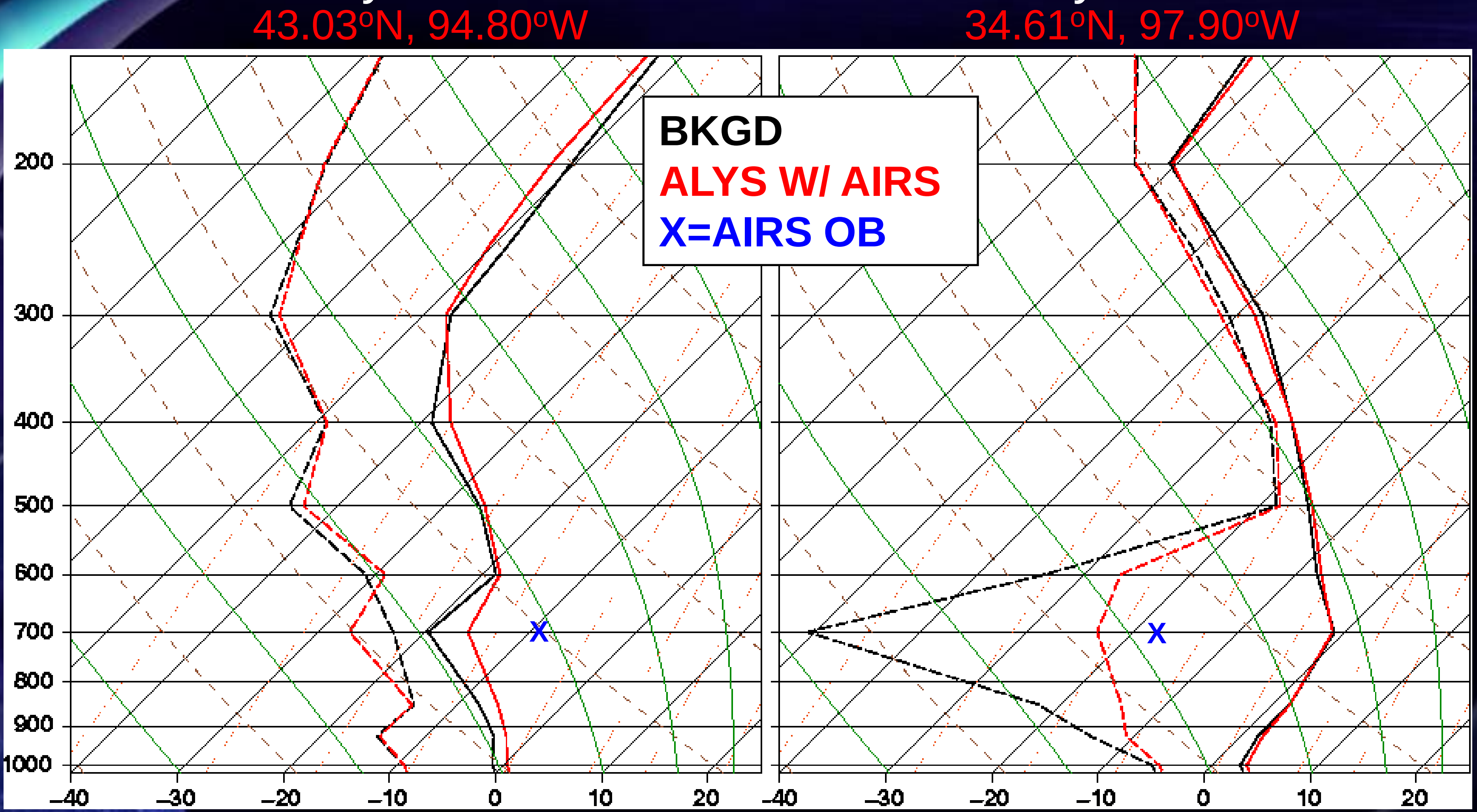


19 January 2007 0800 UTC 700 hPa Analysis Results



- Initial check on 2-D plane shows that analysis moves towards AIRS observations for T and q

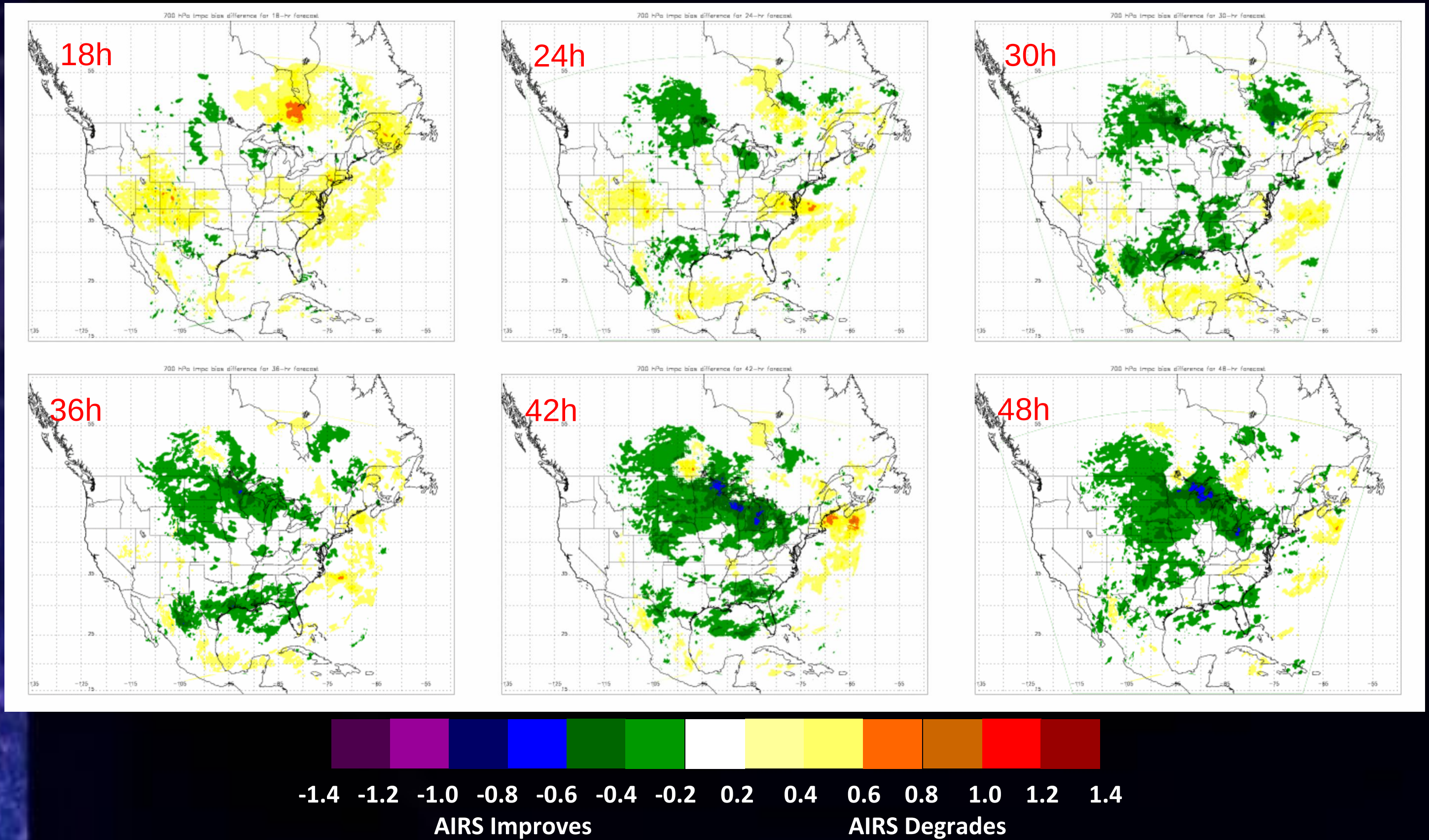
19 January 2007 0800 UTC 700 hPa Analysis Results



- Second check in vertical shows that analysis moves towards AIRS observations for T and T_d

700 hPa Temperature Forecast Validation

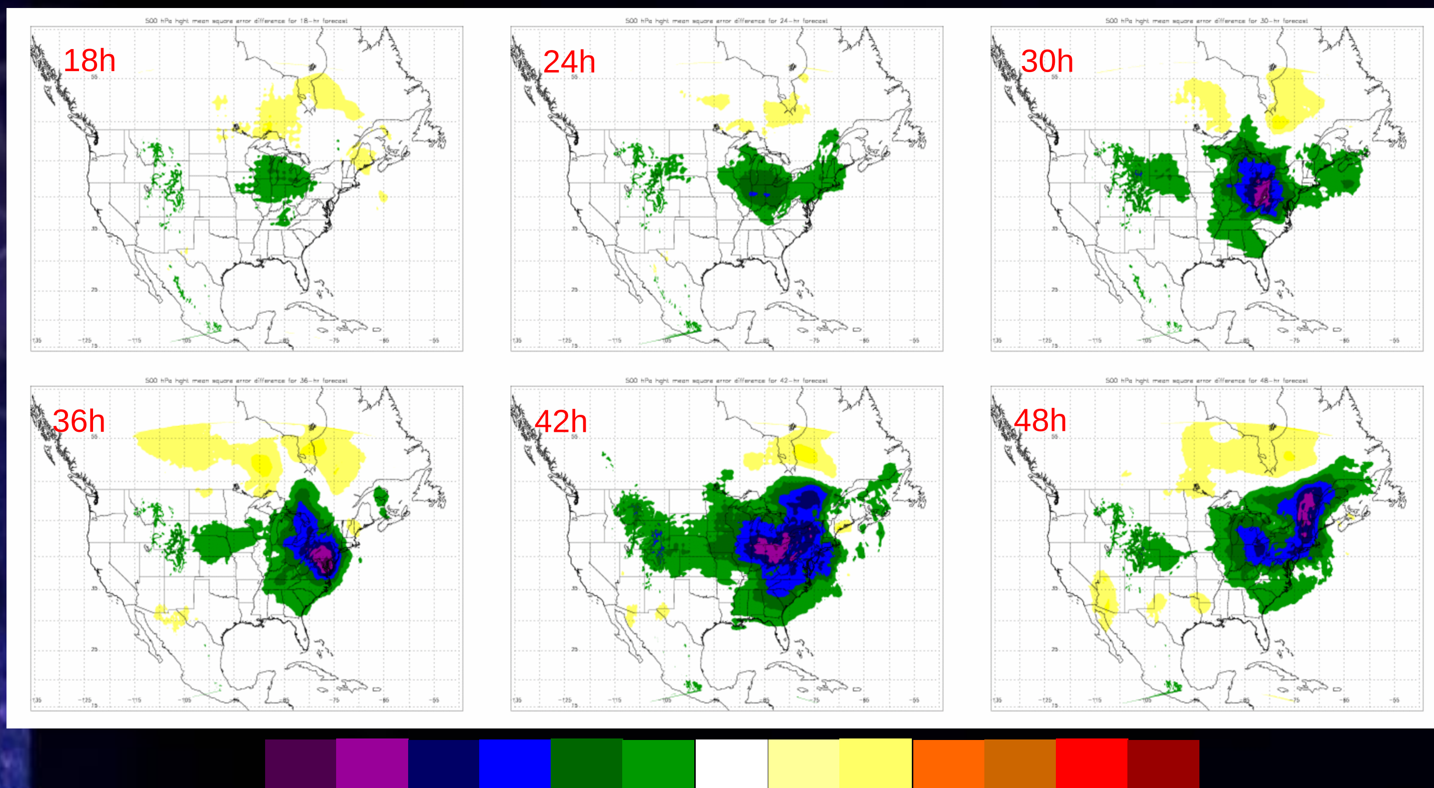
Results are $\Delta|\text{bias}|$ ($|\overline{\text{AIRS-NAM}}|-|\overline{\text{CNTL-NAM}}|$) for entire 37 day case study period (17 January – 22 February 2007)



Surprisingly, AIRS has wide-spread positive impact over much of US land area

500 hPa Geopotential Height Forecast Validation

Results are ΔMSE (AIRS-CNTL) compared to NAM analyses for 17 January – 22 February 2007 case study period



-1225 -1050 -875 -700 -525 -350 -175 175 350 525 700 875 1050 1225

AIRS Improves AIRS Degrades

Heights also positively impacted by AIRS over substantial portion of US

6-h Cumulative Precipitation Forecast Validation

Combined precipitation scores for all grid points at all forecast times for 37 day case study period

