Extraction of Profile Information from Cloud Contaminated Radiances

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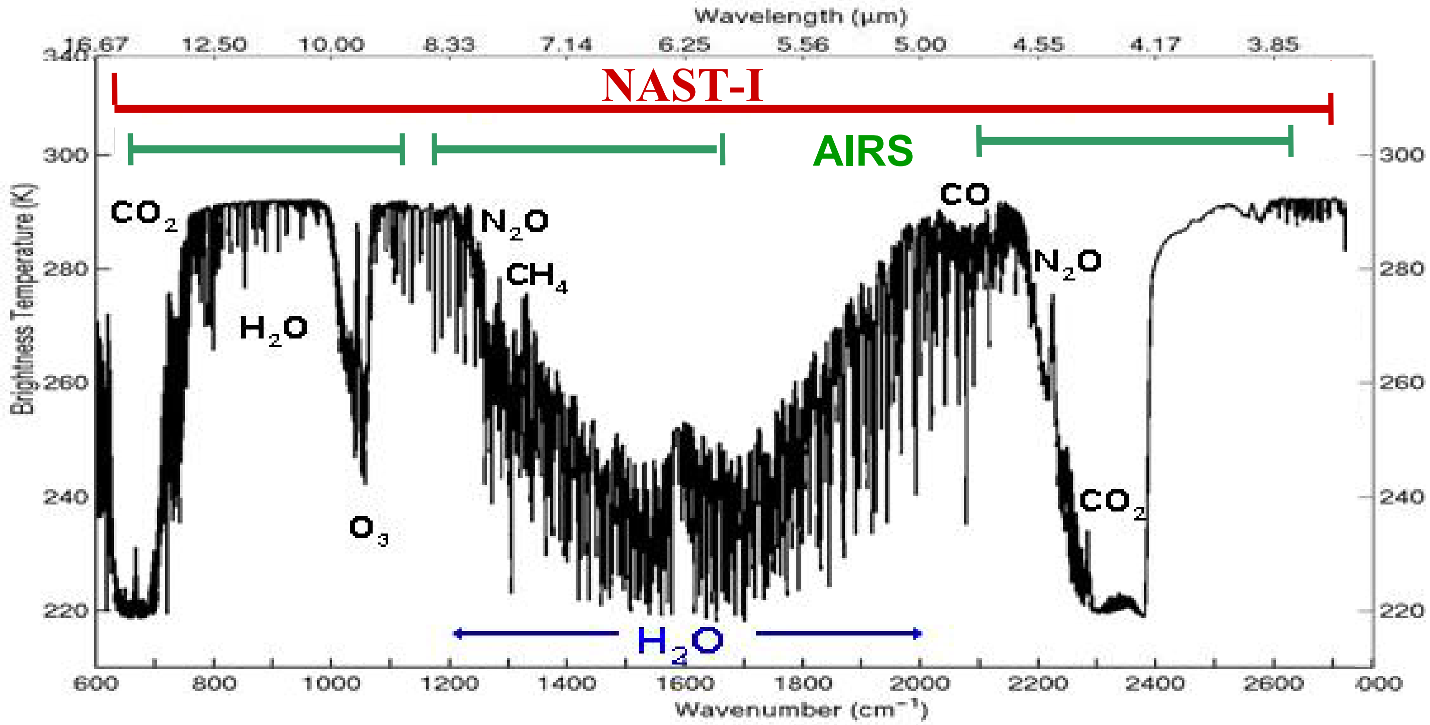
ECMWF Workshop on Assimilation of High Resolution Sounders in NWP (June 28 – July 1, 2004)

Isabel Pays Unwelcome Visit To Seaford VA

The 24-36 hour track forecast was good but the surge was missed by >1 meter

Can Hyerspectral Soundings Improve This!

NAST-I & AIRS Measurement Characteristics



Satellite AIRS (IR Grating Spectrometer)

Spectral Range: 3.7 – 15.4 Microns

Spectral Res: $\nu/\delta\nu$ =1200 (0.5-2.25 cm^{-1})

Ground Resolution: 13.5km @ nadir

Swath Width: 1650 km

Aircraft NAST-I (IR Interferometer)

Spectral Range: 3.5 - 16 Microns

Spectral Res: $\delta\nu$ = 0.25 cm^{-1}

Ground Resolution: 2.5 km @ 20 km

Swath Width: 40 km @ 20 km

Empirical Orthogonal Function (EOF) NAST-I Regression Retrieval

For clear sky and opaque cloud:

$$R = \varepsilon_{s,c} B_{s,c} \tau_{s,c} - \int_{P_{ac}}^{P_{s,c}} B\,d\tau - (1-\varepsilon_{s,c})\,\tau_{s,c} \int_{P_{s,c}}^{0} B\,d\tau^*$$

Radiance EOF Amplitudes

$$C_i = \sum_{j=1}^{nc} R_j E_{ji}$$

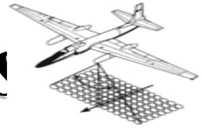
$$\left.\begin{matrix} \mathbf{T_s,} \\ \boldsymbol{\varepsilon_s(\nu)}, \\ \mathbf{T(p),} \\ \mathbf{Q(p)} \end{matrix}\right\} = \sum_{i=1}^{n-1} K_{mi} C_i + K_{mn} P_s$$

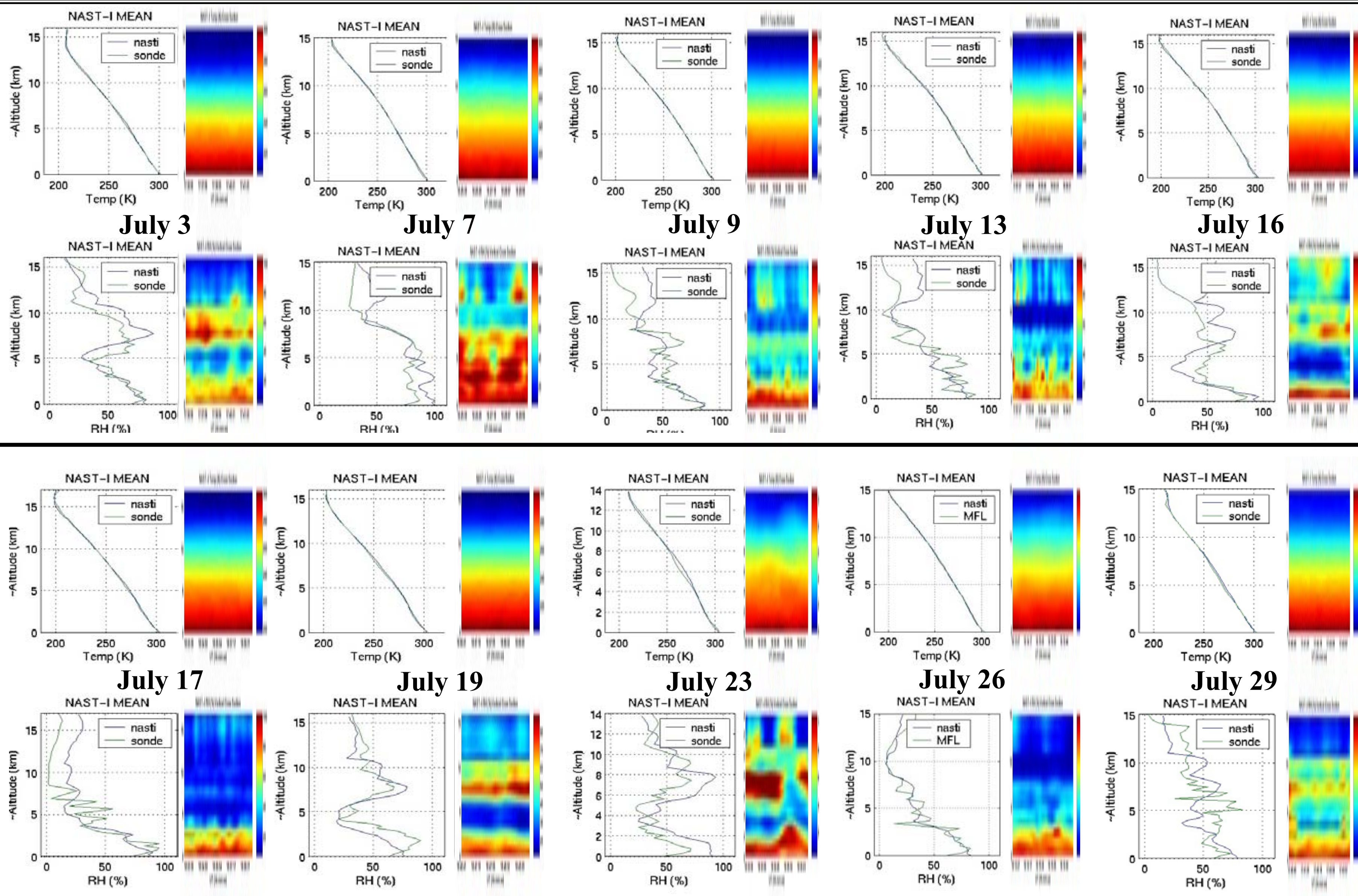
<u>Retrieval Solution</u>

R = radiance
$\varepsilon_{s,c}$ = surface or cloud emissivity
$B_{s,c}$ = surface or cloud Planck radiance
τ = transmittance between aircraft and atmospheric Pressure level (P)
$\tau_{S,c}$=atmospheric transmittance between aircraft and surface or cloud ($P_{S,c}$)
τ^* = atmospheric transmittance between surface or cloud P and aircraft
P_{ac} = aircraft pressure, P_s = surface pressure
$\Re$ = radiance
E = radiance covariance EOFs
C = radiance EOF amplitudes
T = temperature
Q = H_2O mixing ratio
K = regression coefficients

- **Physical Regression – EOFs and regression training based on calculated radiances**
- **Training should include cloud, sfc. emissivity, skin temp, and solar variability**
- **Null radiance errors assumed for PC specification and regression training**
- **EOF # selected by spatial radiance RMSD (observed minus retrieval) minimization**

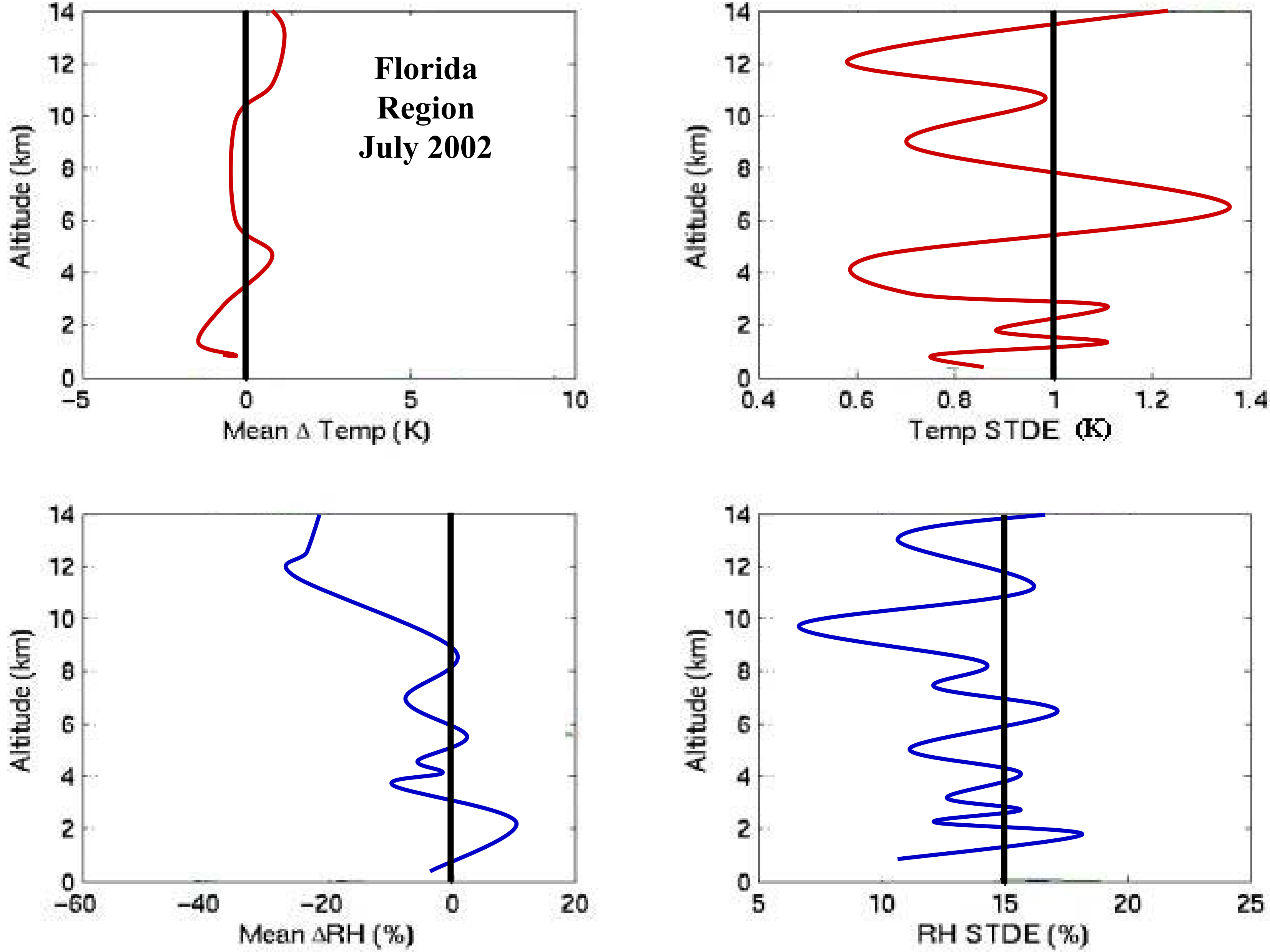
C-F* (July, 2002) NAST-I Vs Radiosondes





* Cirrus Regional Study of Tropical Anvils and Cirrus Layers - Florida Area Cirrus Experiment (CRYSTAL - FACE)

C-F Retrieval Vs Raob Mean and Stde (Clear Cases)



