Contributors

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Topics

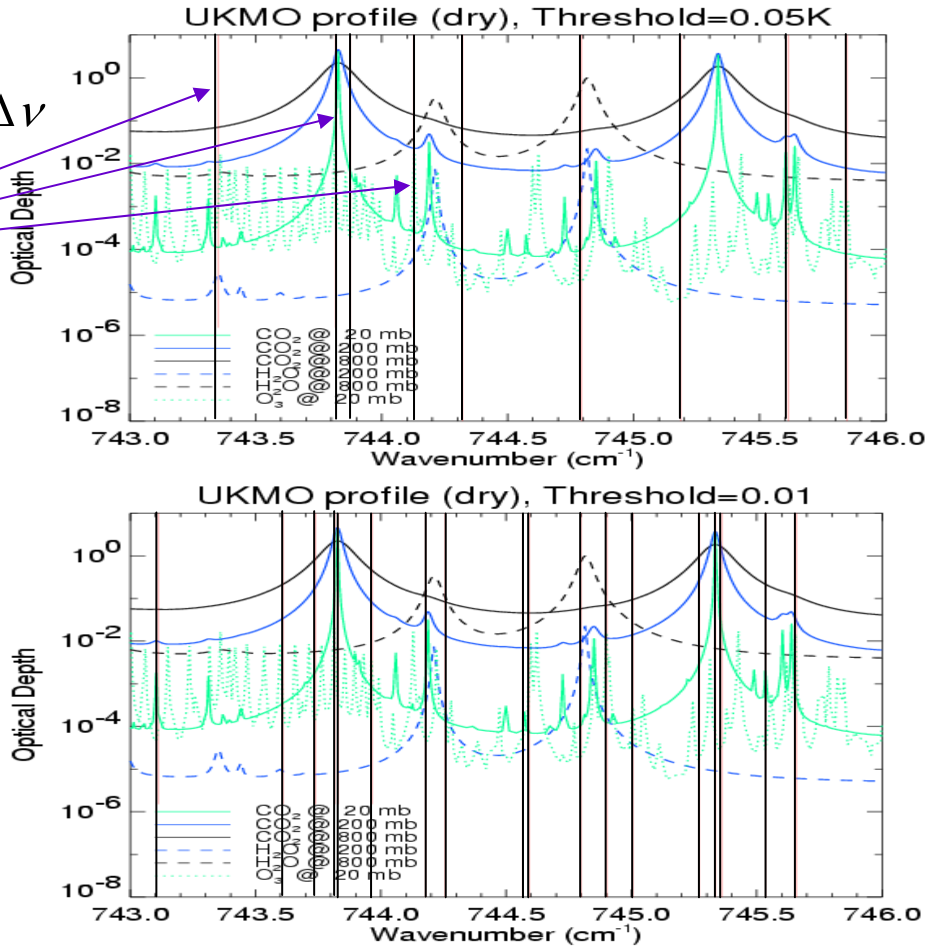
- OSS overview
  - Overview of the approach
  - Forward model
  - General attributes
- OSS/OPTRAN comparison
- Generalized training
  - Clear/cloudy training
  - Inversion issue
- Treatment of multiple scattering
  - Validation against CHARTS
  - Application to AIRS
- Summary/future work

Overview of the OSS approach

- OSS method (Moncet *et al.* 2003, 2001) models the channel radiance as

$$\overline{R} = \int_{\Delta\nu} \phi(\nu) R(\nu)\, d\nu \cong \sum_{i=1}^{N} w_i R(\nu_i); \qquad \nu_i \in \Delta\nu$$

- Wavenumber ***n_i*** (nodes) and weights ***w_i*** are determined by fitting “exact” calculations (from line-by-line model) for globally representative set of atmospheres (training set)
- Radiance training is fast and provides mechanism for directly including slowly varying functions (e.g. Planck, surface emissivity) in the selection process



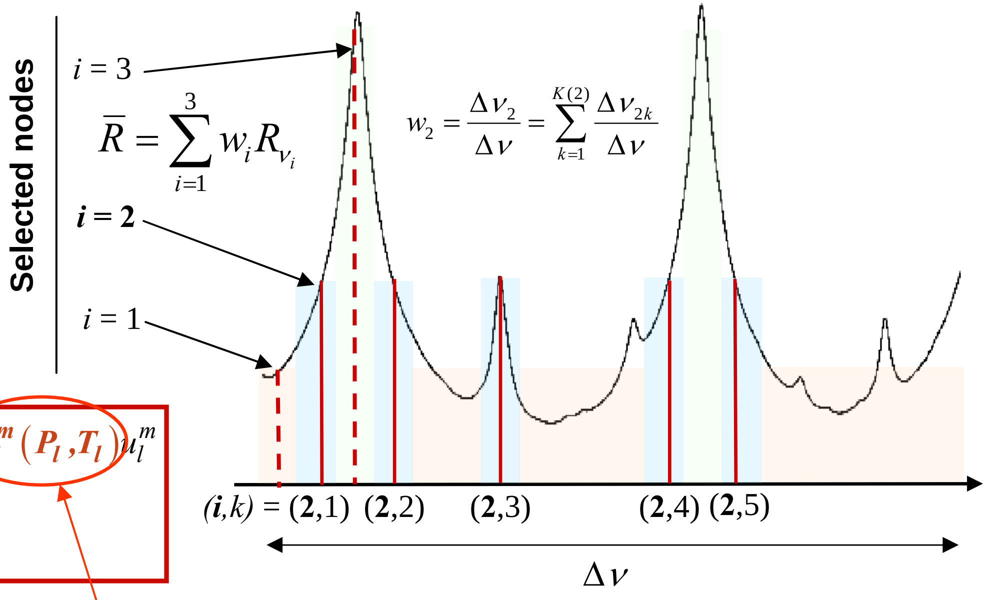
Relationship between OSS and ESFT/correlated-*k* methods

ESFT (Wiscombe and Evans, 1977) for single layer, single absorber case:

$$\bar{\tau}(u) = \int_{\Delta\nu} e^{-k_\nu u} d\nu \approx \sum w_i e^{-k_i u}$$

Extension to multiple absorbers along inhomogeneous path (e.g. Armbruster and Fisher, 1996)

$$\bar{\tau}(p) = \int_{\Delta\nu} \tau_\nu(p) d\nu \approx \sum w_i e^{-\sum_l \sum_m k_i^m(P_l,T_l) u_l^m}$$



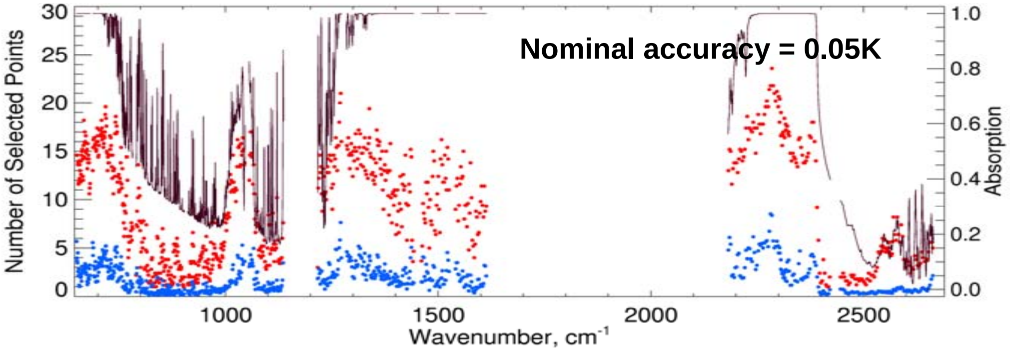
OSS solution:

$$\bar{\tau}(p) \approx \sum w_i e^{-\sum_l \sum_m k_{\nu_i}^m(P_l,T_l) u_l}$$

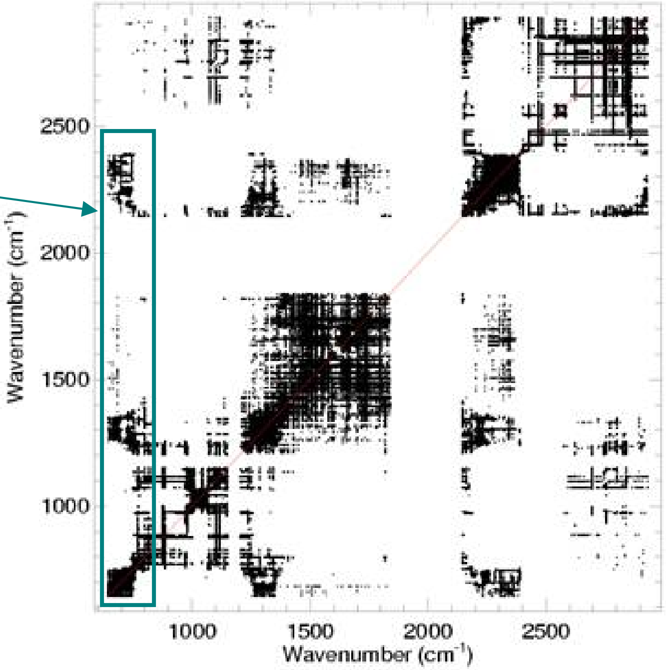
Extension of ESFT to inhomogeneous atmospheres with multiple absorbers reduces the problem to a single (wavenumber) dimension and ensures that the solution is physical

