Recent Advances in Hyperspectral Infrared Sounding Retrieval Science at the CIMSS

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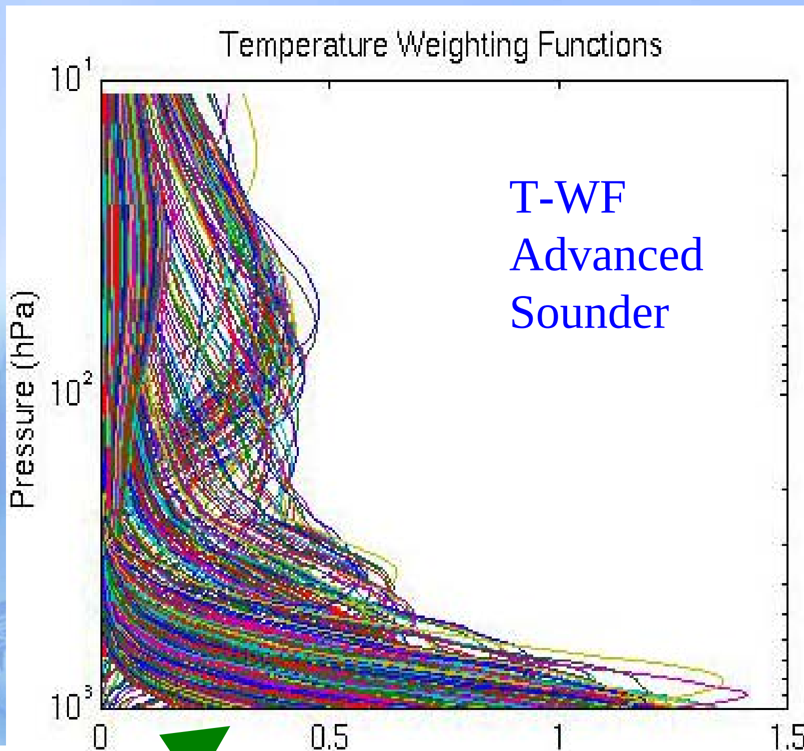
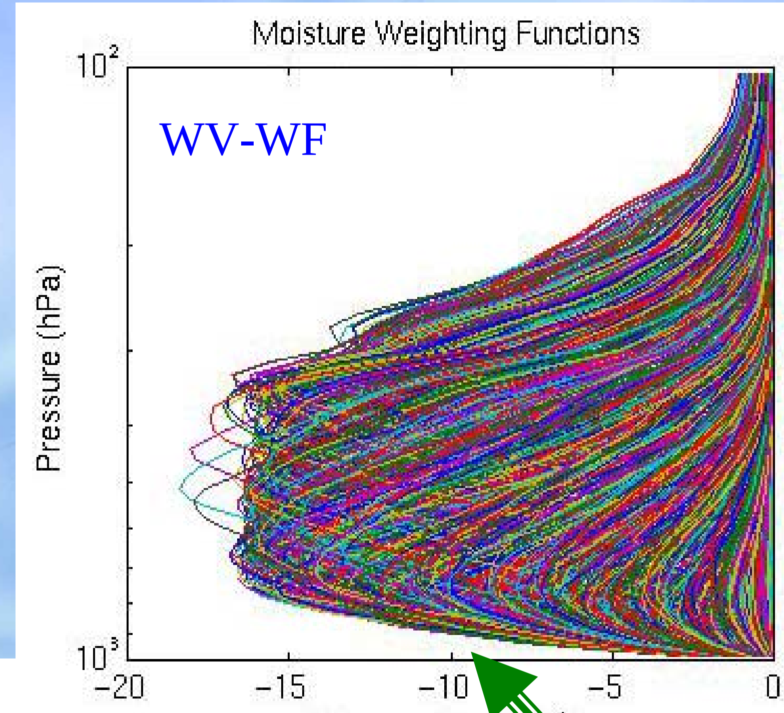
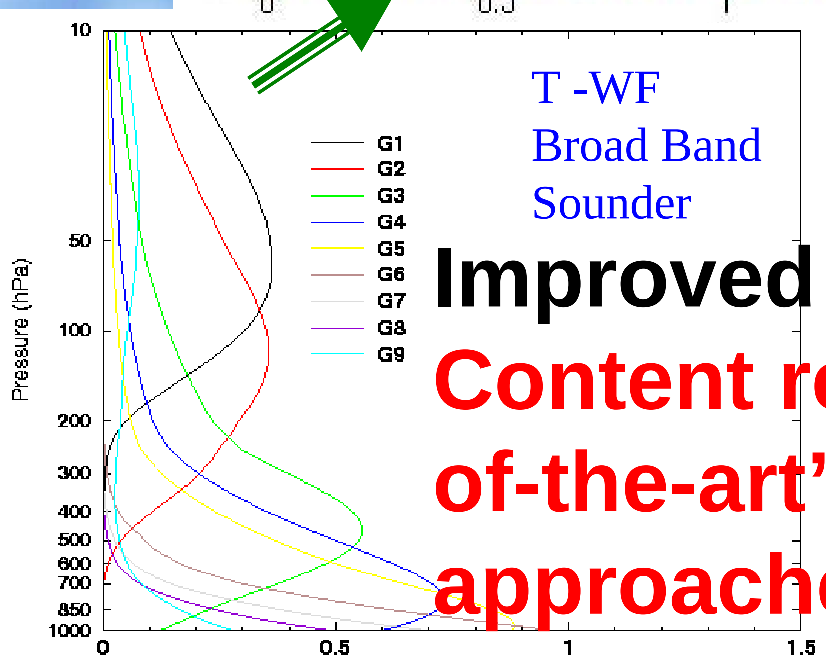
Support Acknowledgement:
NOAA- GOES-R3; GOES-R AWG; GIMPAP
NASA - IMAPP

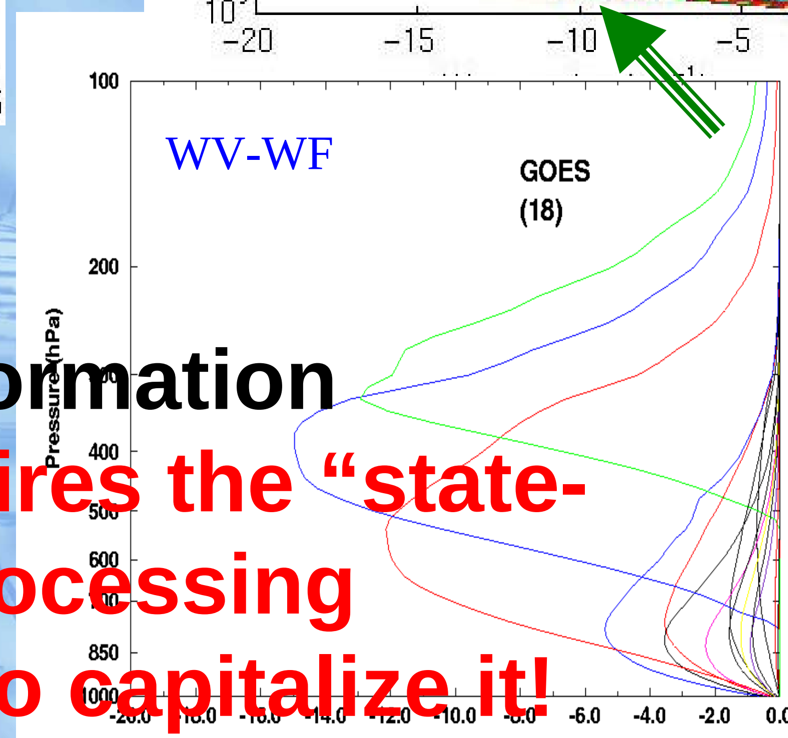
Advanced High Spectral Resolution Infrared Observations Workshop
EUMETSAT
Darmstadt, Germany, 15 – 17 September 2008

#: Retrieval Team Leader; *: Presenter









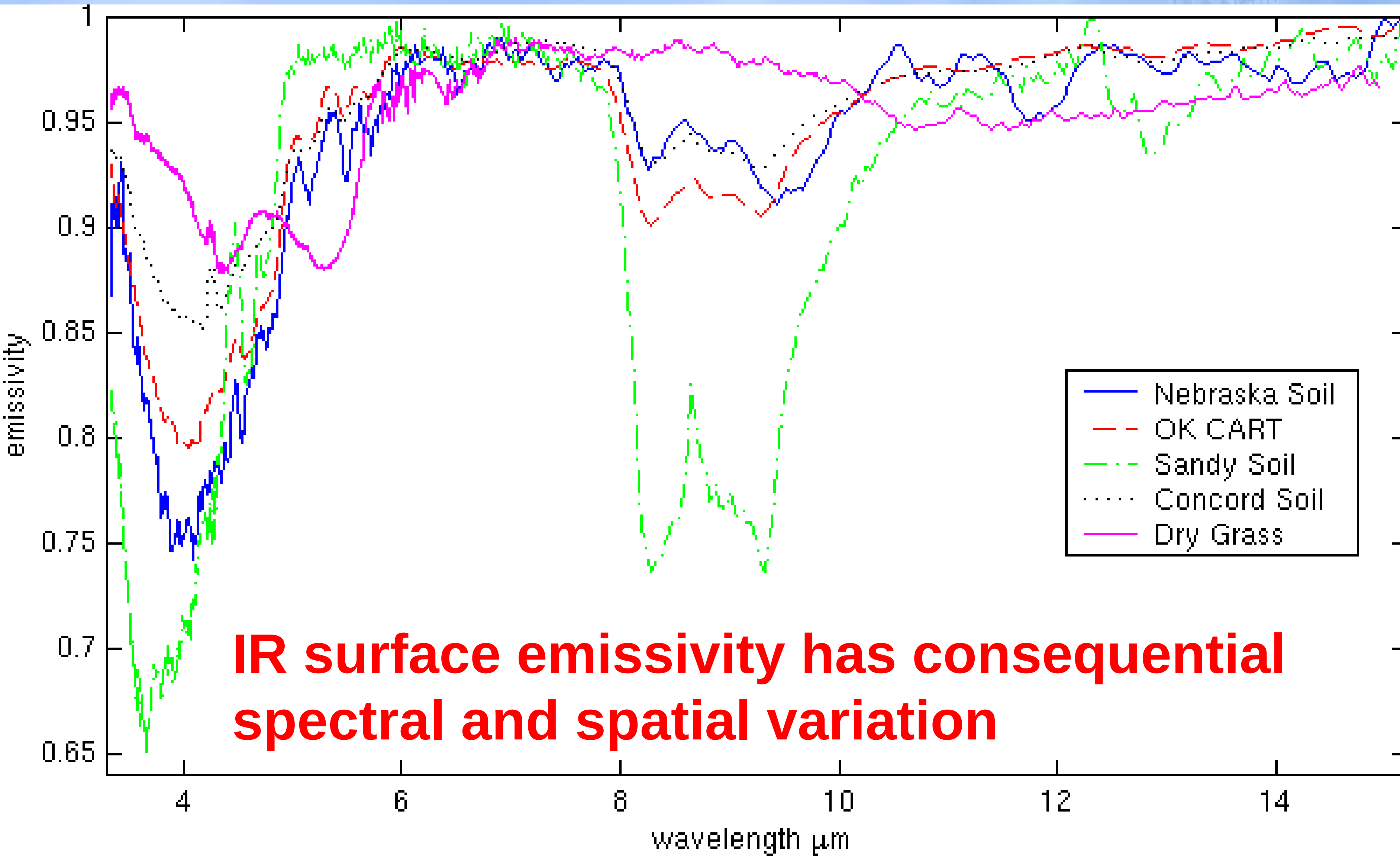
Improved Information

Content requires the "state-of-the-art" processing approaches to capitalize it!

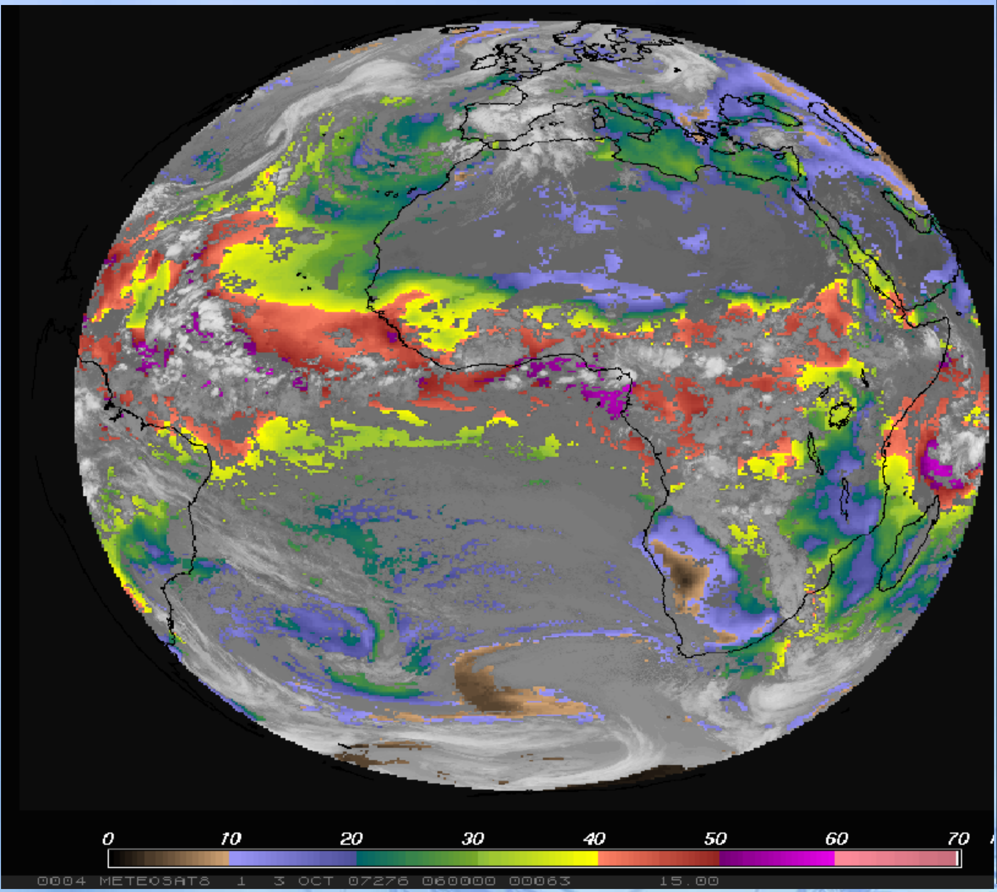
Hyperspectral IR surface, and cloud modeling and multi- sensors/platforms Synergy

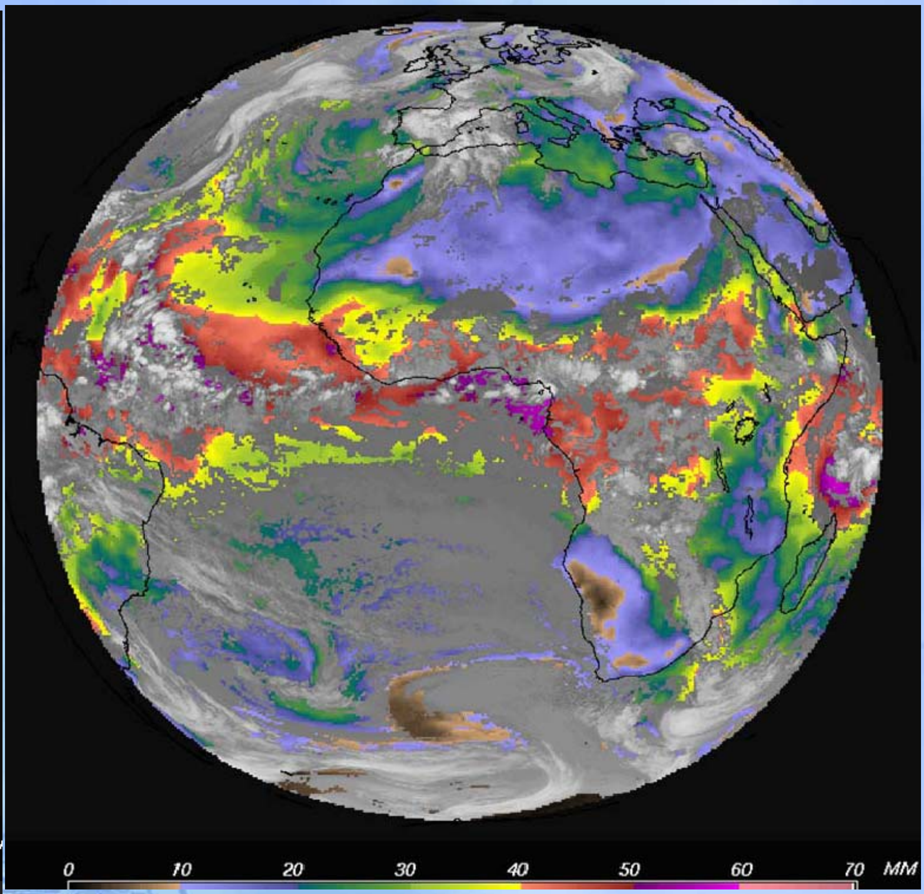
- The use of improved IR surface emissivity database/model in improving boundary layer sounding;
- The treatment of cloud microphysical property in cloud contaminated retrieval;
- Synergistic soundings from multiple sensors on the same platform;
- Synergistic soundings from multiple sensors on different platforms.