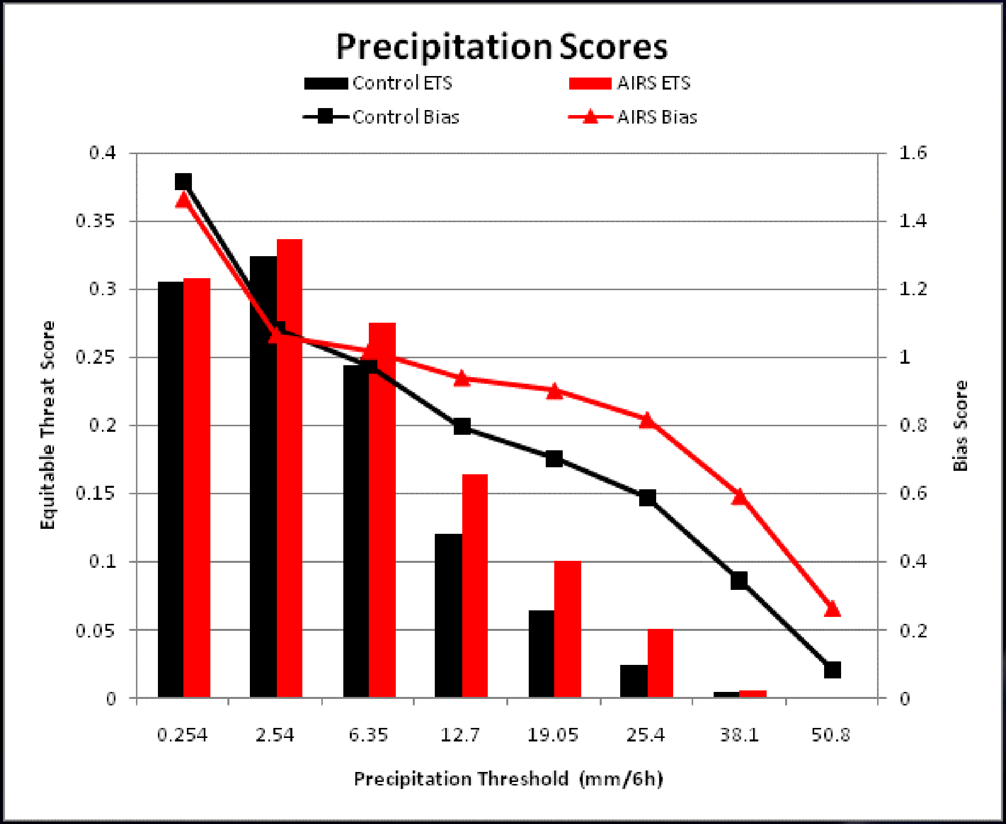
- Bias indicates over- or under-forecasting
- ETS is a ratio of success, where both successful forecasts and non-forecasts are considered
- A "perfect" forecast will have a value of 1 for each score

ETS Results

- Small improvement with inclusion of AIRS at trace and heavy precipitation amounts (<5%)
- Significant improvements with inclusion of AIRS at intermediate precipitation amounts (>10%)

Bias Results

- Improvements in bias score (closer to 1) for AIRS runs at all thresholds



AIRS Profile Conclusions

SPoRT runs WRF-Var for AIRS profile assimilation studies

- generated background error covariance matrix
- added separate land and water observation data sets to source code with separate error characteristics
- standard profiles to avoid vertically correlated soundings

Prudent use of QI's allows use of only the highest quality data

Analyses show impact from AIRS of up to 4ºC and 5 g/kg in the direction of the AIRS observations

Positive forecast impact of AIRS T and q profiles on temperature and geopotential height at most forecast times over much of model domain

- Improvement occurs over land, which is surprising given known issues with overland AIRS soundings

Positive forecast impact in ETS and bias scores at all precipitation thresholds for overall forecasts during the case study period

Knowledge gained through these experiments can be applied to other hyperspectral sounder data (e.g. IASI, CrIS, etc.)

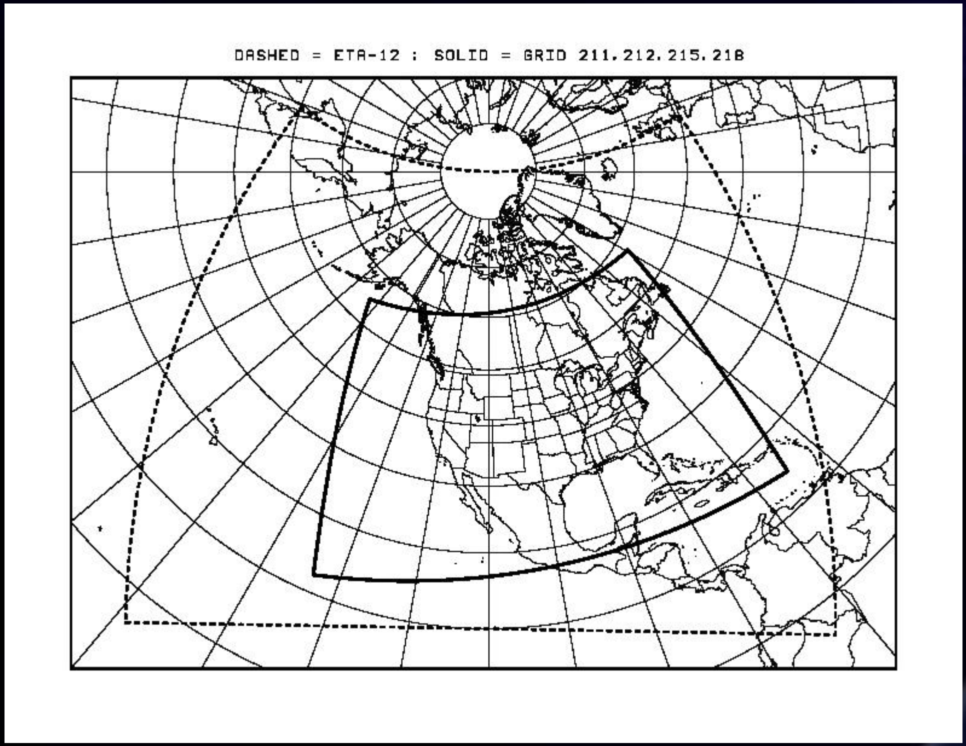
DA/Model System Setup

North American Mesoscale Model (NAM)

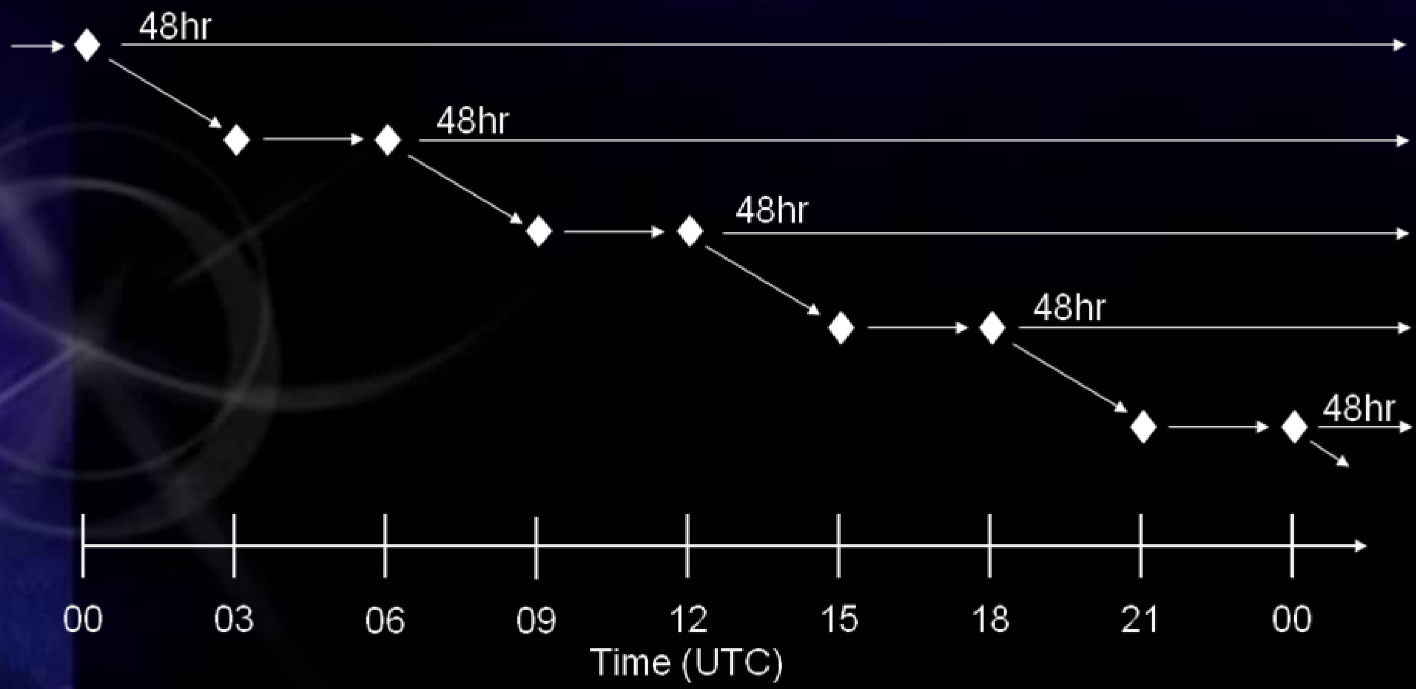
- The operational regional model at NCEP
- WRF-NMM dynamic core
- 12 km gridspacing, on NAM12 grid

NAM Data Assimilation System (NDAS)

- Gridpoint Statistical Interpolation (GSI) 3D-Var
  - Operational in NDAS, GDAS, Rapid Refresh, and GMAO/GEOS-5
- Assimilation in grid space, on variables ψ, χ, $\ln(p_s)$, T, r_v, O_3, T_{sfc}, and CLW



Assimilation Cycle



- 3hr assimilation cycle
- Data cutoff of +/- 1.5 hr
- Model runs, to 48hr, performed 4 times daily (00, 06, 12, 18 UTC)

◆ - Assimilation

⟶ - Model Integration

Experimental Design

Control (CNTL)

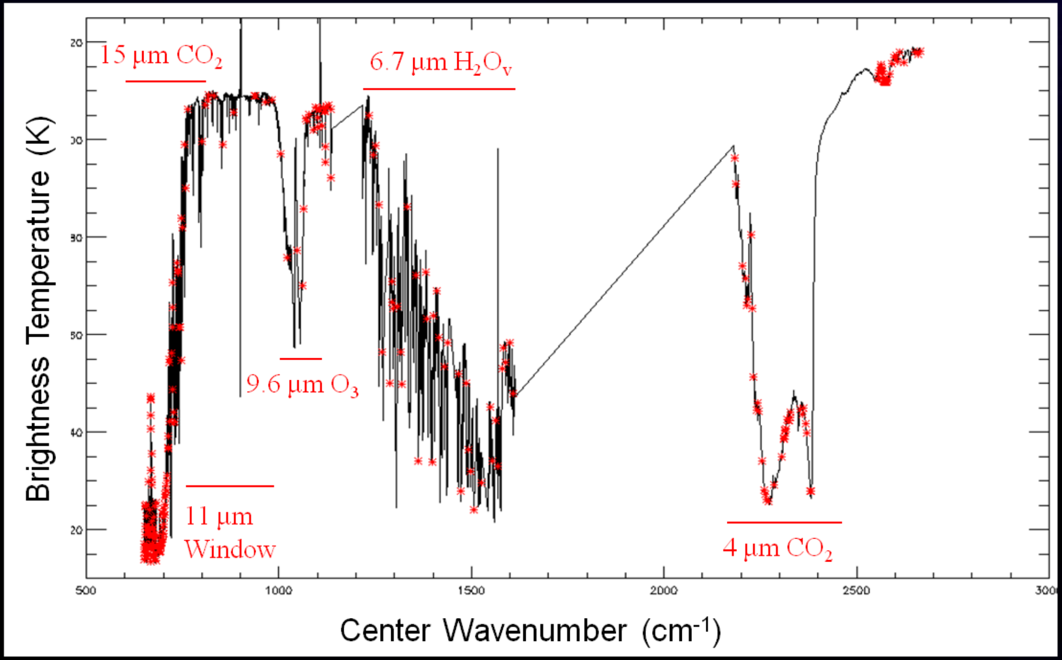
- All data used in the operational system, except Level-II radial winds
- *Conventional Observations*: Sonde, surface, aircraft
- *Unconventional Observations:*
  - *PREPBUFR:* Satellite derived winds, GOES-12 radiances
  - *External:*
    - Infrared Sounders: HIRS
    - Microwave Sounders: AMSU-A (Not Aqua), AMSU-B, MHS
    - NEXRAD Radar: Level II and Level III Radial wind super obs

AIRS Experiment

- All data used in the CNTL
- Atmospheric Infrared Sounder (AIRS) radiances are also assimilated

Atmospheric Infrared Sounder (AIRS)

Hyperspectral Thermal Infrared Measurements



- AIRS measures 2378 channels from 3.75 to 15.4 µm (black)
- AIRS samples many absorption lines and continua with FWHM of ν / 1200
- 89 GB of data per day
- Thinning:
  - 281 channels (red) distributed to operational centers in NRT
  - Every footprint
  - In NAM assimilation, less than 0.1% of total global observations are used routinely

Atmospheric Infrared Sounder (AIRS)