Localized versus non-localized training

- Localized training (***reference***) operates on individual channels, one at a time – node redundancy due to overlapping ILS
  - AIRS (2378 channels):
    - Average # nodes per channel: ~9 nodes/channel
    - Total number of nodes/number of channel (i.e. no redundancy) = 1.9 nodes/channel

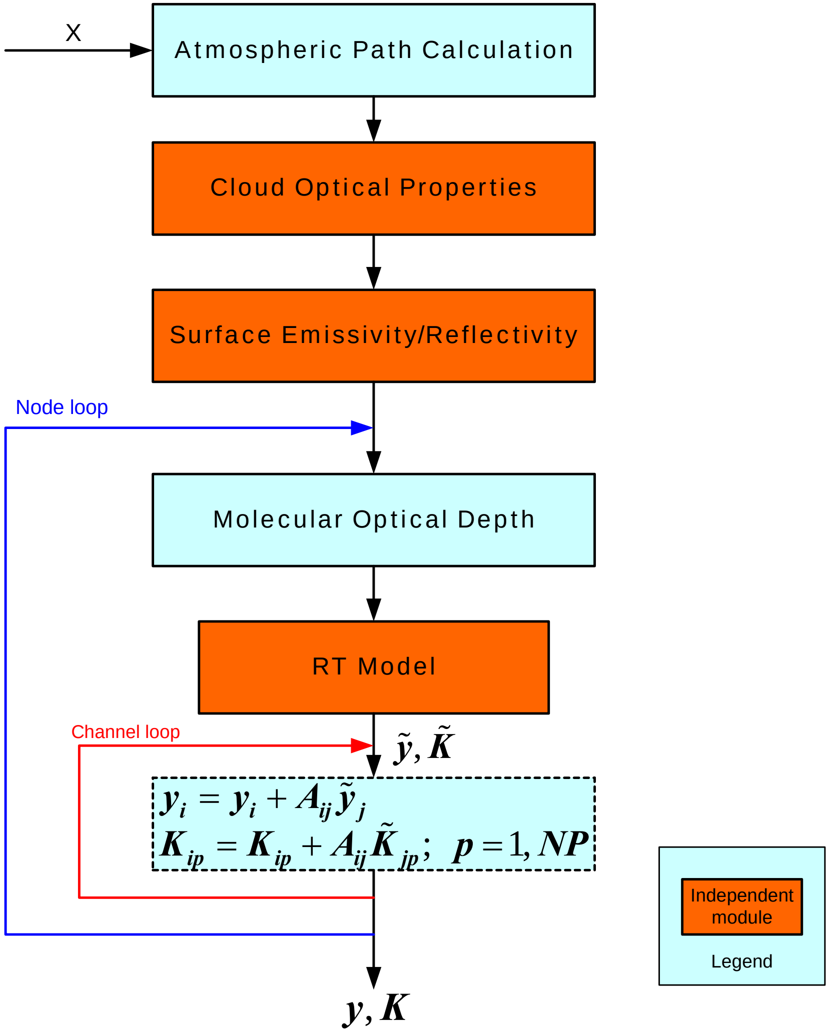


- Non-localized training operates on groups of *N* channels (up to full channel set)
  - Exploits node-to-node correlation to minimize total number of nodes across a spectral domain (regression!!!)
    - Results in significant increase in number of points in any given channel increases
  - Critical for MODTRAN (range 0-50,000 cm^{-1})



OSS Forward Model

- RTM structure
  - Main loop is the node loop
  - Internal channel loop to update channel radiance and Jacobians
  - Similar structure adopted for CRTM
- LUT of *kabs* stored for all relevant molecules as a function of temperature
  - Self broadening included for water vapor
  - Maximum brightness temperature error with current LUT < 0.05K in infrared and <~0.01K in microwave
- Use simple monochromatic RT model (clear or scattering)
  - Jacobians (required for retrieval applications) are straightforward in the clear-sky (e.g. CrIS ATBD)



Trace gases

- RT model designed to handle any number of variable trace species
- Adding a new variable species requires no change in OSS parameterization
  - No change in RTM required
  - Only need to include variability in training (number of nodes may increase as a result)
- # of variable trace gases and molecule type specified on node-by-node basis *(set by the user at run time)*
  - Average number of trace gases absorbing at any given frequency << total number of absorbing species in the atmosphere
  - Computationally efficient and minimizes memory requirements
  - Inexpensive Jacobian computation: $\frac{\partial \boldsymbol{y}}{\partial \boldsymbol{u}_l^m} = \frac{\partial \boldsymbol{y}}{\partial \tau_{abs,l}^0} \boldsymbol{k}_l^m$

Optimal Spectral Sampling (OSS) method

- OSS absorption parameterization leads to ***fast*** and ***numerically accurate*** RT modeling:
  - OSS-based RT model can approach line-by-line calculations arbitrarily closely
    - Adjustable numerical accuracy:
      - Possibility of trade off between accuracy and speed
  - Unsupervised training
    - No empirical adjustment: cuts significantly on cost of testing approximations and validating model
  - Provides flexible handling of (variable) trace molecular species
    - Designed to handle large number of variable trace species w/o any change to model – low impact on computational cost
    - Selection of variable trace gases at run time
  - Memory requirements do not change whether we are dealing with one or more instruments
    - Execution speed primarily driven by total spectral coverage and maximum spectral resolution (not by number of instruments)
  - Leads to accurate handling of multiple scattering (cloudy radiance assimilation)