Measured emissivity spectra from UCSB MODIS Land group's Emissivity Library



IR surface emissivity has consequential spectral and spatial variation





Constant Emis. as 1st guess

UW baseline fit model as 1st guess

IR surface emissivity has substantial impact on TPW

MSG SEVIRI retrieved TPW product coverage for a uniform spectral emissivity (=0.95 left) and for the spectral emissivities taken from the UW/CIMSS BF emissivity database (right). Note the bad coverage, i.e. non-successful retrievals, over the large desert areas. (03 October 2007, 0600 UTC, box size is 15 x 15 MSG pixels)

*Marianne Koenig and Estelle de Coning: The MSG Global Instability Indices Product and its Use as a Nowcasting Tool. Submitted to "**Weather and Forecasting**"*

Approaches for surface emissivity treatment in retrieval

- Emissivity spectrum is expressed in eigenvectors (derived from laboratory measurements)
- Regression retrieval are used as the first guess
- Simultaneous retrieval of emissivity spectrum and sounding in physical iterative approach

Retrieval Algorithm (Li et al. 2007 – GRL)

Atmospheric measurement equation

$$\boxed{y = F(x)} + e$$

$$y = (R_1, R_2, \ldots, R_n)^T;$$

$$x = (t(p); w(p); o(p); t_s; \boxed{\varepsilon_1, \ldots, \varepsilon_n};)^T$$

Emissivity eigenvector coefficients

Regularization and discrepancy principle (Li and Huang 1999)

(Cost function)

$$J(x) = (y_m - y_c(x))^T E^{-1} (y_m - y_c(x)) + (x - x_0)^T \gamma S_0^{-1} (x - x_0)$$

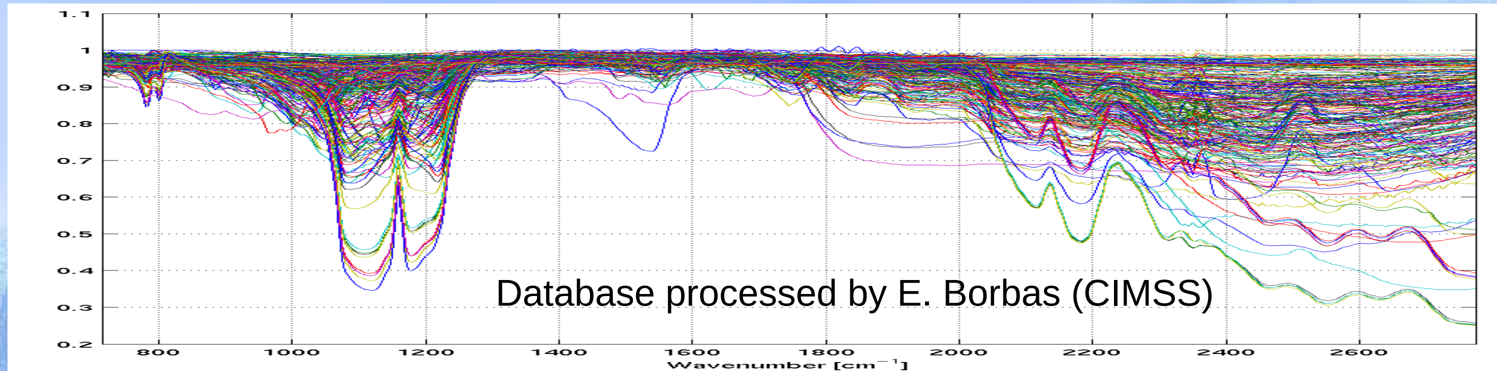
Too many parameters to retrieve if including all channels' emissivities !!!

EOF expansion

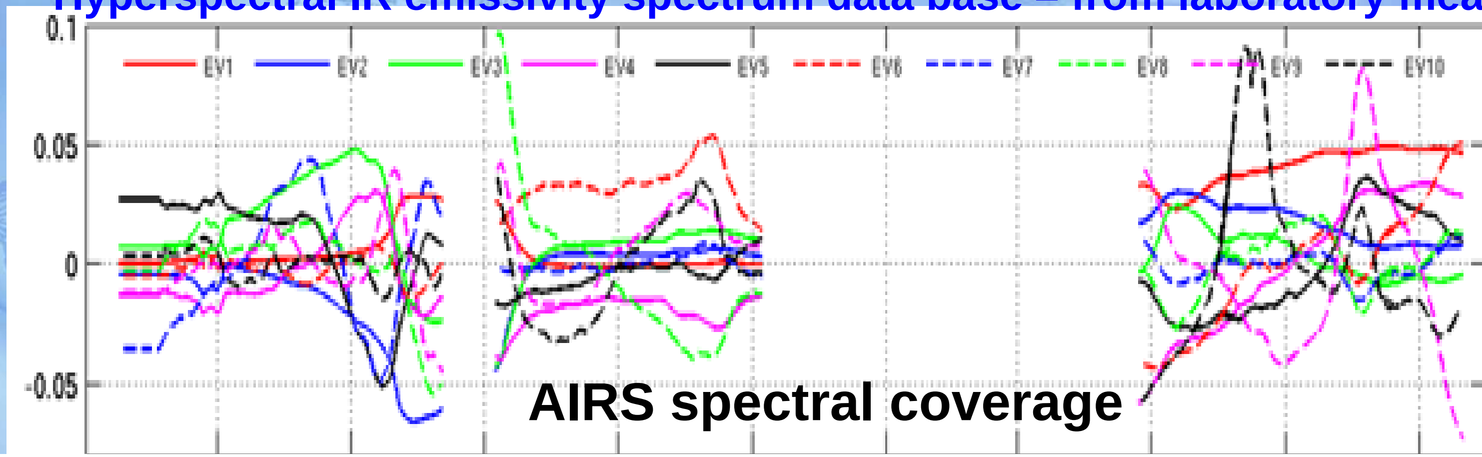
$$x = \sum_i^l a_i \varphi_i = a\phi;$$

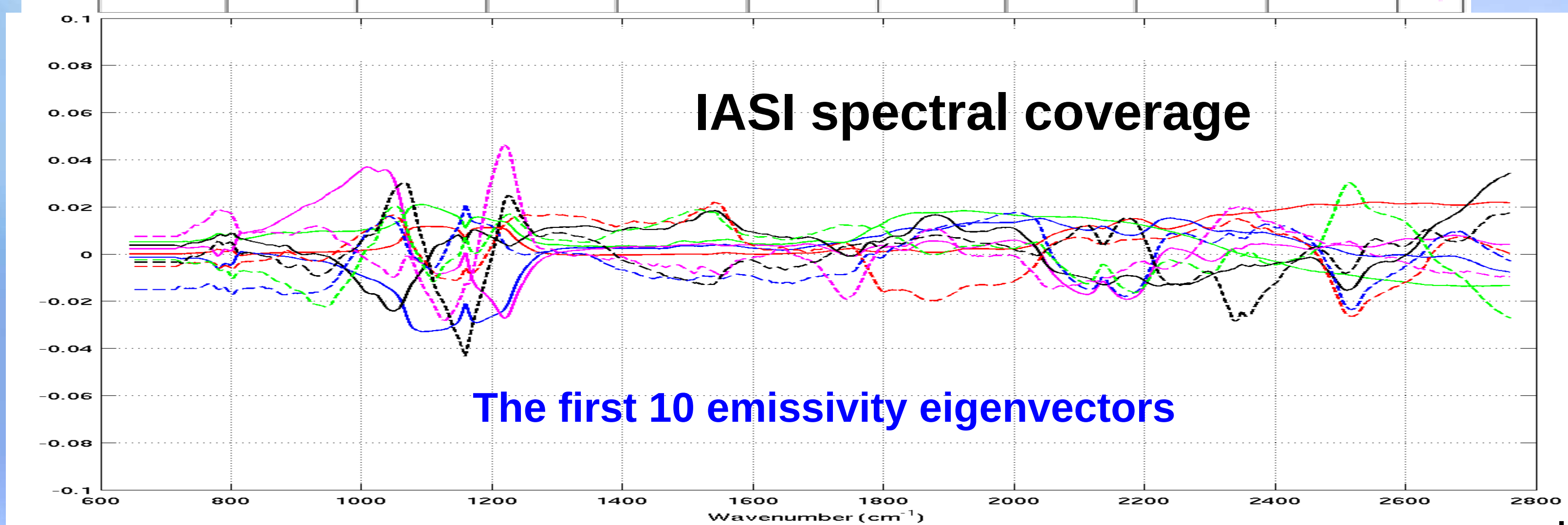
ϕ: eigenvector matrix;

a: eigenvector coefficients **to be retrieved**

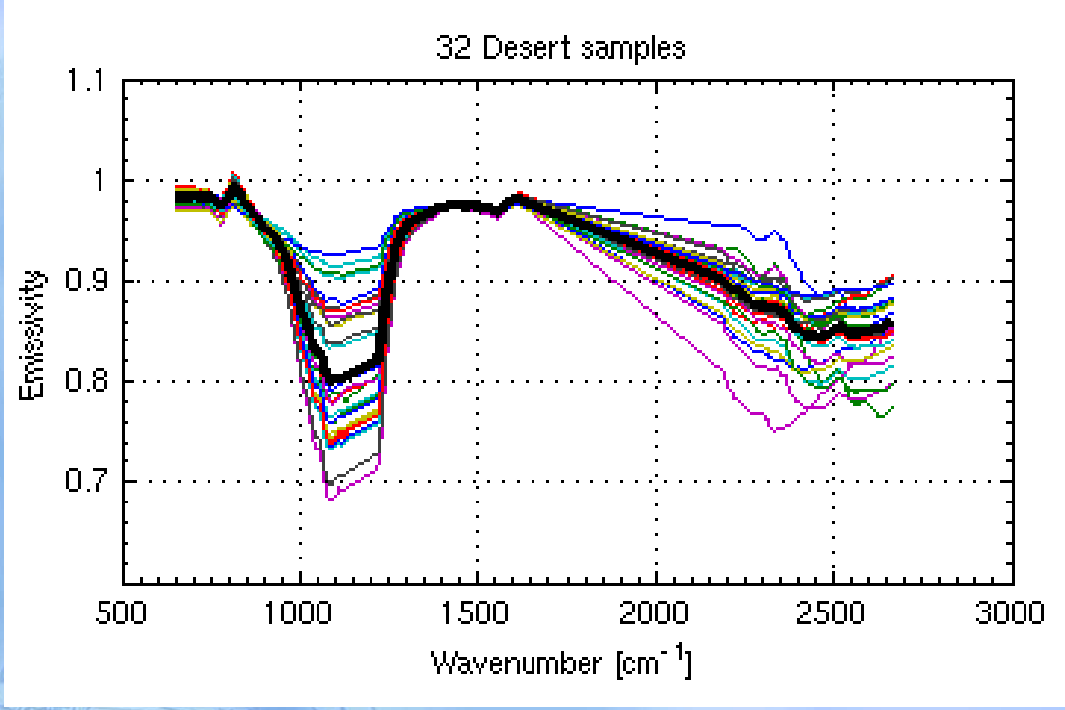


Hyperspectral IR emissivity spectrum data base – from laboratory measurements





Retrieval Experiments – Simulation over desert



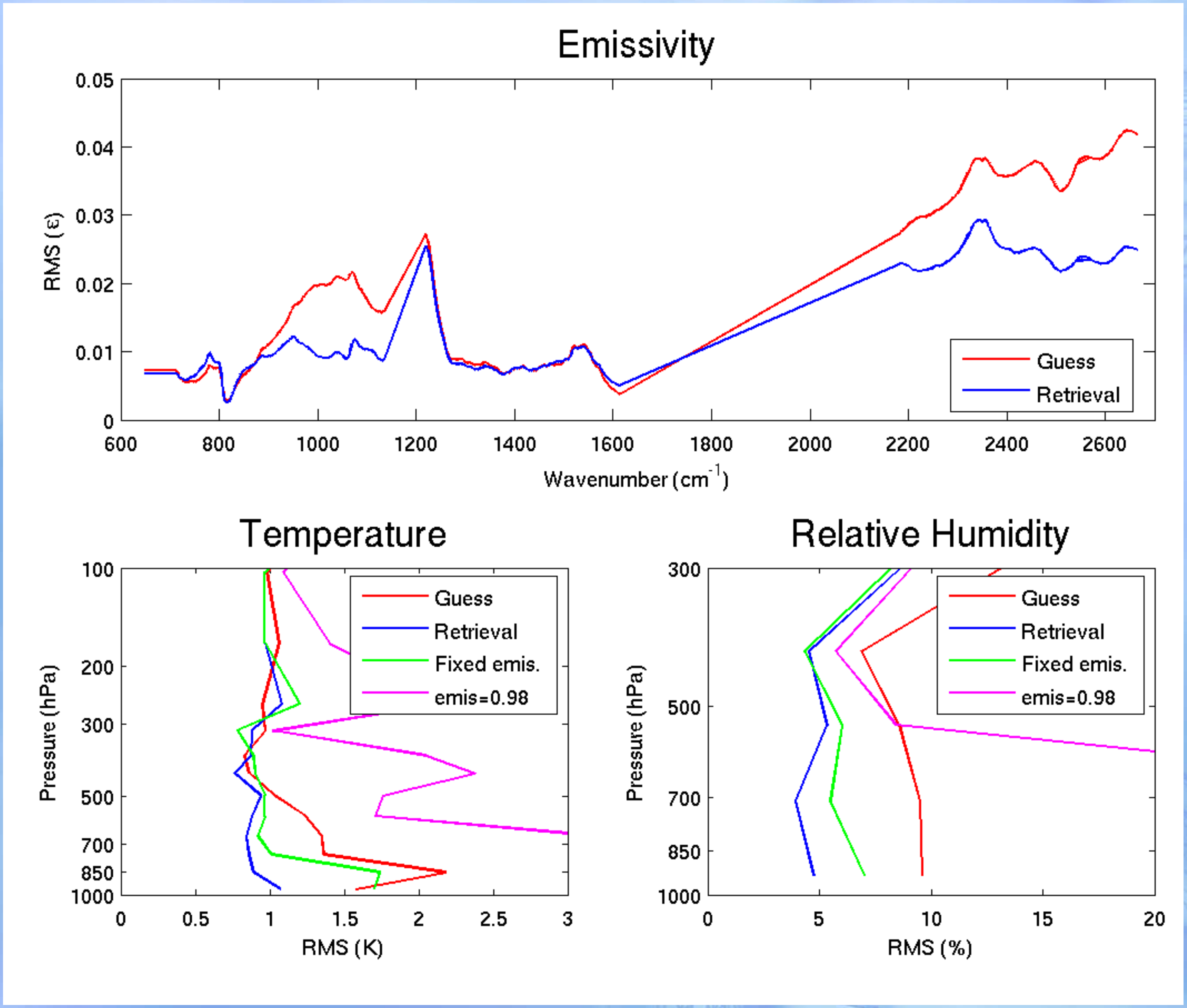
Regression retrieval:

T, W, O_3 profiles,
Ts, Emisssivity

Three types of physical retrieval

1. Using constant emissivities of 0.98 and fixed in iterations.
2. Using regression emissivities and fixed in iterations.
3. Using regression emissivities and updated in iterations.

Simulated Retrieval for Desert (32 profiles)



Tskin RMS (K)	
Reg	0.624
Rtv	0.540
Fixed emis	0.822
Emis=0.98	9.544

Guess E =0.98

Guess E =Regression

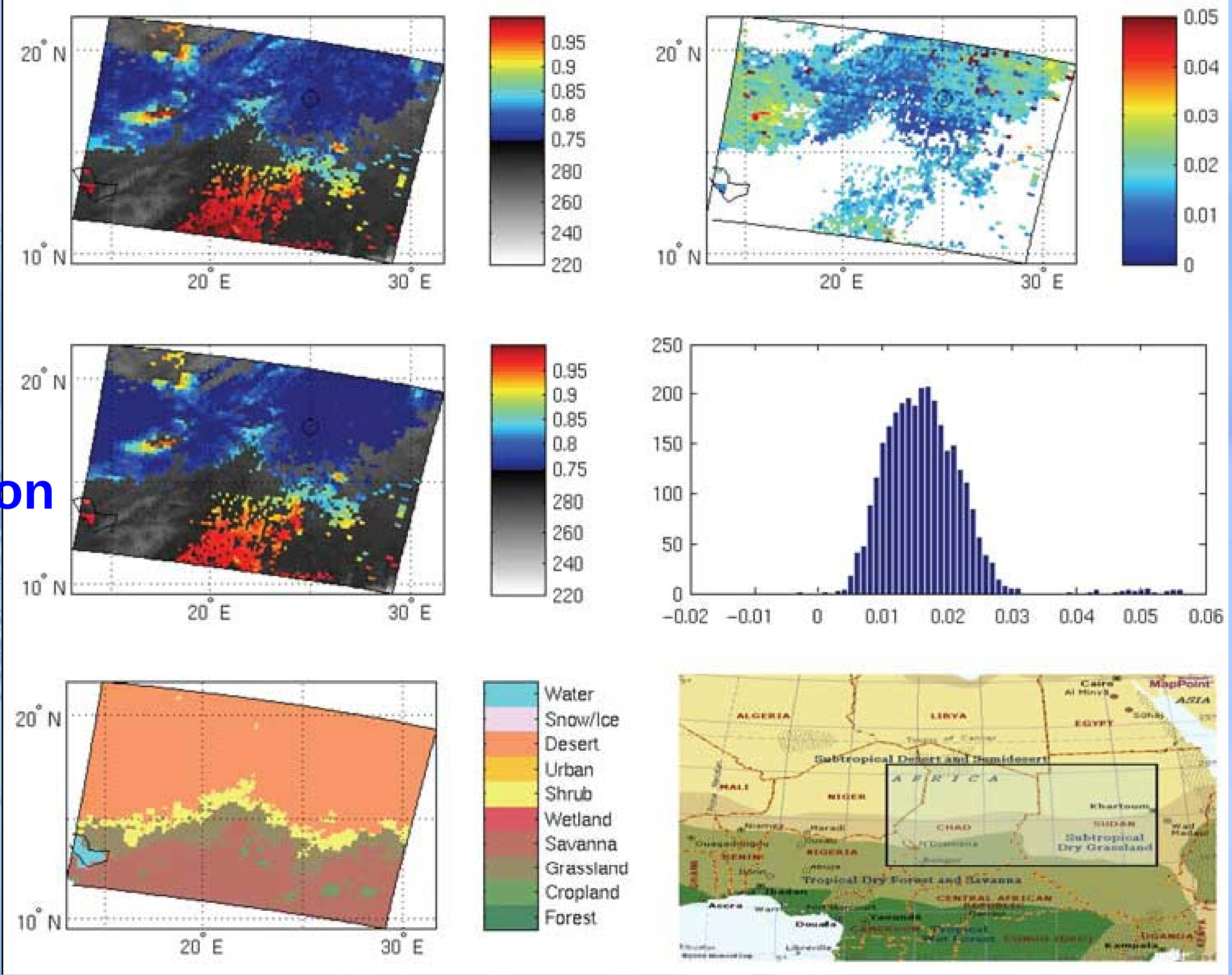
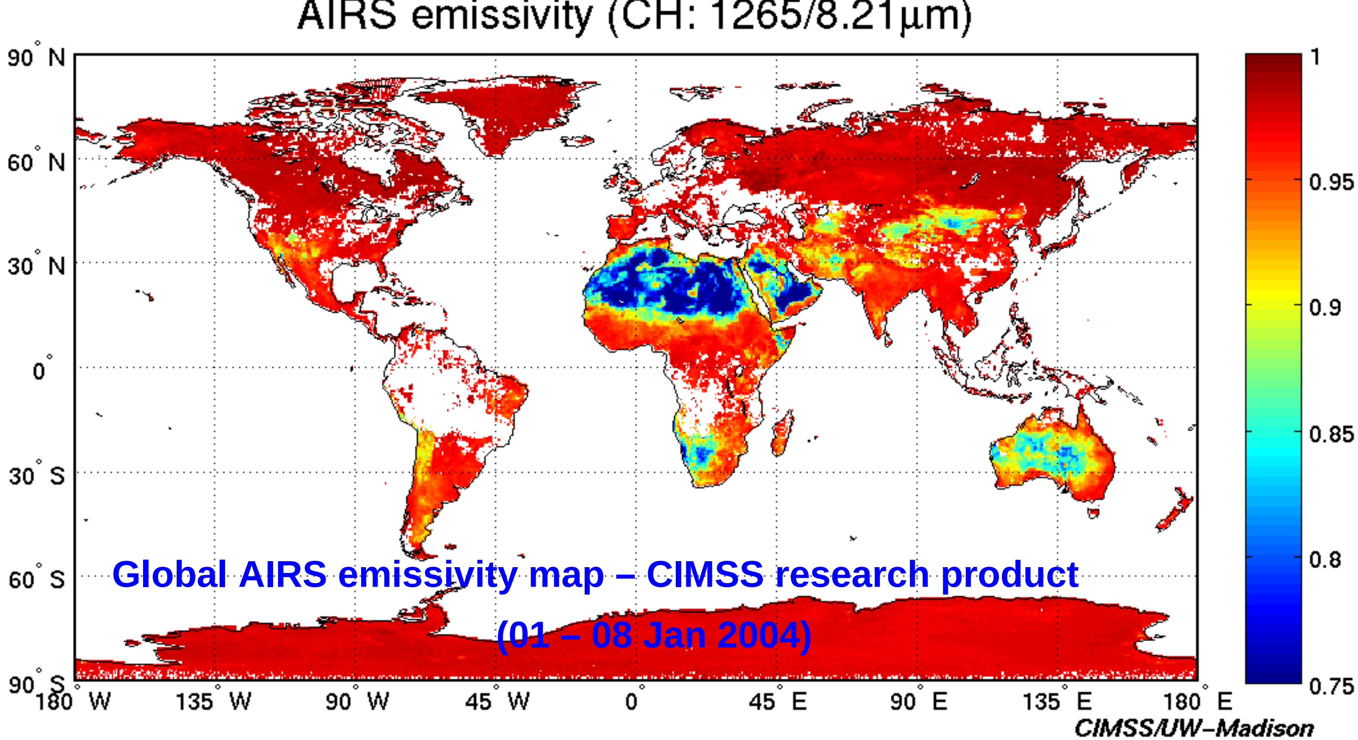
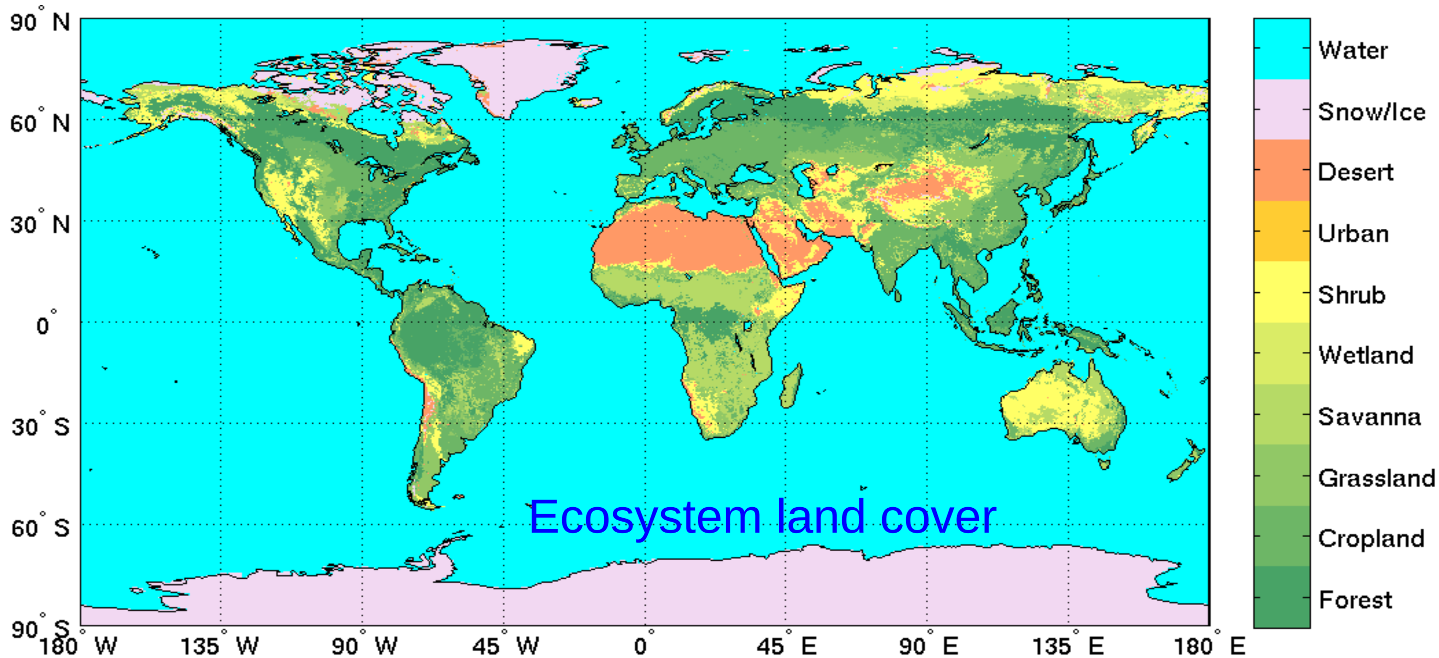