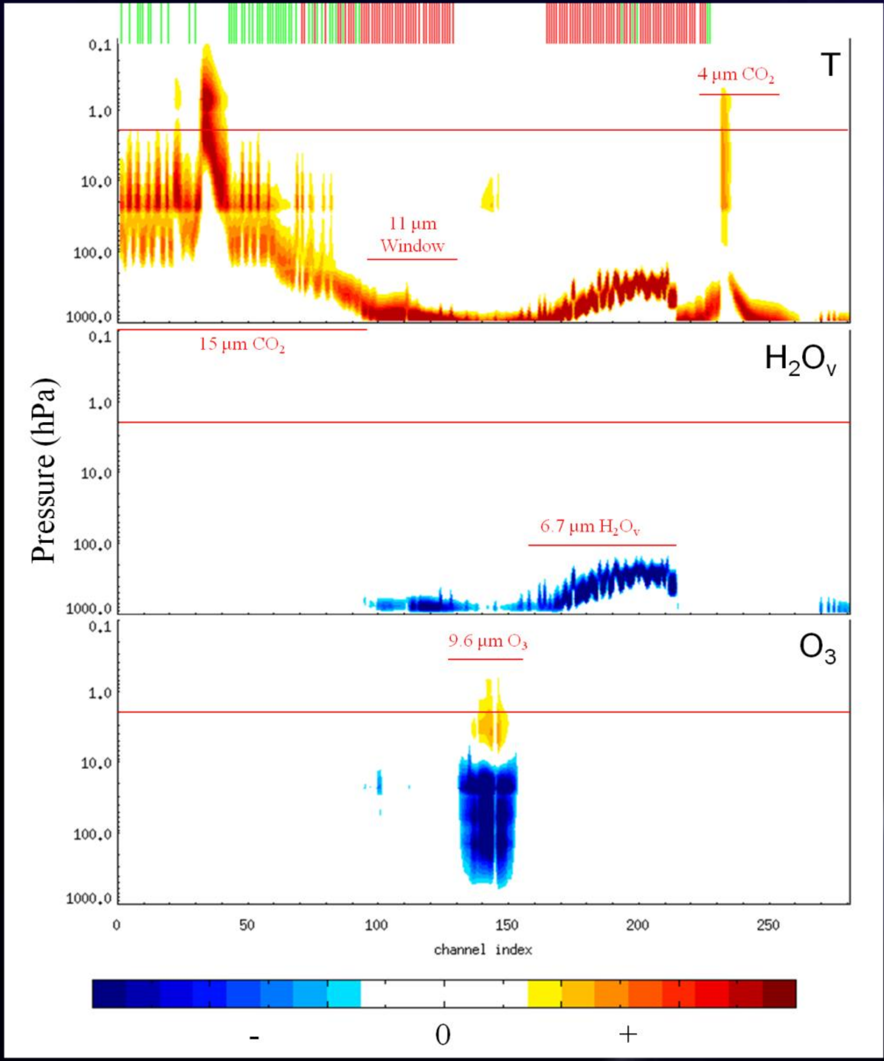
Channel Selection

- Limited to 281 channels available for operational assimilation
- The brightness temperature sensitivity, as defined as

$$\delta T_b^i = \frac{dT_b^i}{dq^i}(\delta q^i)$$

are shown to the right

- The NAM model top is at 2 hPa
  - Channels above this are inapplicable
- The NAM, unlike the GFS, has no O_3
- No 4μm channels are used
- Thus, of the 281 channels, 103 are selected for use (red)
- This is compared to 151 channels used in the global system (green, red inclusive)



Results

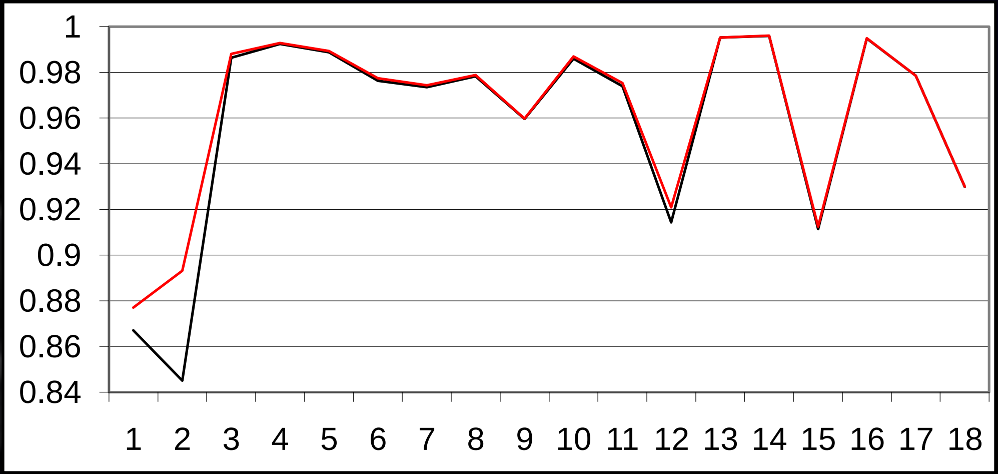
Timeframe

- The two experiments (CNTL and AIRS) are shown
- The results shown are from forecasts spawned between 0000 UTC 09 Apr 2007 and 0000 UTC 16 Apr 2007
- Prior to this, the assimilation cycle is run for two weeks
    - Allows for stabilization of bias correction parameters and for potentially negative impact occurring during this stabilization to propagate out of the domain
    - Allows for impact of AIRS to propagate through the background field

Analysis Verification

- Verifying the analysis itself is difficult in that most validation sources are operationally assimilated, thus not independent
- One source of independent data is GOES-11 sounder measurements that, unlike GOES-12, are not assimilated operationally
- Analysis must then be transformed to observation space via the nonlinear *H* operator.
    - Community Radiative Transfer Model (CRTM)

Analysis Verification



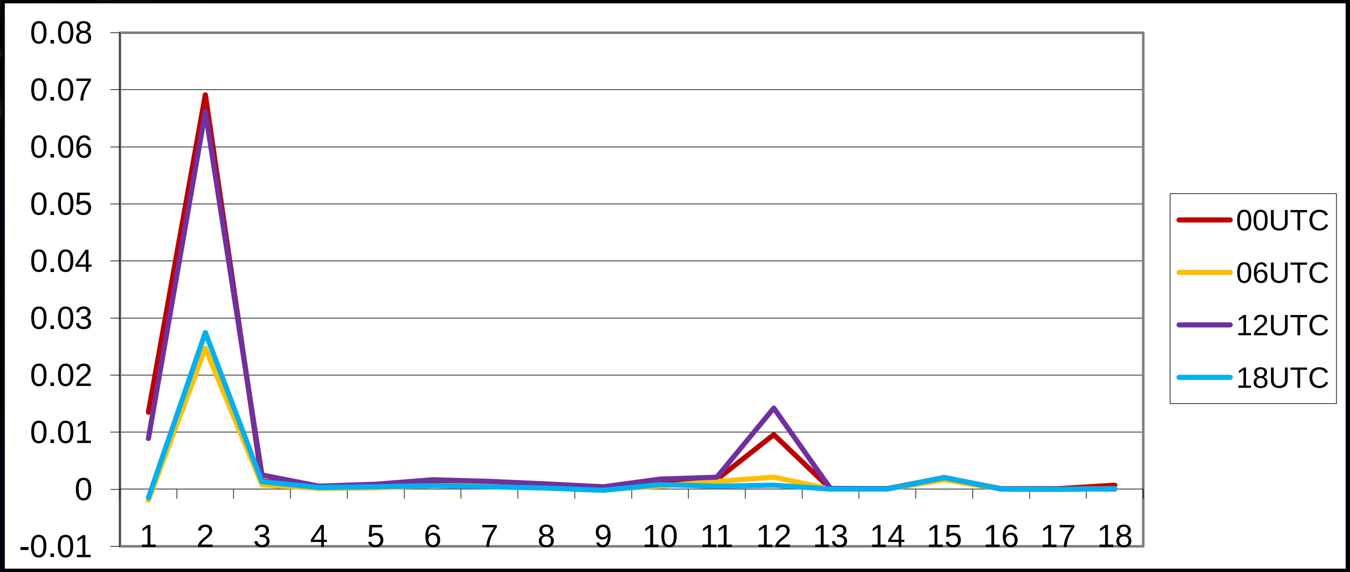
GOES-11 Brightness Temperatures

- The correlation between clear-sky observed brightness temperatures and brightness temperatures calculated from the analysis is shown above for CNTL (black) and AIRS (red)
- AIRS shows a positive improvement in correlation among all channels, with most notable improvement in sounder channels 1 (stratosphere CO_2), 2 (upper-troposphere CO_2) and 12 (upper troposphere H_2O_v)

Analysis Verification

By Initialization Time

- When considering the difference in correlation between the AIRS and CNTL as a function of F00, it is seen that the 00 and 12 UTC analyses and 06 and 18 UTC analysis group together
  - At 00/12 UTC, AIRS measurements are directly coincident to GOES-11
  - At 06/18 UTC, AIRS measurements are over the eastern portion of the domain; Impact is thus from improved background field

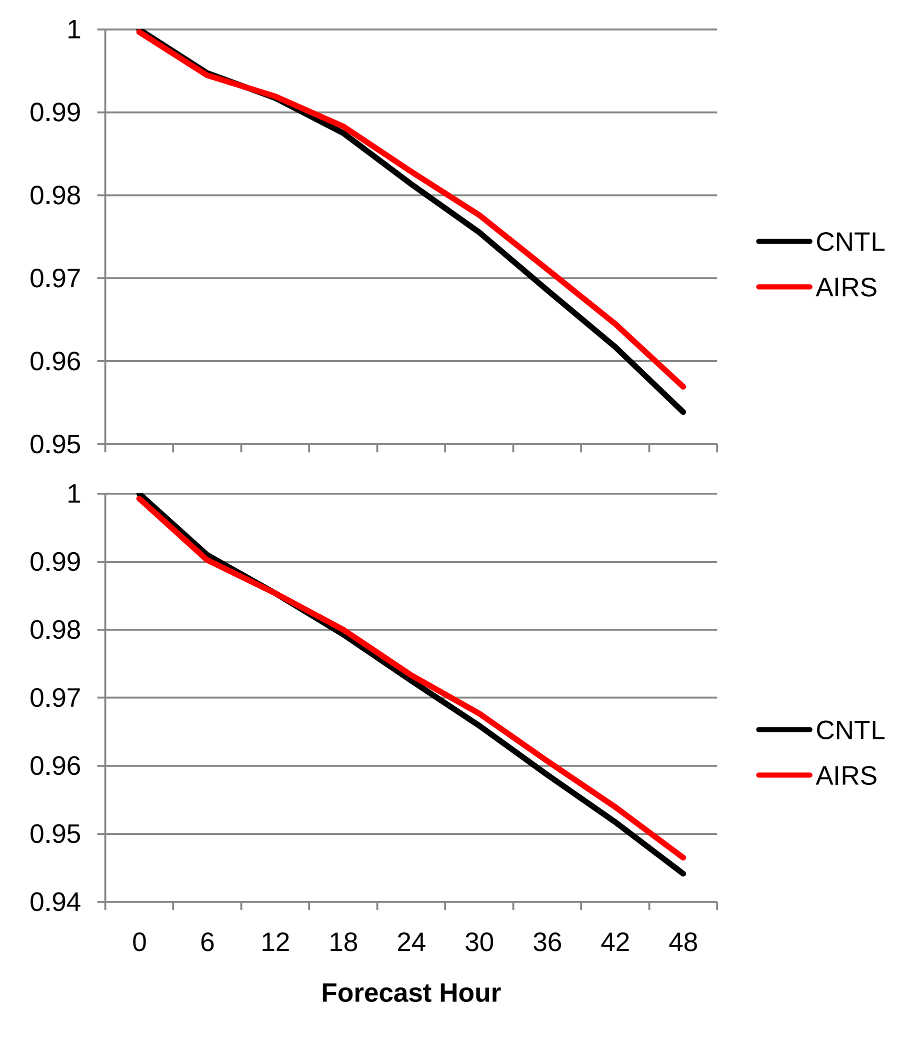


Forecast Verification

Limitations to Analysis Verification

- Verifying the analysis directly is problematic in two ways
  - Limited independent validation
  - The previous methodology, using GOES-11, involves a transformation to observation space
    - The GOES-11 T_b's view layer emission, not point observations. Thus, you're "viewing" broad layers of the atmosphere with contribution from many model levels
    - To a lesser extent, RT errors
- The solution to this is to verify the forecasts
  - An improved analysis will result in an improved forecast
- The forecasts spawned correspond to the analyses verified in the previous step