Approaches to Dealing With Clouds

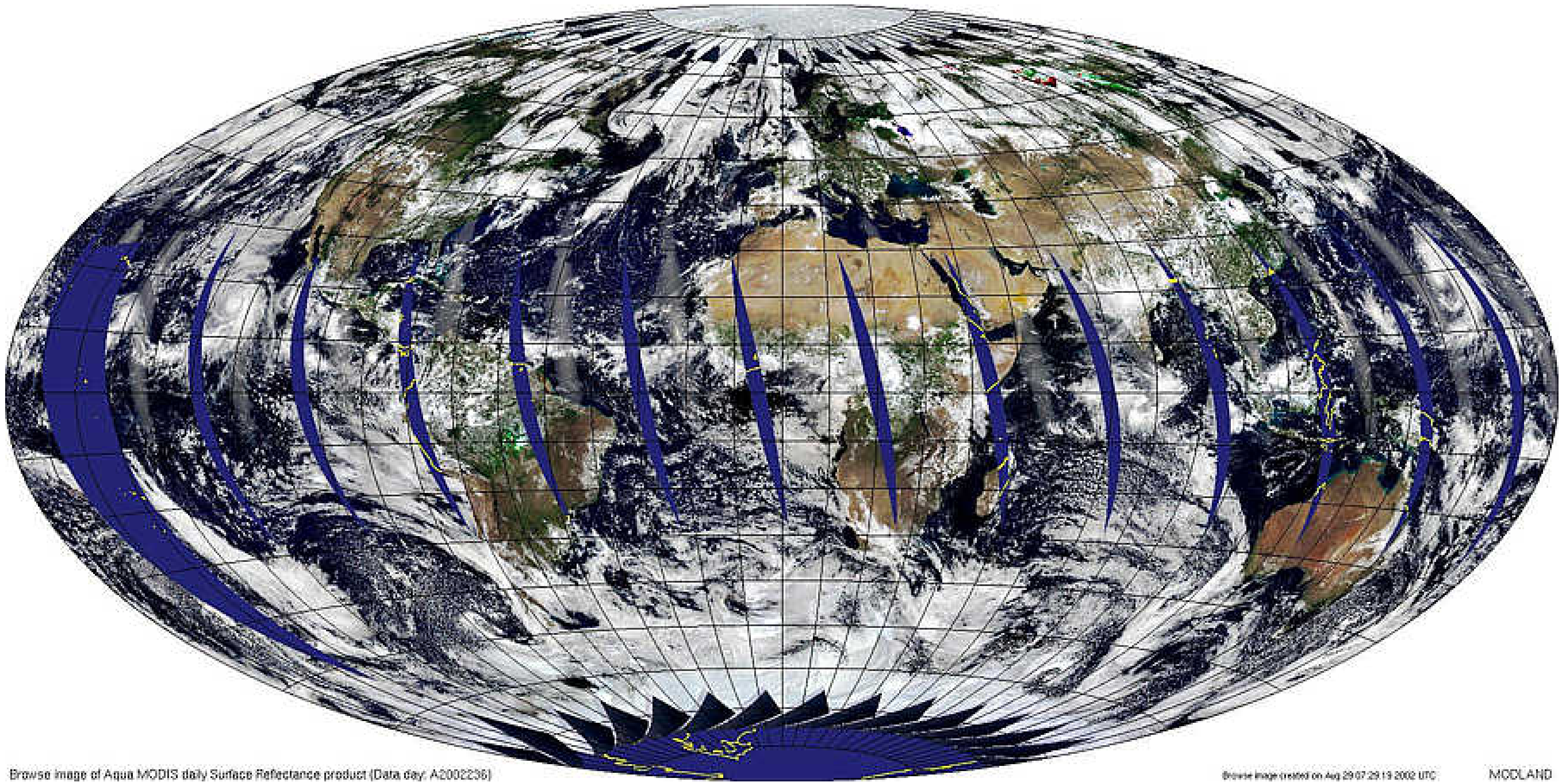
Hole Hunting - Requires small field of view. Produces soundings in clear IFOVs only.

Cloud Clearing - Provides sounding in clear air above and below broken clouds. Requires multi-spectral imager with broadband sounding channels to filter erroneous estimates. Results improve with decreasing field of view size.

Cloud Equivalent Clear Radiance Retrieval - Provides correct sounding down to near cloud top level with a erroneous sounding being produced below cloud level. Below an opaque overcast, an isothermal sounding results whereas for a semi-transparent or broken cloud condition, the sounding below the cloud will lie in-between the true sounding and the isothermal profile

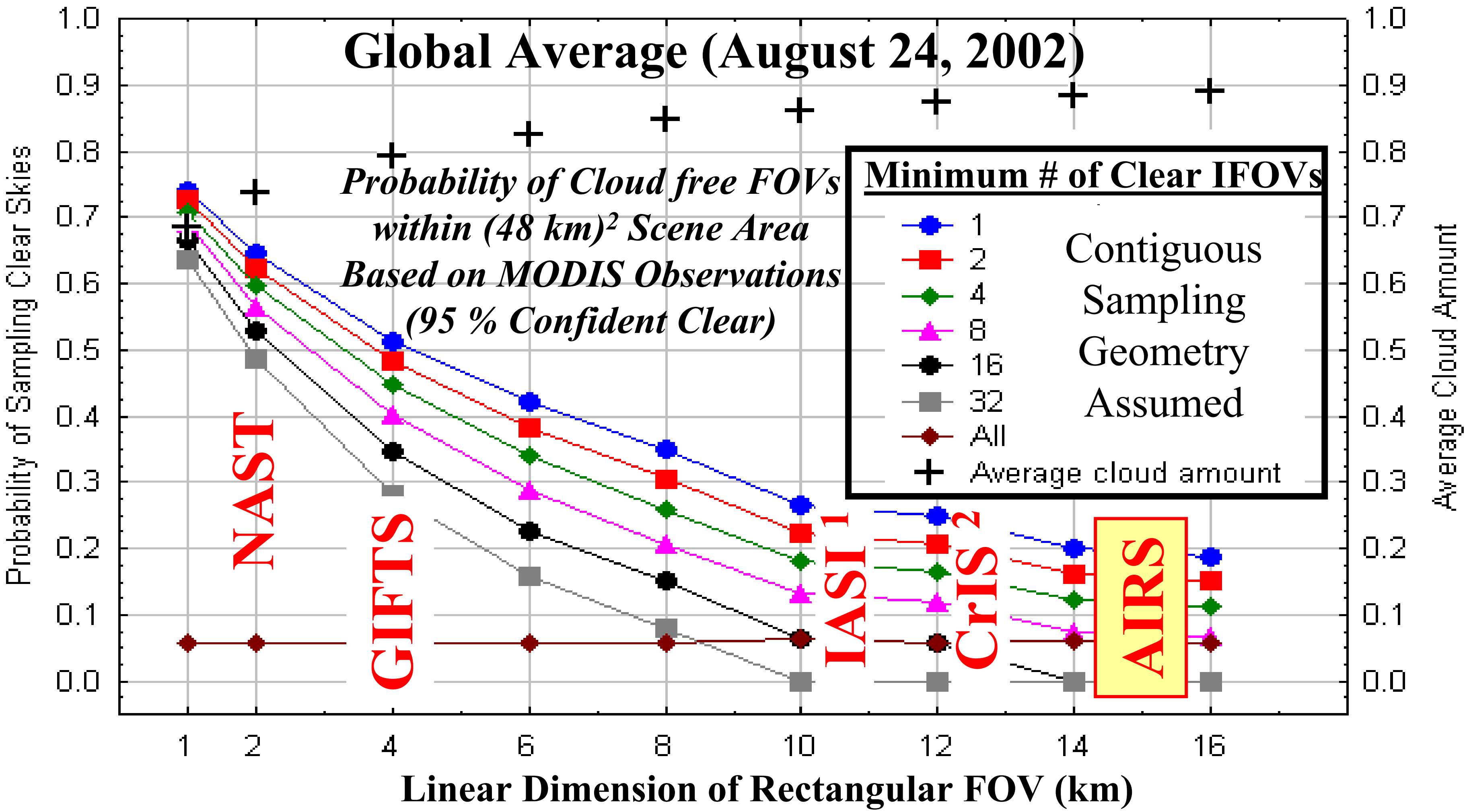
Cloud-Training - Provides sounding above and below semi-transparent and/or broken clouds, and above opaque overcast clouds. Enables cloud microphysical parameters to be retrieved for input to a physical/matrix inverse retrieval or the direct assimilation of radiances into the forecast model

Spatial resolution is important for resolving clear radiances



MODIS True Color Image – 24 August, 2002

***Hole Hunting* - Requires small field of view**

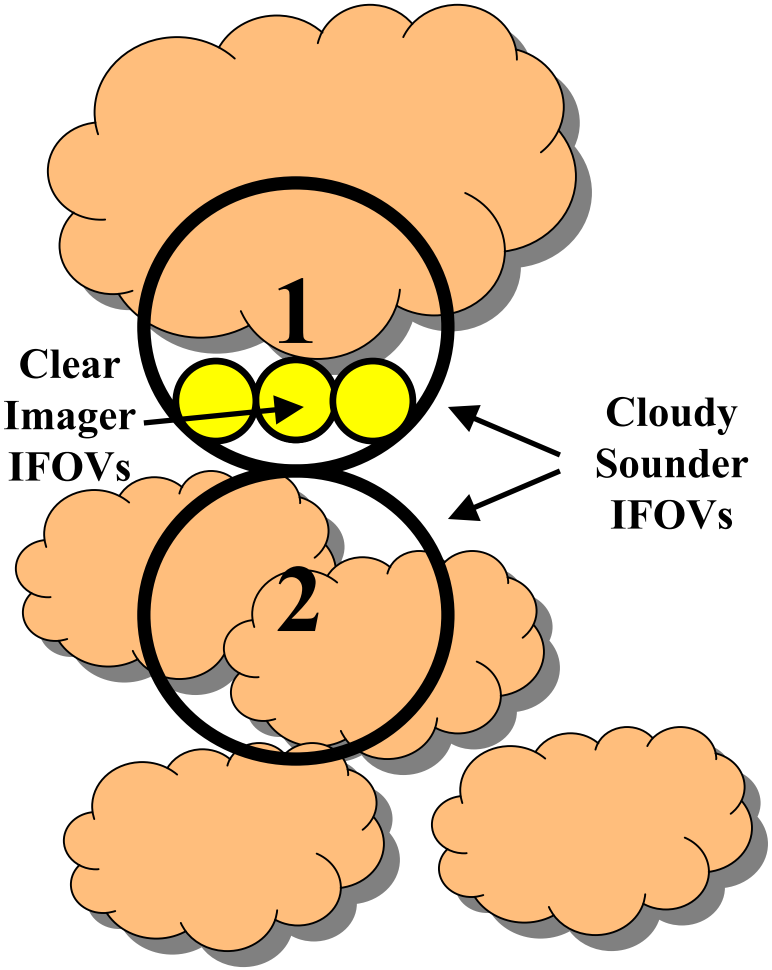


We must be able to treat clouds in the retrieval !

[1] IASI is circular with a diameter of 12 Km, [2] CrIS is circular with a diameter of 14 km

Basic <u>Cloud Clearing</u> Methodology

(Assumes Horizontally Uniform Cloud Height and Cloud Microphysics)



$$R_{clr}(\nu) = \frac{R_1(\nu) - N^*(\nu)R_2(\nu)}{1 - N^*(\nu)}$$

where $N^*(\nu) = \varepsilon(\nu)_1 N_1 / \varepsilon_2(\nu) N_2$.

$$N^*(W) = \frac{R_1(W) - \overline{R}_{clr}(\Delta W)}{R_2(W) - \overline{R}_{clr}(\Delta W)}$$

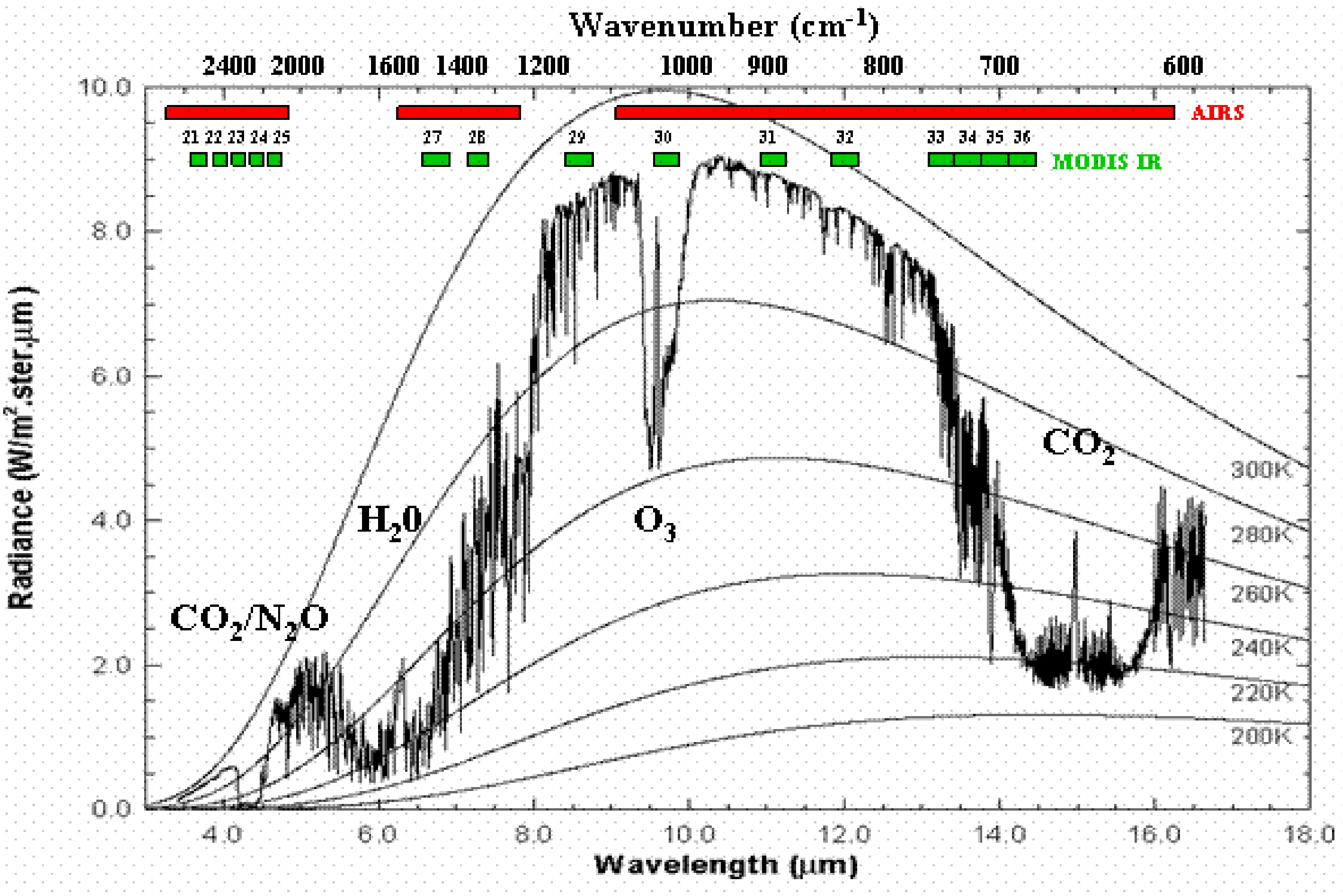
$$\hat{R}_{clr}(\Delta\nu) = \int \theta(\nu) R_{clr}(\nu) d\nu$$