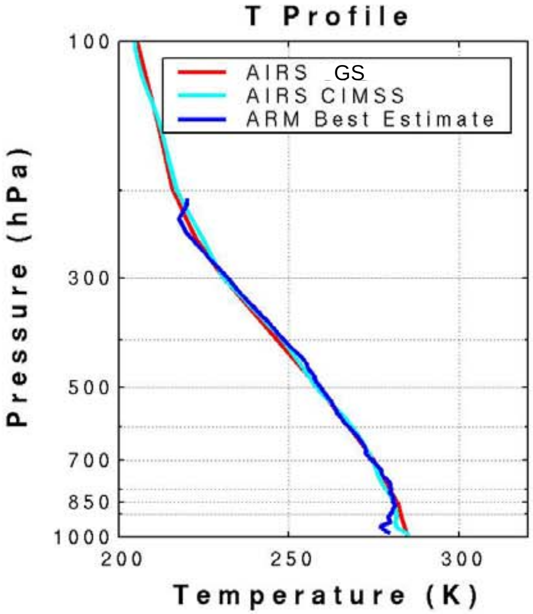
Figure 1 from Li and Li [2008 – GRL]: The AIRS 9.3 mm surface emissivity retrieval images overlaying on AIRS brightness temperature (K) image (black/white) for Granule 002 on 06 January 2004 with (top left) 0.98 (constant spatially and spectrally) as first guess and (middle left) regression as first guess, respectively. (top right) The difference image and (middle right) the histogram of differences. (bottom left) The IGBP ecosystem land type map, and (bottom right) the location of the AIRS granule over central African.

Re-group from IGBP category:

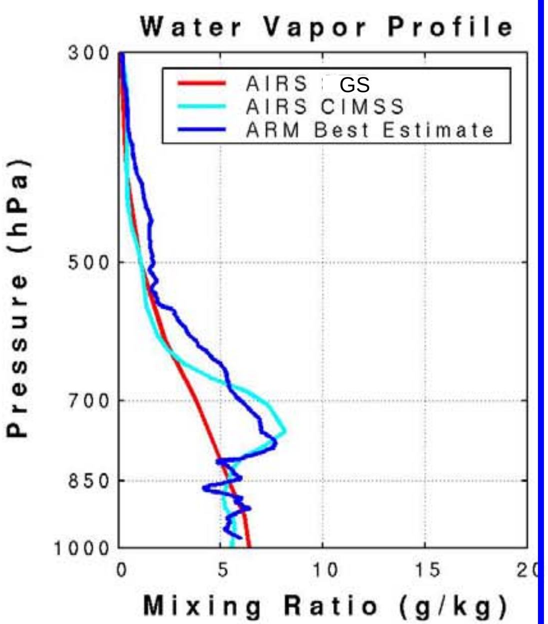
Forests: Evergreen needle forests Evergreen broad forests; Deciduous needle forests; Deciduous broad forests; mixed forests;
Shrubs: Opened shrubs; Closed shrubs;
Savanna: Woody savanna; Savanna;
Cropland: Cropland; Crop mosaic;
Snow/Ice: Snow; Ice; Tundra;
Desert: Desert/Barren;

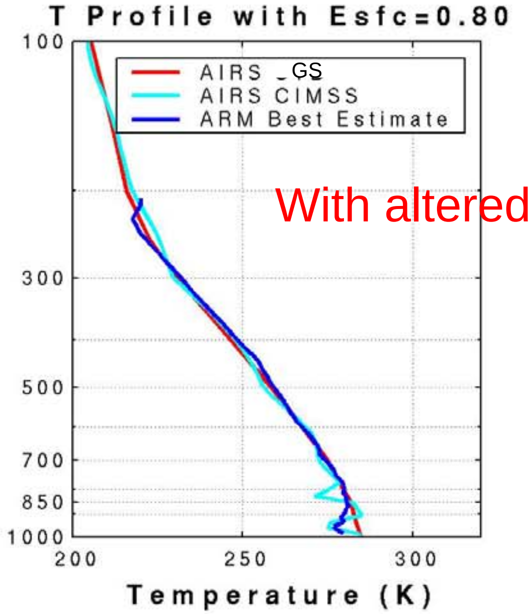




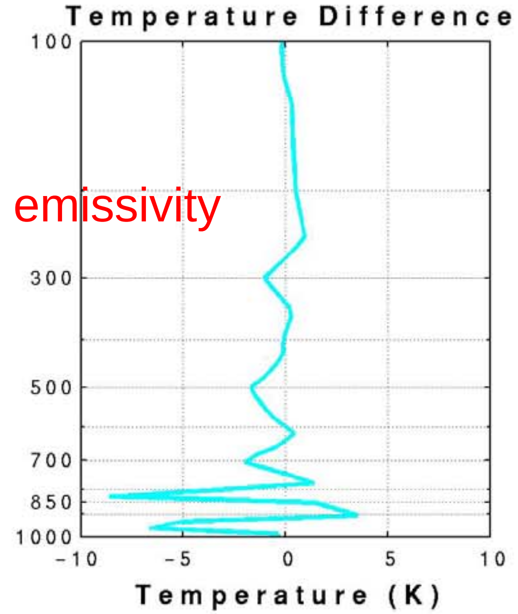


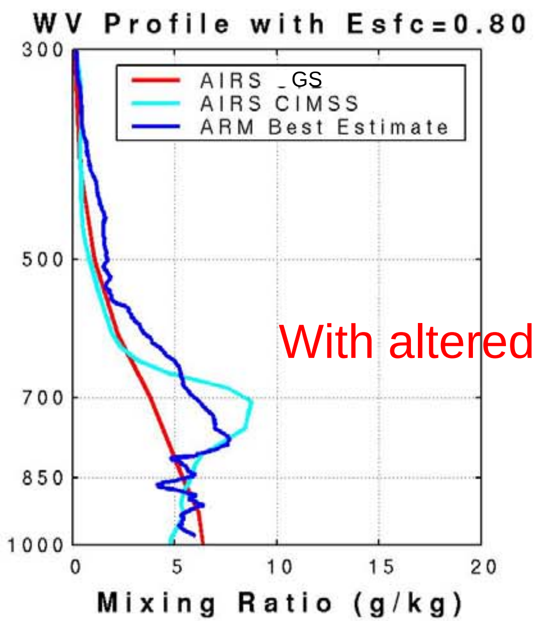
Simultaneous method



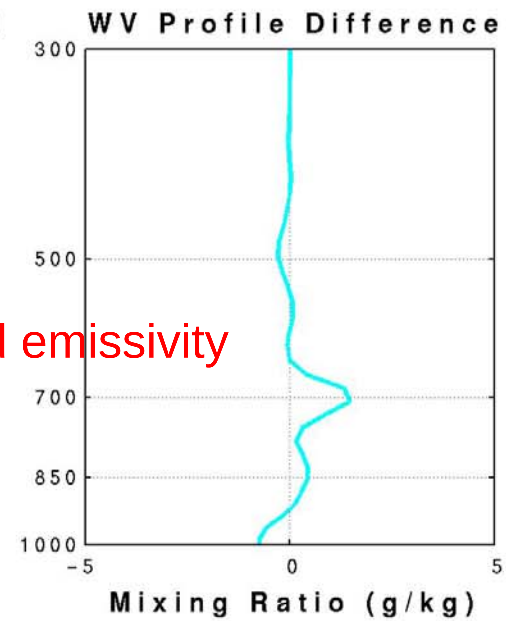


With altered emissivity

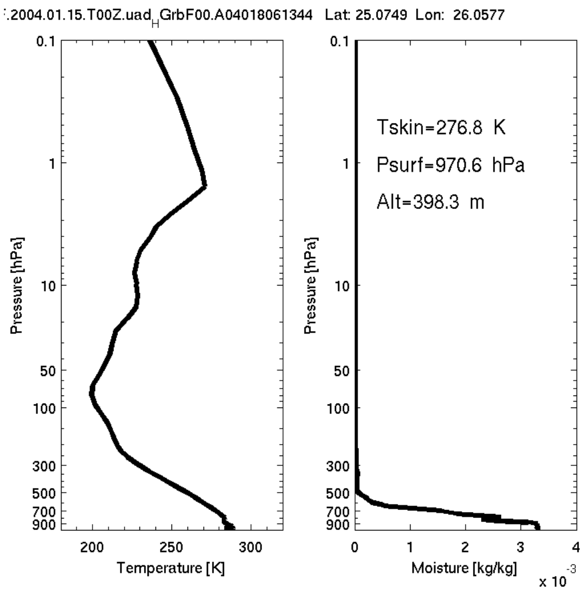




With altered emissivity

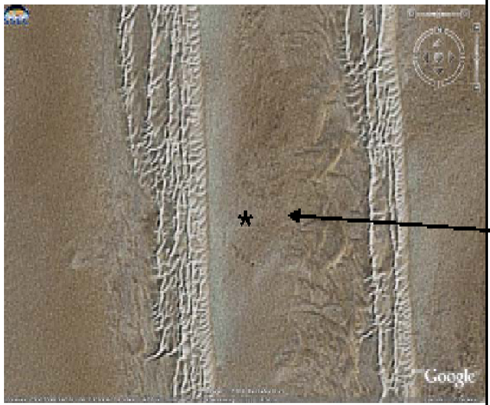


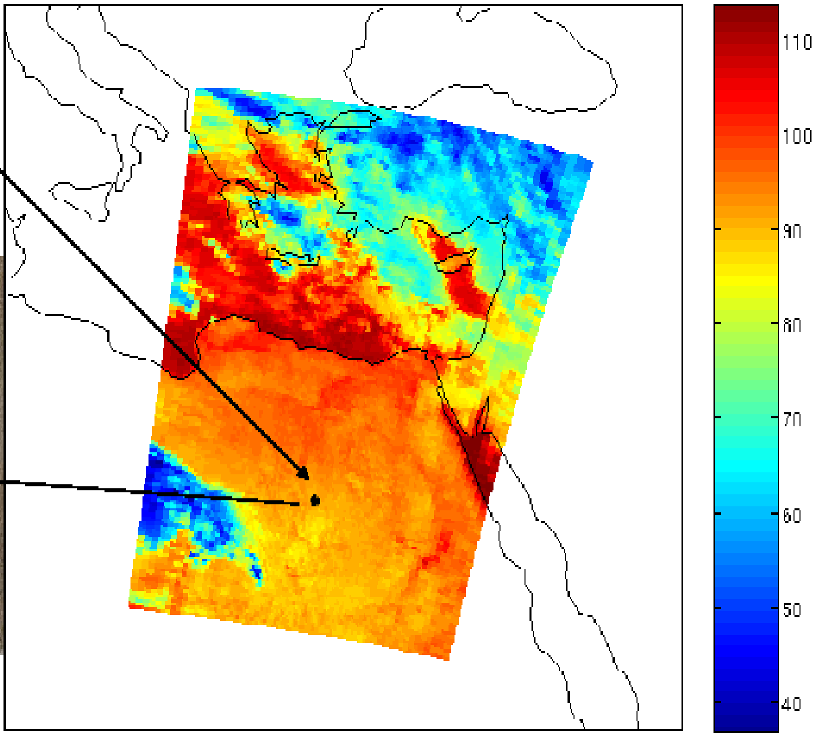
Atmospheric state from ECMWF analyses



Emissivity Validation
A case study

AIRS granule January 15 2004 00:03 UTC, 12 µm radiances

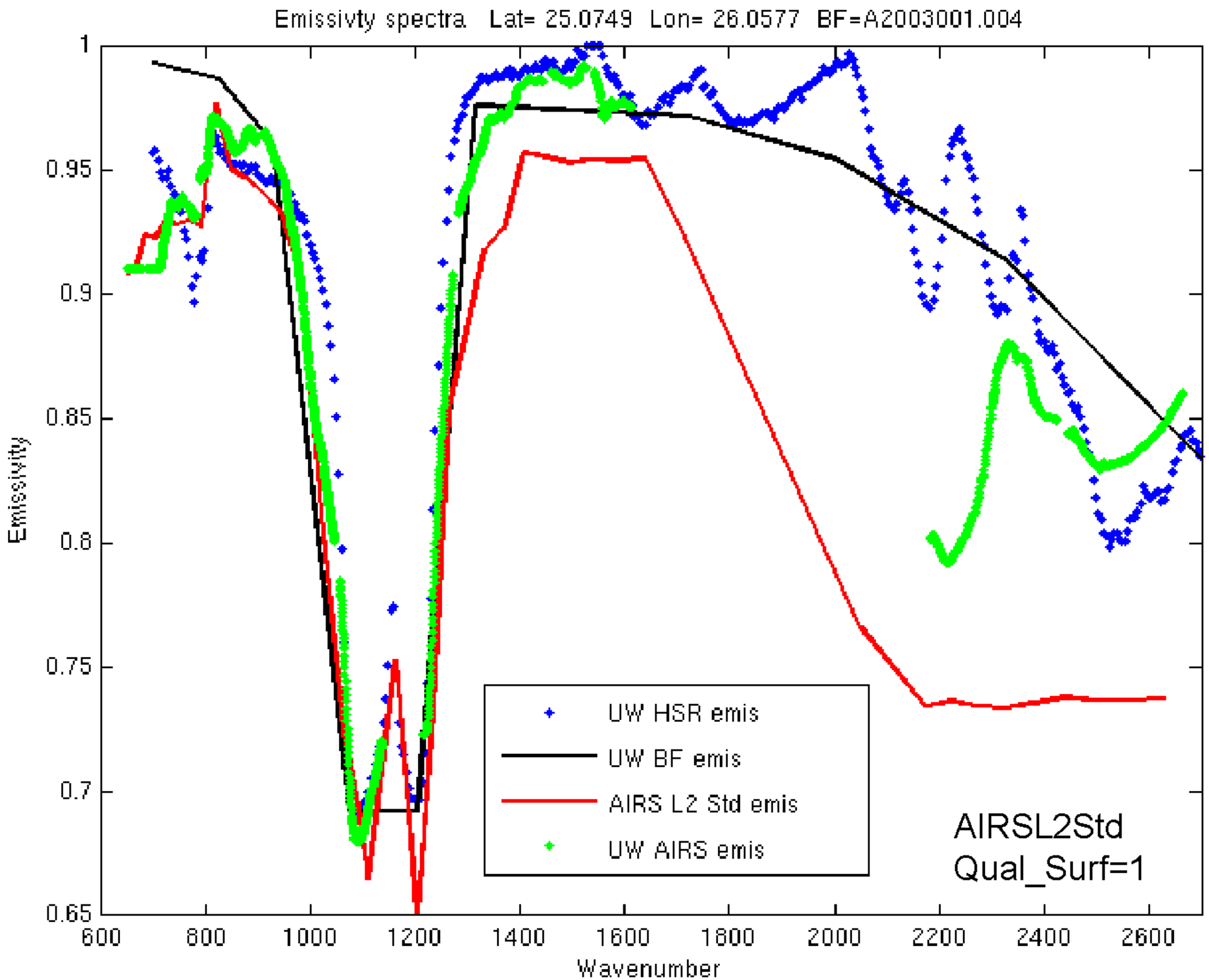




(Borbas et al. 2008, ITSC16)