Forecast Verification



Height Anomalies

- A height anomaly is defined as

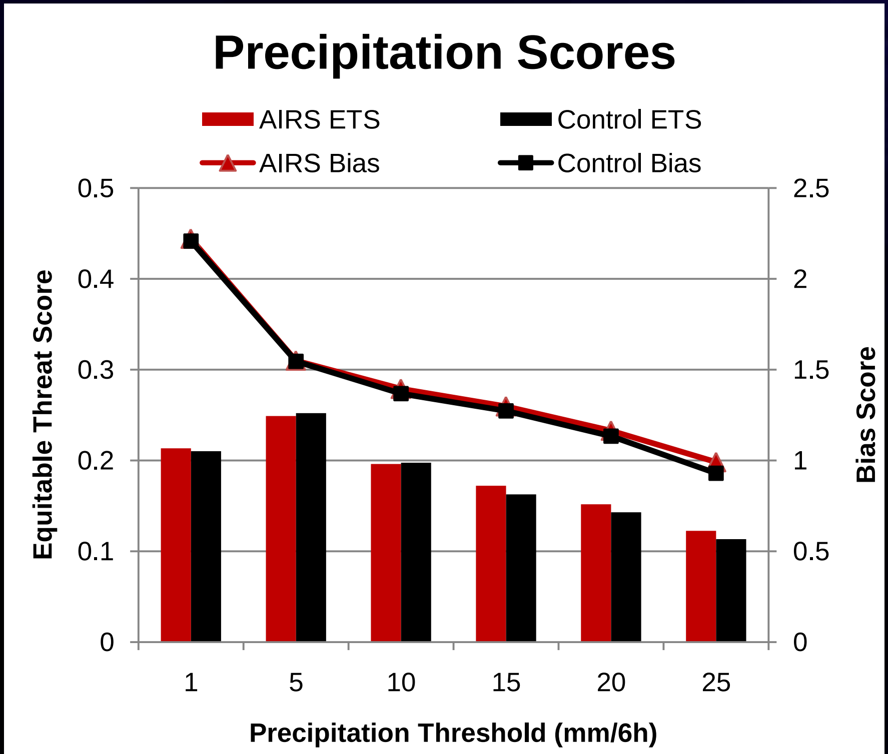
$$Z' = Z - \bar{Z}(\phi)$$

- Height anomaly correlations are calculated as the correlation between a forecast and a corresponding analysis
- To the left, 500 hPa (top) and 1000 hPa (bottom) height anomaly correlations over the CONUS are shown
- A forecast improvement of 2.4 hours at 500 hPa and 1.9 hours at 1000 hPa are seen at 48 hr

Forecast Verification

Precipitation Scores

- Bias and Equitable Threat Scores (ETS) are shown
  - Bias indicates over- or under-forecasting
  - ETS is a ratio of success, where both successful forecasts and non-forecasts are considered
  - A "perfect" forecast will have a value of 1 for each score
- AIRS bias scores are comparable (< 5% improvement/degradation) to CNTL for all thresholds < 25mm/6h
  - Positive for the threshold of 25mm/6h, which shows a 7% improvement



- ETS shows negligible impact for thresholds < 15mm/6h, but improvements of 6%, 6%, and 8% for the three thresholds ≥ 15mm/6h

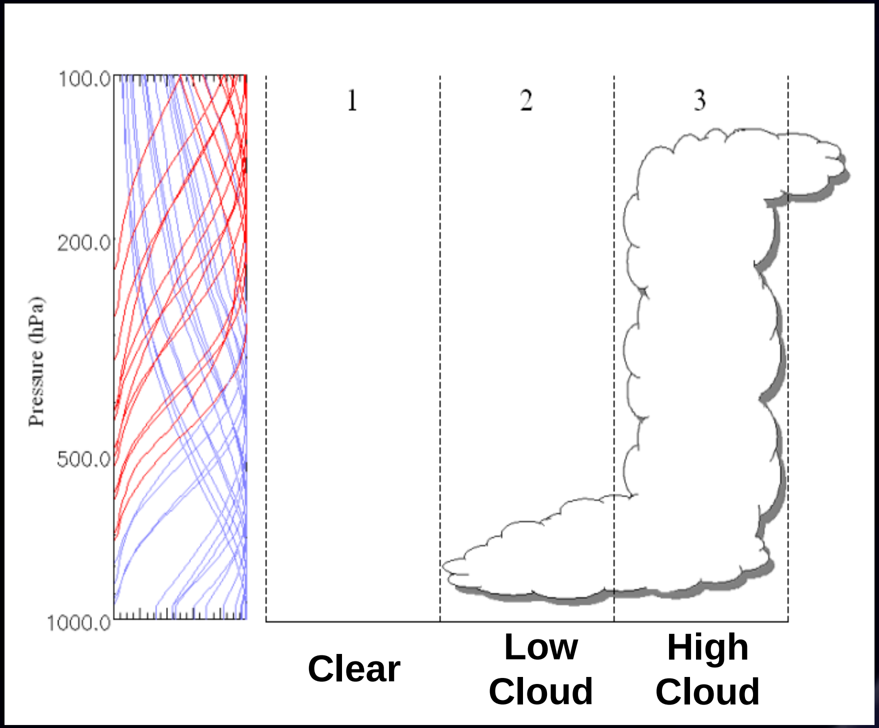
Detection of Cloud Contamination in AIRS Data

Cloud detection already inherent within GSI

- Example of the impact of clouds on Infrared measurements shown to the right
- Cloud detection technique for radiances is instrument independent
- Technique is applied to ALL infrared sounders (GOES Sounder, HIRS, and AIRS)

Additional technique implemented within the GSI

- Utilize hyperspectral nature of AIRS to improve cloud detection



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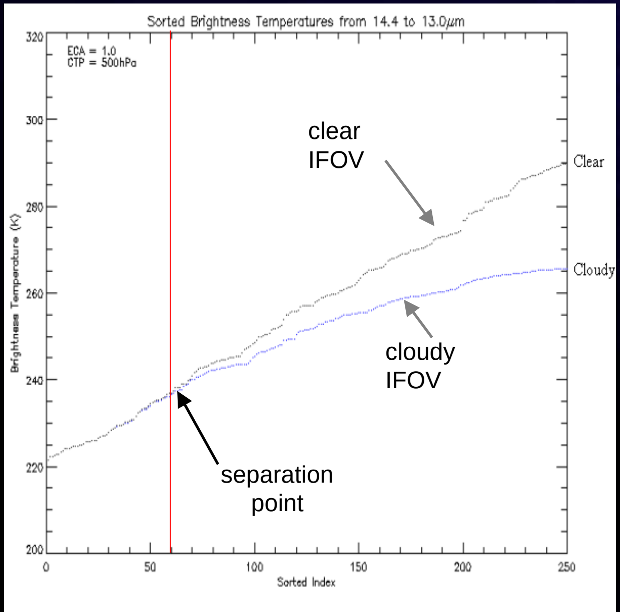


The determination of those in IFOV 2 which are usable

- The CO_2 sorting technique (Holz et al. 2006) is adapted for this purpose
- Originally for cloud height assessment, it is used to distinguish between contaminated and uncontaminated radiances

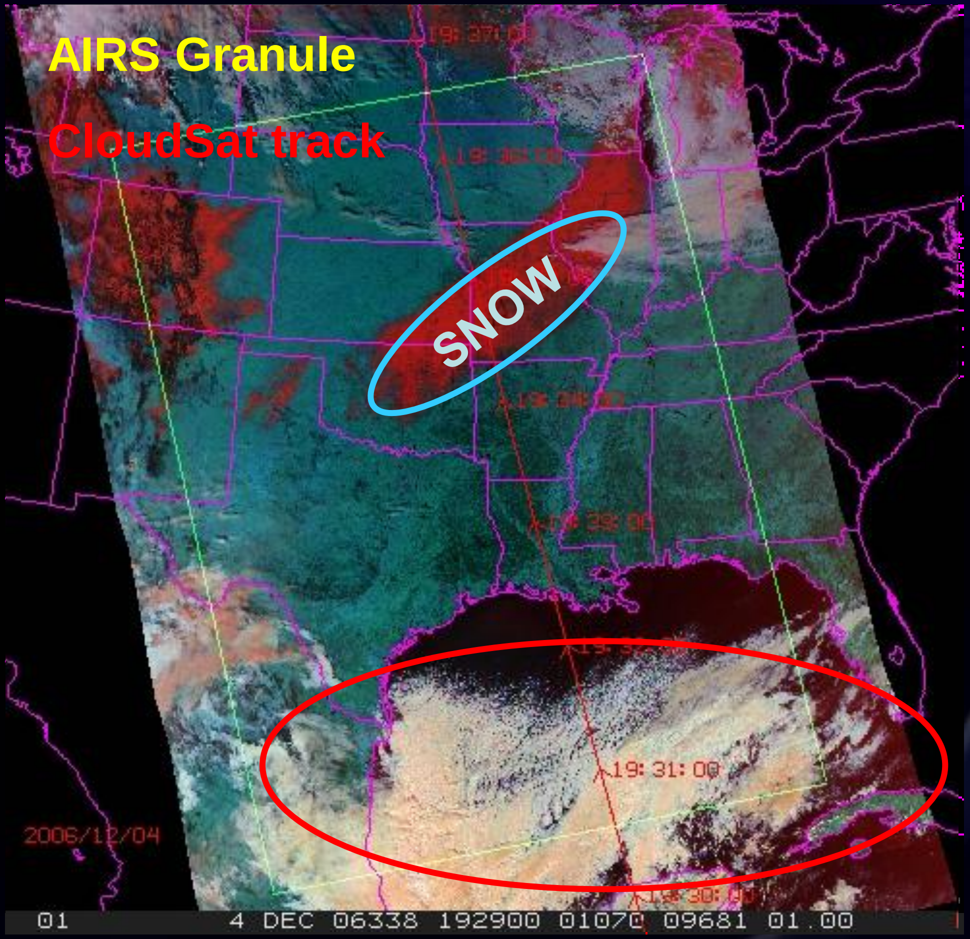
Approach

- Clear spectrum generated using forward radiative transfer calculation
- Spectra (clear and cloudy) sorted by brightness temperature
- Separation point determined by a number of tests (see preprint for more details)
- Channels determined as uncontaminated to the left of the separation point and contaminated to the right

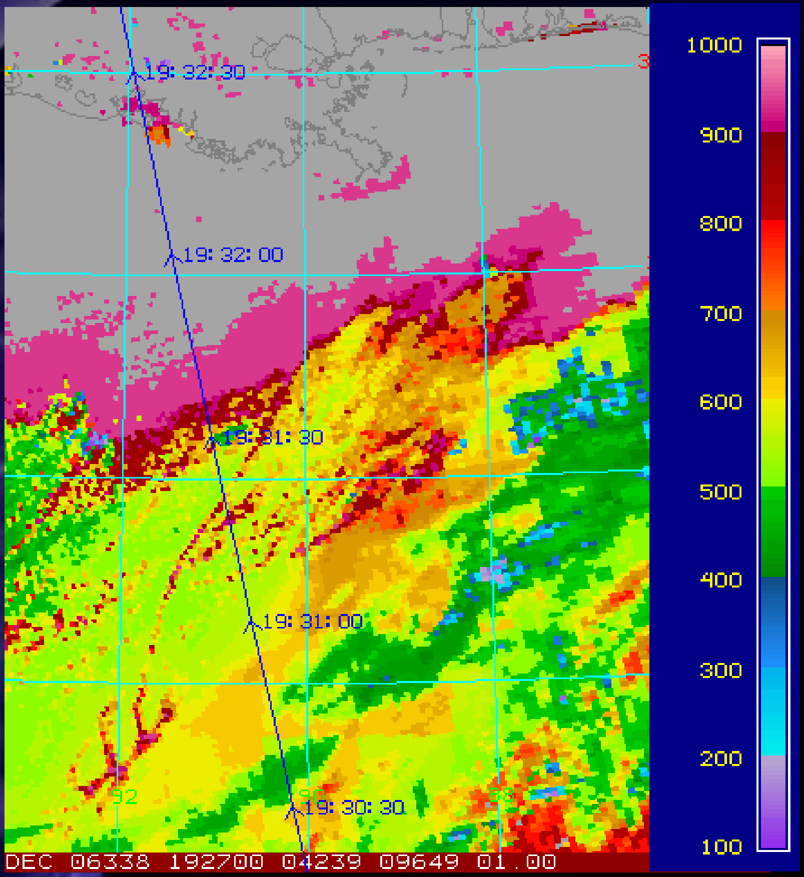
Example Case Study

4 Dec 2006

- Case was selected because of Aqua & CloudSat (A-Train) overpasses of two notable cloud formations
- Gulf formation relatively homogeneous towards south, broken towards north



MODIS CTP vs. AIRS Usable Channels (Gulf)