<u>**Filter**</u>:

$$|\hat{R}_{clr}(\Delta\nu) - R_{clr}(\Delta\nu)| \geq \delta$$

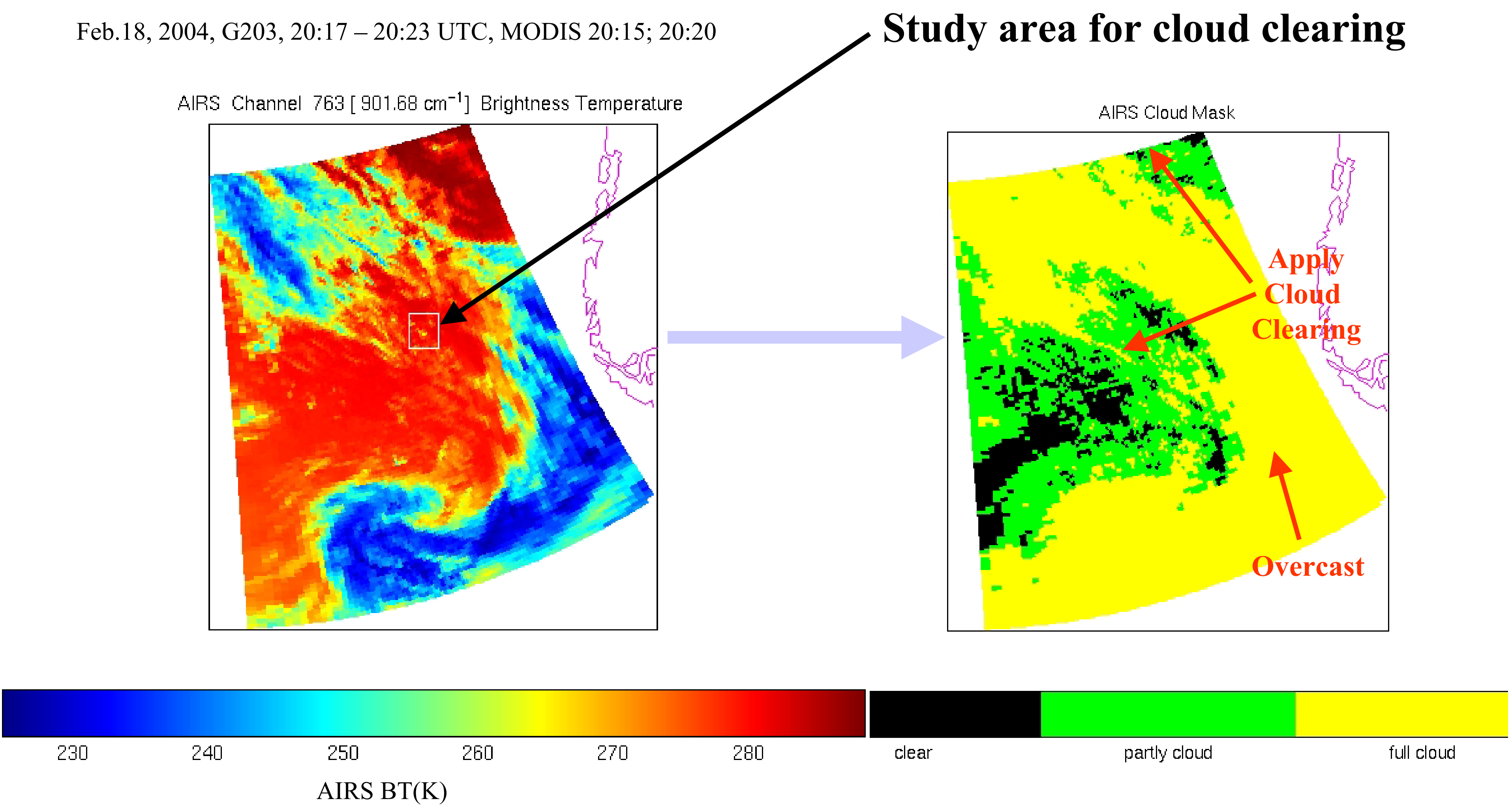
R_1(W) and **R_2(W)** are sounder window radiance measurements in FOVs 1 and 2. **$R_{clr}(\Delta W)$** is the clear window radiance measured by the imager. **$R_{clr}(\Delta\nu)$** is the clear radiance measured in the absorption channel(s) of the imager. δ is the expected error, due to measurement noise, between the true and reconstructed imager clear radiances.

Spectrum measured at AIRS spectral resolution (δν=ν/1200 cm⁻¹) with MODIS Infrared channels and AIRS sounding spectral bands shown



An AIRS/MODIS Cloud-Clearing Example

Feb.18, 2004, G203, 20:17 – 20:23 UTC, MODIS 20:15; 20:20



AIRS cloud detection from MODIS 1km cloud mask

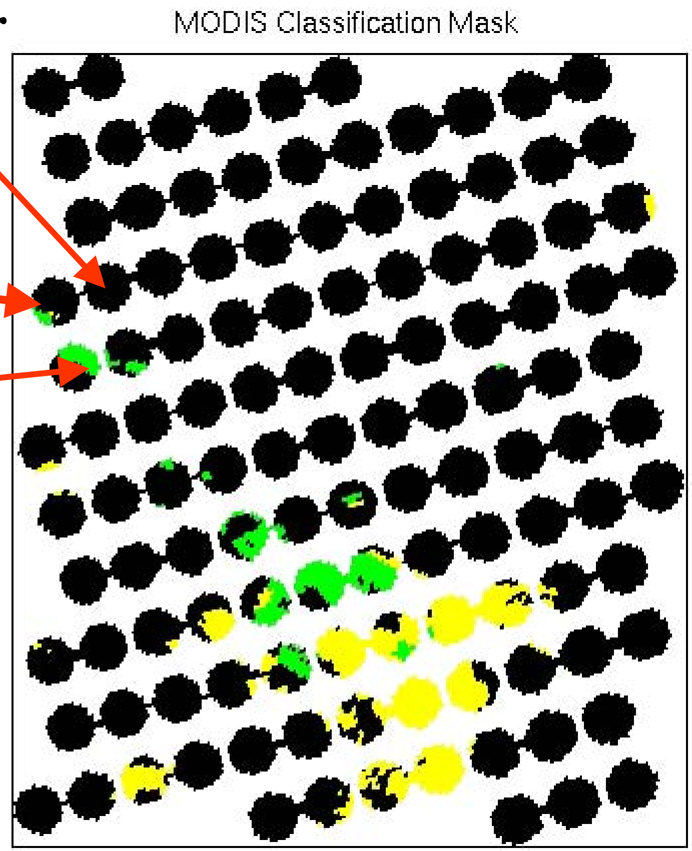
AIRS Derived Clear Radiance Vs Clear Sky Neighbor

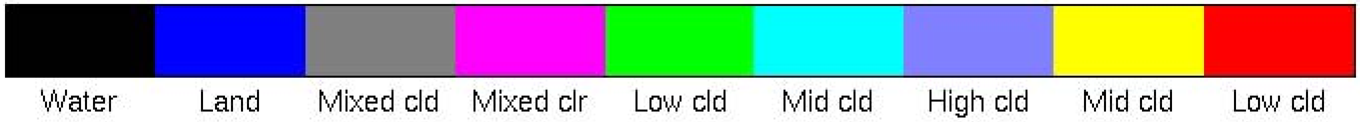
Clear neighbor for reference

Partly Cloudy FOV

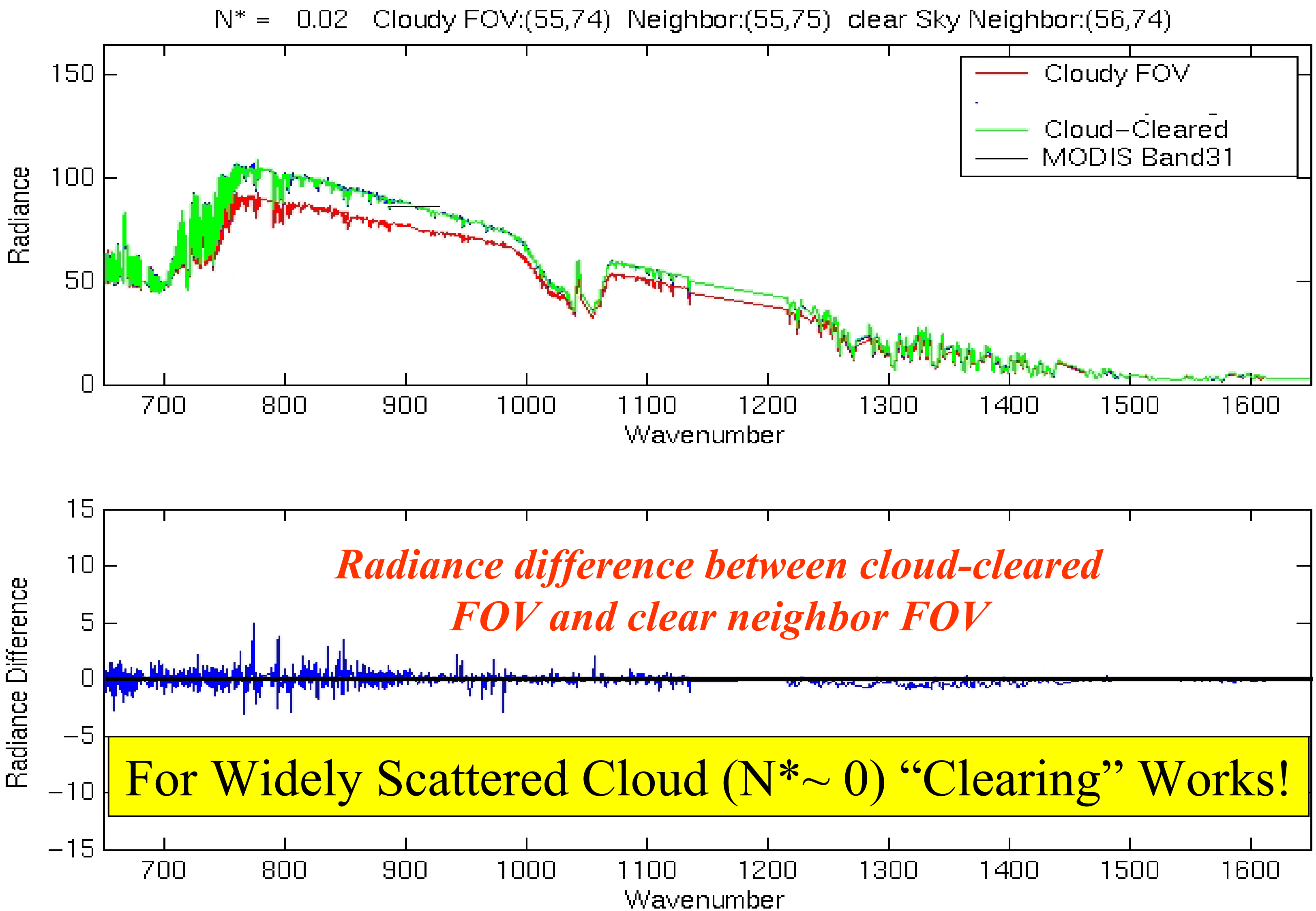
(Line 74, column 55)