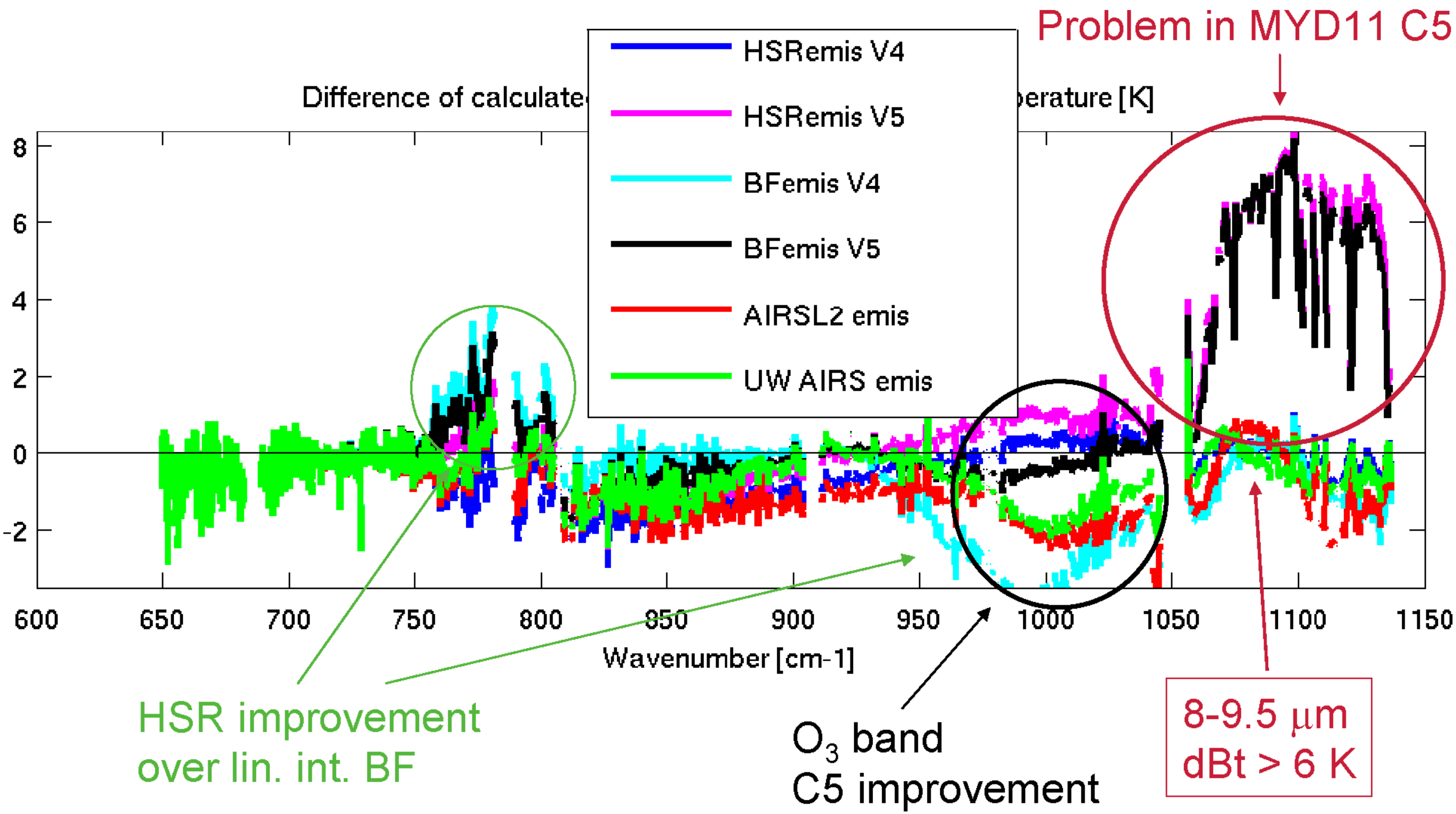
Emissivity

BF (black), HSR(blue) using MYD11 *collection 4*



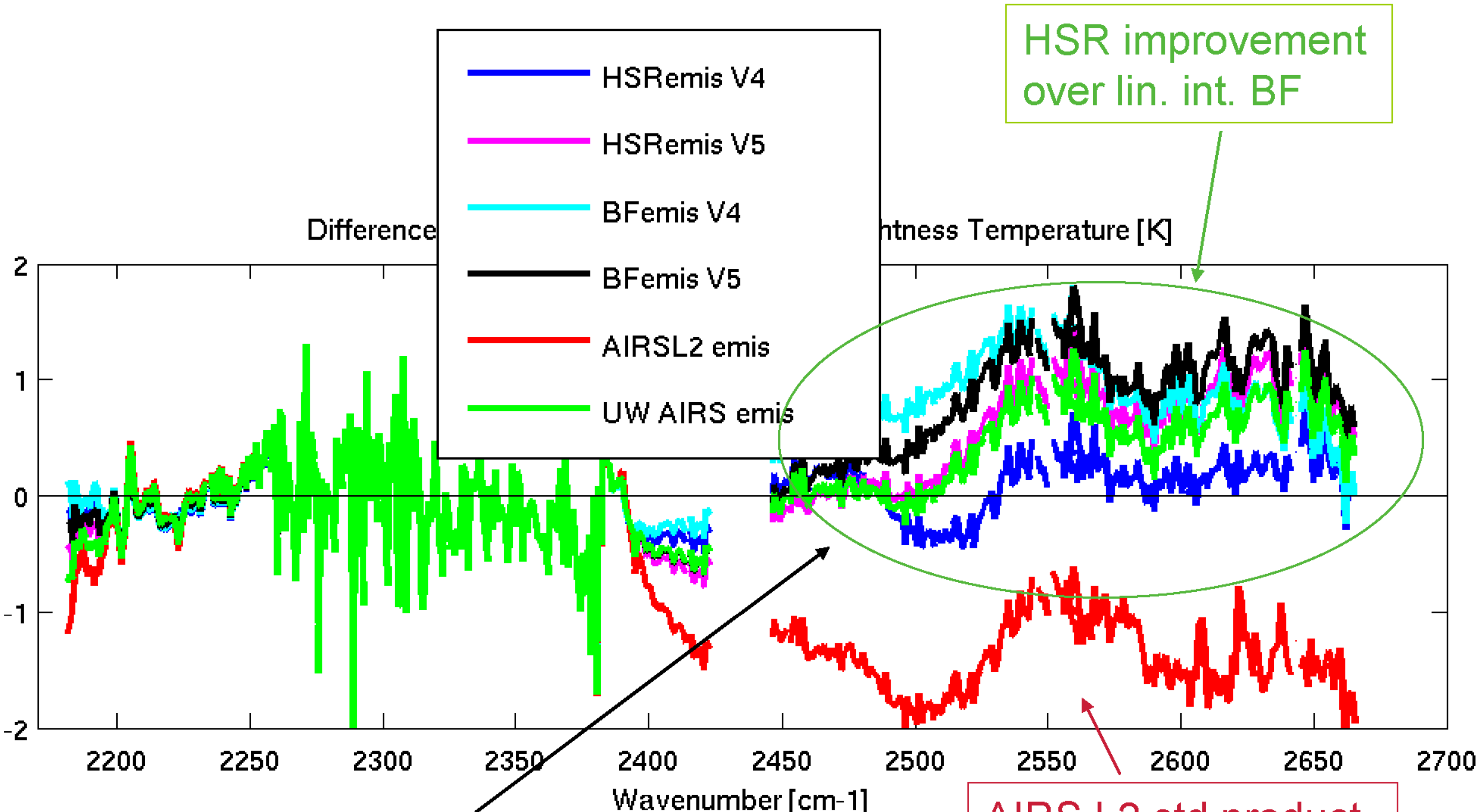
(Borbas et al. 2008, ITSC16)

BT Residuals (Calc - Obs) (LW)



(Borbas et al. 2008, ITSC16)

BT Residuals (Calc - Obs) (SW)



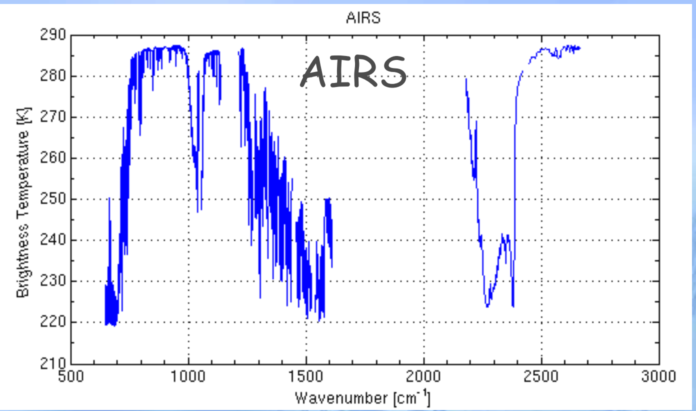
UW AIRS emissivity agrees very well with C5 HSRemis / C5 improvement vs C4

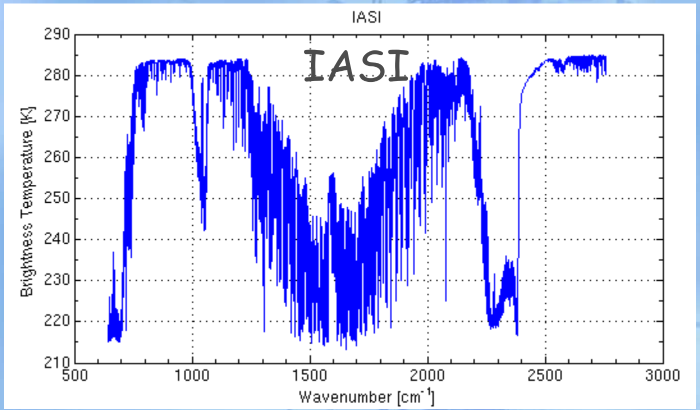
AIRS L2 std product underestimates emissivity in SW

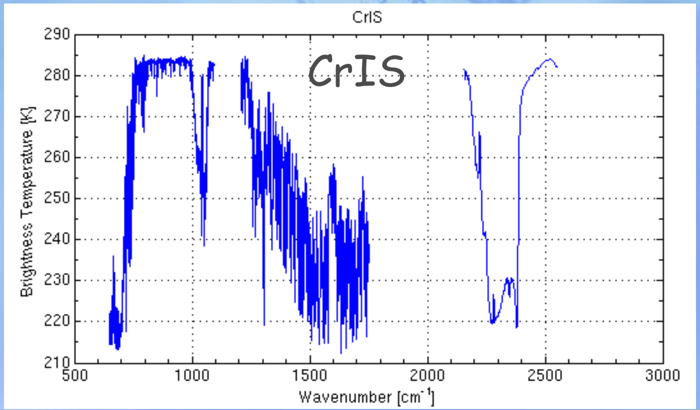
(Borbas et al. 2008, ITSC16)

Handling clouds

- Only limited coverage is clear for IR radiances
- Soundings in cloudy regions are more important for forecast
- SFOV sounding products at high vertical and spatial resolution are important for monitoring/predicting mesoscale features in regional forecast models.







Our goal is to provide a physically based optimal retrieval algorithm to simultaneously derive T,Q, O_3 profiles, surface parameters and cloud parameters from hyperspectral IR measurements (e.g. from AIRS, IASI, CrIS) alone at single FOV resolution.

Fast cloudy radiative transfer model

- Developed in collaboration with Texas A&M University (H. Wei, P. Yang)
- Cloudy radiances can be computed from coupled clear-sky optical thickness (computed by SARTA) and cloud single-scattering properties.

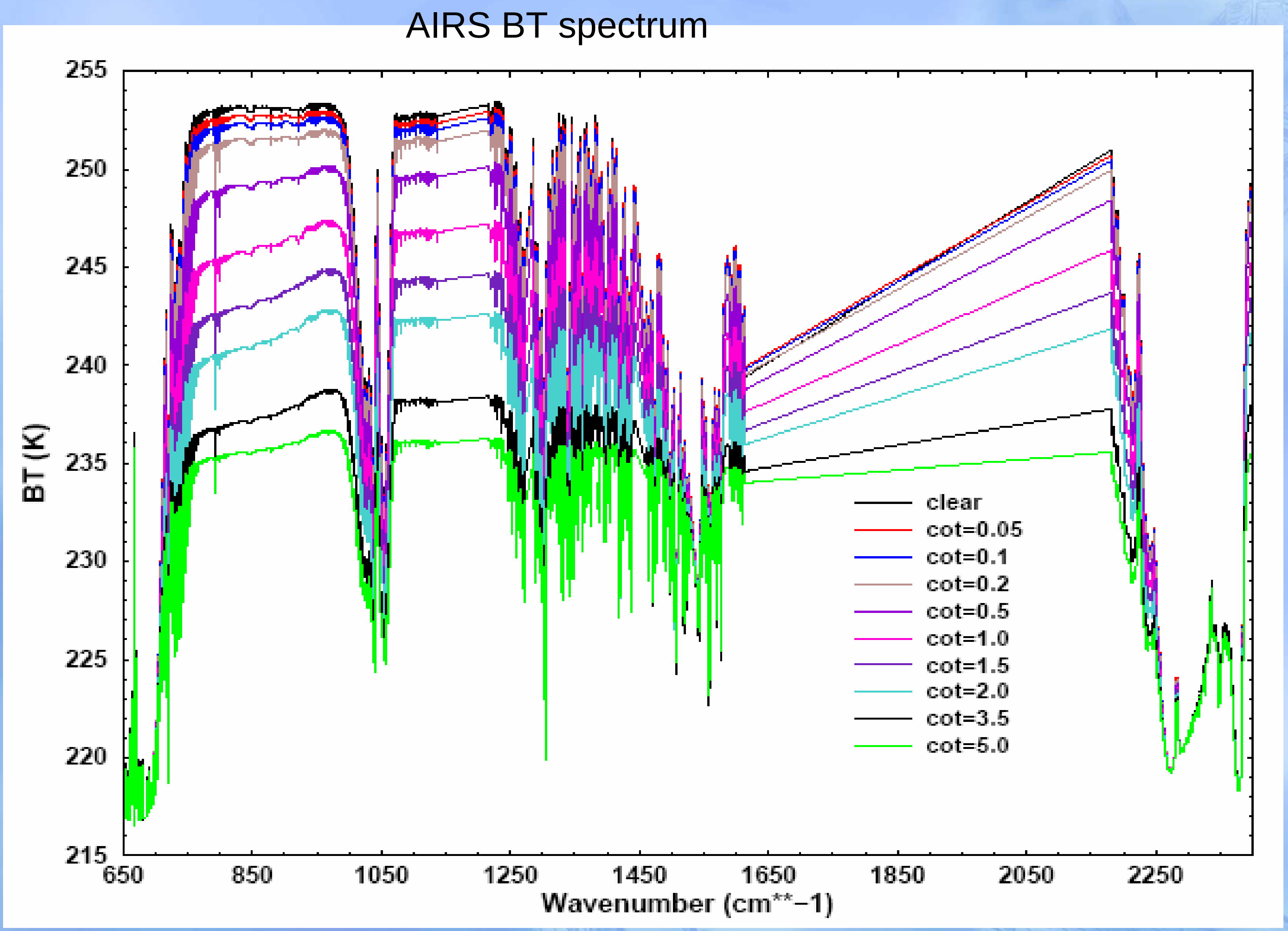
$$R = R_o F_T \tau_c + (1 - F_T - F_R) B_c \tau_c - \int_0^{pc} B \, d\tau + F_R \tau_c \int_0^{pc} B_c d\tau^*$$

R_0…radiance below cloud (=R_s+$R\uparrow$+$R\downarrow$), B…Planck function, pc …cloud top pressure,

τ_c…transmittance of cloud top, $\tau^* = \tau_c^2/\tau$ … downwelling transmittance,

F_R…cloud reflectance function, F_T…cloud transmissive function

- Reflectance (albedo) and transmissive functions for various CPS (Cloud Particle Size) and COT can be obtained from a pre-described parameterization of the bulk single-scattering properties of ice and water clouds
- Ice clouds: assumption of aggregates, hexagonal geometries and droxtals for large (>300 μm), moderate (50 - 300 μm) and small particles (0-50 μm) respectively.
- Water clouds: assumption of spherical droplets and application of classical Lorenz-Mie theory.