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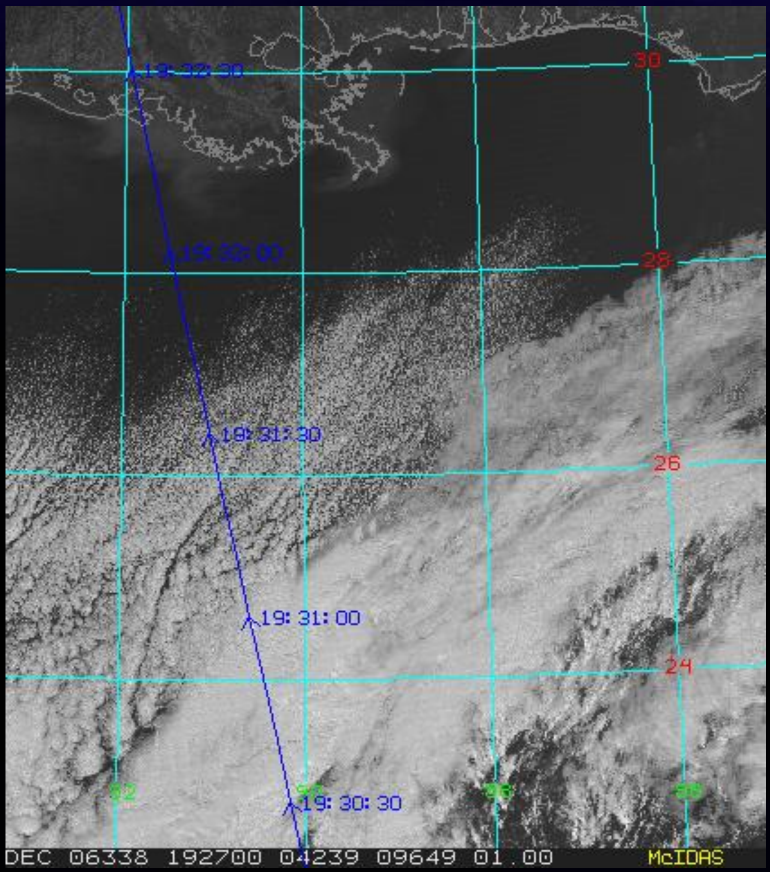

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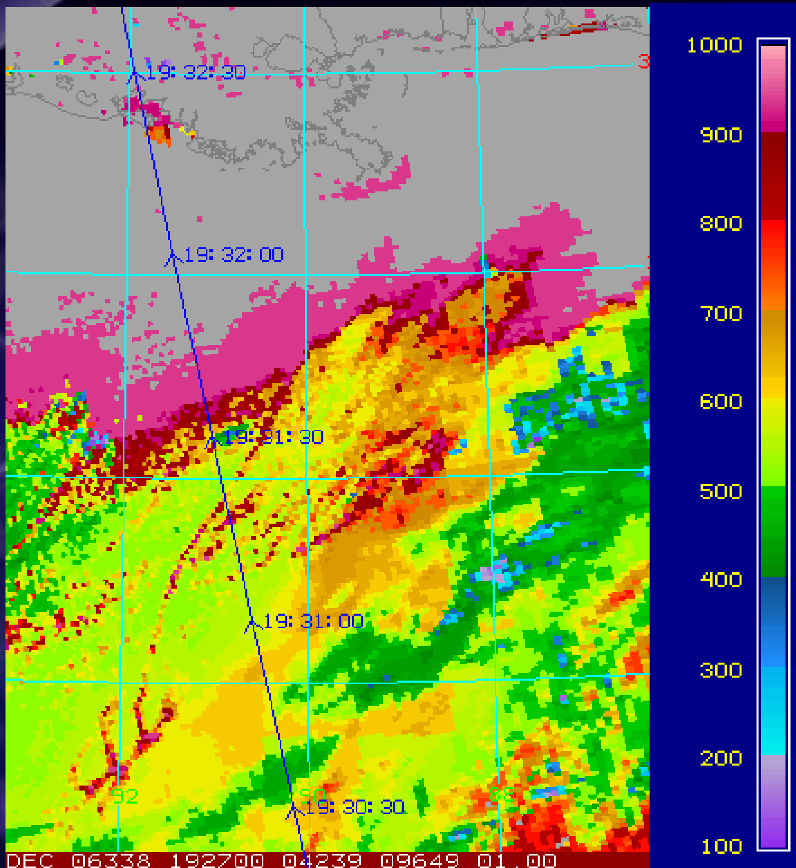

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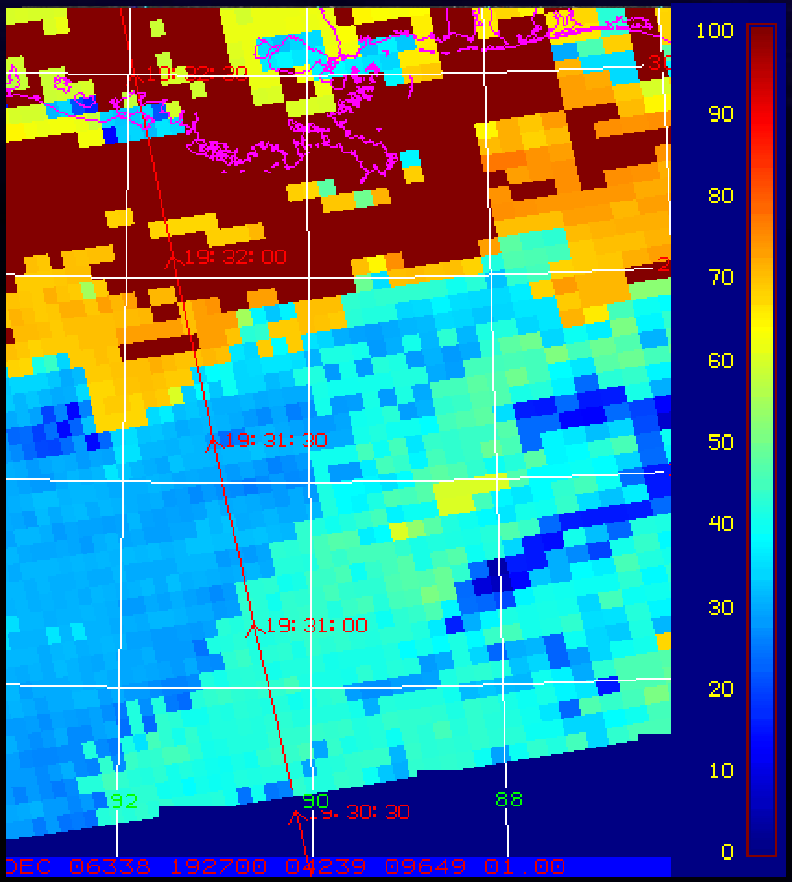

Channels for Assimilation (%)

- Visible agreement is seen between the MODIS CTPs and AIRS usable channels
- Higher % of usable channels in clear regions, lower % as clouds get higher

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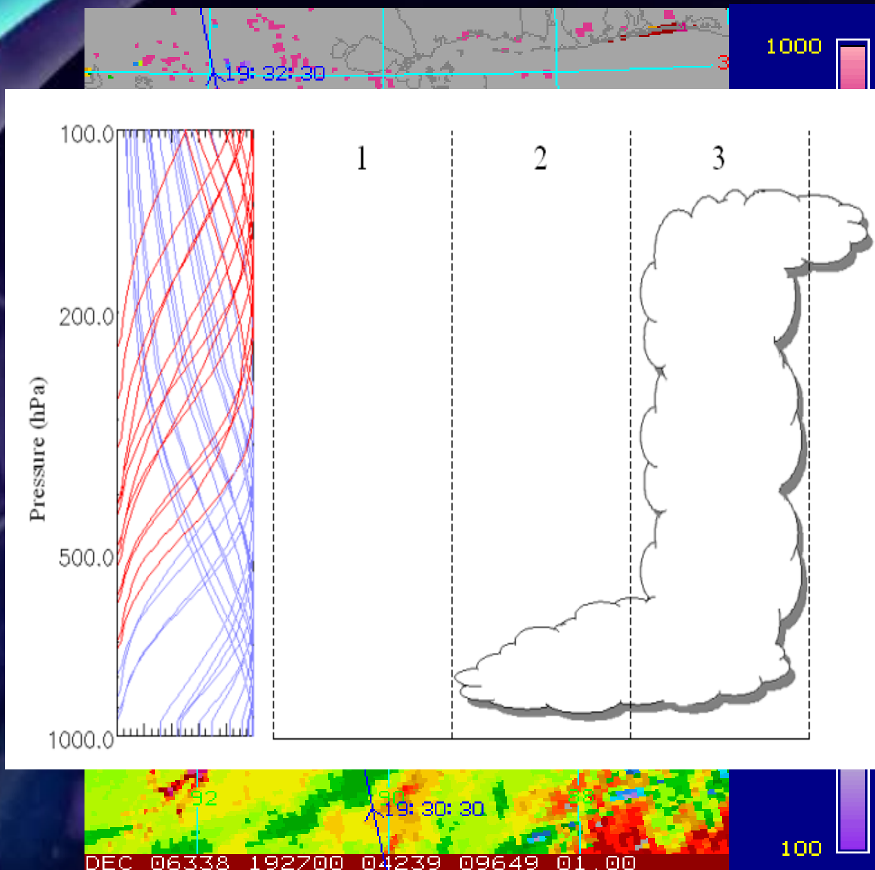

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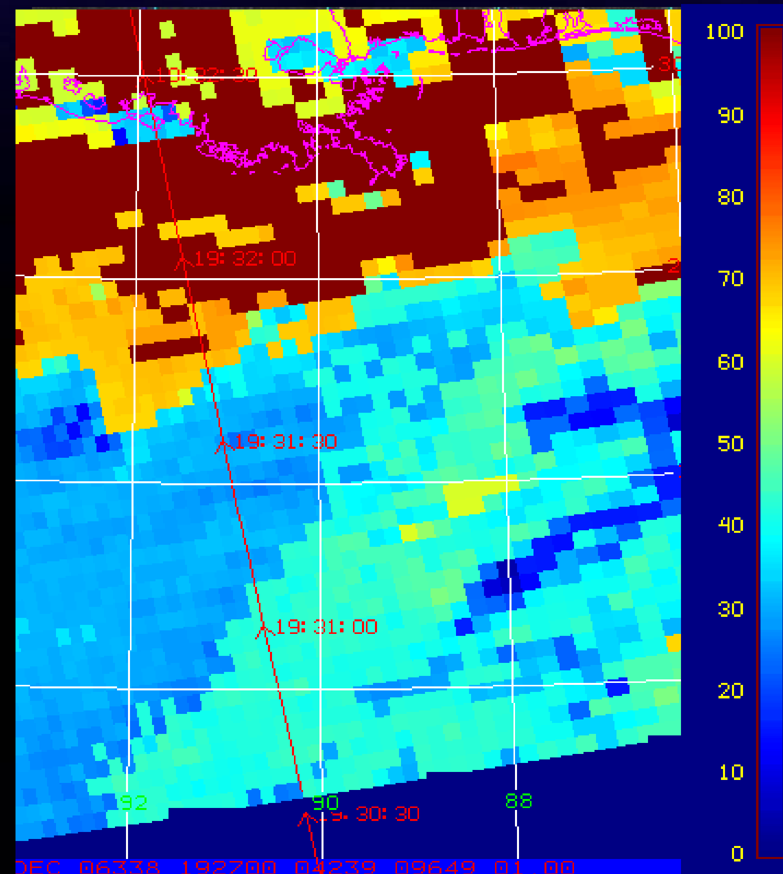