Partly Cloudy Neighbor



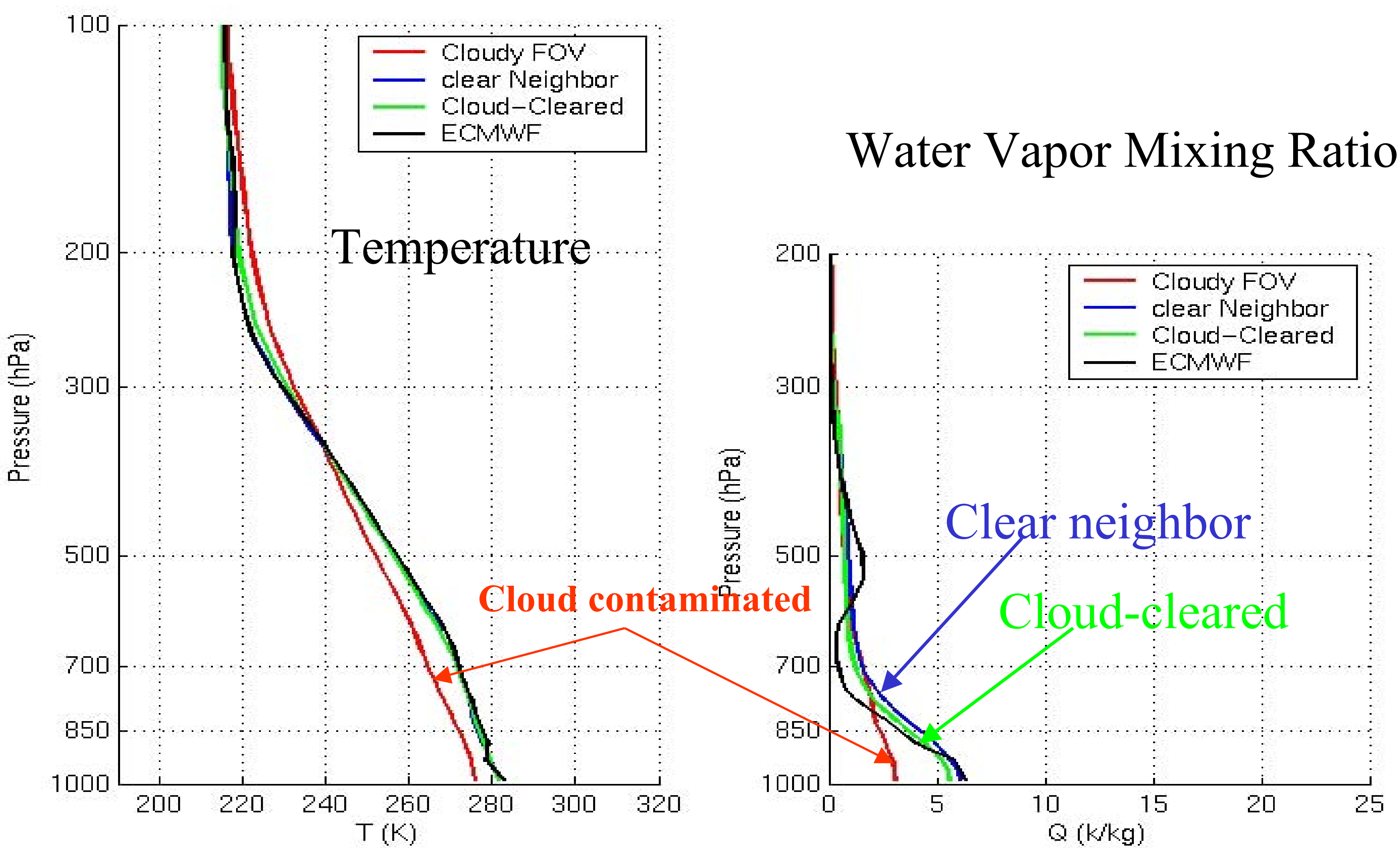


AIRS Derived Clear Radiance Vs Clear Sky Neighbor

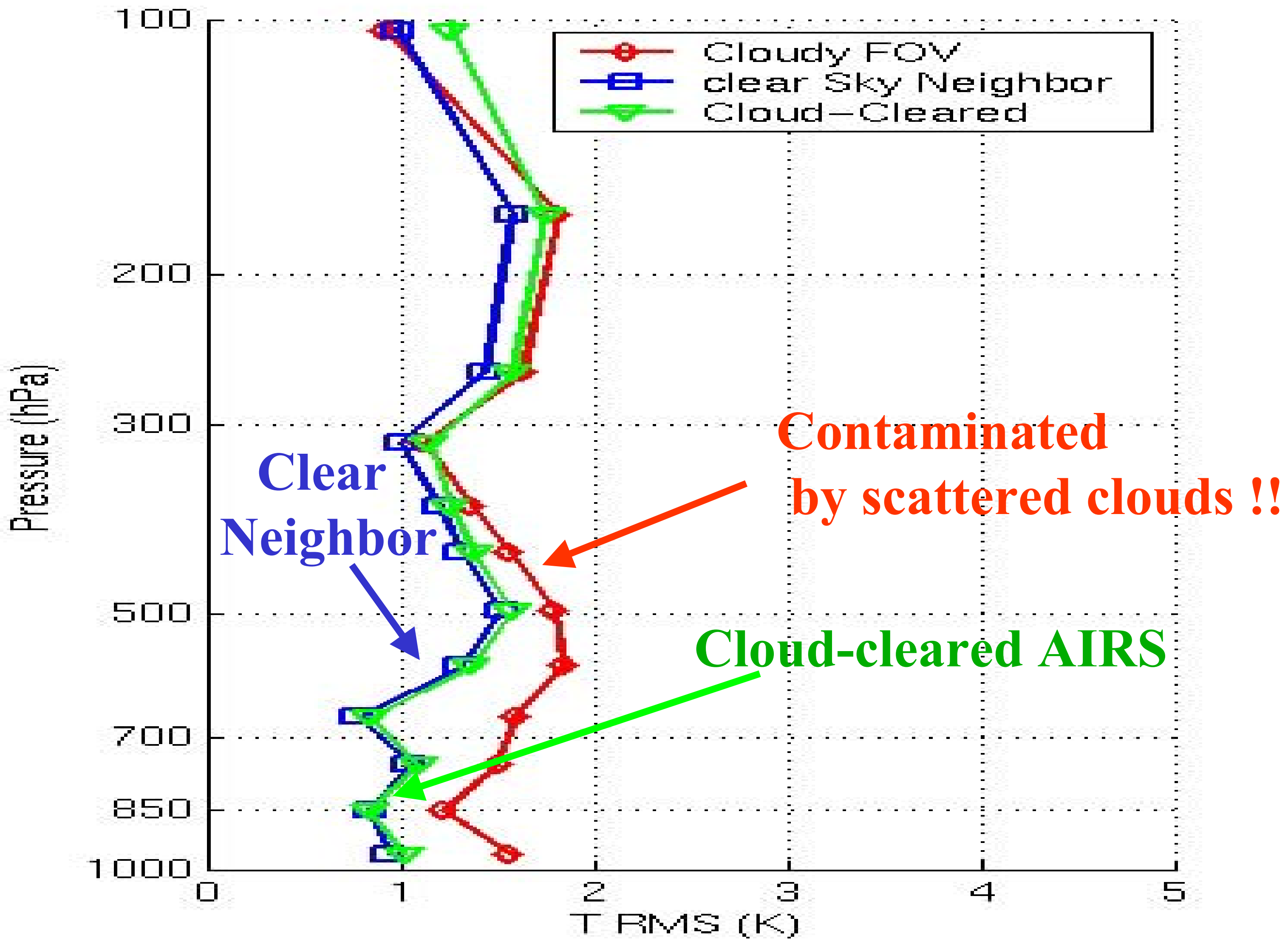


For Widely Scattered Cloud (N*~ 0) "Clearing" Works!

AIRS Profile Retrievals Vs ECMWF Analysis



Entire Granule Temperature RMS Difference (250 cases) Between AIRS and ECMWF (Scattered Clouds)*



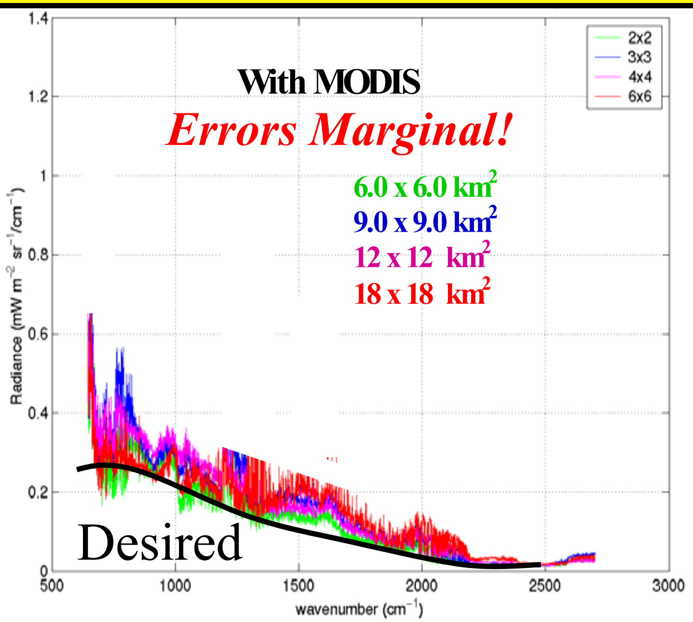
* Jun Li (CIMSS, 2004)

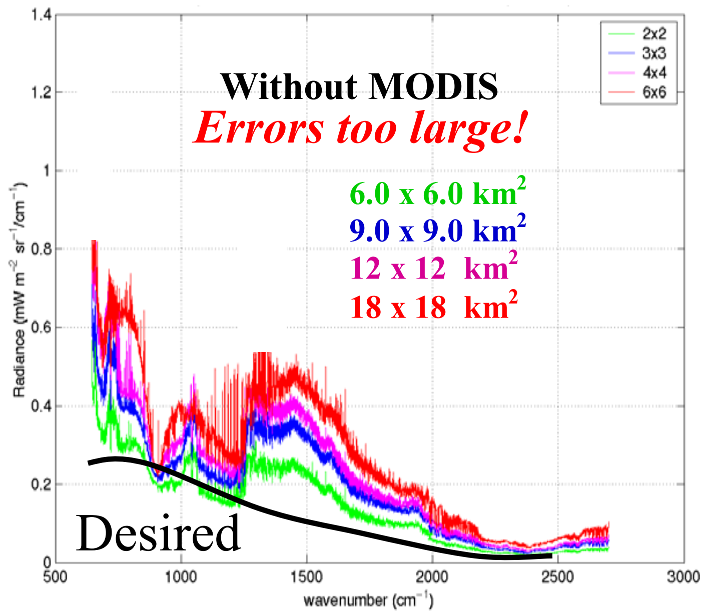
Cloud Clearing with/without MODIS Imaging Data

40 x 40 km Sounding Area Clear Column Radiance* Yields (%)

Spatial Resolution	3km	6km	9km	12 km	18 km
Total Number of FOVs/ FOR	**144**	**36**	**16**	**9**	**4**
≥ 1 Observed Clear FOV/FOR (%)	46	40	33	28	21
Total (Clr + CCR) w/o MODIS (%)	66	62	56	53	45
Total with MODIS (%)	**64**	**58**	**52**	**47**	**39**

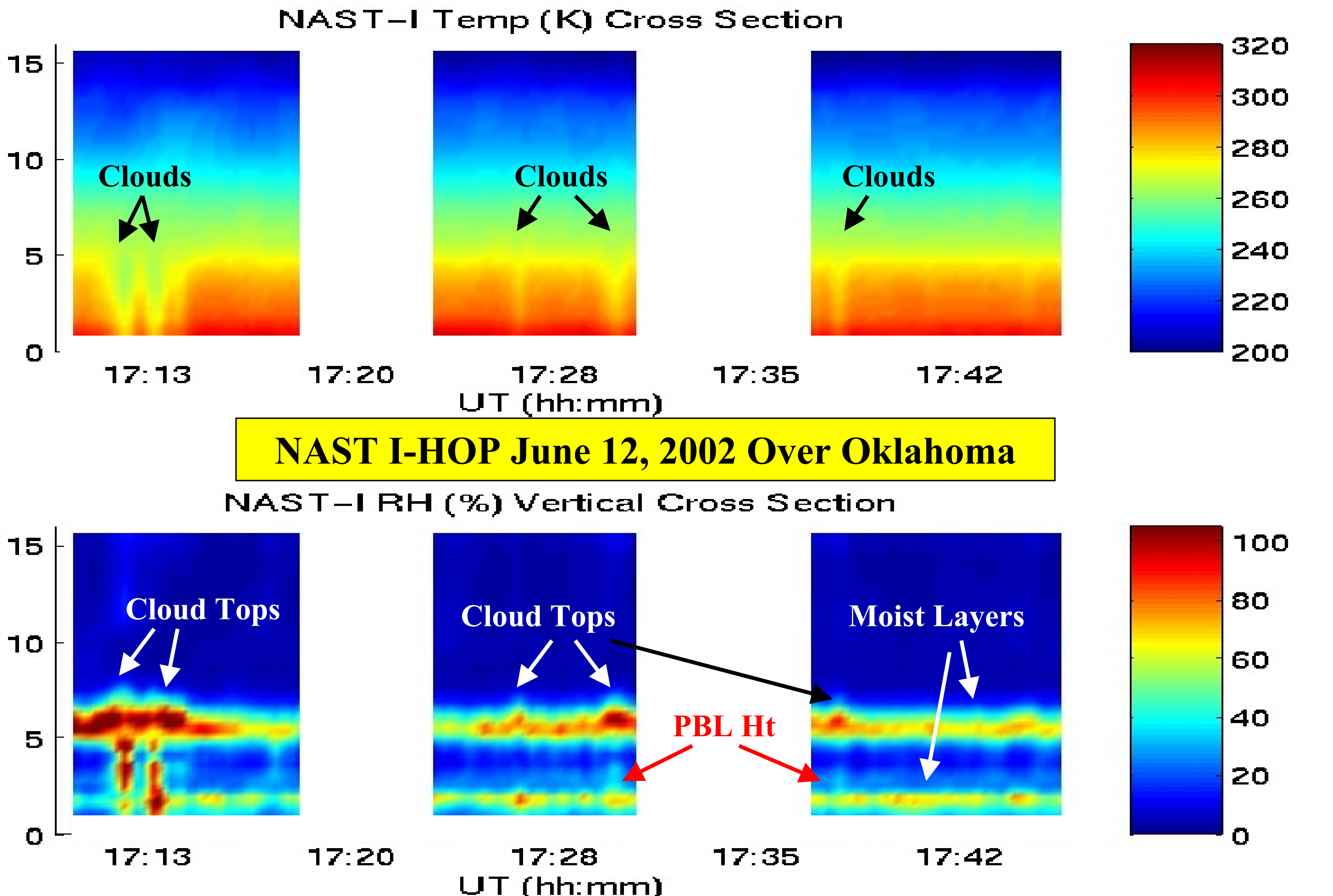
< 50 % yield, at 40 km spacing, for 12 km sounding resolution
.: Need to perform cloudy retrievals for AIRS/IASI/CrIS !!





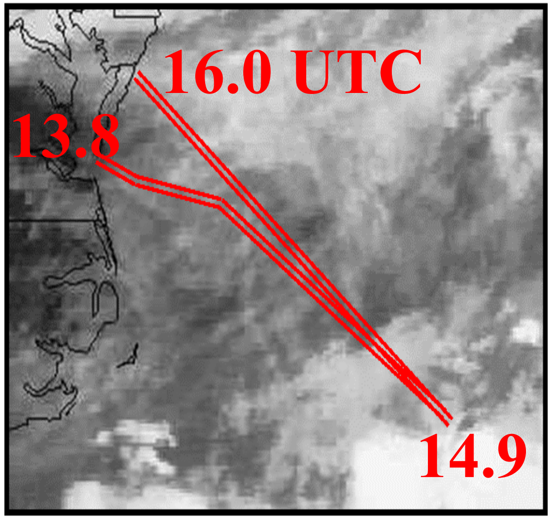
****19 Different NAST-I Flights covering all season/all latitude cloud conditions***

Cloud Equivalent Clear Radiance Retrieval

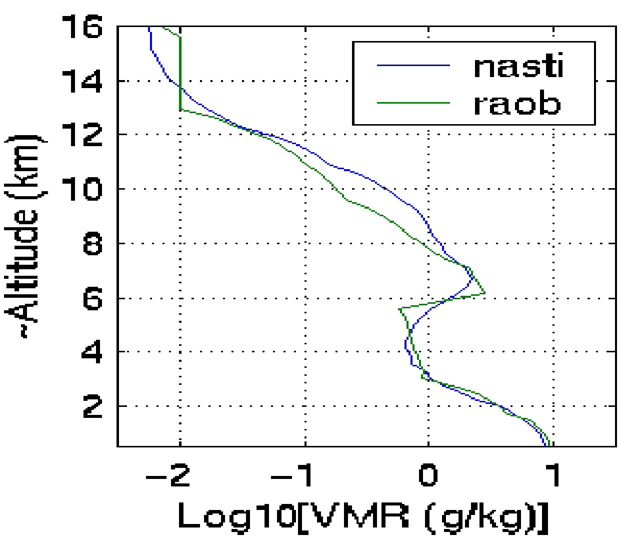


Cirrus Cloud "Venetian Blind Effect"