Whole sounding in broken clouds and above-cloud sounding in thick clouds can be derived

Regression

IMAPP RTV Software v1.3

CLEAR

Training data set (SeeBor V5)

Radiance calculations
SARTA v1.7 (UMBC)

BT and Scanang Classification

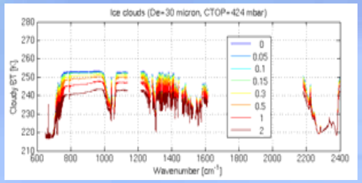
Clear Regr Coeffs

T, Q, O3, STemp, Emissivity at single FOV

CLOUDY

Cloudy Training data set (ice, water)

Radiance calculations
Fast RT cloud model (Wei, Yang)



Scanang Classification

Ice Cloud Regr Coeffs
Water Cloud Regr Coeffs

T, Q, O3, STemp, CTOP, COT at single FOV

Common steps

Additional Predictors (spres, solzen)

PC regression

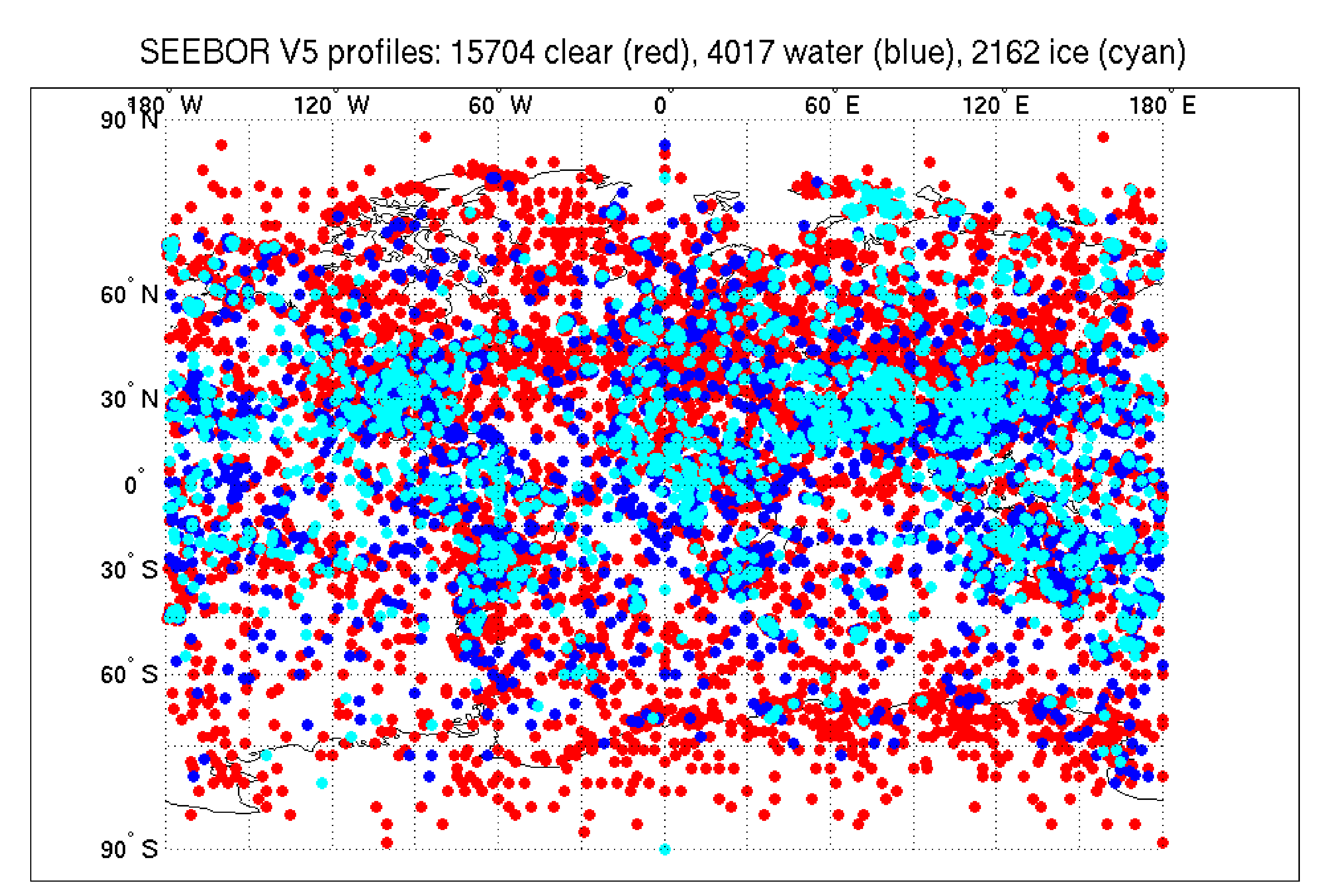
$$C = dXA^T(AA^T)^{-1}$$

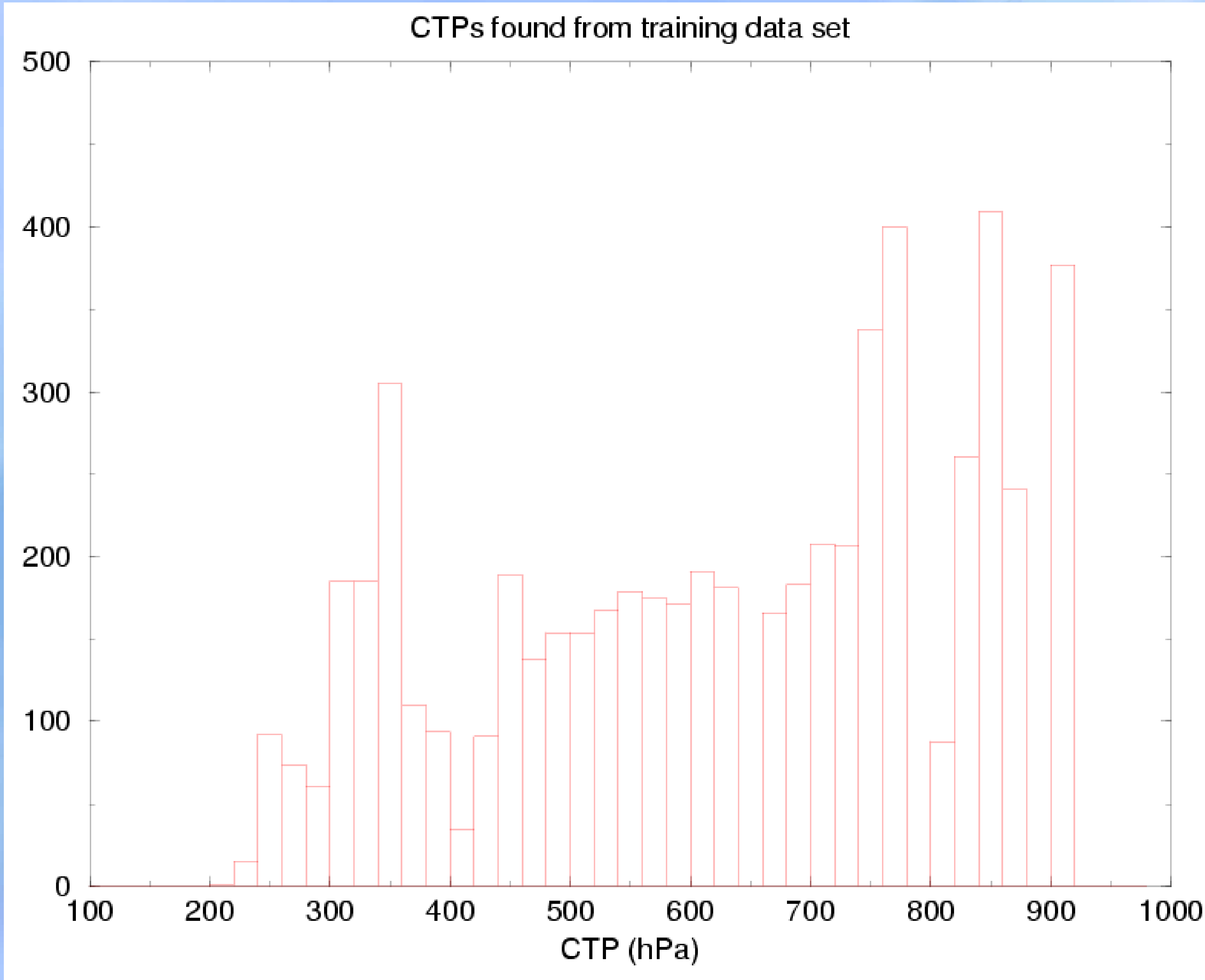
Regression RTV

$$X = \overline{X_{tr}} + CA_{obs}$$

To physical inversion

From 15704 profiles, profiles 4017 profiles are water clouds and 2162 are ice clouds




CTPs found from training data set
500
400
300
200
100
0
100
200
300
400
500
600
700
800
900
1000
CTP (hPa)

Physical Inversion

Cost function for a quasi non-linear case:

$$J = (y - F(x))^T S_\varepsilon^{-1} (y - F(x)) + (x - x_a) S_a^{-1} (x - x_a)$$

Newton-Gauss Iteration with regularization parameter γ:

$$x_{i+1} = x_a + (K_i^T S_\varepsilon^{-1} K_i + \gamma S_a^{-1})^{-1} K_i^T S_\varepsilon^{-1} [y - F(x_i) + K_i(x_i - x_a)]$$

x, x_a	current /a priori atmospheric state vector
K	Jacobian
S_a, S_ε	A priori / measurement covariance matrix
F	Forward model

Transform to EOF space:

$$c_{i+1} = (\tilde{K}_i^T S_\varepsilon^{-1} \tilde{K}_i + \gamma \tilde{S}_a^{-1})^{-1} \tilde{K}_i^T S_\varepsilon^{-1} [y - F(x_i) + \tilde{K}_i c_i]$$

$c = \tilde{x} - \tilde{x}_a$ $\quad$ $\tilde{K} = K\phi$ $\quad$ ϕ eigenvector matrix

$\tilde{x} = x\phi$ $\quad$ $\tilde{S}_a = \phi^T S_a \phi$

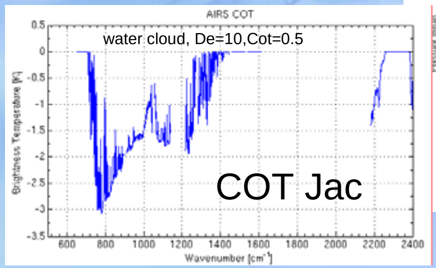
Physical Inversion - flow chart

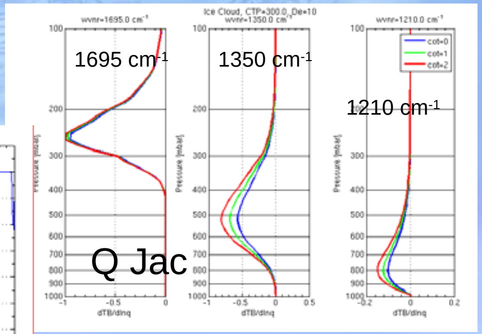
Regression
T,Q,O3,ctp,cot,de,emiss

Eigenvector matrix ϕ
Matrices S_a and S_ε

Forward model calculations

Jacobian calculations





$$dy = y - y_c$$

$$d\bar{y}_i < d\bar{y}_{i-1}$$

yes → Decrease γ

no (fail) → Increase γ

Physical Inversion

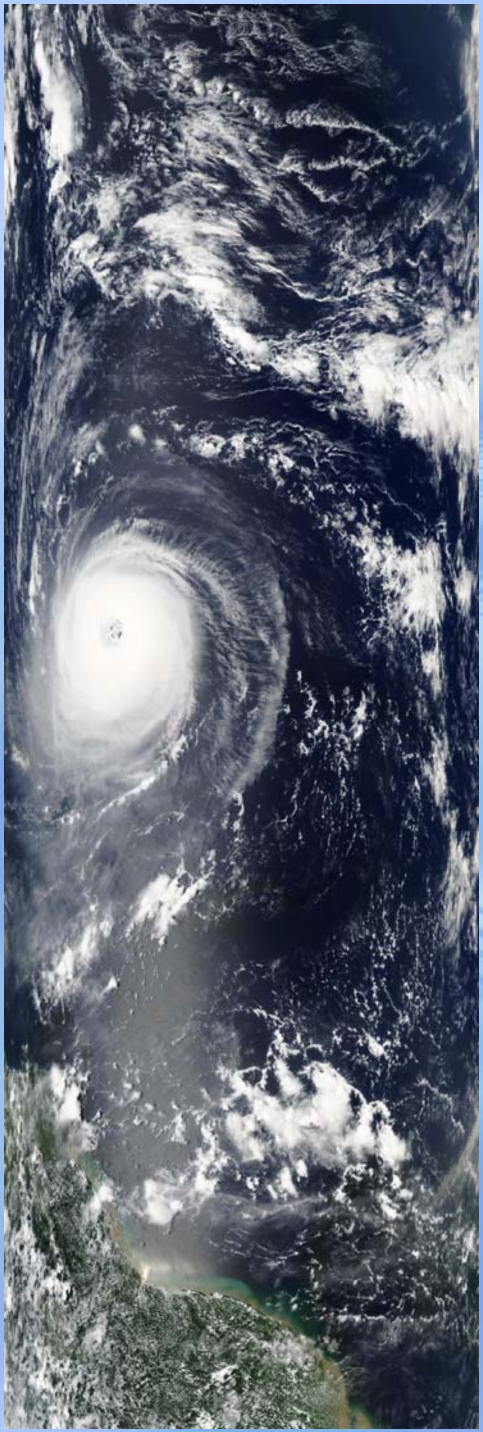
Update Profiles

\# fails < f max
\# iterations < it max
$dy > dy_{crit}$

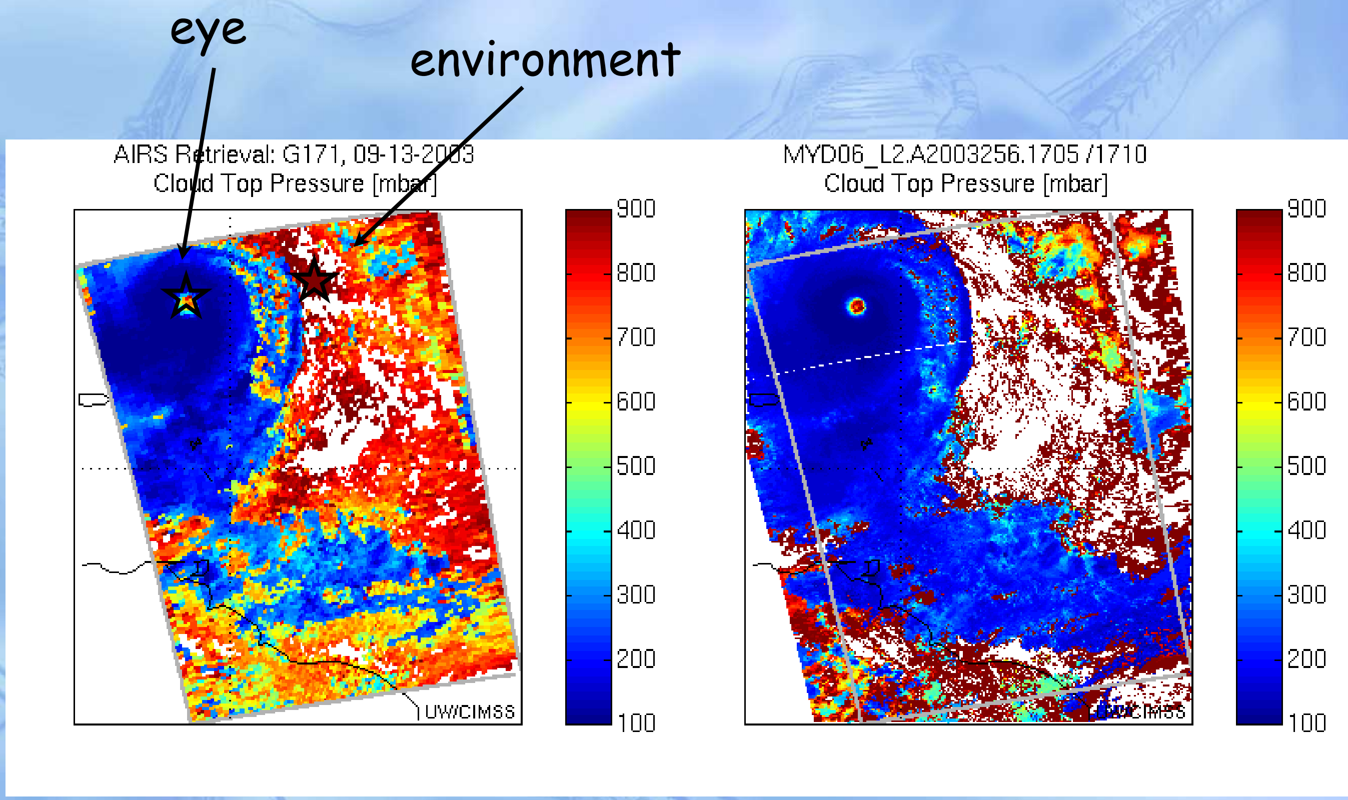
yes → Next iteration

no → Physical RTV results
T,Q,O3,ctp,cot,de,emiss

Hurricane Isabel case study

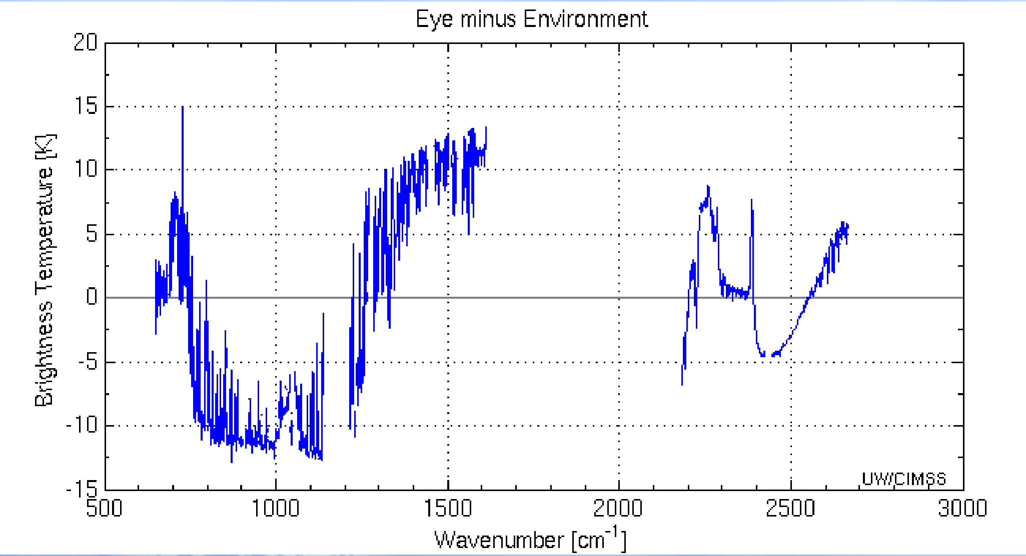


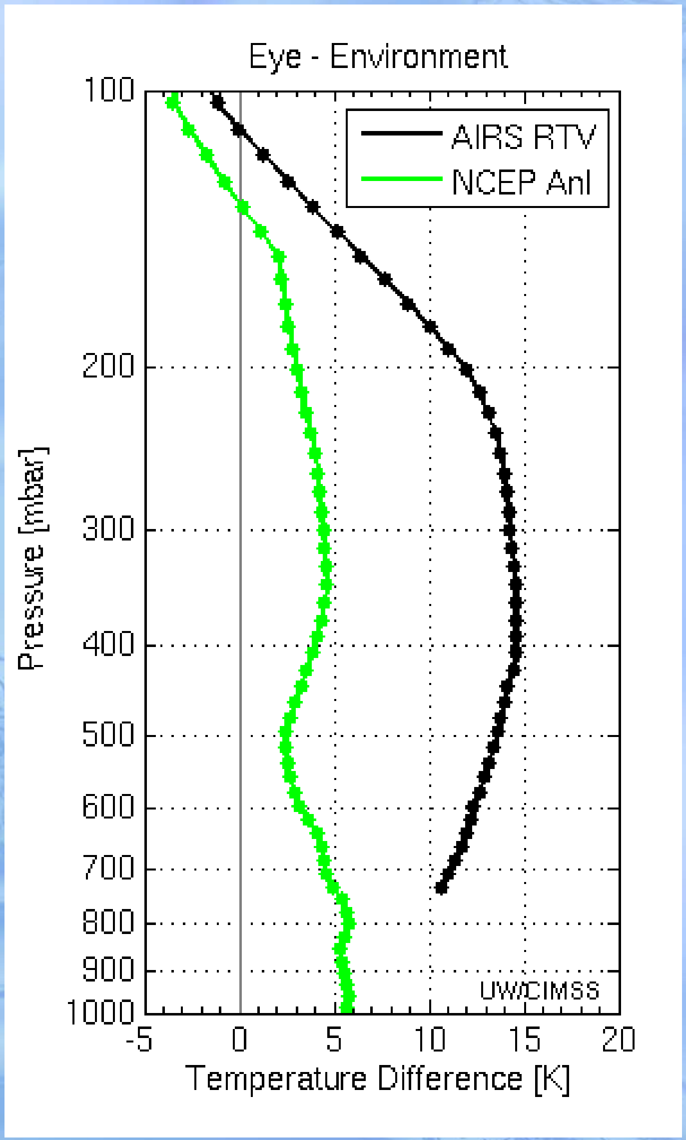
MODIS 1km images (1705, 1710)