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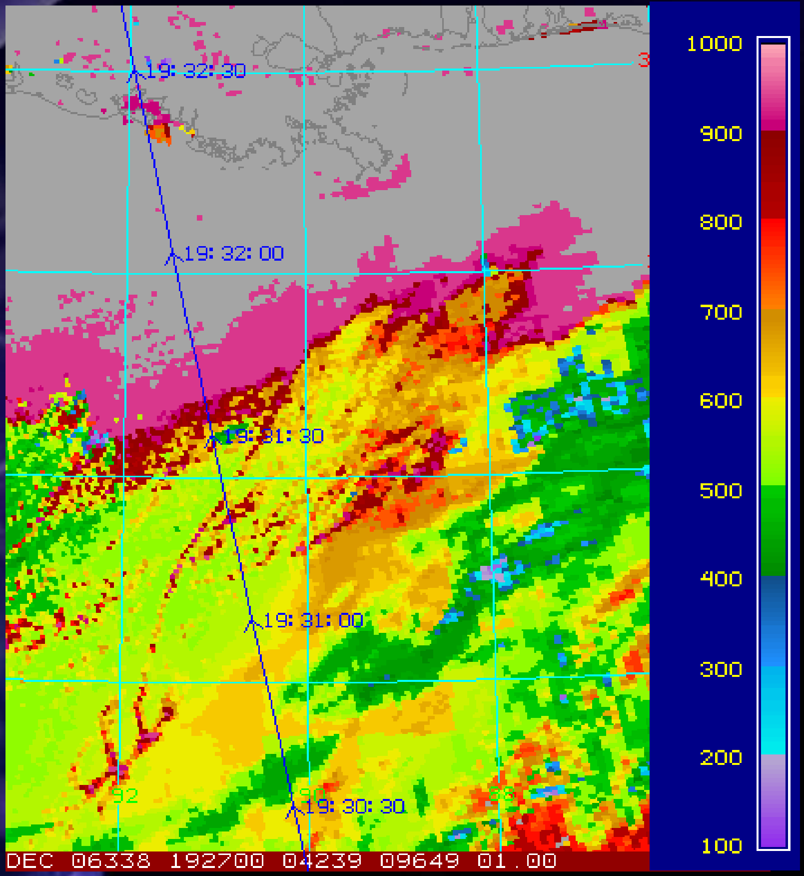
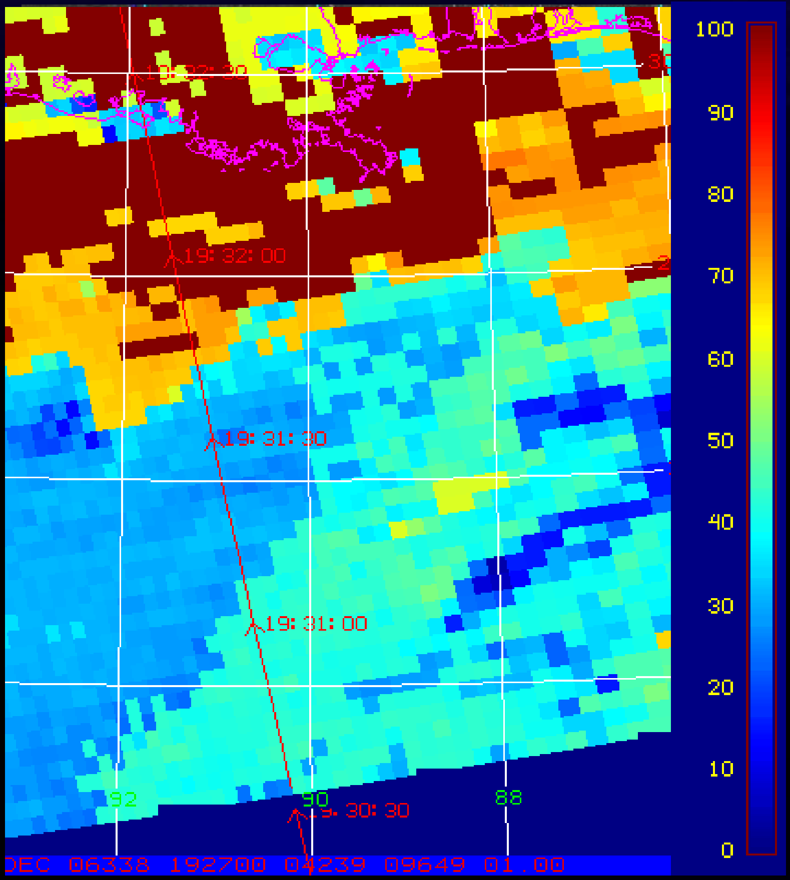


MODIS CTP



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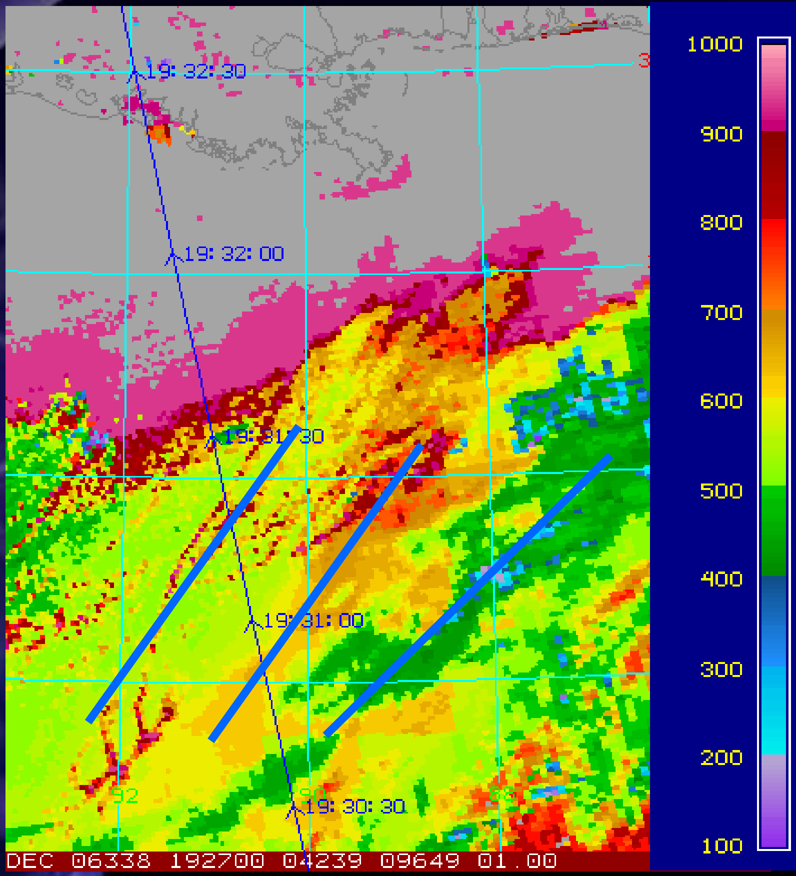
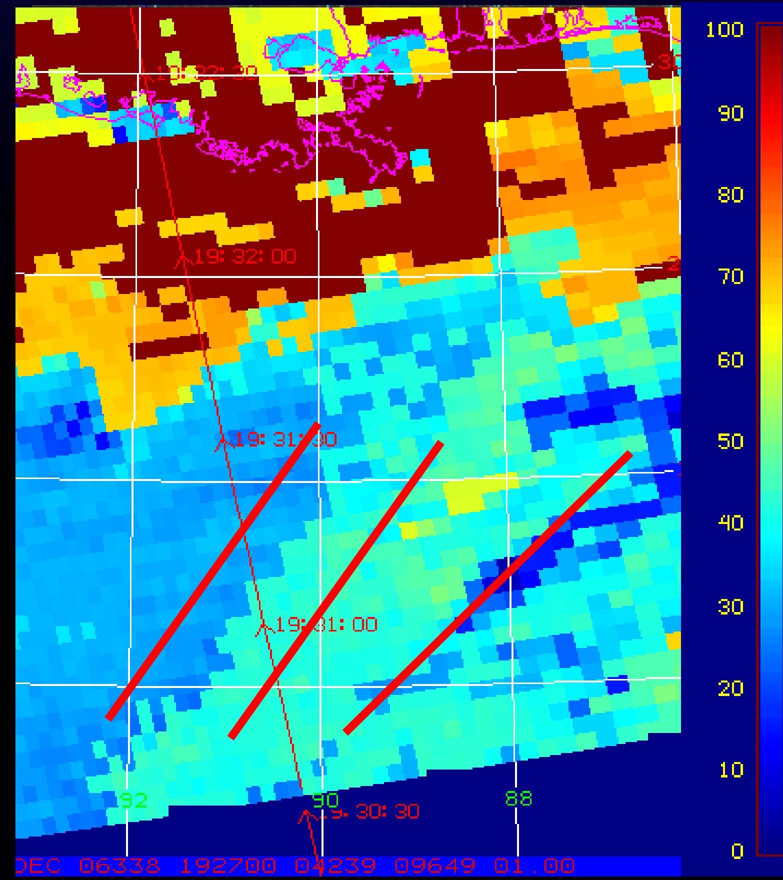


MODIS CTP



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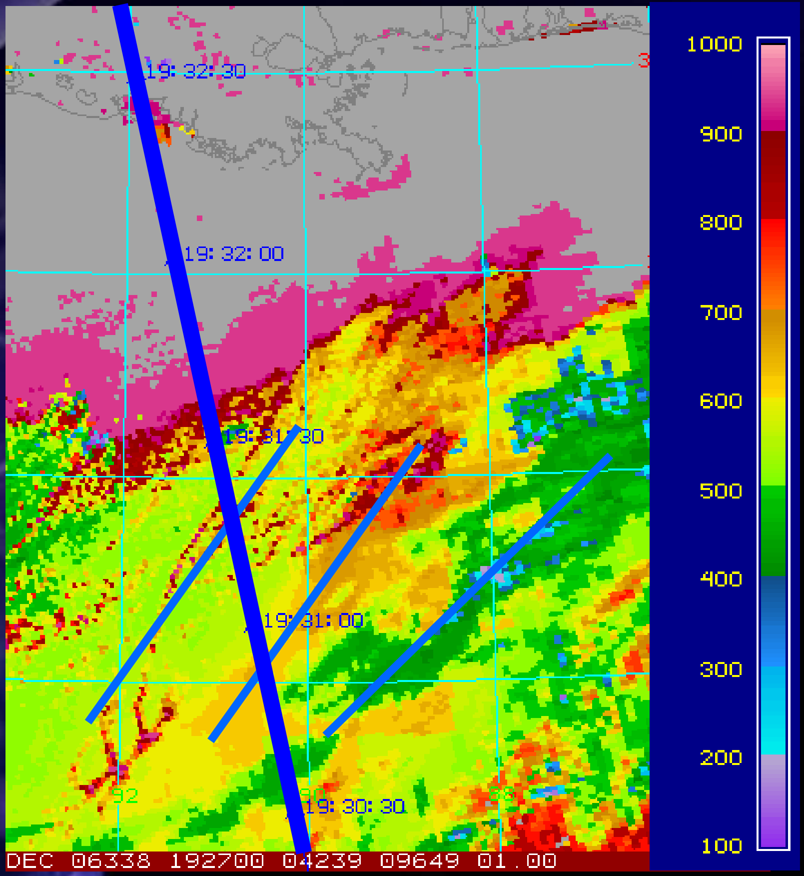
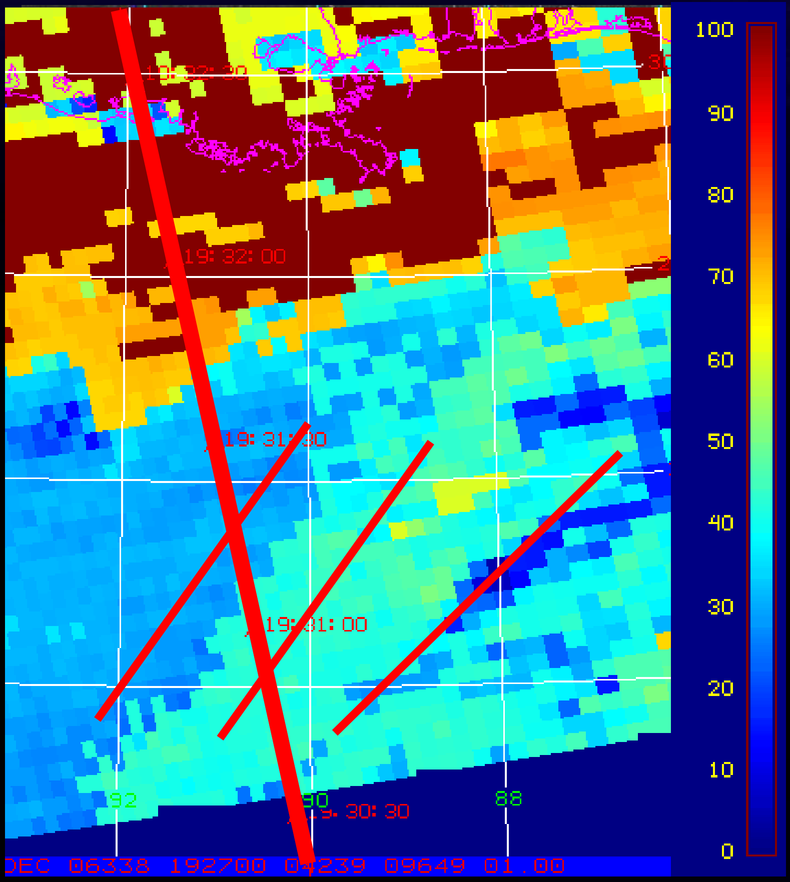