Ongoing OSS efforts

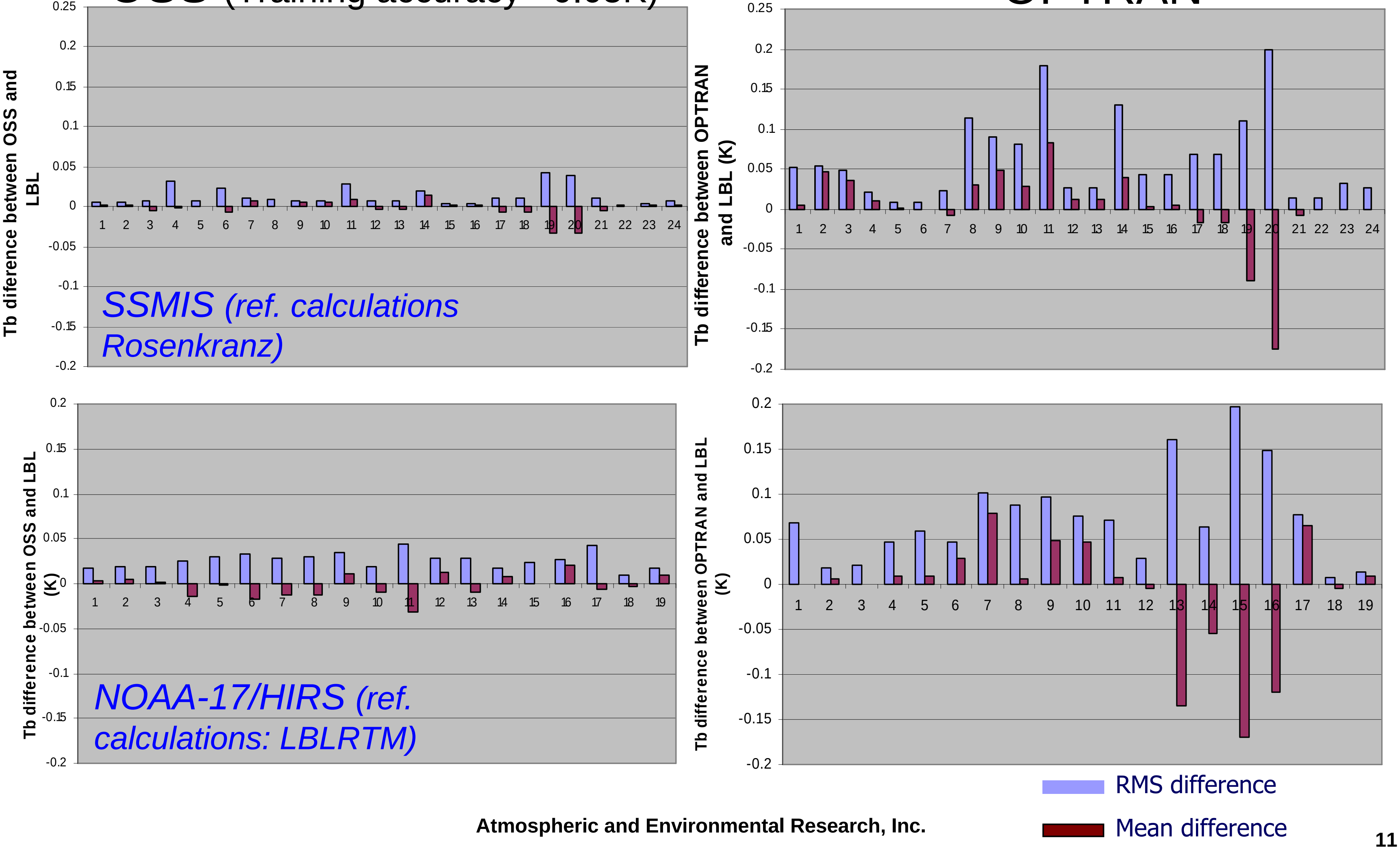
- Used in NPOESS/ CrIS, CMIS and OMPS (IR) retrieval algorithms
- JCSDA CRTM
  - Compared with OPTRAN at NOAA for AMSU, SSMIS, HIRS-3, GOES imager/sounder, AIRS
    - Accuracy and timing
  - Beta version of OSS-based CRTM about to be tested at NCEP to evaluate impact on forecast
  - Other comparison results from ITSC comparison (Garand et al. 2001), and recent ITSC AIRS comparison (Saunders et al., 2005)
- Currently working on integrating into MODTRAN (AFRL- sponsored effort)
  - Wide array of users and applications
    - Same method should cover it all
- NASA's Mars Fundamental Research Program: OSS forward model has been developed for the Thermal Emission Spectrometer (TES) onboard the Mars Global Surveyor spacecraft (Christensen et al. 2001).

JCSDA OPTRAN/OSS (localized training) comparison

OPTRAN/OSS comparison: SSMIS & HIRS
(from NOAA, 2005)

OSS (Training accuracy =0.05K)

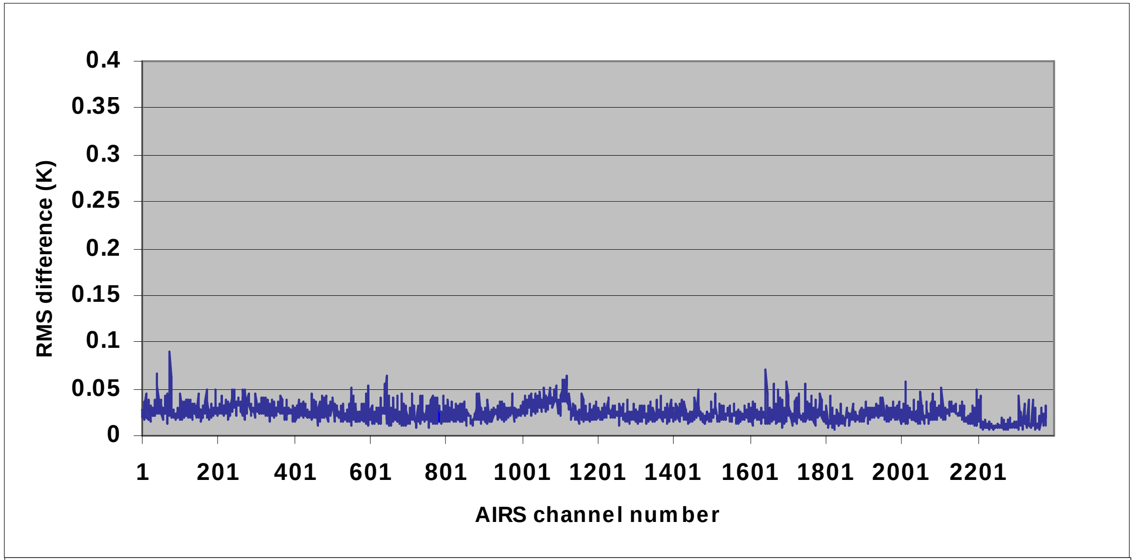
OPTRAN



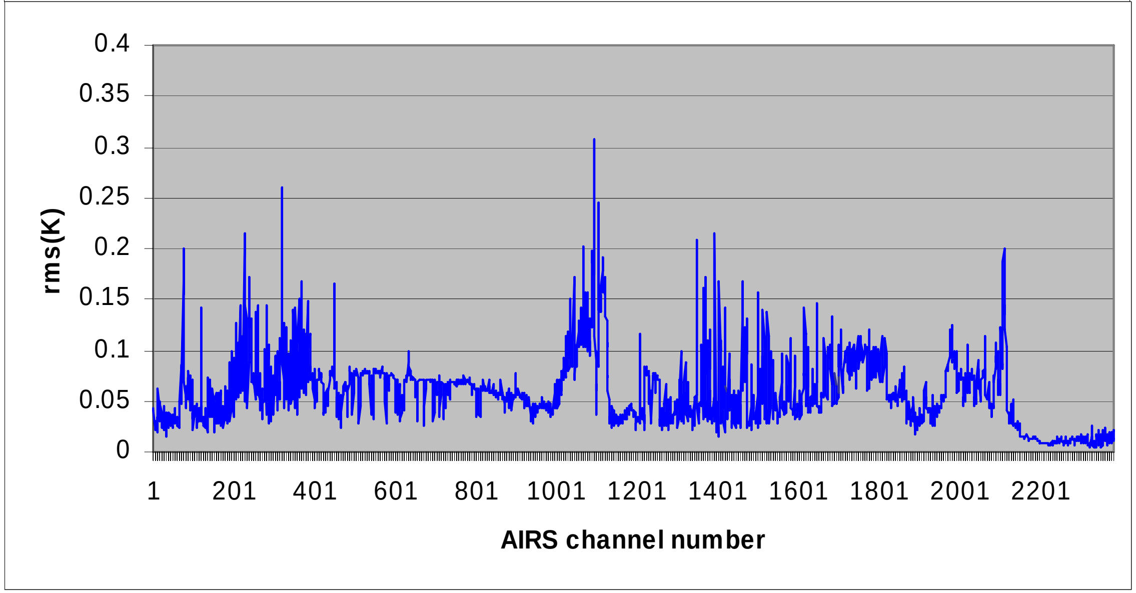
SSMIS (ref. calculations Rosenkranz)

NOAA-17/HIRS (ref. calculations: LBLRTM)

OPTRAN/OSS comparison: AIRS
(from NOAA, 2005)



OSS
Trained with ECMWF set
Tested with UMBC set
(Training accuracy = 0.05K)



OPTRAN
Trained with UMBC set
Tested with ECMWF set

OPTRAN/OSS Comparison: Computation & Memory Efficiency (from NOAA, 2005)

Time needed to process 48 profiles with 7 observation angles (336 profiles)

	OPTRAN-V7 Forward, Jacobian + Forward	OPTRAN-comp Forward, Jacobian + Forward	OSS Jacobian + Forward
AIRS	7m20s, **22m36s**	10m33s, **35m12s**	**3m10s**
HIRS	4s, 13s	5s, 17s	9s

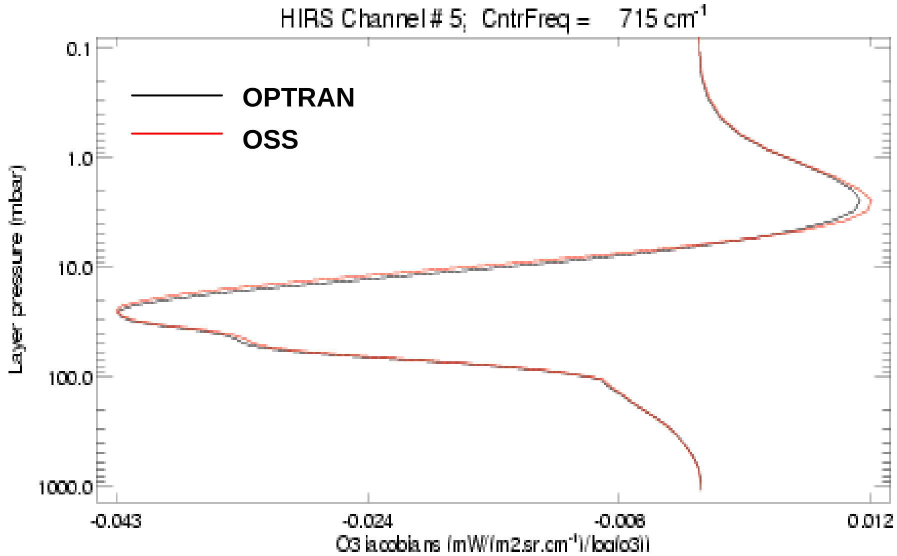
Memory resource required (Megabytes)