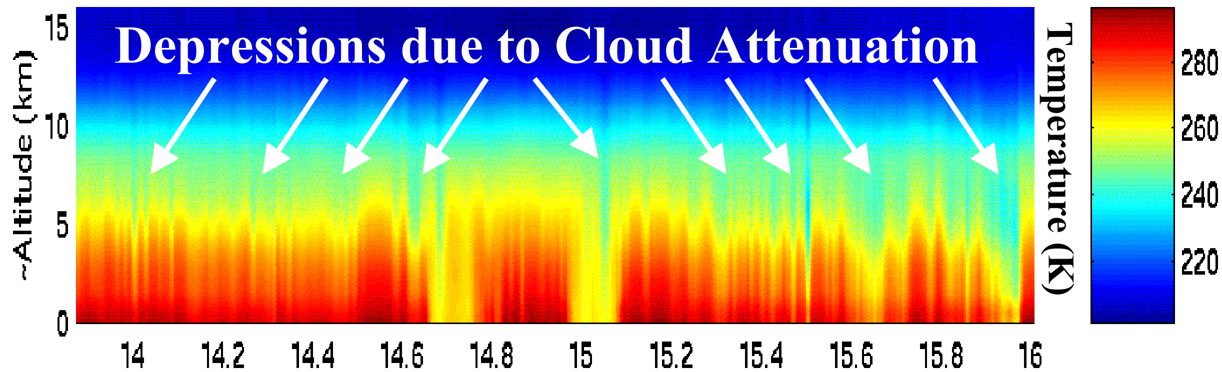
Proteus Flight Track (July 12, 2001)



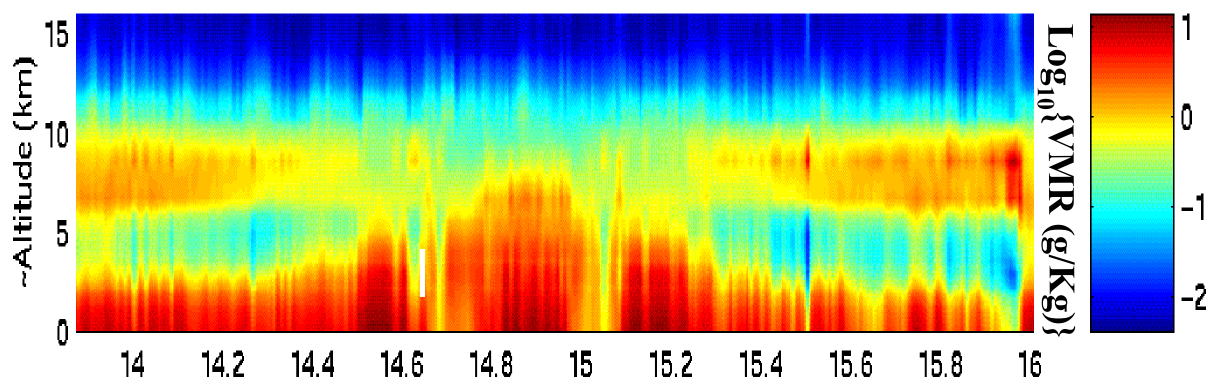
GOES IR (1515 GMT)



NAST-I Temperature (K) Vertical Cross Section

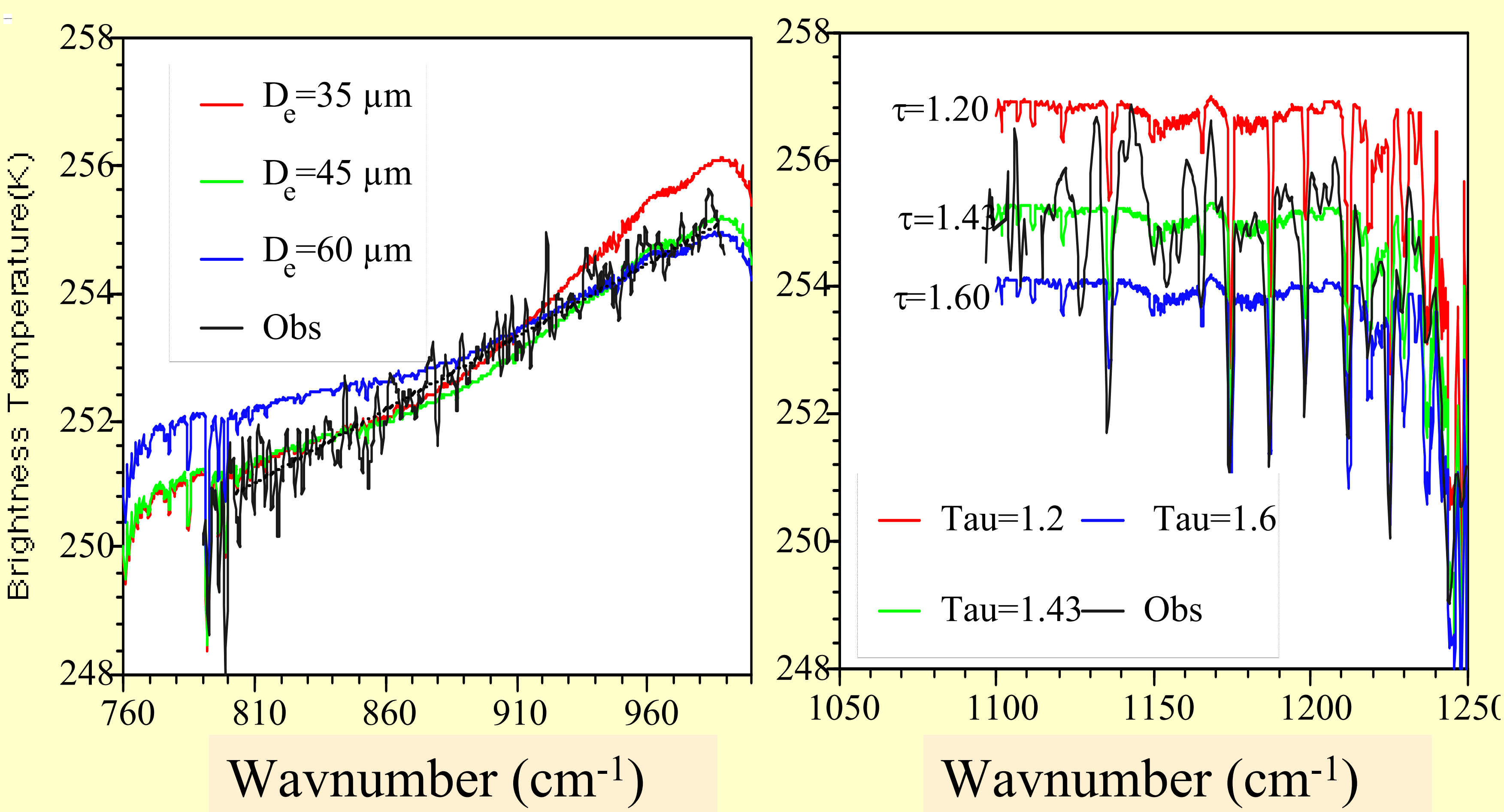


NAST-I Log10[VMR (g/kg)] Vertical Cross Section



These retrievals, uncorrected for cloud attenuation, demonstrate the ability of a high spatial resolution sounder to sense the spatial structure of moisture below a scattered and semi-transparent cirrus cloud cover

Basis for Cloud Training Algorithm!



Radiance spectral slope is sensitive to particle size
Radiance magnitude is sensitive to optical depth

Cloud Retrieval Training !

- **Perform a realistic simulation of clouds for synthetic EOF radiance training**
- **Diagnose 0-2 cloud layers from radiosonde relative humidity profile**
  - A single cloud layer (either ice or liquid) is inserted into the input radiosonde profile.
  - Approximate lower level cloud using opaque cloud representation (i.e., isothermal/saturated)
- **Use parameterization of Heymsfeld's* balloon and aircraft cloud microphysical data base (2003) to specify cloud effective particle radius, r_e, and cloud optical depth, τ, (i.e., $r_e = a\,\tau^{\alpha} / [\tau - b\tau^{\alpha}]$) .**
  - Different habitats can be specified (Hexagonal columns assumed here)
  - Different clouds microphysical properties are simulated for same radiosonde using random number generator to specify visible cloud optical depth within a pre-specified range. 10 % random error added to parameterized effective radius to account for real data scatter.
- **Use LBLRTM/DISORT "lookup table" to specify cloud radiative properties**
  - Spectral transmittance and reflectance for ice and liquid clouds interpolated from multi-dimensional look-up table based on DISORT multiple scattering calculations for the (wavenumber range 500 – 2500 cm^{-1}, zenith angle 0 – 80 deg., Deff (Ice: 10 – 157 um, Liquid: 2 – 100 um), OD(vis) (Ice: 0.04 - 100, Liquid 0.06 – 150)
- **Compute EOFs and Regressions from cloudy radiance data base**
  - Regress cloud properties (p, τ, r_e) and surface and profile parameters against radiance EOFs
  - For small optical depth, output entire profile down to surface or lower opaque cloud level
  - For large upper level cloud optical depth, output profile above the upper cloud level

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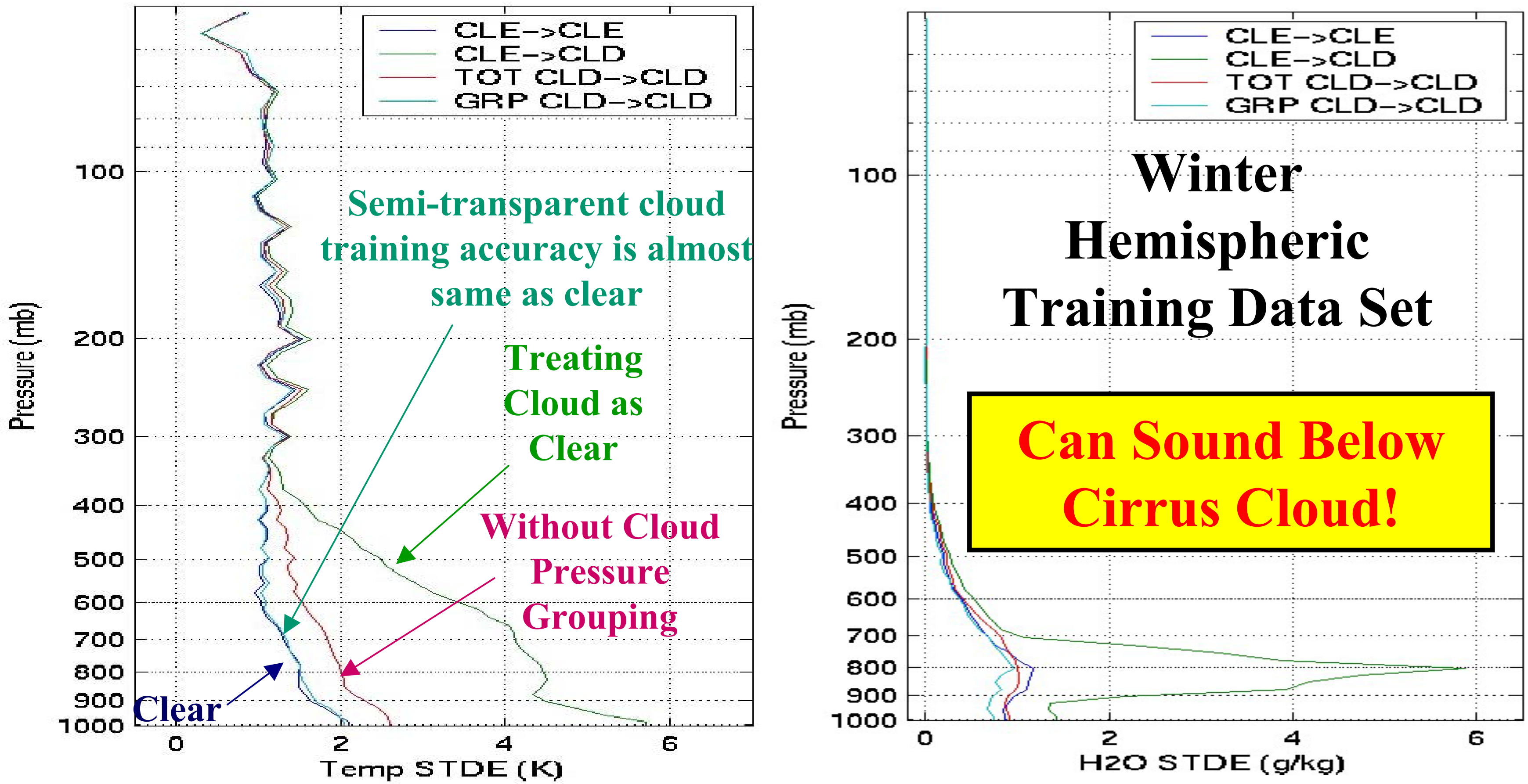
Heymsfield, A. J., S. Matrosov, and B. A. Baum: Ice water path-optical depth relationships for cirrus and precipitating cloud layers. *J. Appl. Meteor*. October 2003

Semi-transparent Cloud ($\tau \leq 1$) Training Skill



<u>Procedure for Finding Correct Upper Level Cloud Height:</u>

(1) Predict cloud pressure height using uncategorized statistics (i.e., without pressure grouping)

(2) Predict cloud pressure height, p(n) using categorized statistics for p(n-1) cloud height obtained in (1)

(3) Use statistics for cloud height p(n) to predict an n+1 cloud height p(n+1)

(4) Compare new cloud height, p (n+1) with previously determined cloud height, p (n):

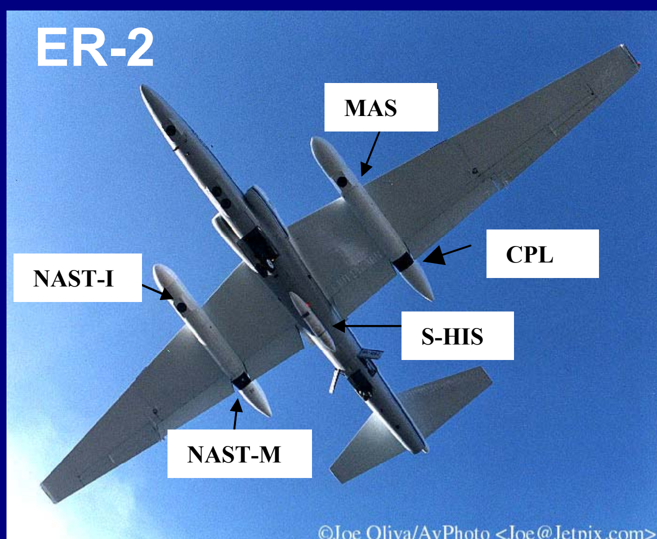
- **(a) <u>if p(n+1)=p(n)</u>: obtain geophysical parameter retrievals using statistics for p(n+1)**
- **(b) <u>if p(n+1)≠ p(n):</u> let p(n)=p(n+1) and predict a new p(n+1) using p(n) cloud statistics**

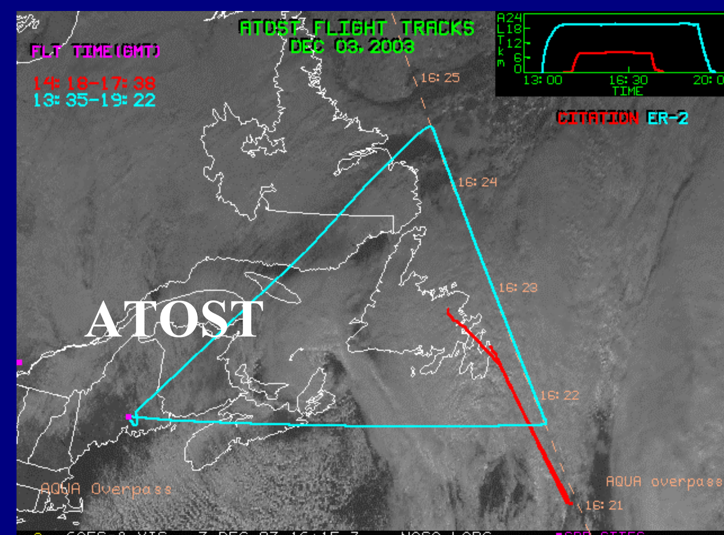
(5) Repeat step (4) until convergence in cloud height is obtained, and parameter retrievals, is obtained.