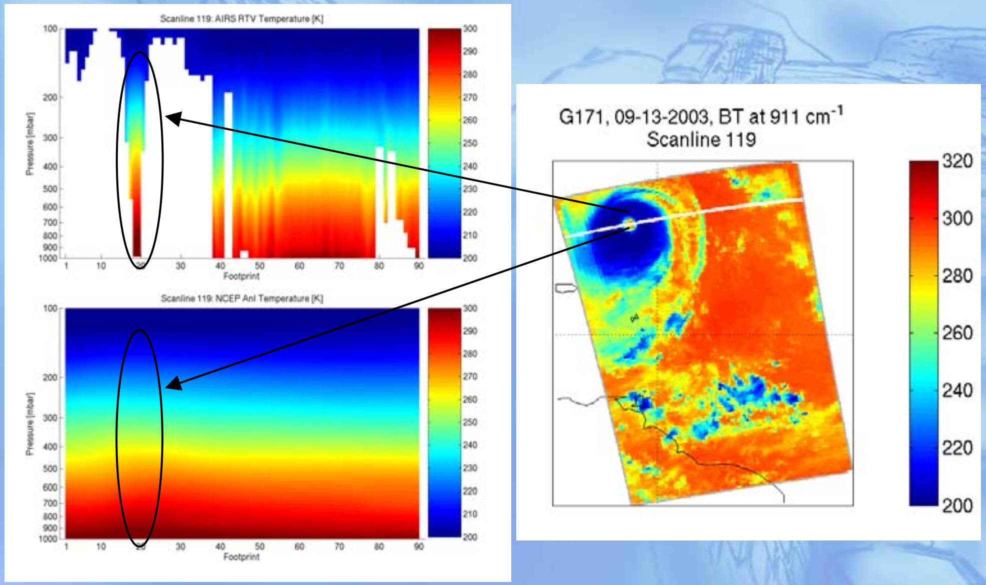


	Eye	Environment
AIRS Index	19 / 118	66 / 129
Lat / Lon [°]	22.4 / -61.9	25.3 / -55.7
Cld Frac	0.88	0.51
Ctop [hPa]	732.0	568.3

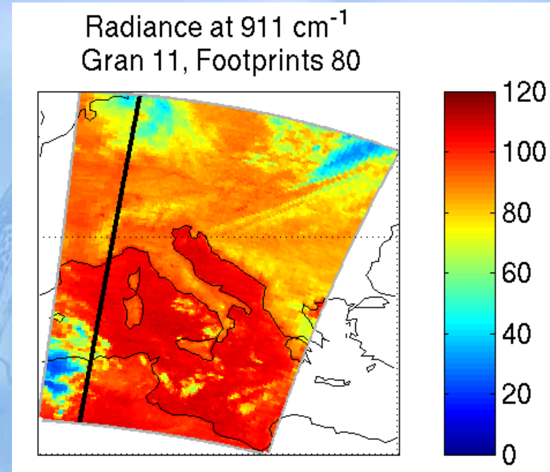
Hurricane Isabel case study



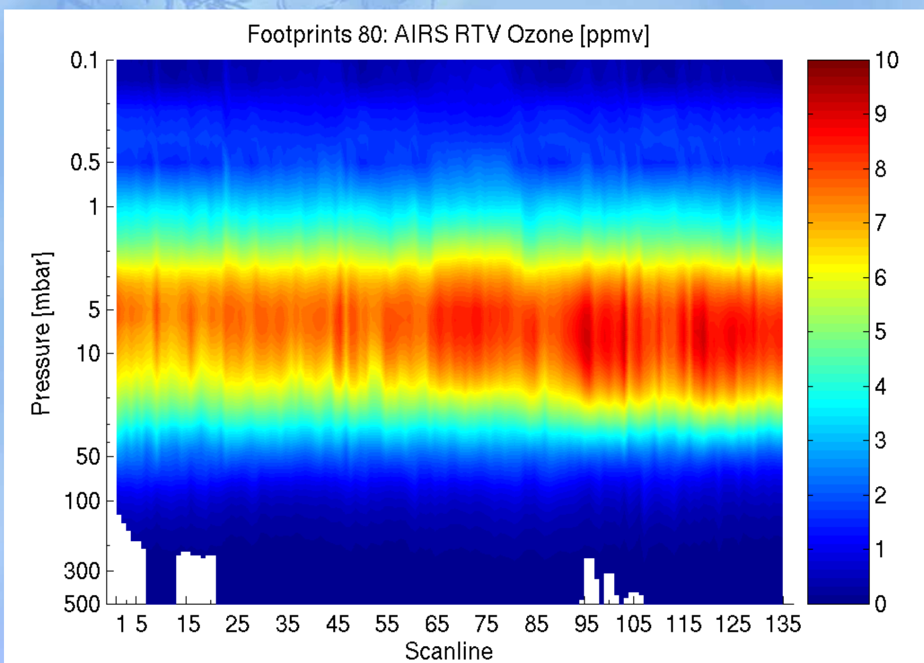




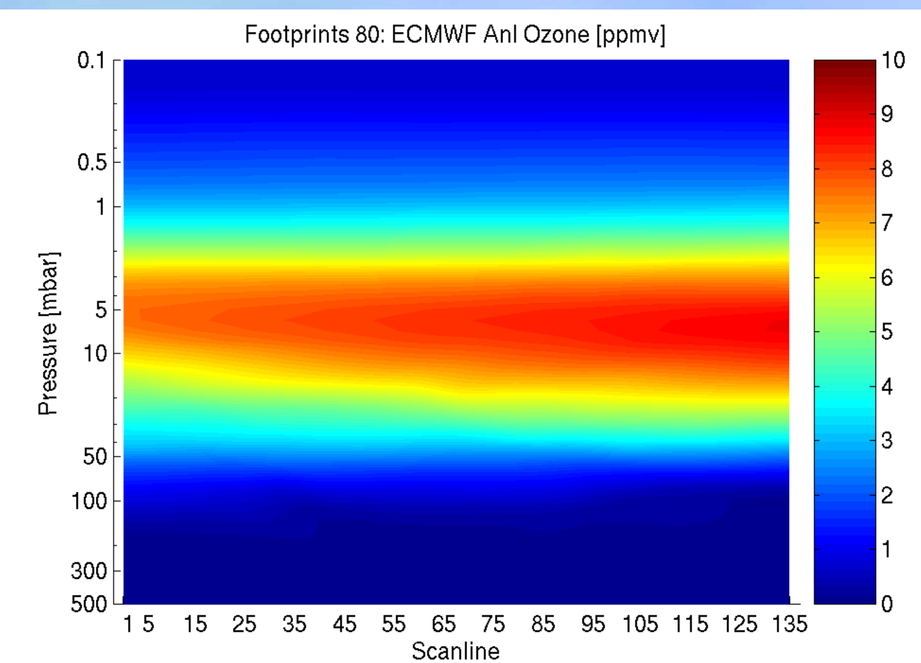
Retrieved Ozone along Footprints 80



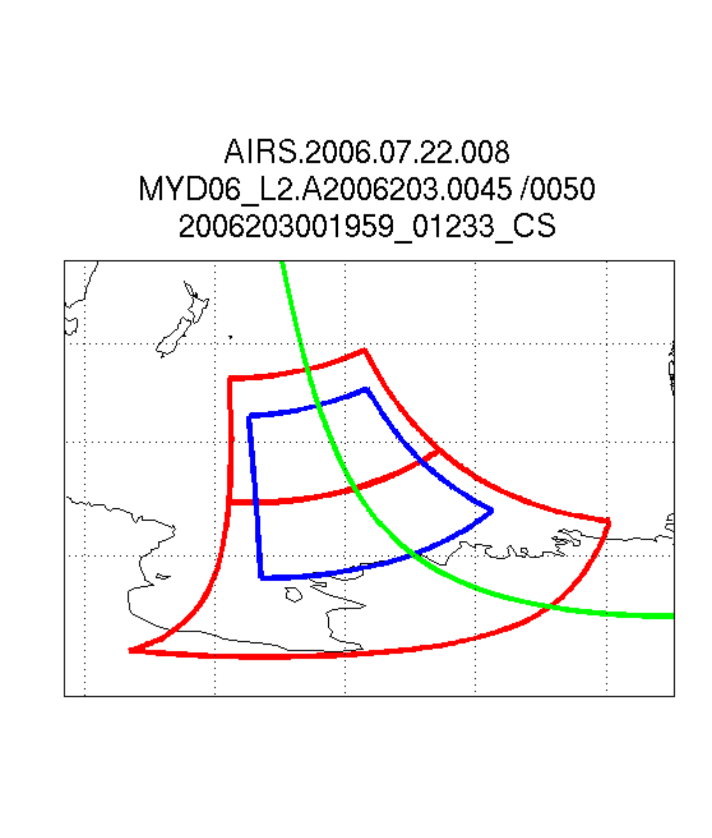
Cloudy RTV

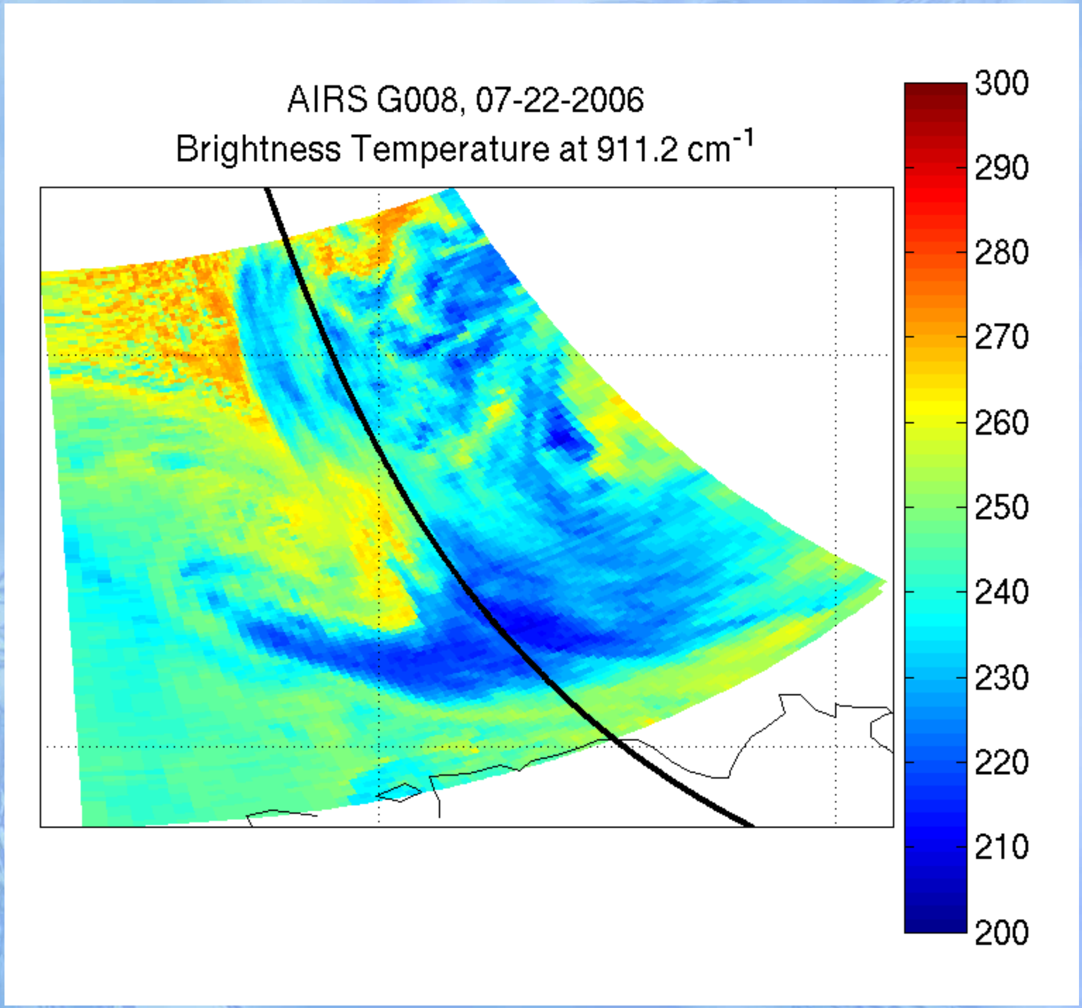


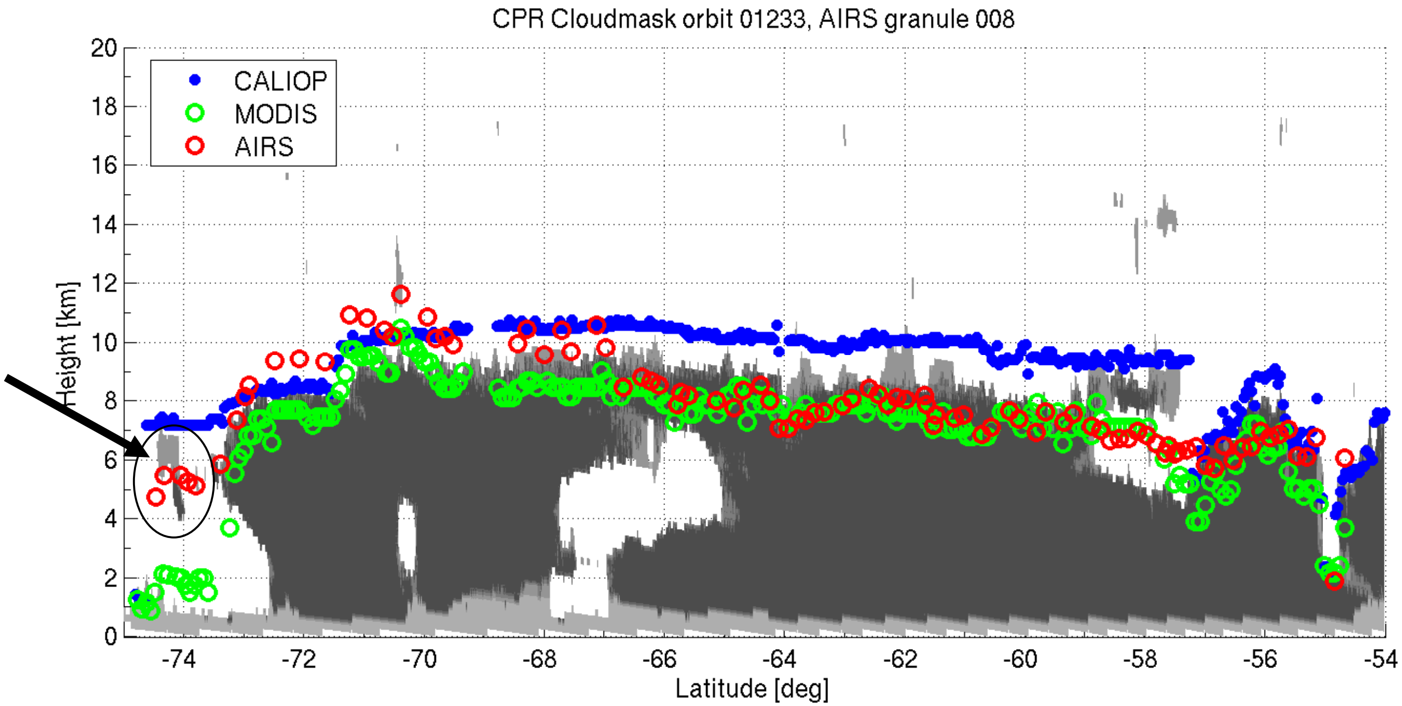
ECMWF

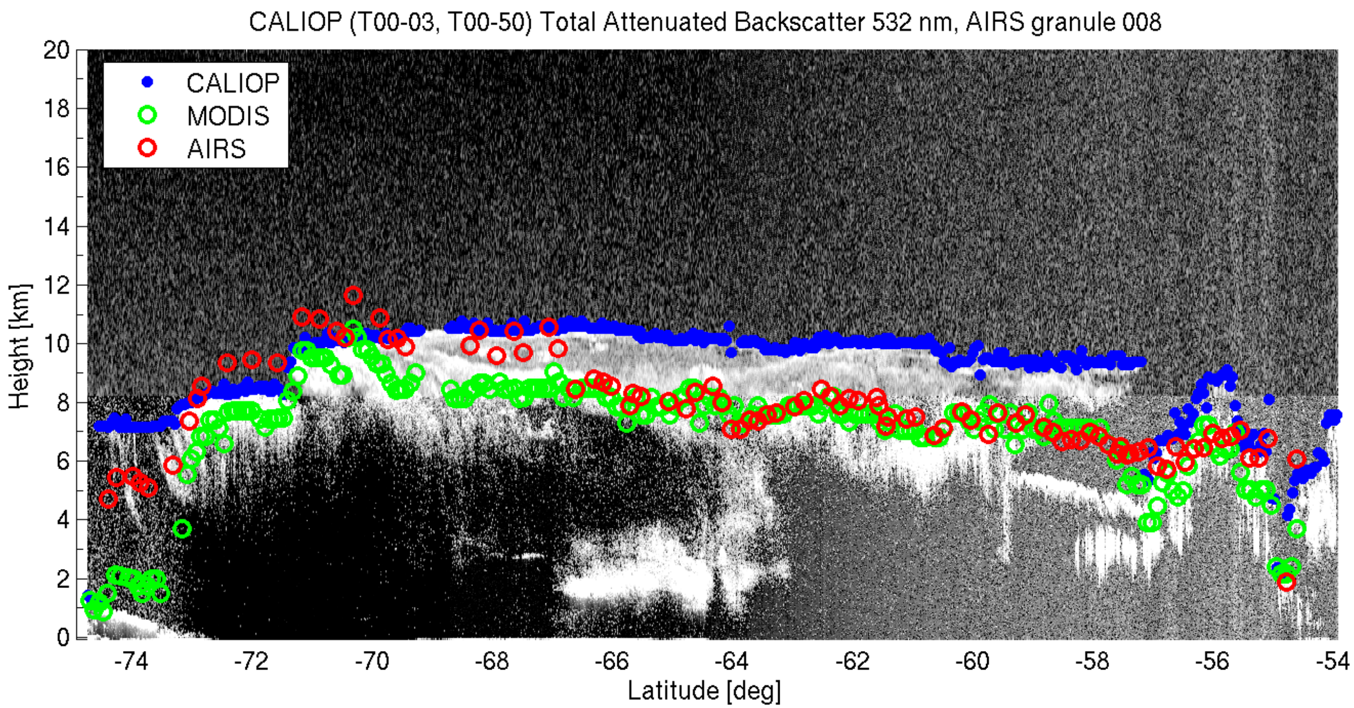


Case Study 1: 07-22-2006, AIRS granule 8 (asc)
"Interesting SH 2-layer cloud structure"