MODIS CTP



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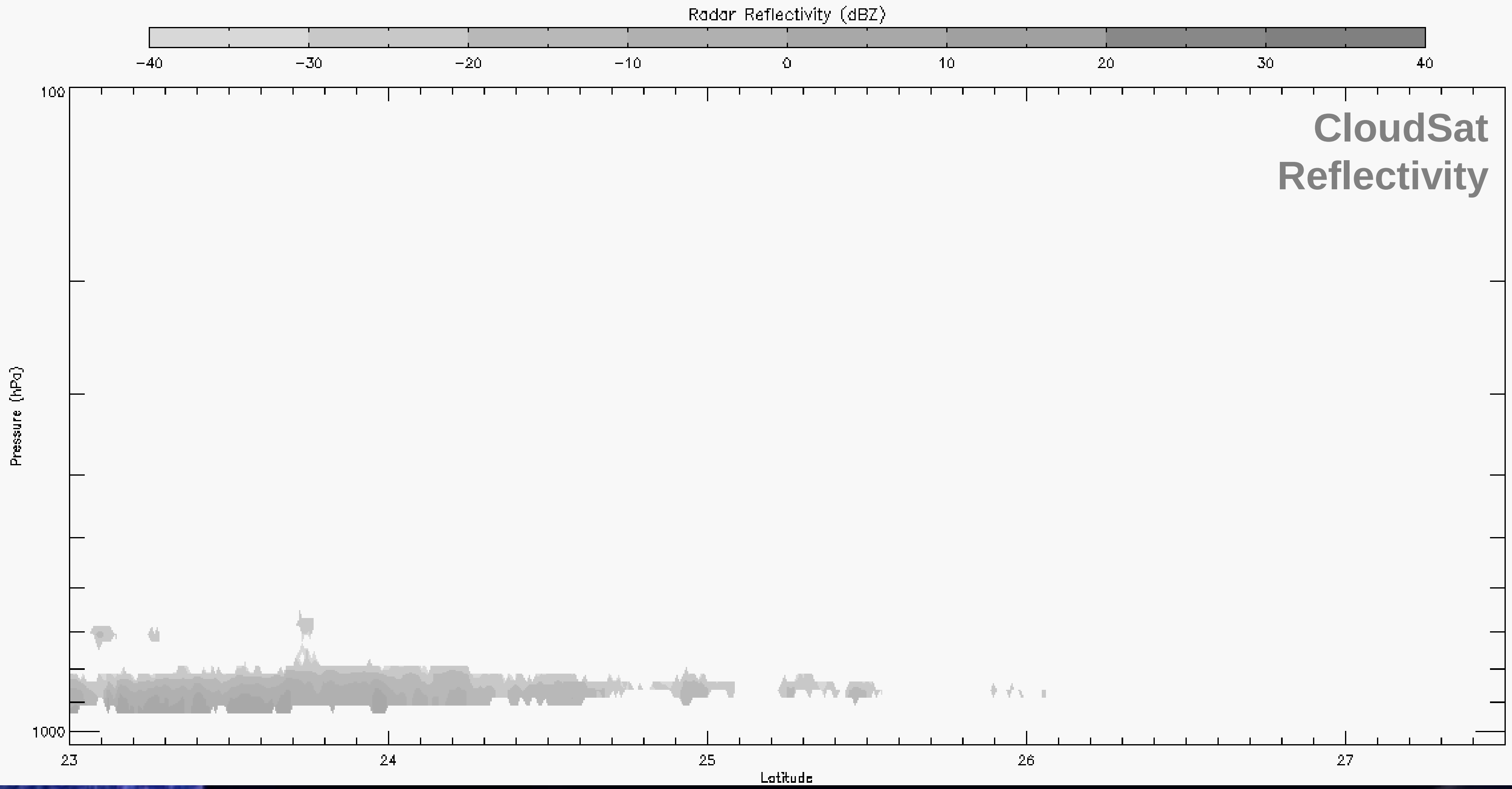
AIRS/MODIS/CloudSat Intercomparison (Gulf)



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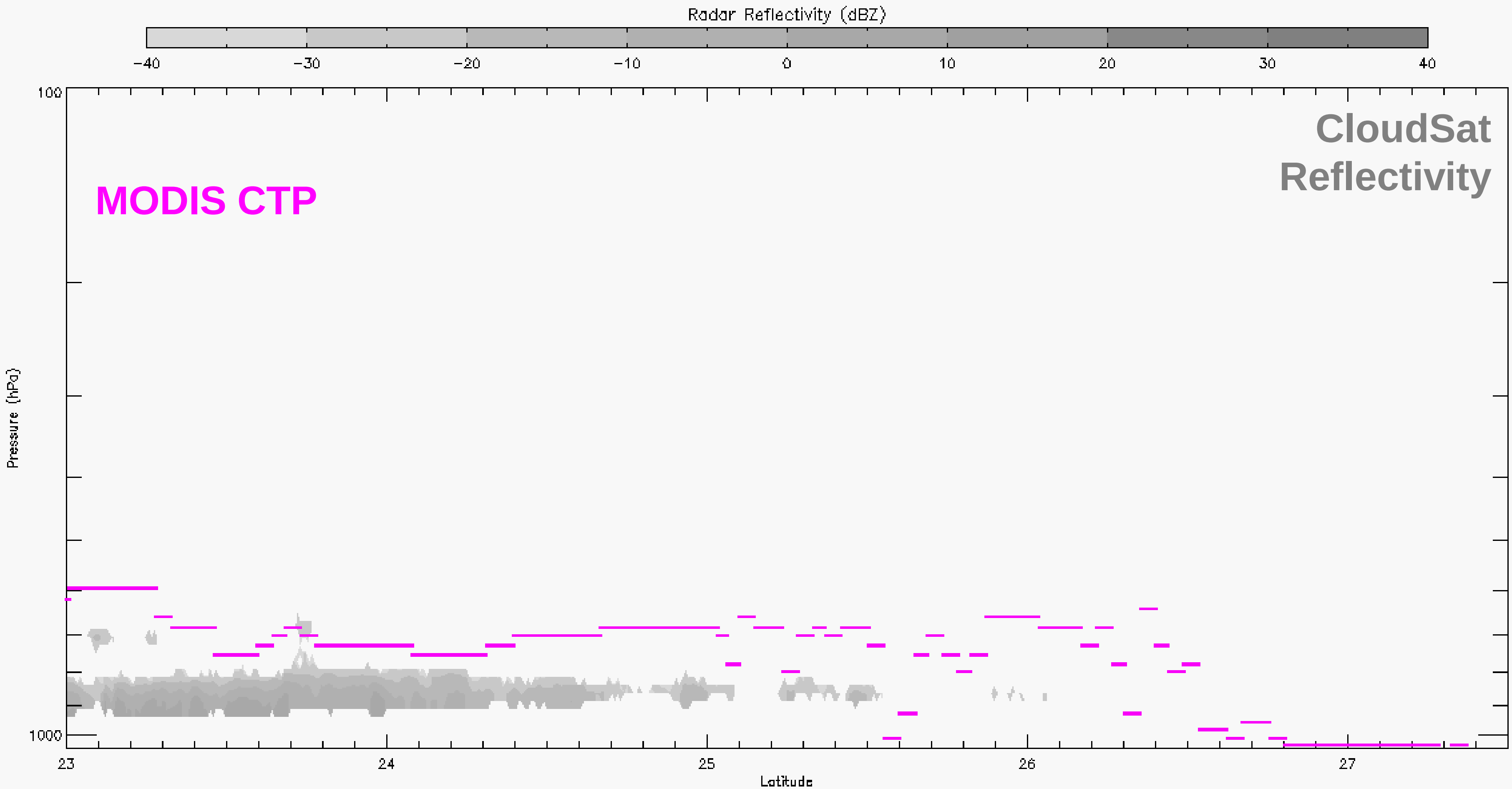
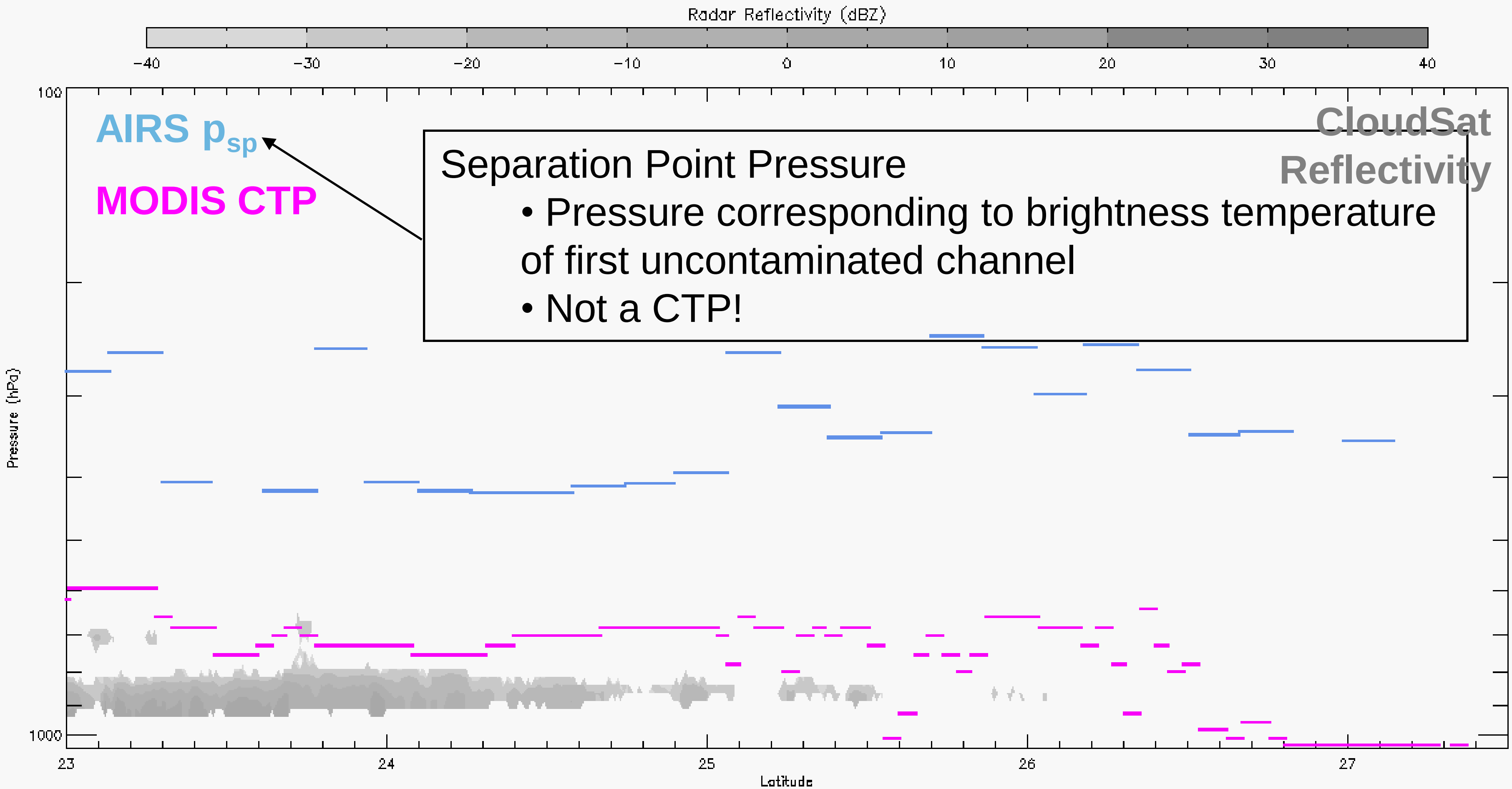
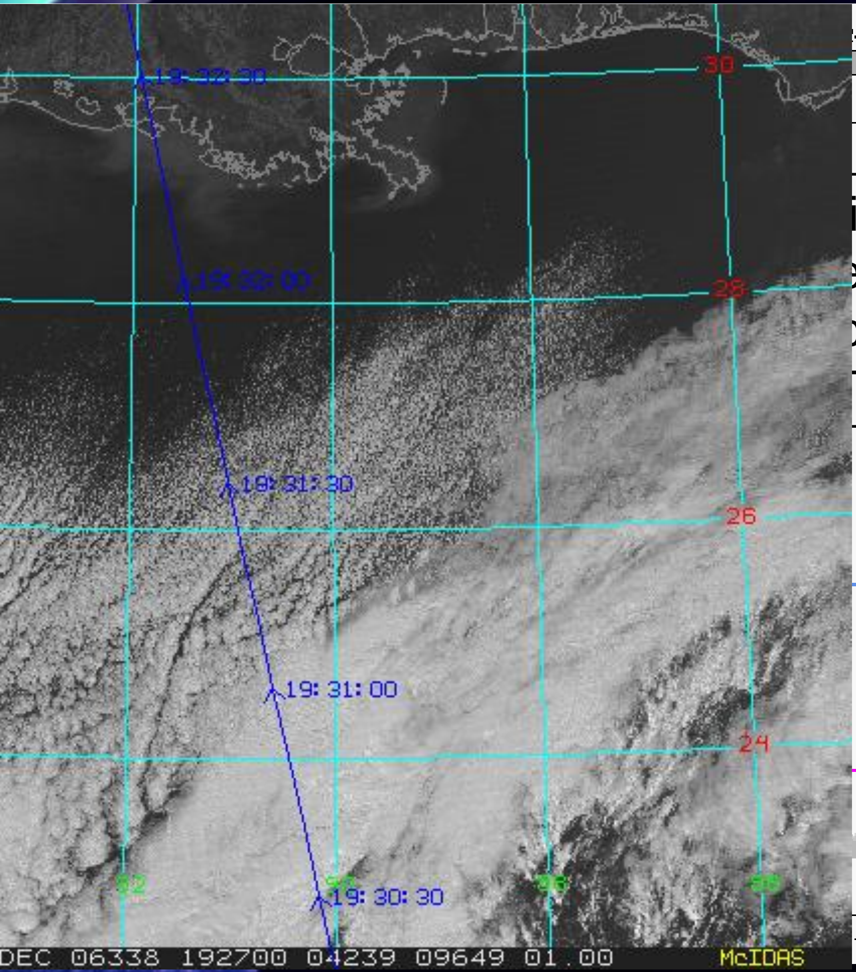
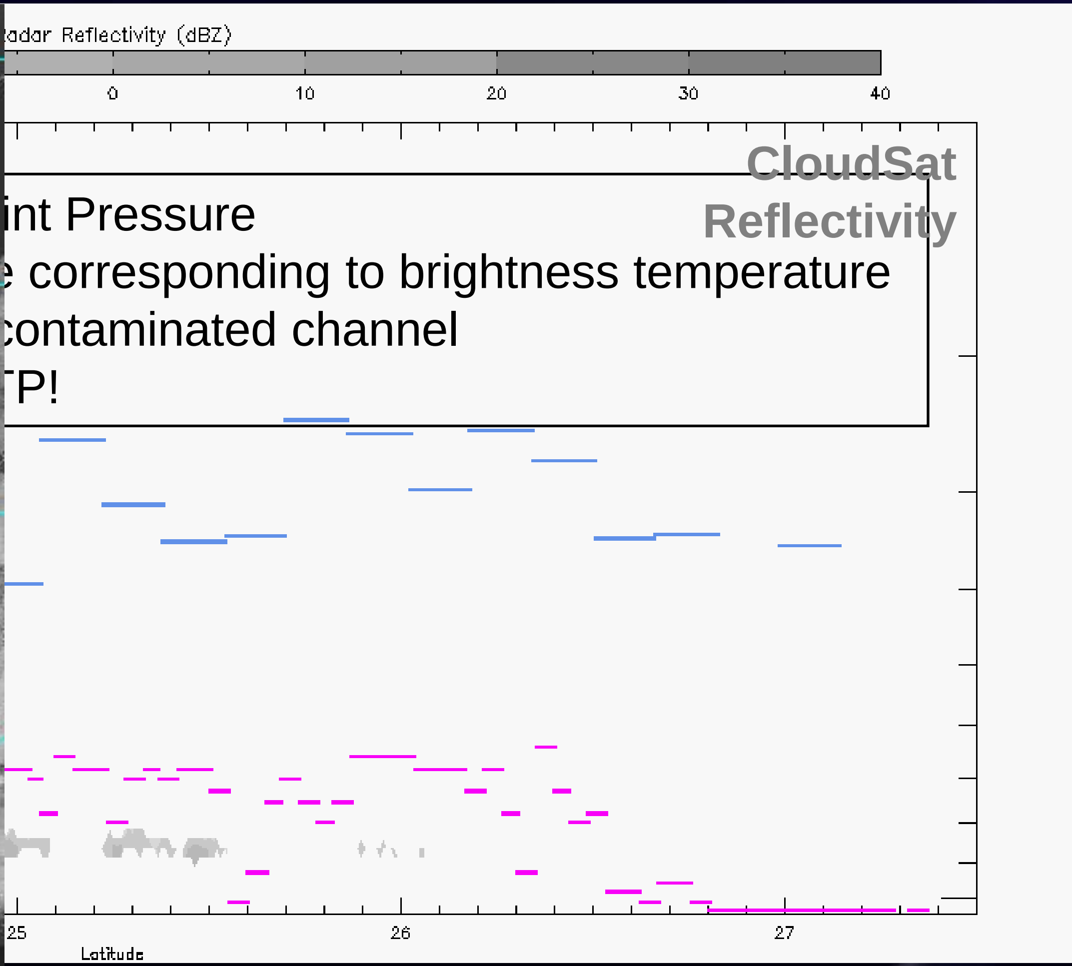