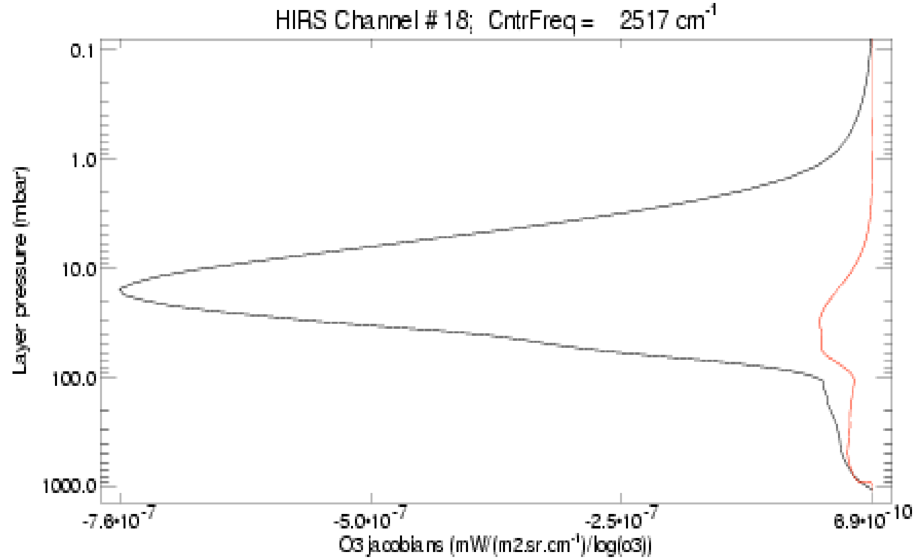
	OPTRAN-V7 single, double precision	OPTRAN-comp double precision	OSS
AIRS	33, 66	5	97**
HIRS	0.26, 0.5	0.04	4

**With OSS: Based on 0.05K accuracy -
No increase in size when adding other IR instruments

Jacobians

- OSS Jacobian accuracy commensurate with model accuracy
  - Unlike OPTRAN (trained to fit transmittances for individual absorbers), OSS fits total transmittance/radiance (OPTRAN equivalent training obtained by zeroing out major absorber concentration)
  - Jacobians for weakly absorbing constituents not as accurate when impact on radiances of (global) variability in concentration is less than model accuracy

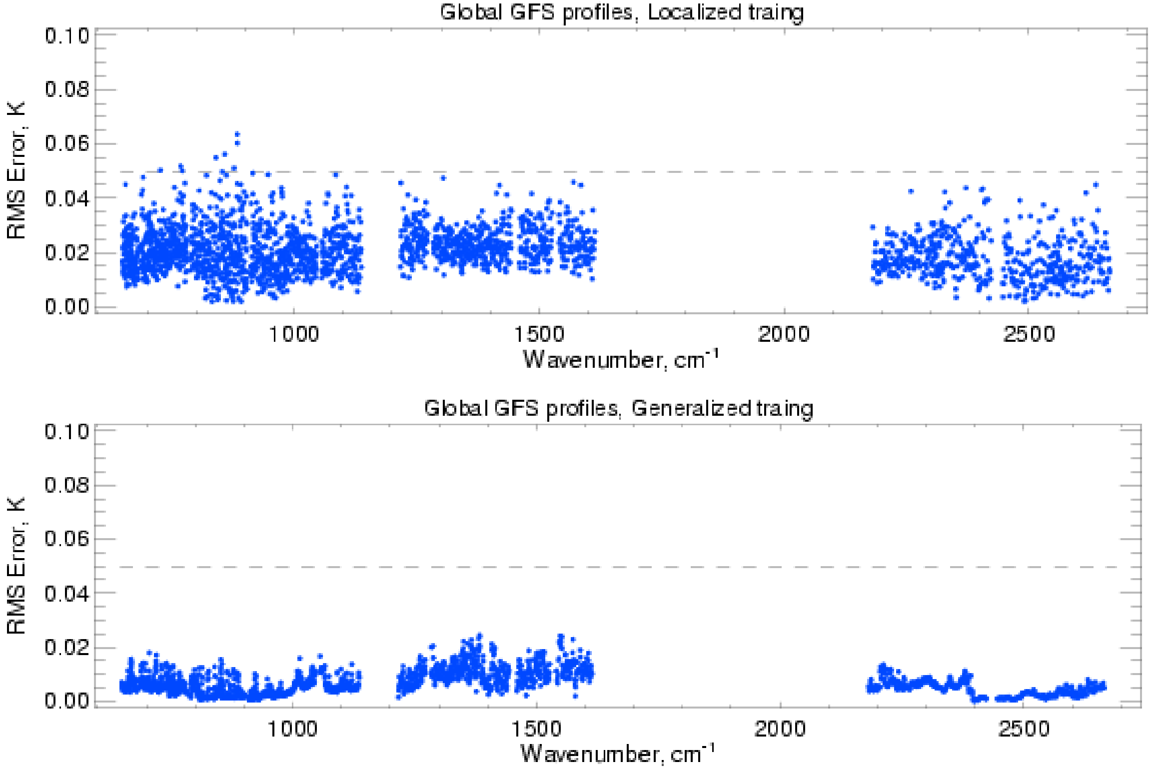

HIRS Channel # 5; CntrFreq = 715 cm^{-1}


HIRS Channel # 18; CntrFreq = 2517 cm^{-1}

Generalized training

Performance example (AIRS)

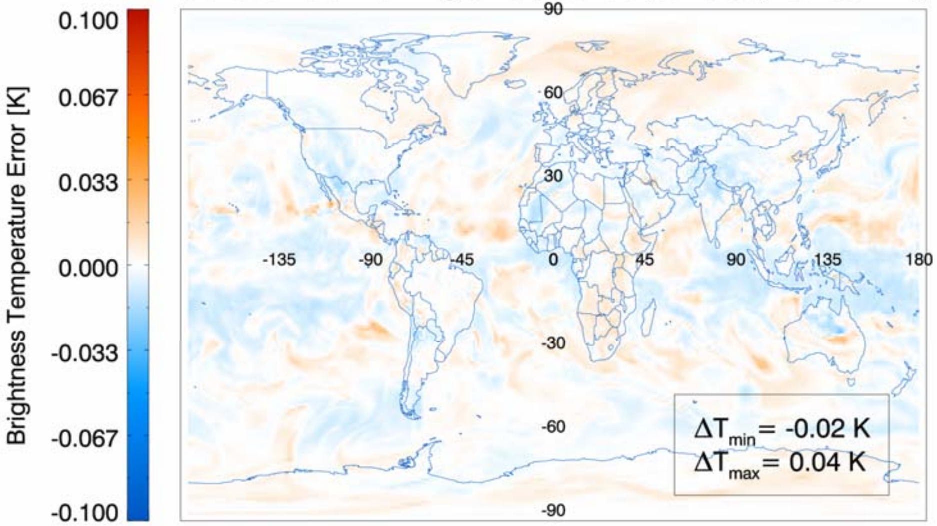
- Localized training (0.05K accuracy):
  - ~2nodes /channel
  - ~5000 monochromatic calculations for full AIRS channel set
- Generalized training:
  - ~0.1 node/channel
  - Reduces number of monochromatic calculations to ~250