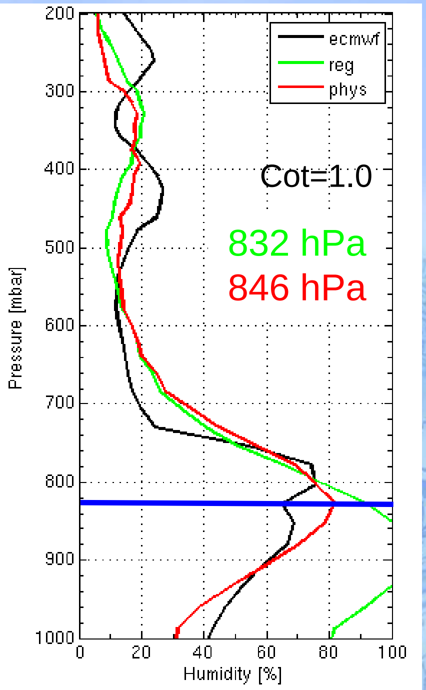


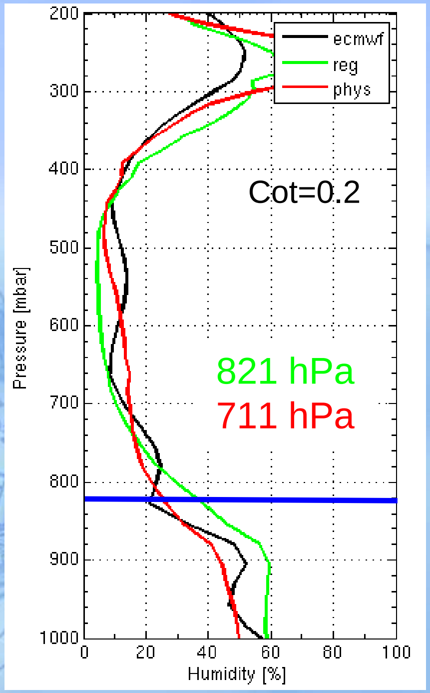

CPR Cloudmask orbit 01233, AIRS granule 008
CALIOP
MODIS
AIRS
Height [km]
Latitude [deg]
20
18
16
14
12
10
8
6
4
2
0
-74
-72
-70
-68
-66
-64
-62
-60
-58
-56
-54

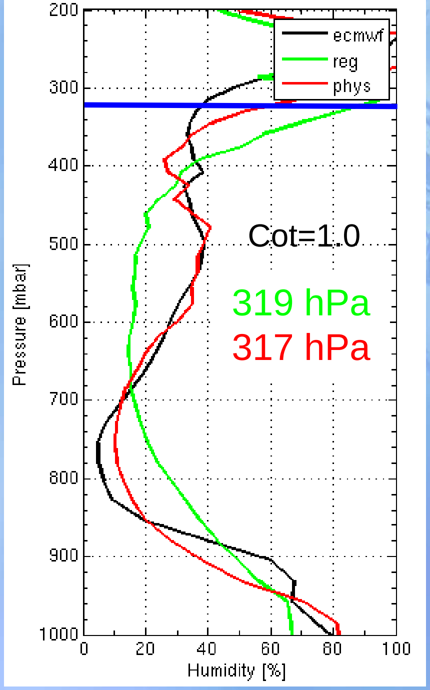

CALIOP (T00-03, T00-50) Total Attenuated Backscatter 532 nm, AIRS granule 008
CALIOP
MODIS
AIRS
Height [km]
Latitude [deg]
20
18
16
14
12
10
8
6
4
2
0
-74
-72
-70
-68
-66
-64
-62
-60
-58
-56
-54

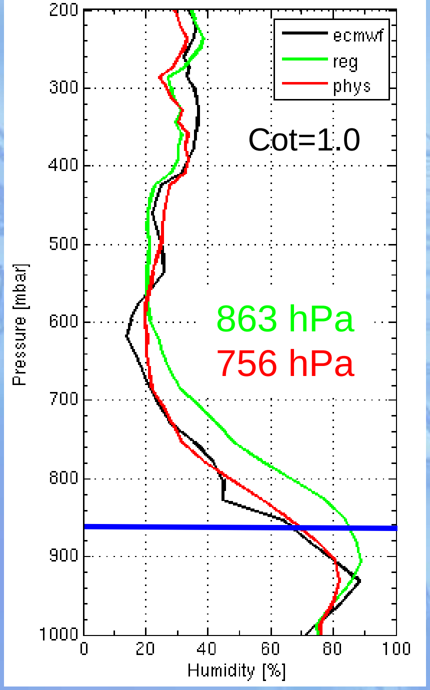
Examples of Relative Humidity RTV and ECMWF profiles

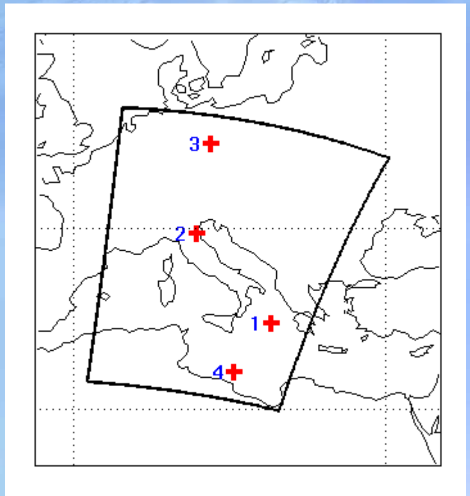
Selected profiles from AIRS G011, Sept-8, 2006.



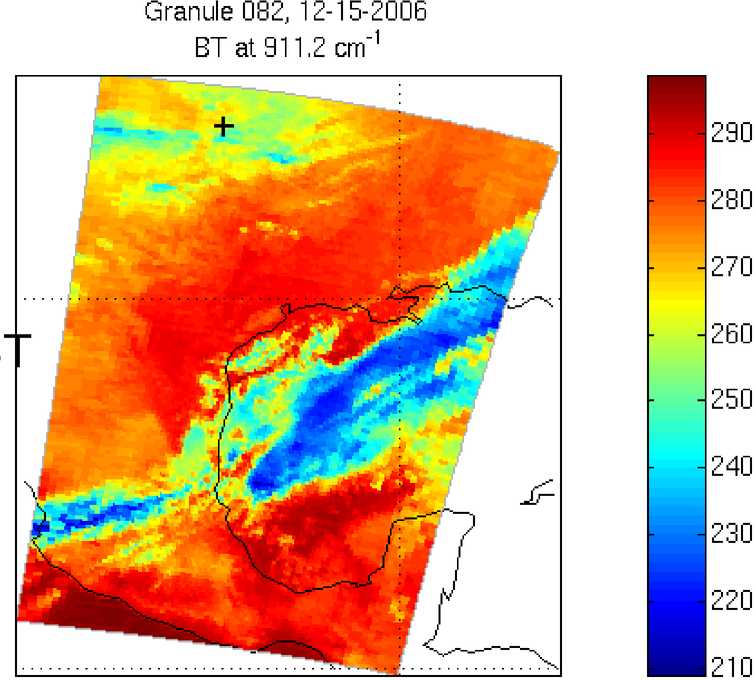




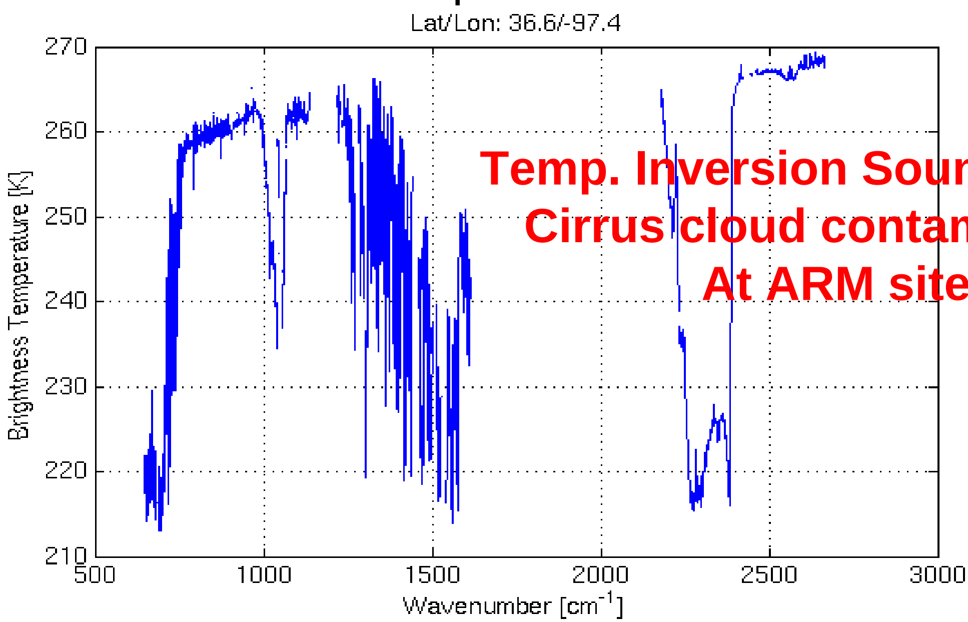


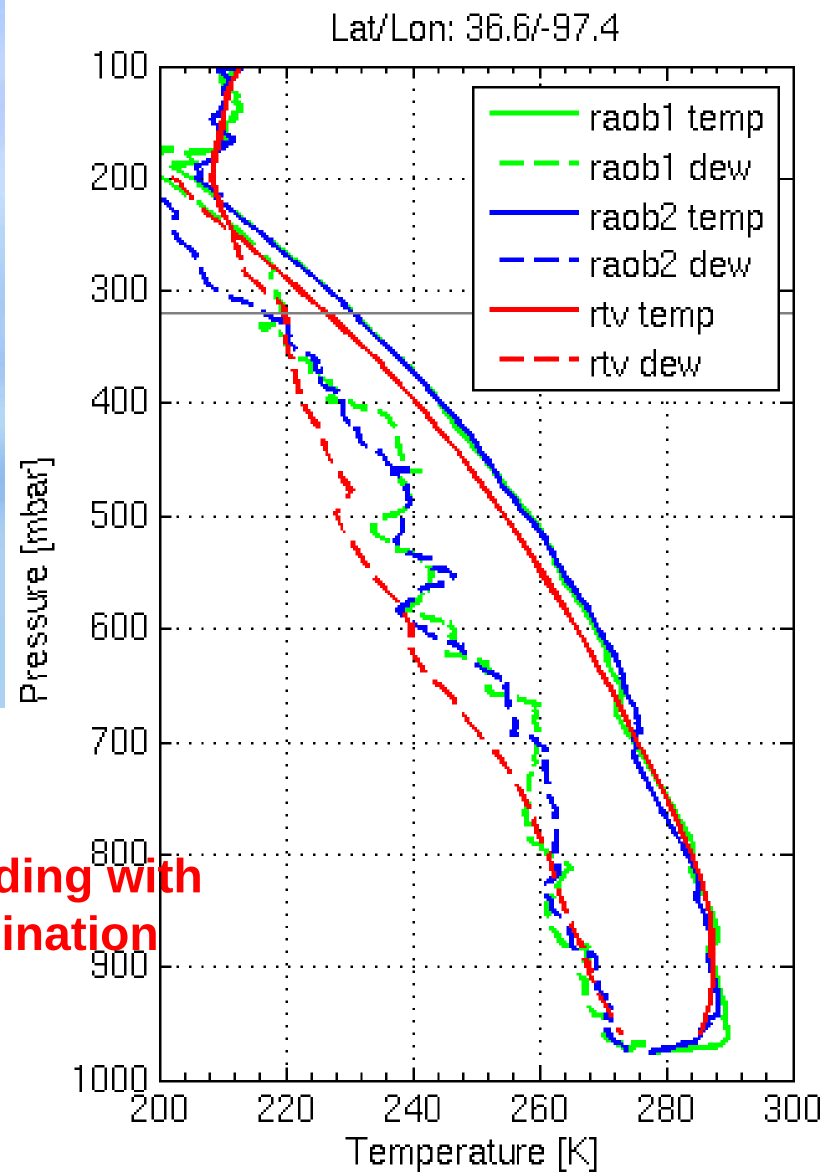


AIRS BT Image



AIRS BT Spectrum at ARM



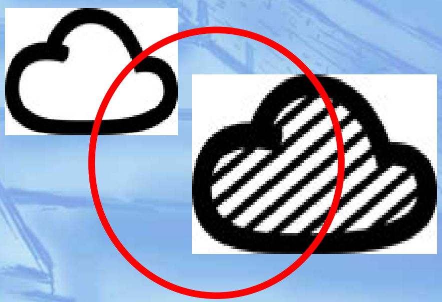


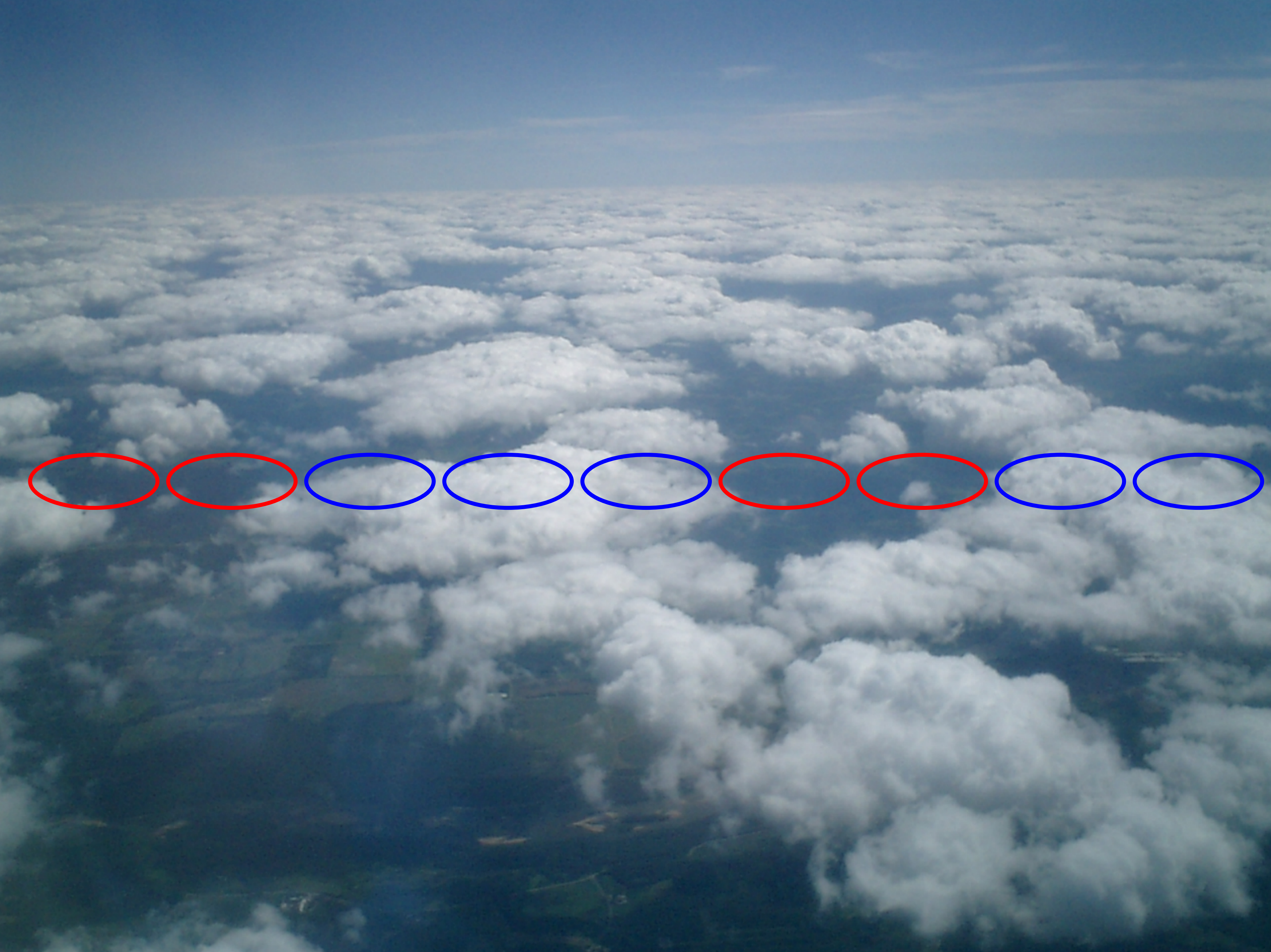
Temp. Inversion Sounding with Cirrus cloud contamination At ARM site

(UW/CIMSS)

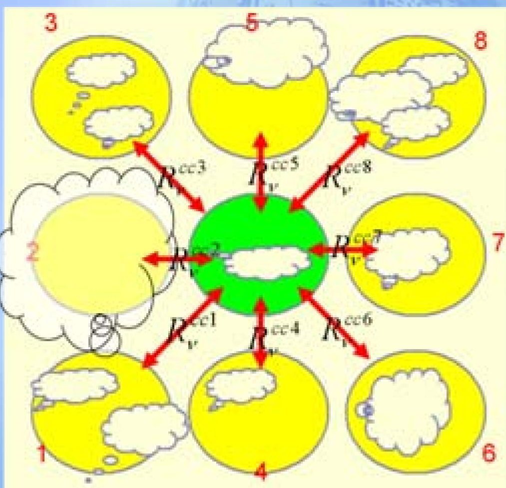
Synergistic use of imager/sounder for sounding performance improvement

- Advanced IR sounder has limited information BELOW clouds
- IR imager data has high spatial resolution, which give “clear holes” within partially cloudy sounder footprints
- Cloudy soundings can be improved through imager/sounder cloud-clearing, or imager/sounder direct sounding approach