ATReC ER-2 Deployment

- **ATReC (November 18 - December 15, 2003, Bangor, Maine).** The Atlantic-THORPEX Regional Campaign (**ATReC**) focused on reducing the number and size of significant weather forecast errors over Europe and the eastern USA by infusing extra remote sensing and in-situ observations over sensitive (i.e. oceanic) regions. ER-2 flights contributed to ATReC as focusing on satellite sensor validation underflights (TERRA, AQUA, & DMSP)

- NAST Research Objective: Profiling under complex cloud conditions



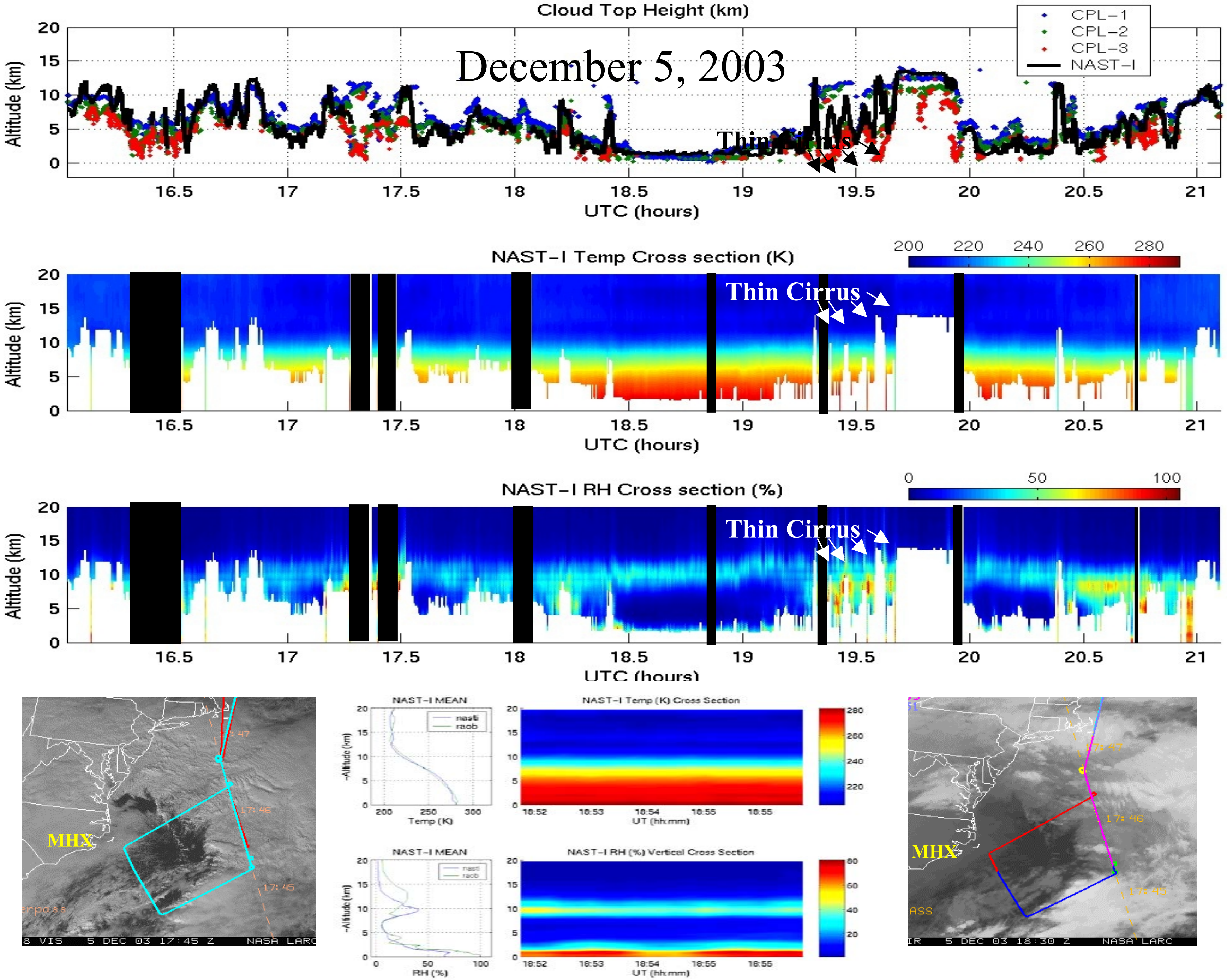


Aircraft Payload Included:

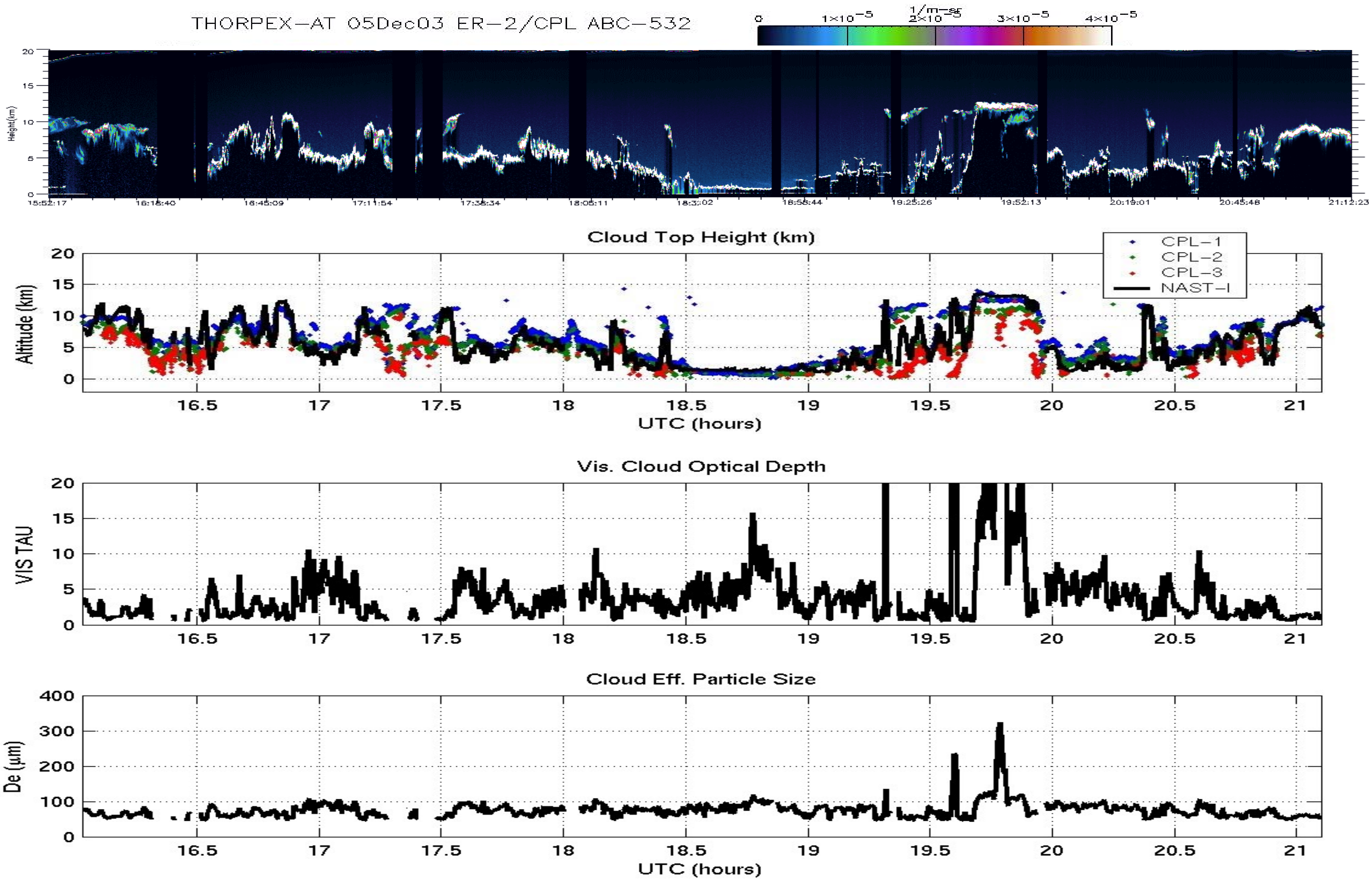
NASA ER-2 (NAST-I, NAST-M, S-HIS, MAS, CPL, in-situ O3

Dropsondes (NOAA G-4 and Cessna Citation)

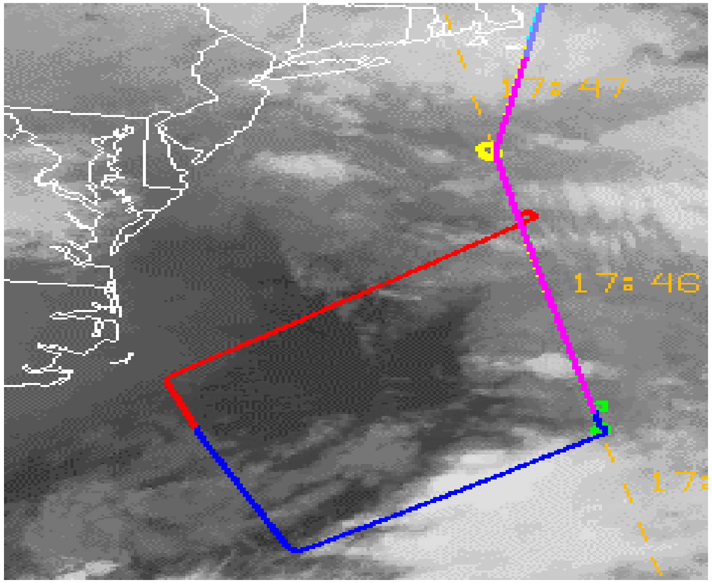
Satellite Platforms Included: Aqua, DMSP, Terra, and WindSat/Coriolis

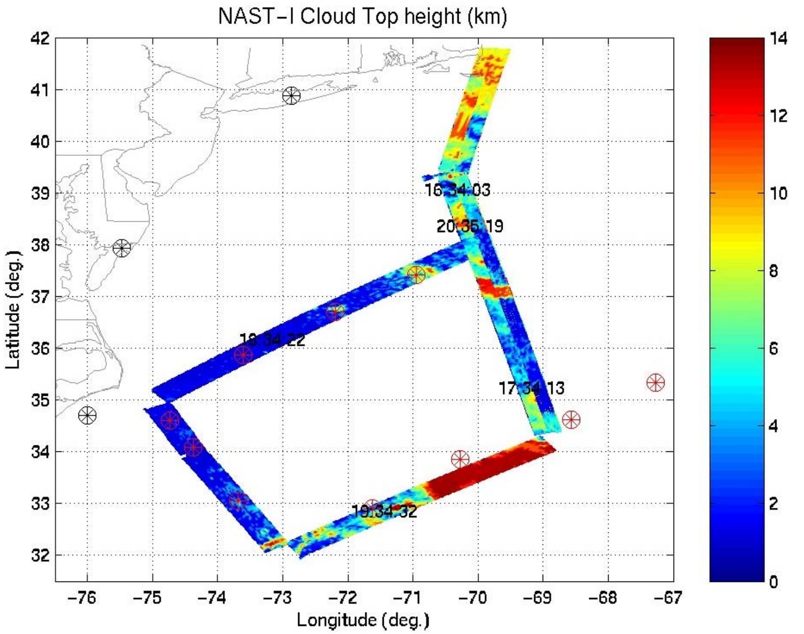

December 5, 2003
Cloud Top Height (km)
CPL−1
CPL−2
CPL−3
NAST−I
Altitude (km)
UTC (hours)
Thin Cirrus
NAST−I Temp Cross section (K)
200 220 240 260 280
NAST−I RH Cross section (%)
0 50 100
MHX
5 DEC 03 17:45 Z NASA LARC
NAST−I MEAN
Temp (K)
RH (%)
NAST−I Temp (K) Cross Section
NAST−I RH (%) Vertical Cross Section
UT (hh:mm)
5 DEC 03 18:30 Z NASA LARC