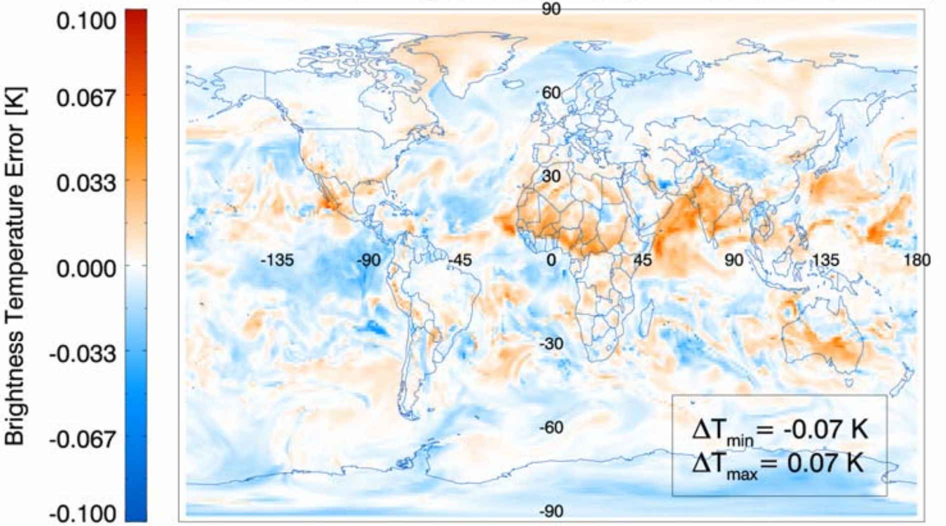
Speed gain ~ 20 compared to localized training for AIRS

Examples of error spatial distribution

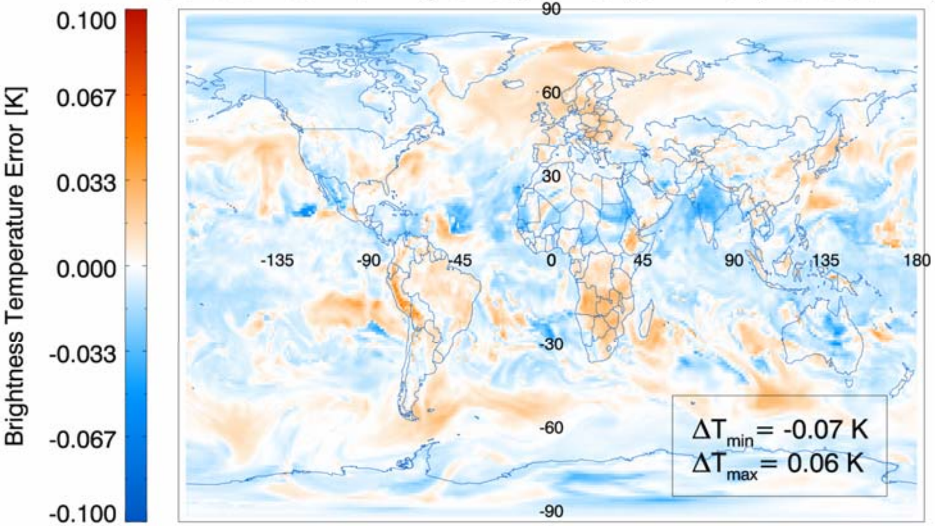
Generalized Training GFS profiles (CH 305, 737.3cm $^{-1}$)



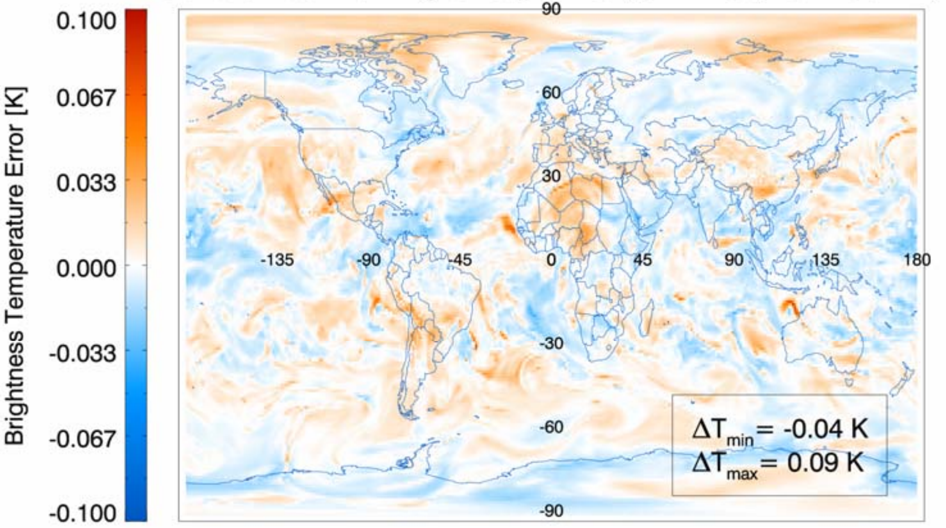
Generalized Training GFS profiles (CH 1090, 1040.1cm $^{-1}$)



Generalized Training GFS profiles (CH 1437, 1323.8cm $^{-1}$)



Generalized Training GFS profiles (CH 1766, 1344.3cm $^{-1}$)



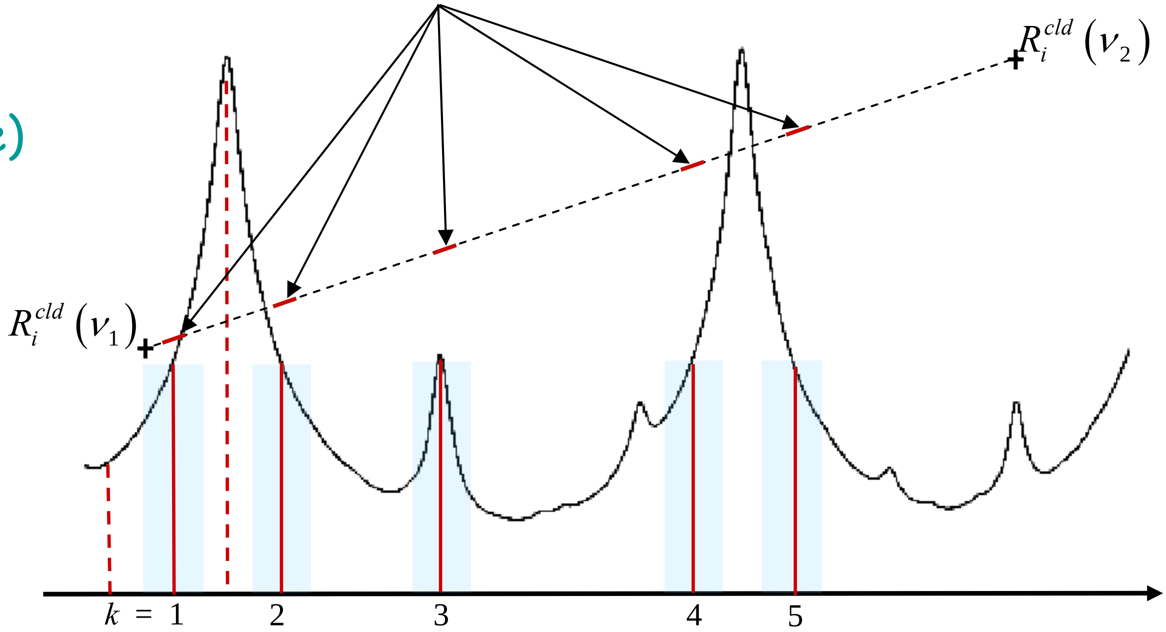
Non-localized cloudy training

- Must include slowly varying cloud/aerosol optical properties in training
  - Over wide bands: training can be done by using a database of cloud/aerosol optical properties
  - More general training obtained by breaking spectrum in intervals of the order of 10 cm^{-1} in width (impact of variations in cloud/aerosol properties on radiances is quasi-linear) and by performing independent training for each interval
    - lower computational gain but increased robustness
- Direct cloudy radiance training not recommended !
  - Clouds tend to mask molecular structure which makes training easier
  - If "recipe" for mixture of clear and cloudy atmospheres in direct training not right: clear-sky performance degrades

Single/multi-channel cloudy training over wide spectral domains

- Alternate two-step training preserves clear-sky solution
  - **First step:** normal clear-sky (transmittance/radiance) training to model molecular absorption
  - **Second step:** duplicate + redistribute nodes across spectral domain and recompute weights to incorporate slowly varying functions into the model

$$R_i^{cld}(\nu_k) = a_{ik} R_i^{cld}(\nu_1) + (1 - a_{ik}) R_i^{cld}(\nu_2)$$



$$\bar{R} = \sum_i w_i \sum_k \left(a_{ik} R_i(\nu_1) + (1 - a_{ik}) R_i(\nu_2) \right) \frac{\Delta\nu_{ik}}{\Delta\nu_i} = \sum_i w_i' R_i(\nu_1) + (w_i - w_i') R_i(\nu_2)$$