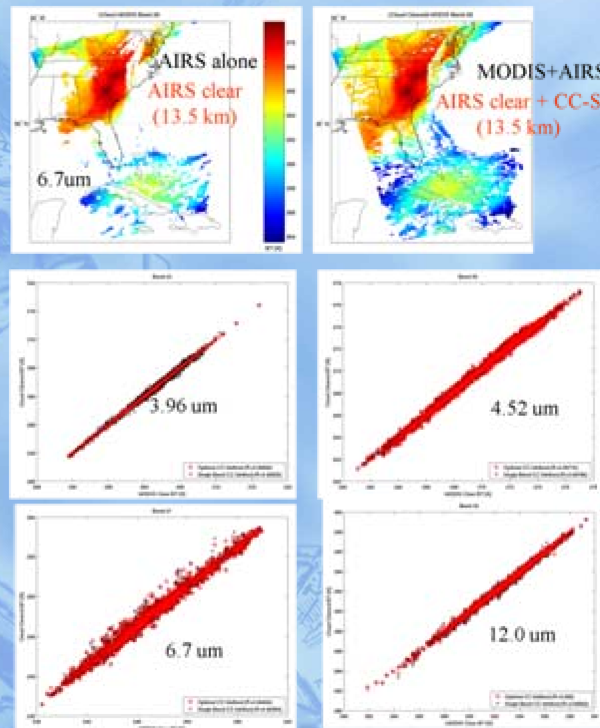


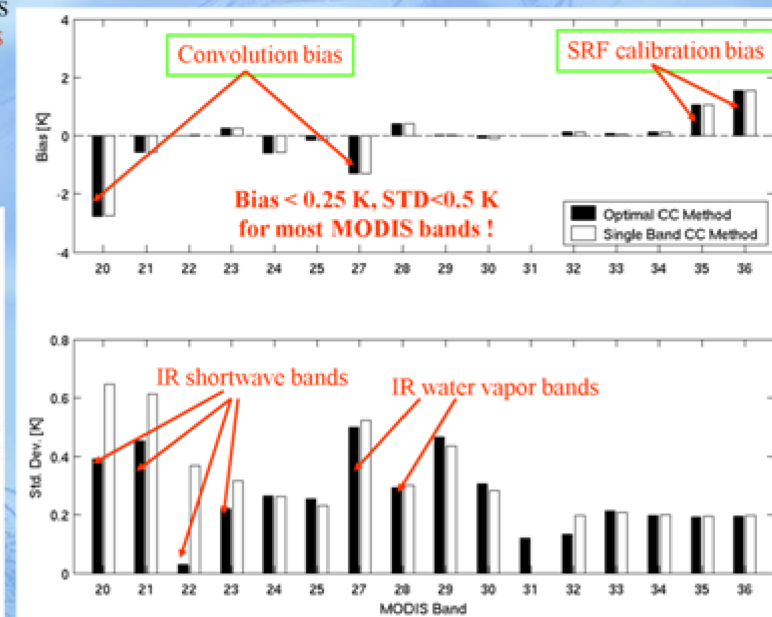
Cloud Clearing (Li *et al*., 2005)



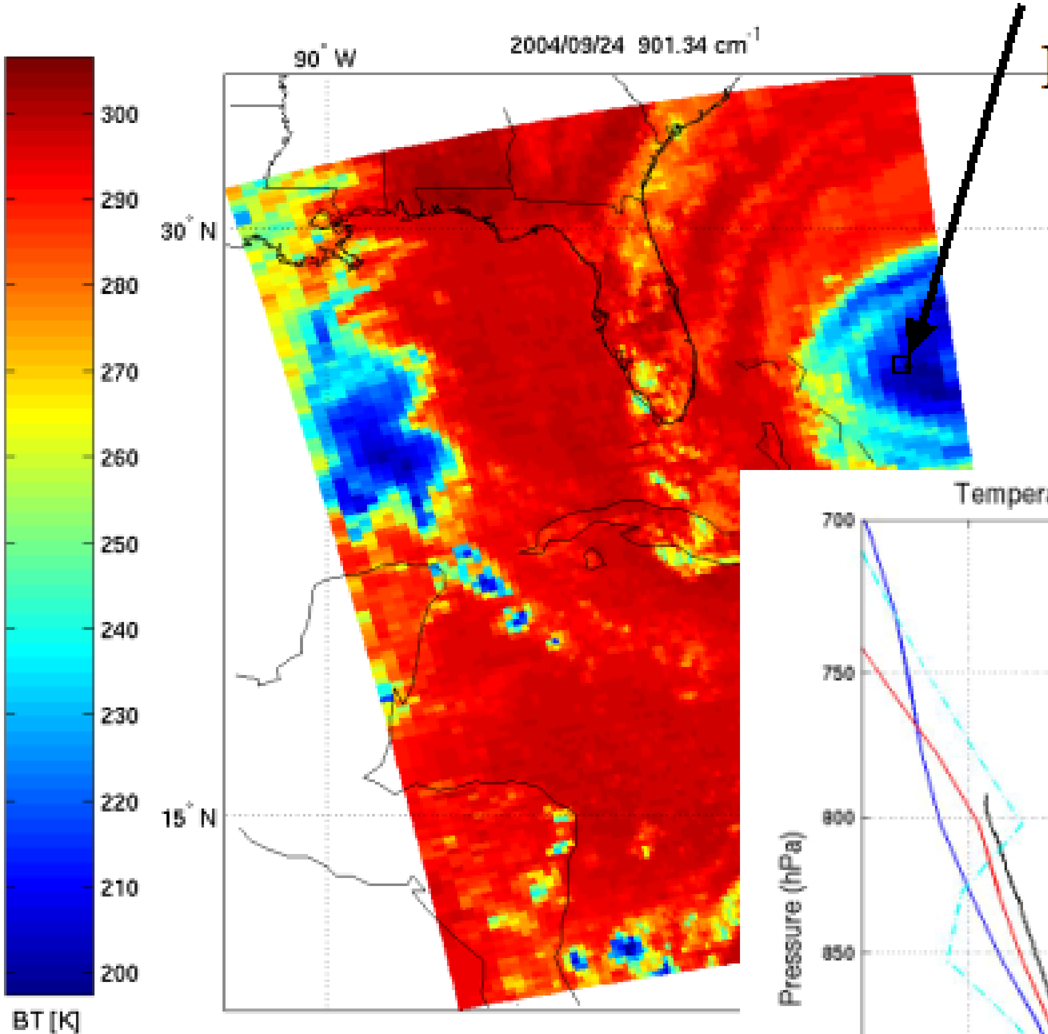
$$J(N^*) = \sum_i \frac{1}{\sigma_i}[(R^{clr}_{M_i} - f_i(R^{cc}_v)]^2$$

$$R^{cc}_v = \frac{R^1_v - R^2_v N^*}{1 - N^*}$$





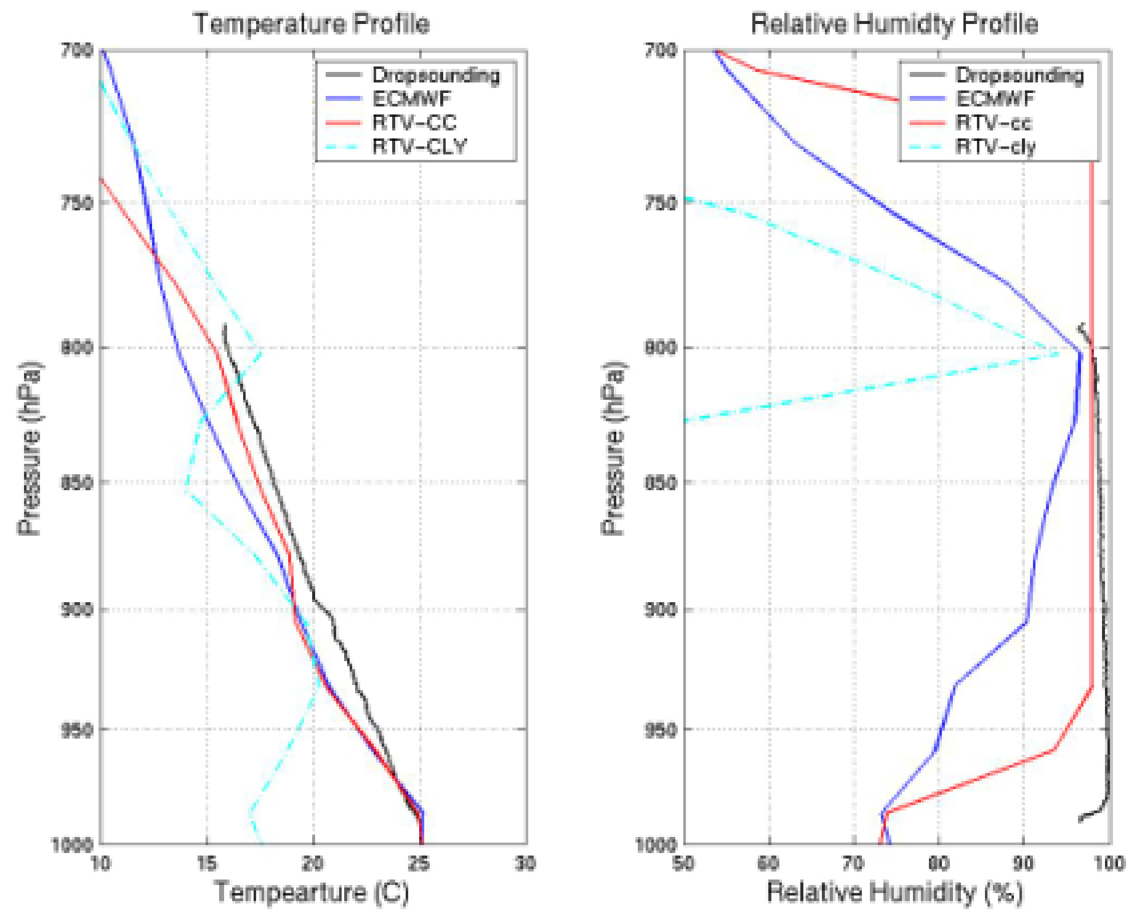
- Cloud clearing of hyperspectral radiance is dealing with “clear” scene.
- It may encounter with instrumental noise problem.



Dropsonde location

AIRS/ECMWF/Dropsonde comparison (Sept.24, 2004)

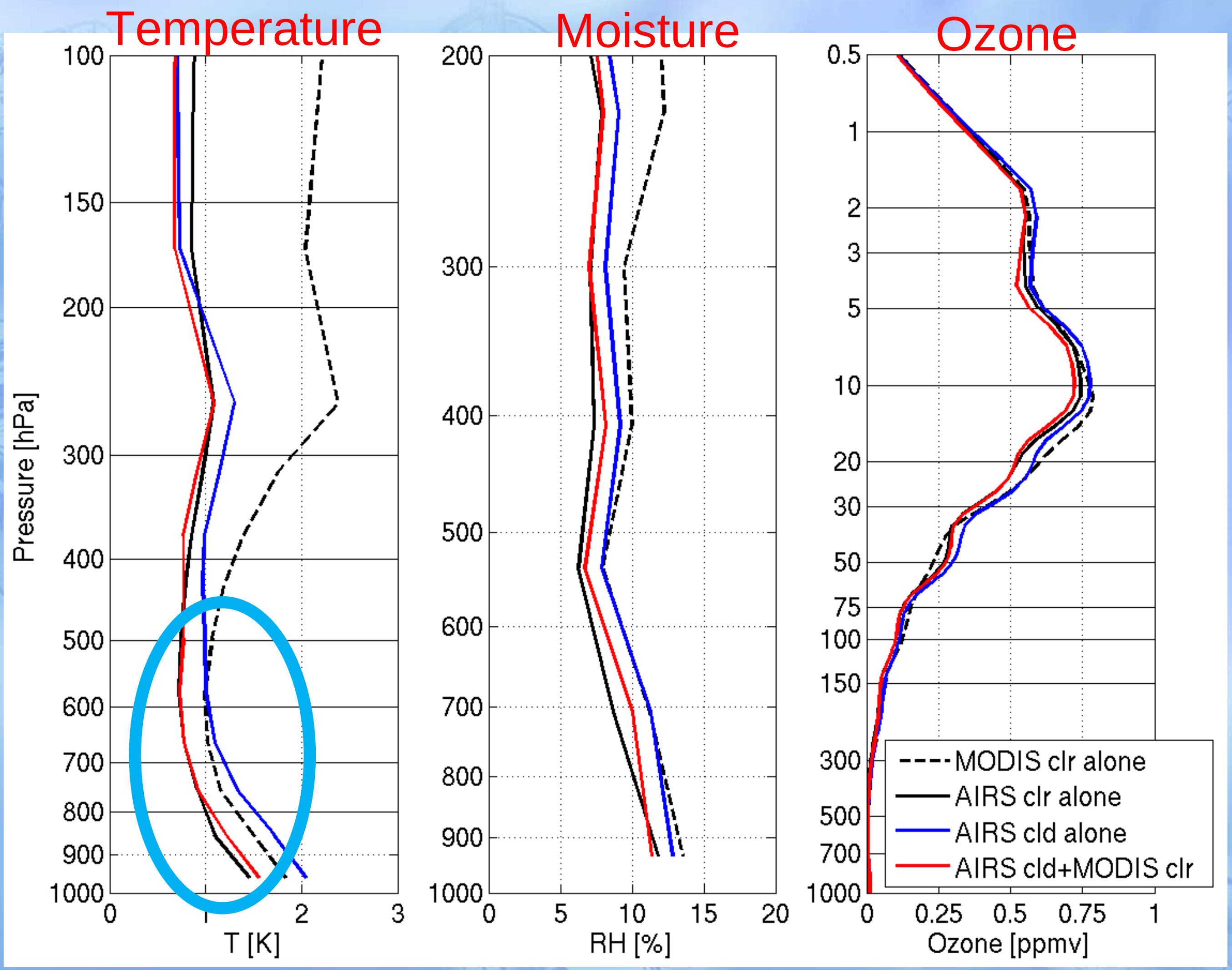
AIRS BT (11.7 um) image (granule 184)



Imager/Sounder CC Pros/Cons

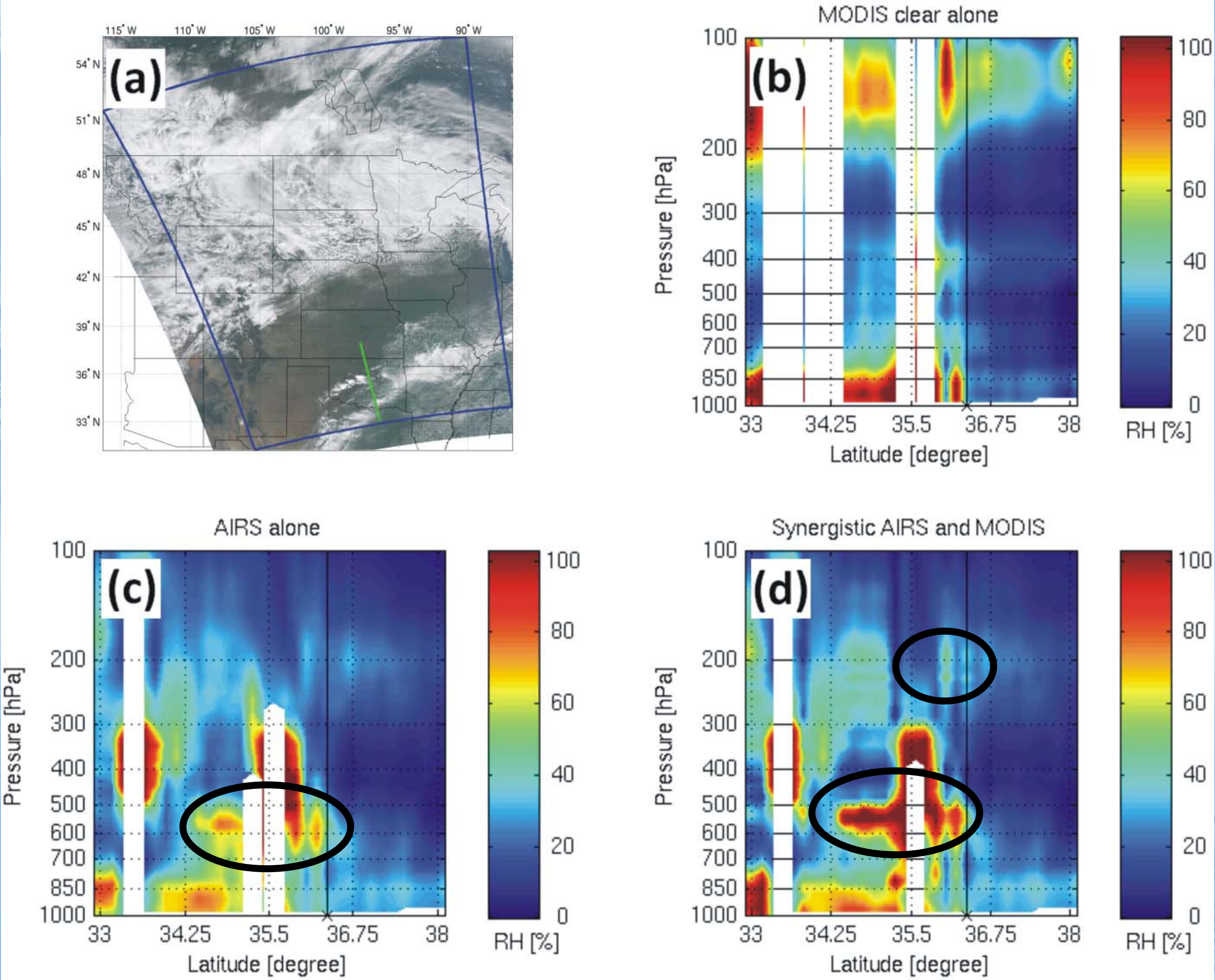
- Advantages
  - No cloudy RTM needed
- Disadvantages
  - Limited cloudy (uniform) situations
  - Noise amplification in cloud-cleared radiances

Imager/Sounder direct sounding - Retrieval Simulations



- With clear MODIS pixels information, RMSE is reduced in AIRS cloudy retrieval, especially in atmospheric boundary layer.

Case Study (1)
Granule 196, 09 May 2003



Summary & Conclusions (1/2)

- Handling surface IR emissivity is critical for the improved hyperspectral IR sounding retrieval, since suboptimal treatment of surface emissivity is not only negatively affecting the boundary layer sounding performance but it is also degrade profile in mid-tropospheric layers:
  - CIMSS has developed retrieval algorithm with improved initial emissivity (Seebor databases, et al.) and simultaneously retrieve emissivity spectrum (in P.C. domain) together with sounding profiles in clear skies.
  - In cloudy skies, the emissivity is fixed with the initial guess assigned from the database;

Summary & Conclusions – (2/2)

- IR alone cloudy sounding algorithm has been developed for simultaneous retrieval of cloud properties and soundings:
  - Future work will focus on the effective treatment of cloud parameterization especially those variables such as size, and optical thickness and phase.
- Synergistic use of sounder and imager measurements are demonstrated with limited case studies:
  - For now preprocessing of the co-registration between and the optimal use of the clear/cloudy sounding sub-pixels (imager IFVOs) are the road blocks.