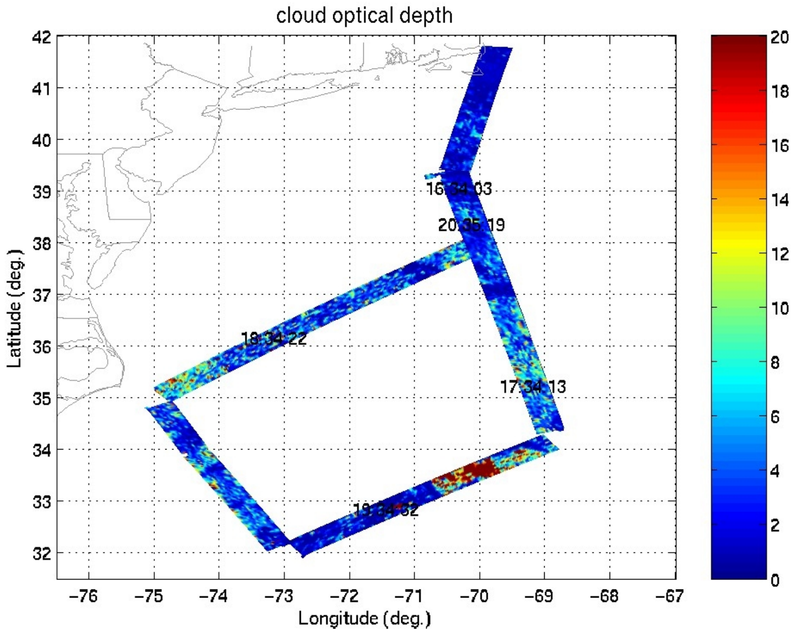
December 5, ATReC Cloud Results

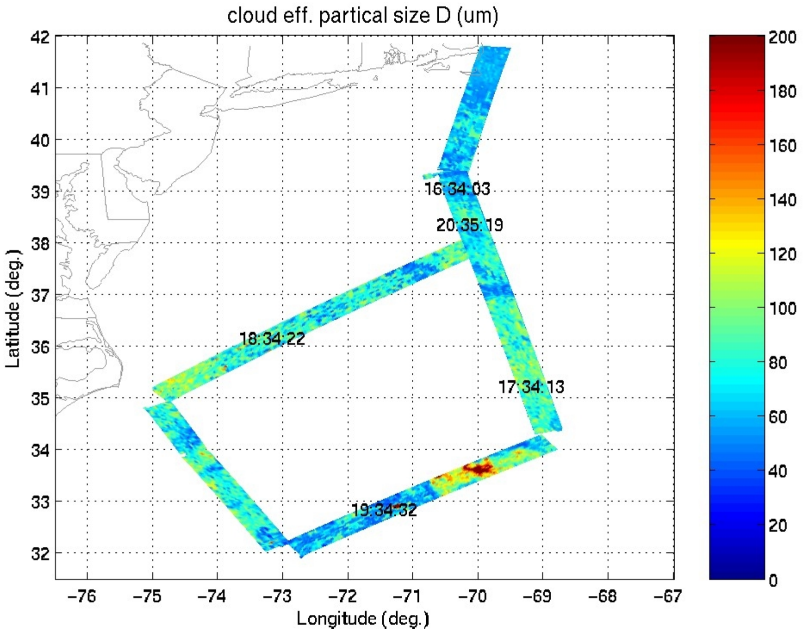


December 5, ATReC Cloud Results

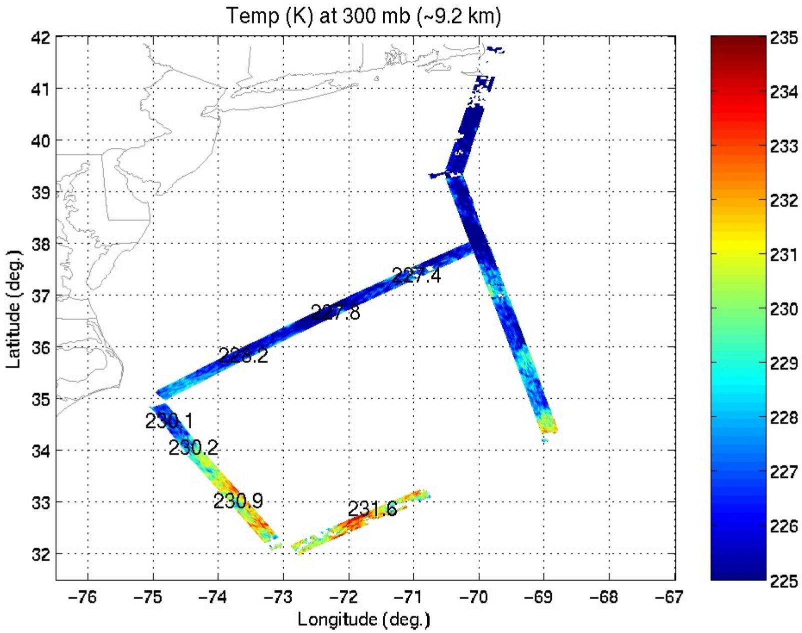


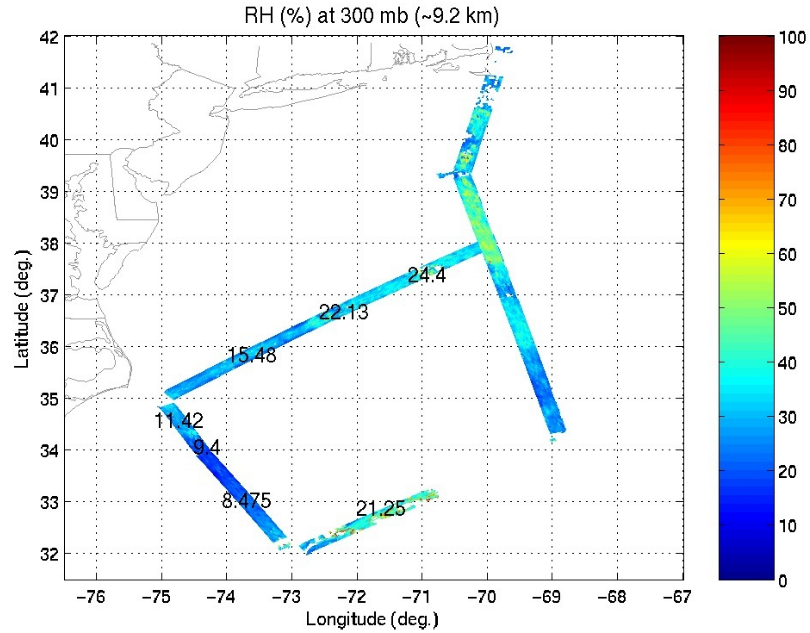


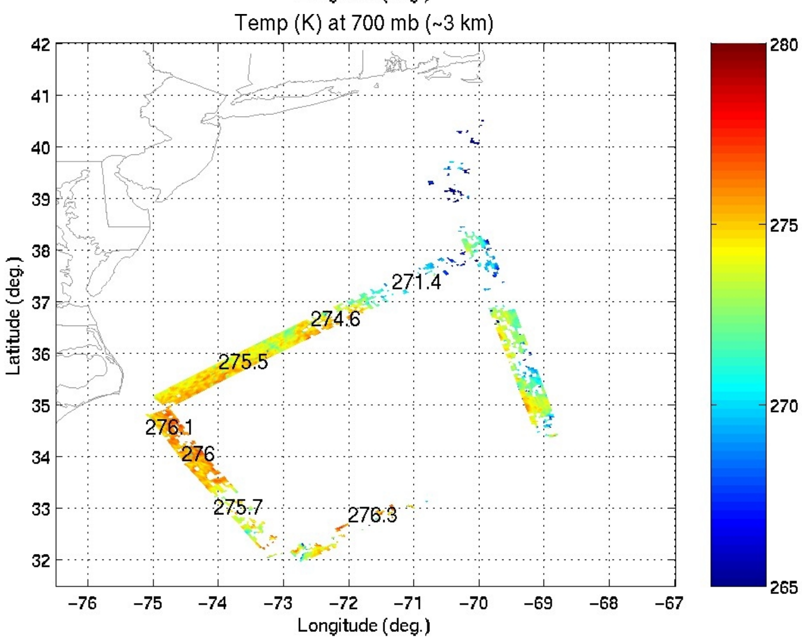


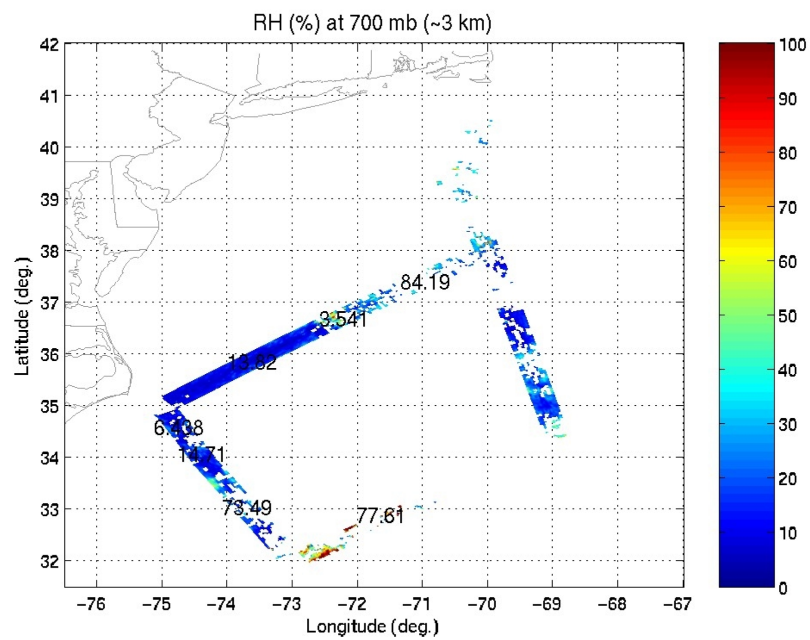


December 5, ATReC Profile Results

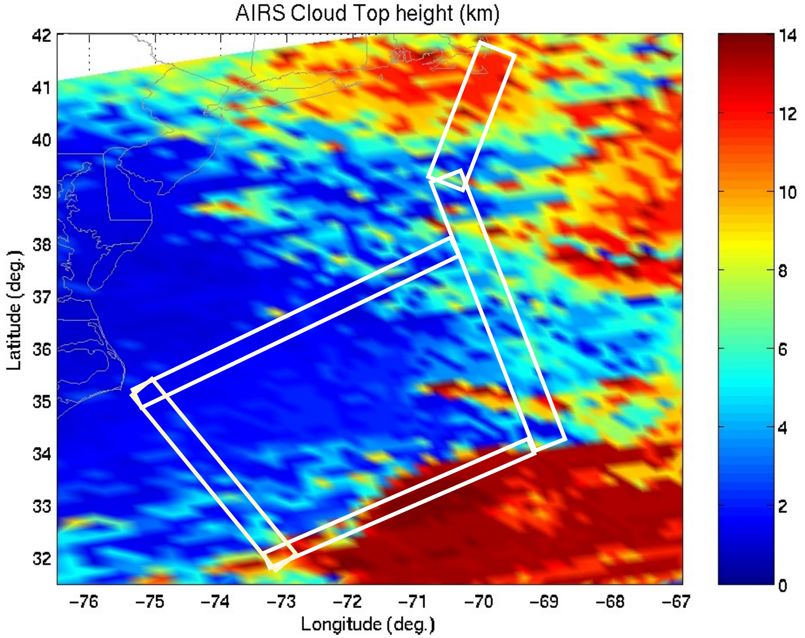


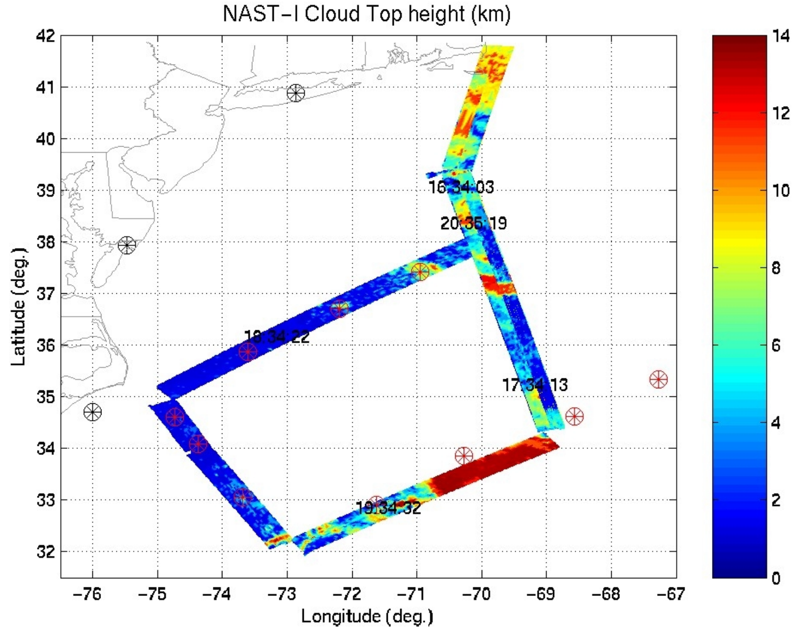


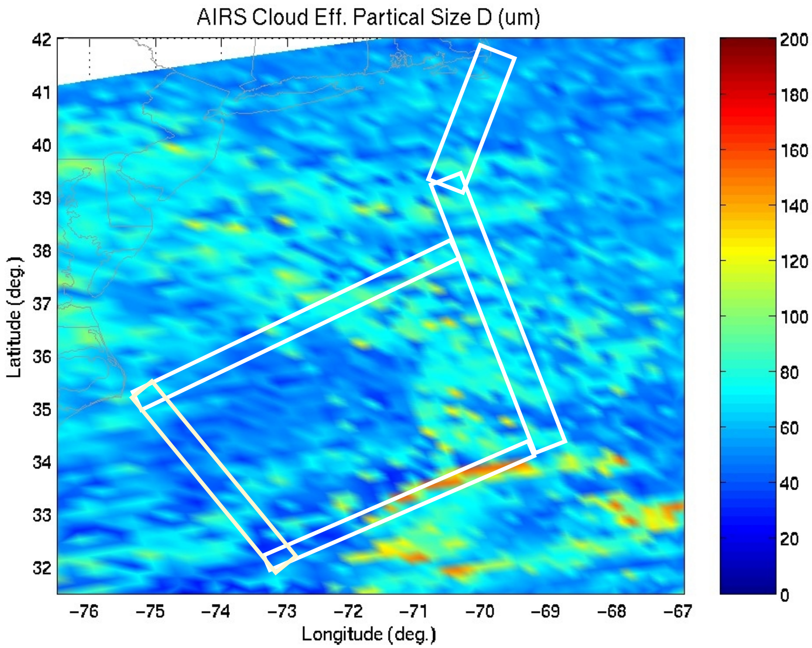


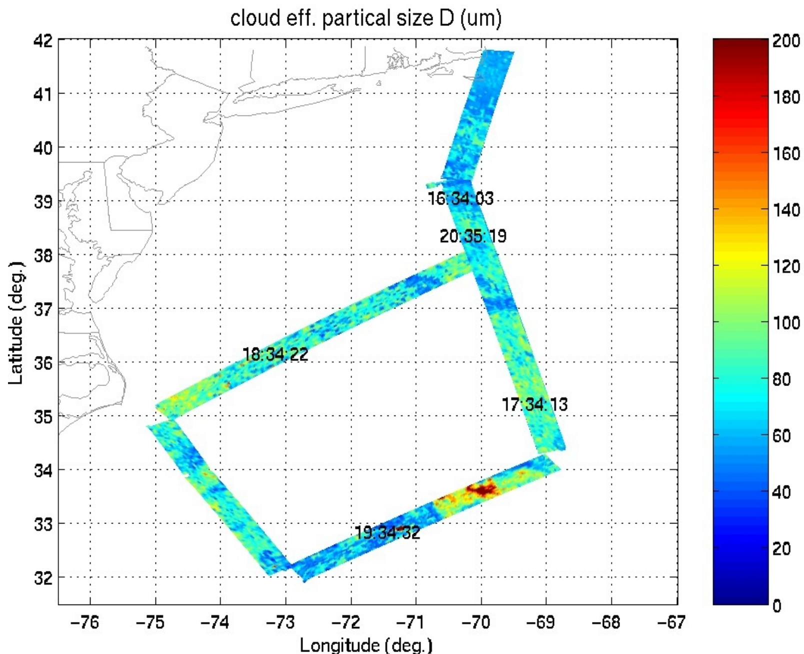


AIRS Vs NAST-I Cloud Properties

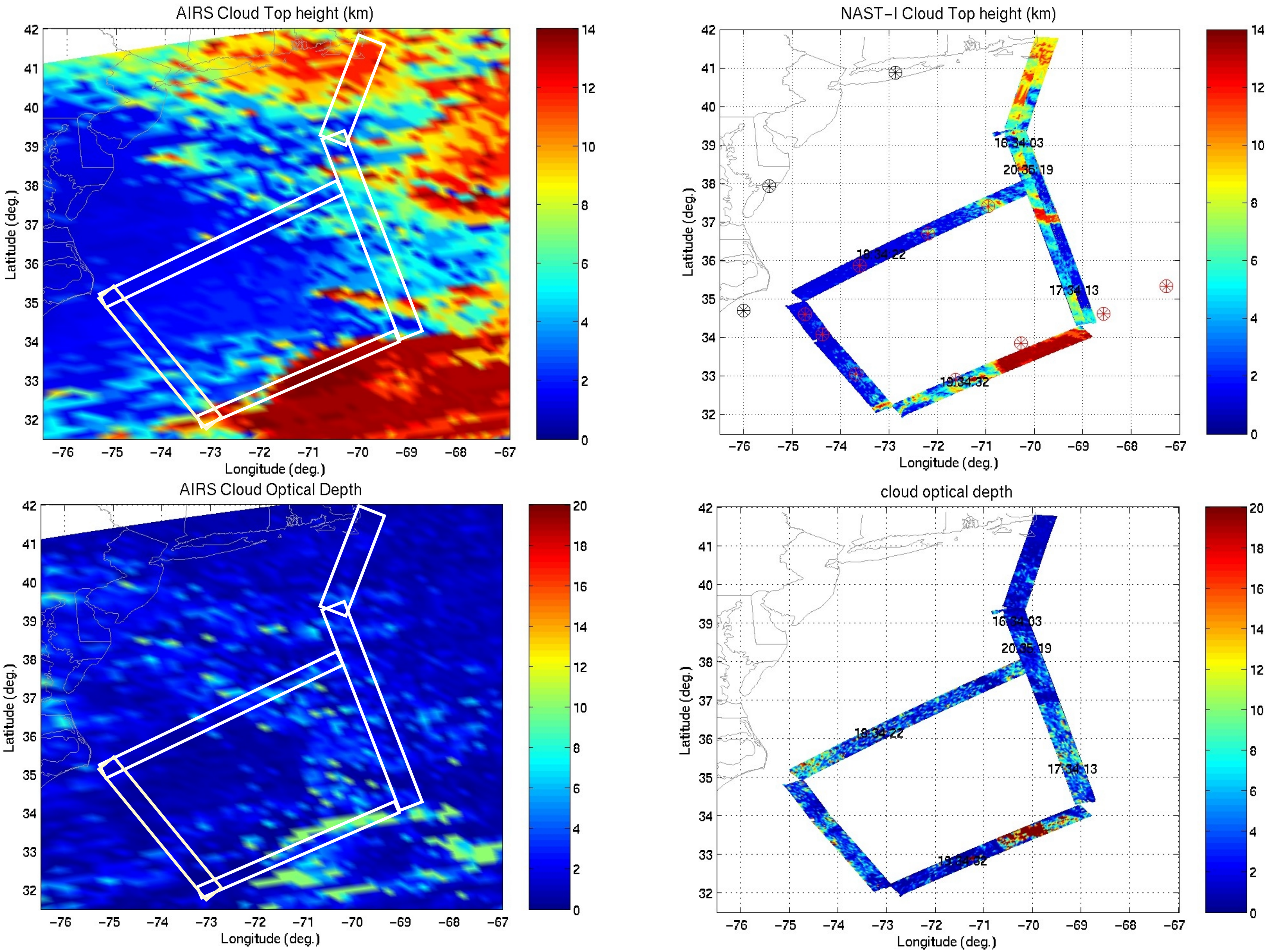




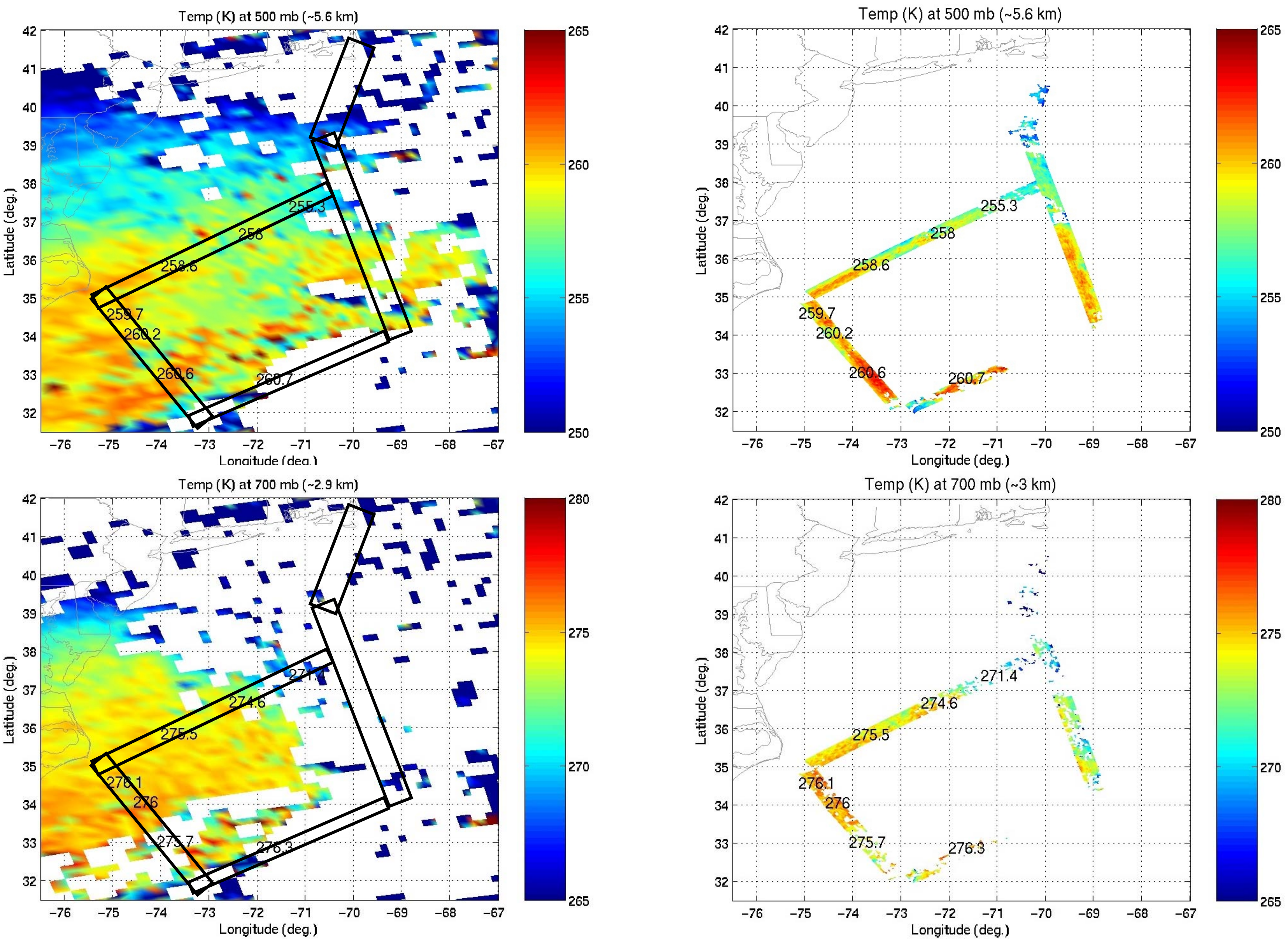




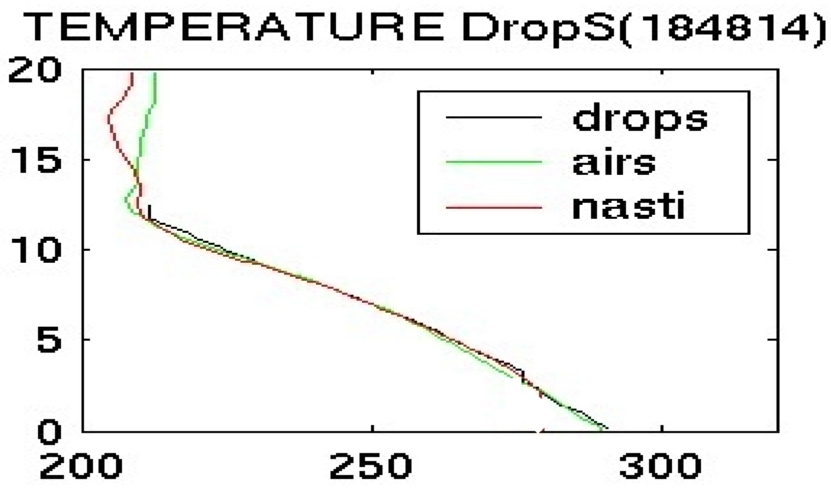
AIRS Vs NAST-I Cloud Properties

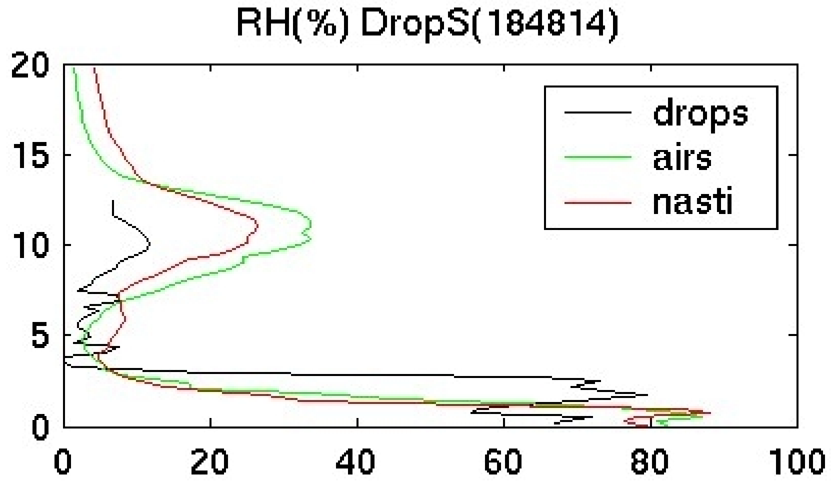


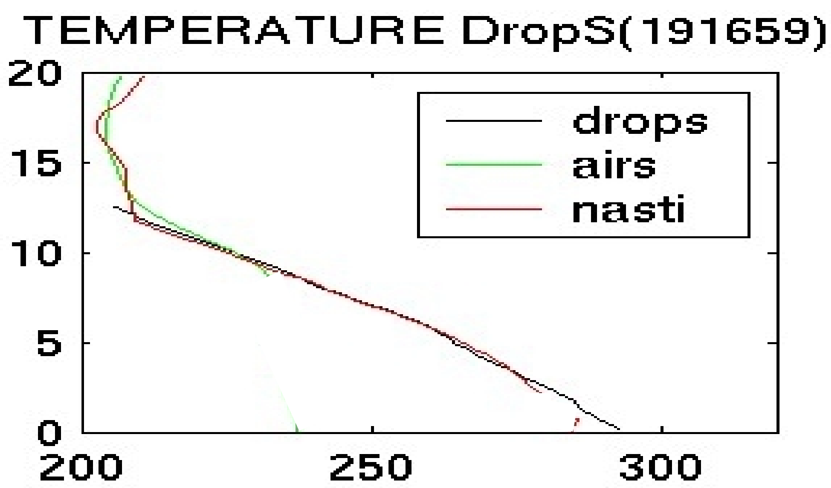
AIRS Vs NAST-I Profile Properties