Robust, physical approach for including slowly varying functions (e.g. cloud optical properties, surface emissivity) into OSS formalism

Cloudy training preserves clear-sky solution

Inversion

- Variational retrieval methods:
  - *Average channel uses ~150 nodes*
  - *Mapping Jacobians from node to channel space partially offsets speed gain*
- Alternatives:
  - *A. PC (reduces first dimension of matrix A)*
  - *B. Operate directly in node space*

$$\mathbf{y}^{\mathbf{m}} = \mathbf{A}\tilde{\mathbf{y}}^{\mathbf{m}} \rightarrow \hat{\tilde{\mathbf{y}}}^{\mathbf{m}} = \mathbf{H}\mathbf{y}^{\mathbf{m}}$$

- ○ Avoids Jacobians transformation all together and reduce K-matrix size (inversion speed up)
  - for AIRS: 2378 channels -> 250 nodes

$$\delta x_{n+1} = \left(\mathbf{K}_{\mathbf{n}}^{\mathbf{T}}\mathbf{S}_{\boldsymbol{\varepsilon}}^{\mathbf{-1}}\mathbf{K}_{\mathbf{n}} + \mathbf{S}_{\mathbf{x}}^{\mathbf{-1}}\right)\mathbf{K}_{\mathbf{n}}^{\mathbf{T}}\mathbf{S}_{\boldsymbol{\varepsilon}}^{\mathbf{-1}}\left[\left(y_n - y^m\right) + \mathbf{K}_{\mathbf{n}}\delta x_n\right],$$

where,

$$\mathbf{y} = \mathbf{A}\tilde{\mathbf{y}} \text{ and}$$

$$\mathbf{K} = \mathbf{A}\tilde{\mathbf{K}}$$

$$\tilde{\mathbf{y}}^{\mathbf{m}} = \left(\mathbf{A}^{\mathbf{T}}\mathbf{S}_{\boldsymbol{\varepsilon}}^{\mathbf{-1}}\mathbf{A}\right)^{\mathbf{-1}}\mathbf{A}\mathbf{S}_{\boldsymbol{\varepsilon}}^{\mathbf{-1}}\mathbf{y}^{\mathbf{m}}$$

$$\tilde{\mathbf{S}}_{\boldsymbol{\varepsilon}}^{\mathbf{-1}} = \mathbf{A}^{\mathbf{T}}\mathbf{S}_{\boldsymbol{\varepsilon}}^{\mathbf{-1}}\mathbf{A}$$

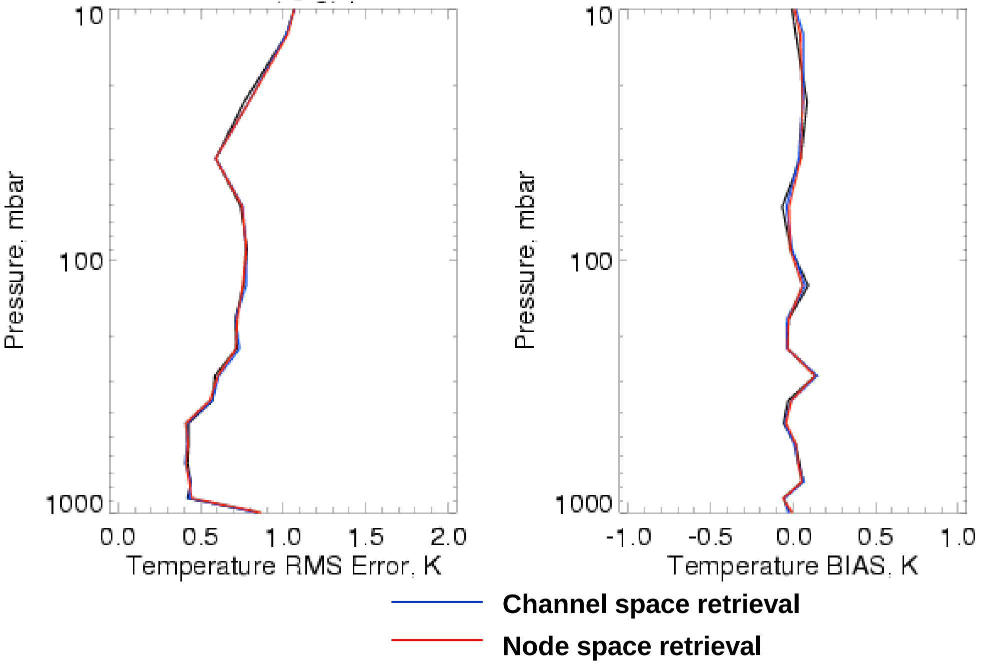
$$\boldsymbol{\delta}\mathbf{x}_{\mathbf{n+1}} = \left(\tilde{\mathbf{K}}_{\mathbf{n}}^{\mathbf{T}}\tilde{\mathbf{S}}_{\boldsymbol{\varepsilon}}^{\mathbf{-1}}\tilde{\mathbf{K}}_{\mathbf{n}} + \mathbf{S}_{\mathbf{x}}^{\mathbf{-1}}\right)\tilde{\mathbf{K}}_{\mathbf{n}}^{\mathbf{T}}\tilde{\mathbf{S}}_{\boldsymbol{\varepsilon}}^{\mathbf{-1}}\left[\left(\tilde{\mathbf{y}}_{\mathbf{n}} - \tilde{\mathbf{y}}^{\mathbf{m}}\right) + \tilde{\mathbf{K}}_{\mathbf{n}}\boldsymbol{\delta}\mathbf{x}_{\mathbf{n}}\right]^{**}$$

****Equivalent to**

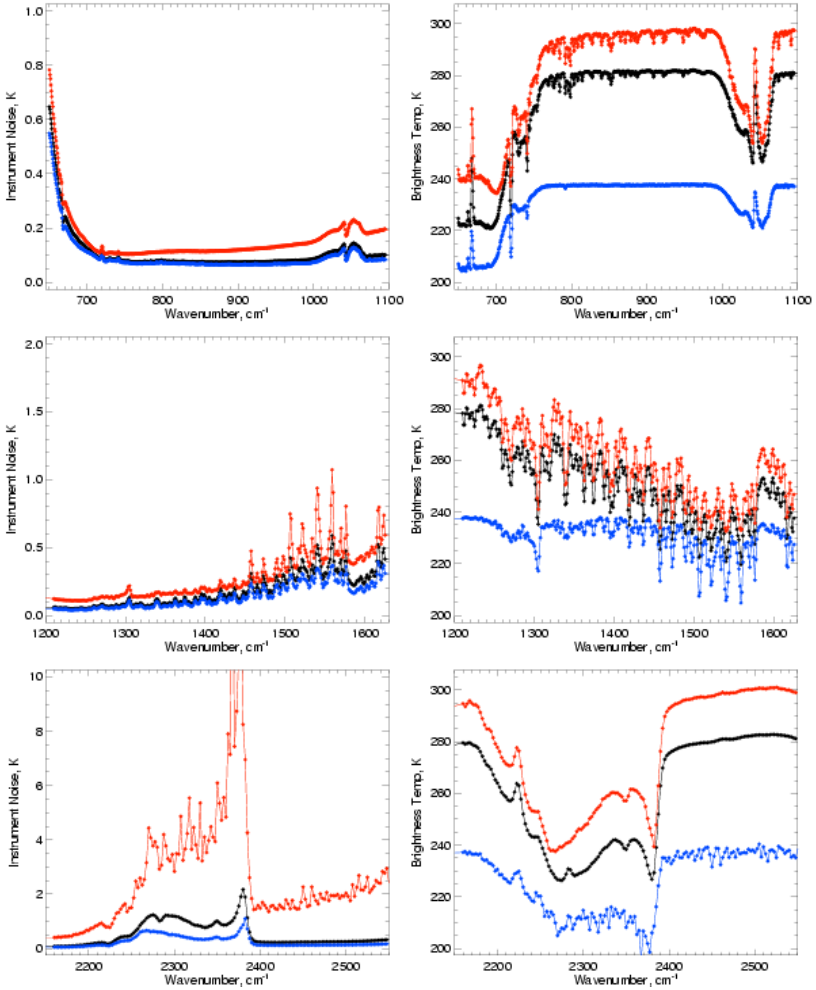
$$\boldsymbol{\delta}\mathbf{x}_{\mathbf{n+1}} = \left(\mathbf{K}_{\mathbf{n}}^{\mathbf{T}}\mathbf{S}_{\boldsymbol{\varepsilon}}^{\mathbf{-1}}\mathbf{K}_{\mathbf{n}} + \mathbf{S}_{\mathbf{x}}^{\mathbf{-1}}\right)\mathbf{K}_{\mathbf{n}}^{\mathbf{T}}\mathbf{S}_{\boldsymbol{\varepsilon}}^{\mathbf{-1}}\left[\left(\mathbf{A}\mathbf{H}\mathbf{y}_{\mathbf{n}} - \tilde{\mathbf{y}}^{\mathbf{m}}\right) + \mathbf{K}_{\mathbf{n}}\boldsymbol{\delta}\mathbf{x}_{\mathbf{n}}\right]$$

Inversion (cont.)