AIRS/MODIS/CloudSat Intercomparison (Gulf)



AIRS/MODIS/CloudSat Intercomparison (Gulf)





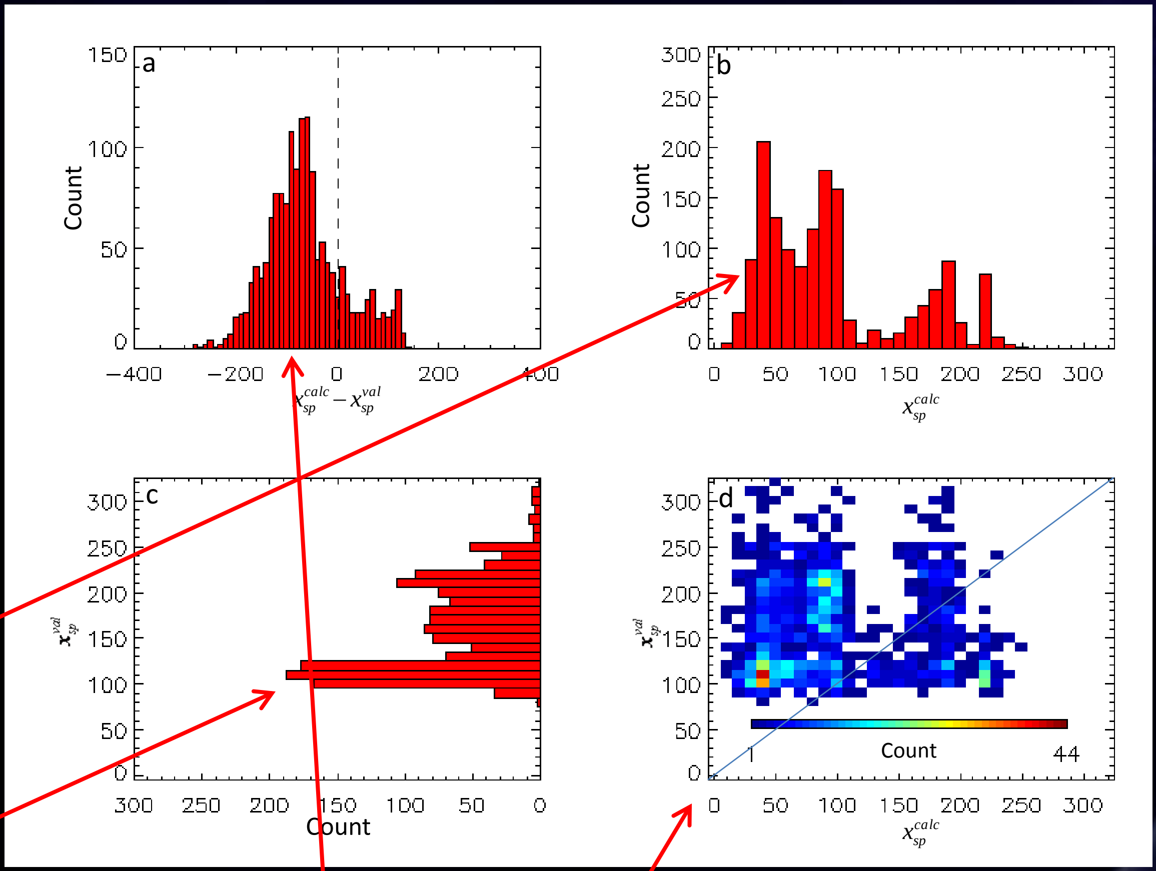
Direct Validation of Sorting Technique

Validation Dataset

- Manually created for a variety of environments
- Separation Point, a nonphysical quantity, is difficult to validate directly from MODIS or CloudSat

Distributions

- Calculated SP biased towards high clouds, but shows some skill for low clouds
- Validation data shows notable peak for low SP (high clouds)



- Differences and bivariate distribution show technique tends to be conservative, with reduced skill with lower clouds

Sorting Technique with 281 Subset

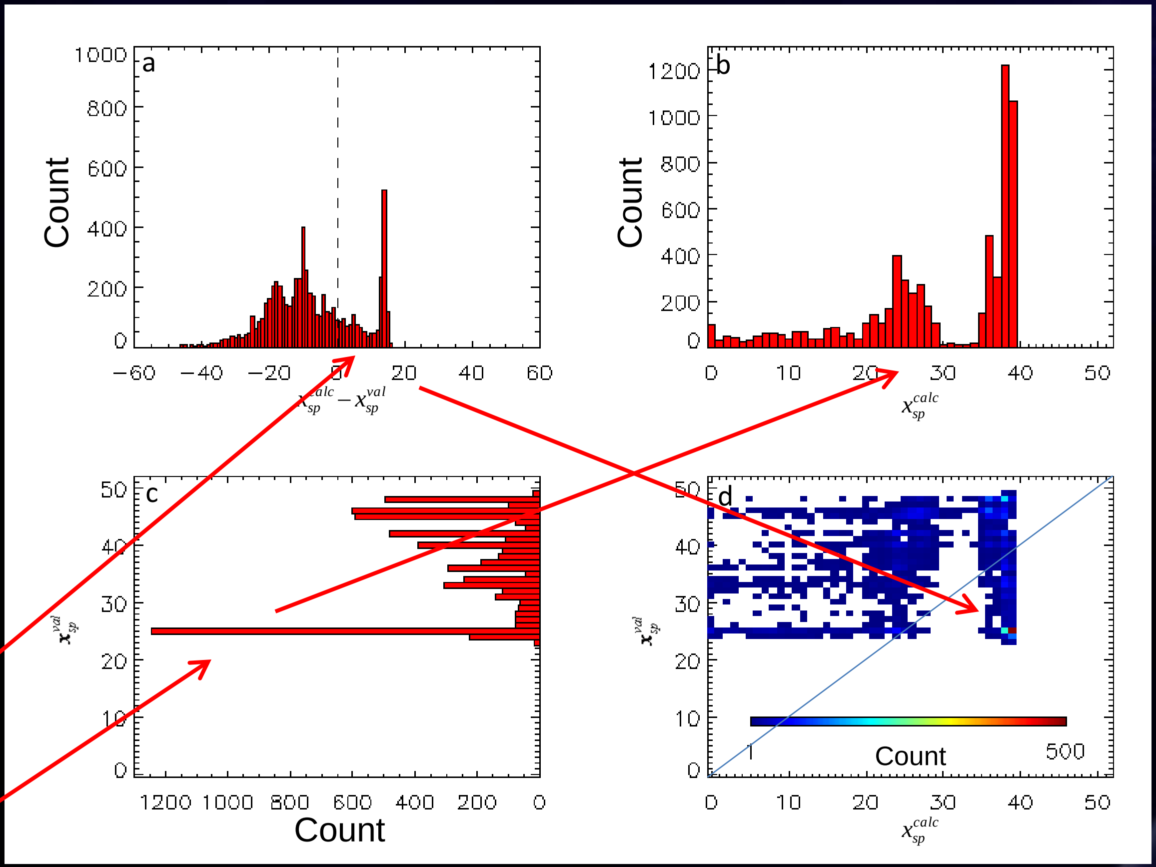
***Operational* Subset**

- The technique was adapted to the 281 channel subset
- Two tests of Separation were inapplicable

- Generally conservative tests inapplicable
- Validation Dataset same, but spectrally reduced

Distributions

- Calculated SP biased shows degradation and more aggressive performance
- High cloud peak in validation not retained



Conclusions

Impact of AIRS

- The addition of AIRS data to an NDAS-style system has shown to have a positive impact on analyses via comparison to GOES-11 observations
- Limitations of direct verification of the analyses are addressed with the verification of forecasts
- Forecast show a net positive improvement from the addition of AIRS data
- Cloud detection within the GSI (analysis) system may need further improvement, particularly in the Arctic regions, where cloud detection is difficult with infrared instruments
  - The cloud detection is instrument independent. In other words, cloud contamination of AIRS measurements is detected only using AIRS, no ancillary (i.e. visible) information is used
- Precipitation scores indicate that high-impact events, 25mm (~1 in) per six hours, are most significantly improved

Conclusions

The CO_2 sorting technique can be used to detect clouds in advanced thermal infrared measurements

- The approach has the potential to add important information above low level clouds
- Substantial increase over masking approach
- Direct adaptation of technique to operational system degrades performance
  - Reduced Spectral Coverage results in certain tests being inapplicable

These results are promising with the launch of additional hyperspectral infrared sounders such as IASI and the future launch of CrIS

SPoRT Future DA Work/Collaboration with JCSDA

Two manuscripts on AIRS radiance/GSI work submitted for publication; one manuscript on AIRS profile/WRF-Var work in preparation

SPoRT DA would like to assist with current DA/forecast problems recognized by operational centers related to remotely-sensed observations

- With expertise in both areas, SPoRT can assist in regional scale applications of both radiance and profile projects

Perform an "apples-to-apples" test of AIRS radiance assimilation and profile assimilation using the operational system (GSI and WRF-NMM)

- Use AIRS error estimates (part of L2 products) to populate off-diagonal terms in observation error matrix
- AIRS averaging kernels to properly assimilate profiles (instead of assuming they are uncorrelated observations such as radiosondes)
- Continue to pursue new methods of detecting cloudy radiances within the context of the operational system (leveraging data mining techniques developed at UAHuntsville)

Apply lessons learned to IASI, CrIS, and future hyperspectral sounders

Thank you for the invitation to speak

Questions? Comments?

For more information about SPoRT, visit our website at http://weather.msfc.nasa.gov/sport