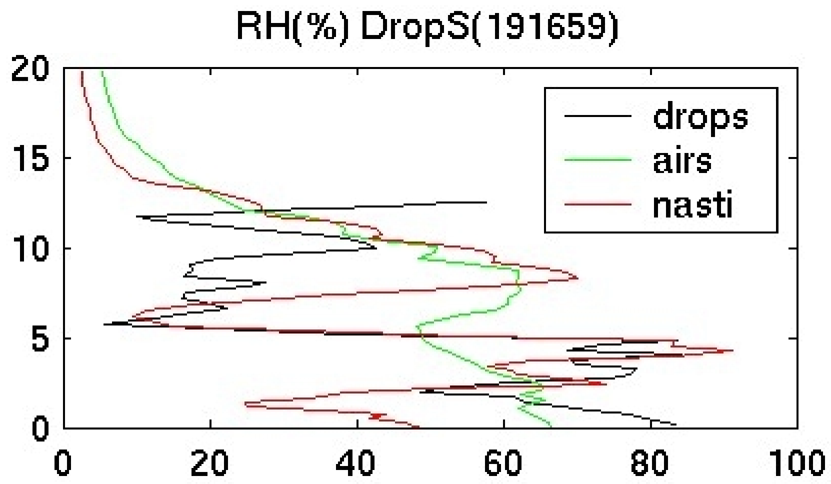


Example Profile Comparisons









Conclusions

- **<u>High spatial resolution</u>**
  - Sampling clear air
  - Optimizing cloudy sky retrievals
- **<u>Cloud clearing</u>**
  - Cloud clearing is useful for sounding under scattered clouds
  - AIRS can benefit from 1 km MODIS sounding channels
  - Cloud clearing causes loss of spatial resolution and clear air bias
- **<u>Cloud training</u>**
  - Permits sounding beneath semi-transparent cloud (i.e., thin cirrus)
  - Permits sounding to cloud level for opaque cloud conditions
  - Retrieved cloud properties can be used for 1-d Var Retrieval or for the direct assimilation of radiances into forecast model

Ultimate approach for sounding retrieval or radiance assimilation with clouded hyperspectral radiances should employ a combination of cloud clearing and cloud training algorithms