Retrieval performance – constant noise



Example of IR sounder noise characteristics (clear sky)

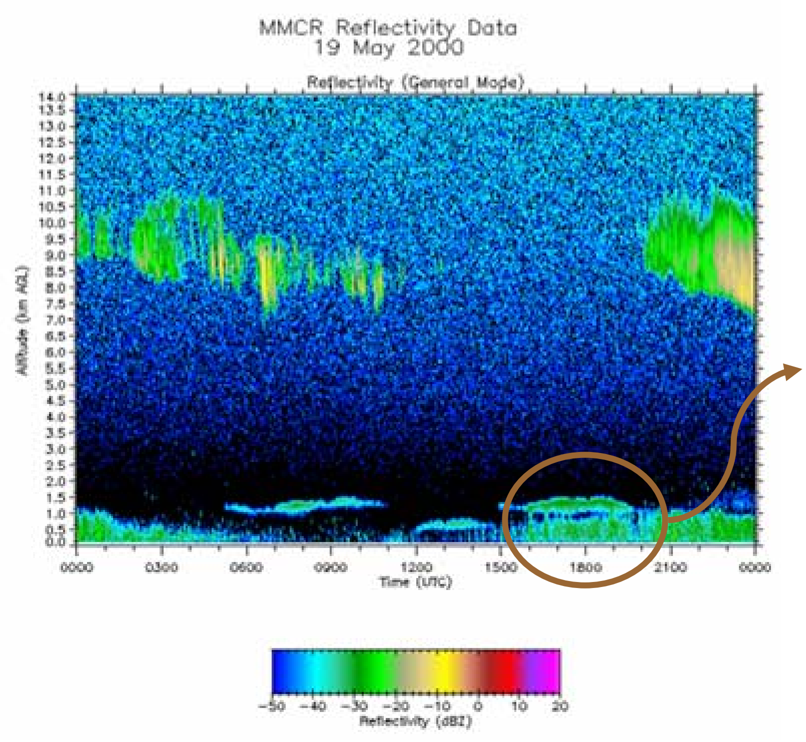


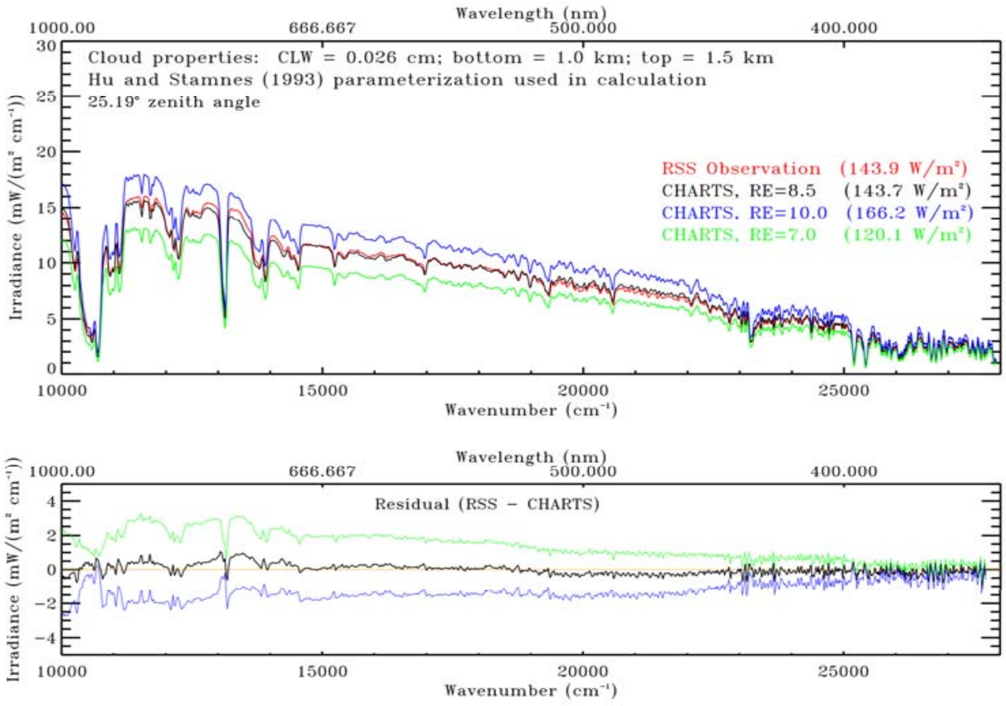
- Need strategy for handling input dependent noise
  - Scene temperature dependence (clear/cloudy)
    - worse in SW band
  - Cloud clearing noise amplification
- H-transformation not overly sensitive to noise
  - For clear retrievals: sufficient to update noise covariance regionally

Application to Scattering Atmospheres

OSS/CHARTS Comparison

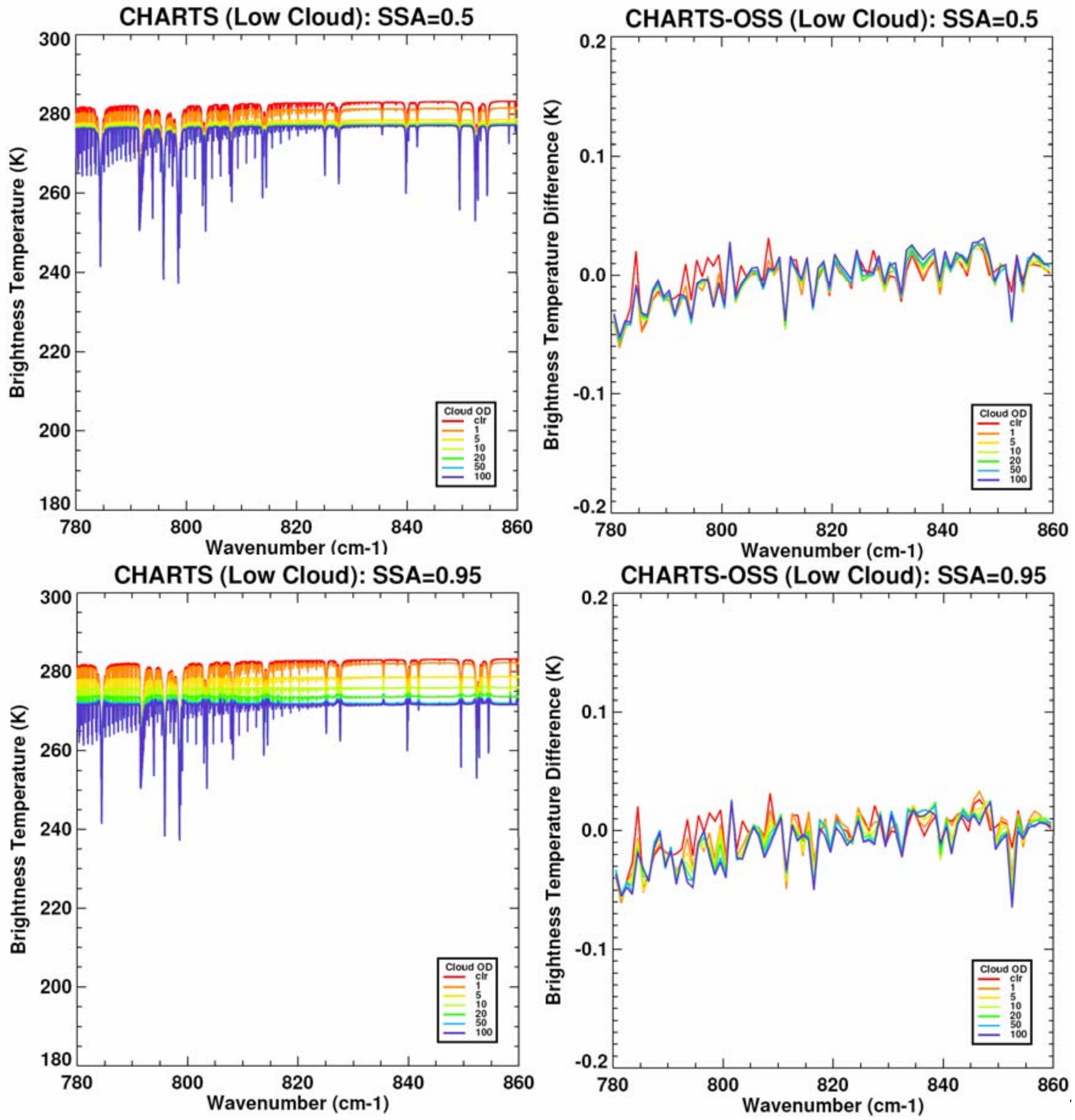
- CHARTS (Moncet and Clough, 1997):
  - Fast adding-doubling scheme for use with LBLRTM
    - Uses tables of layer reflection/transmittance as a function of total absorption computed at run time
  - Validation against measurements from Rotating Shadowband Spectroradiometer (RSS) spectra at the ARM/SGP site





OSS/CHARTS Comparison (2)

- OSSSCAT:
  - Single wavelength version of CHARTS (no spectral interpolation)
- Cloudy validation:
  - Molecular absorption from 740-900 cm^{-1} domain
  - $1cm^{-1}$ boxcars, thermal only
  - Cloud extinction OD range: 0-100
- Example:
  - 780-860 cm^{-1}
  - Low cloud case (925-825 mb)

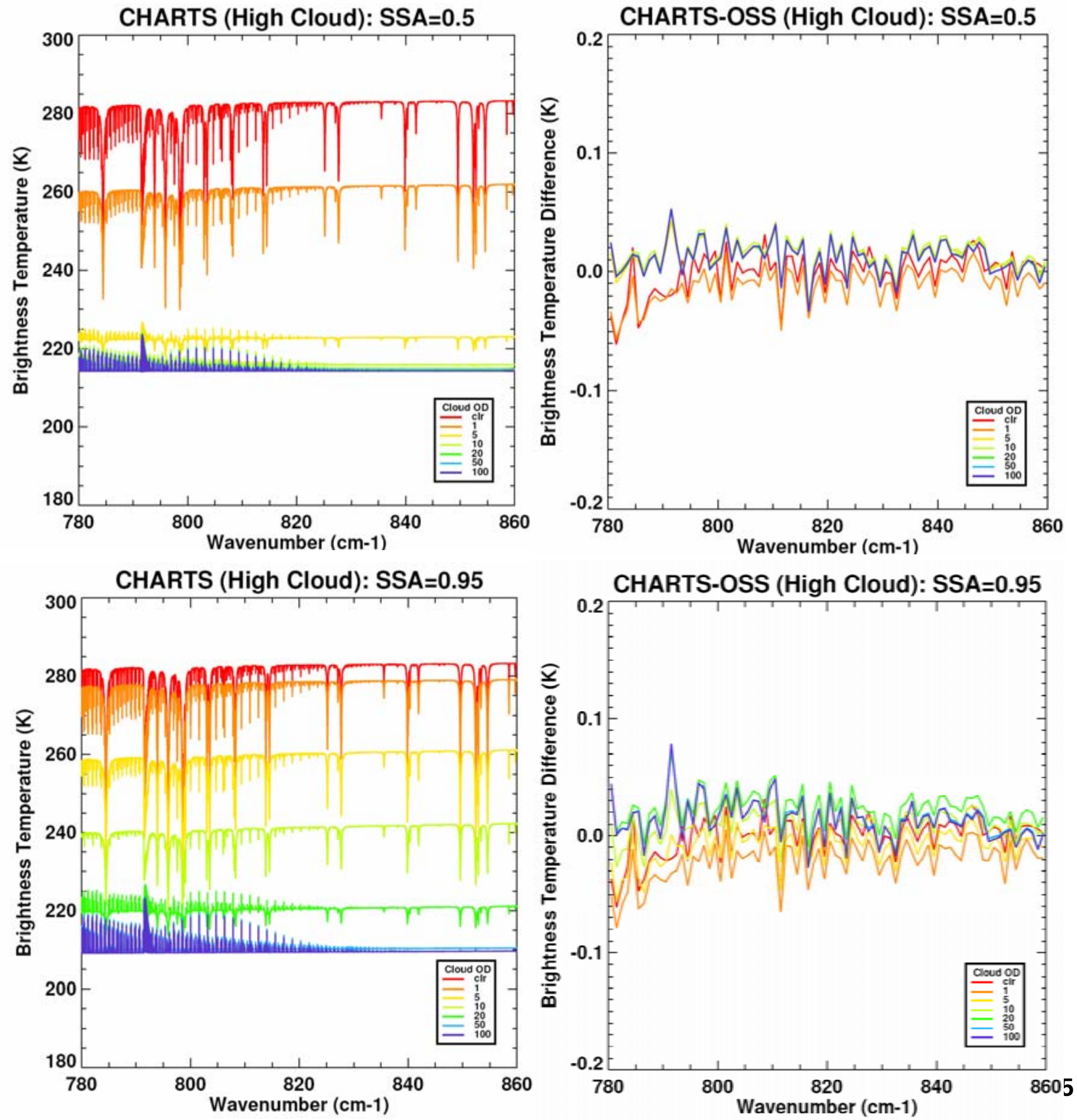


OSS/CHARTS Comparison (3)

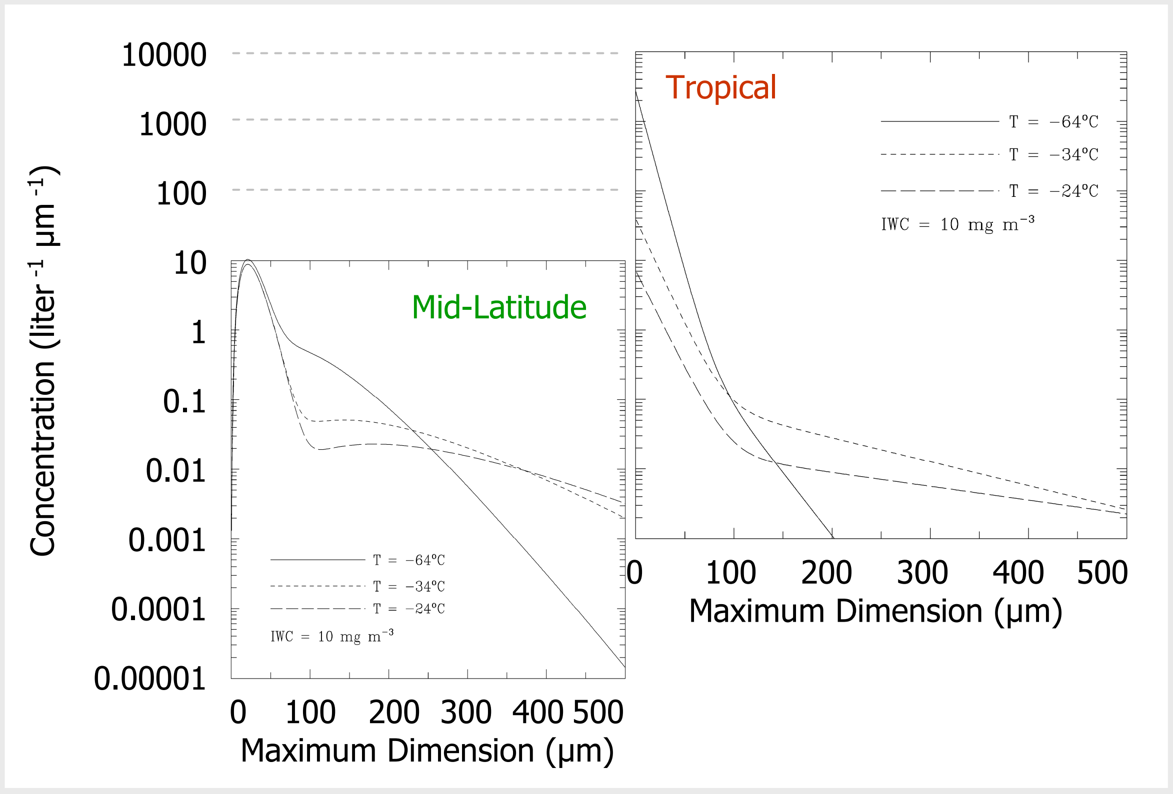
- **Same as previous**
- High cloud case (300-200 mb)

Clear sky training adequate in thermal regime

Refinement in training needed for thick clouds (OD > 50) when SSA approaches 1 and high scan angles



Cirrus cloud microphysics parameterization

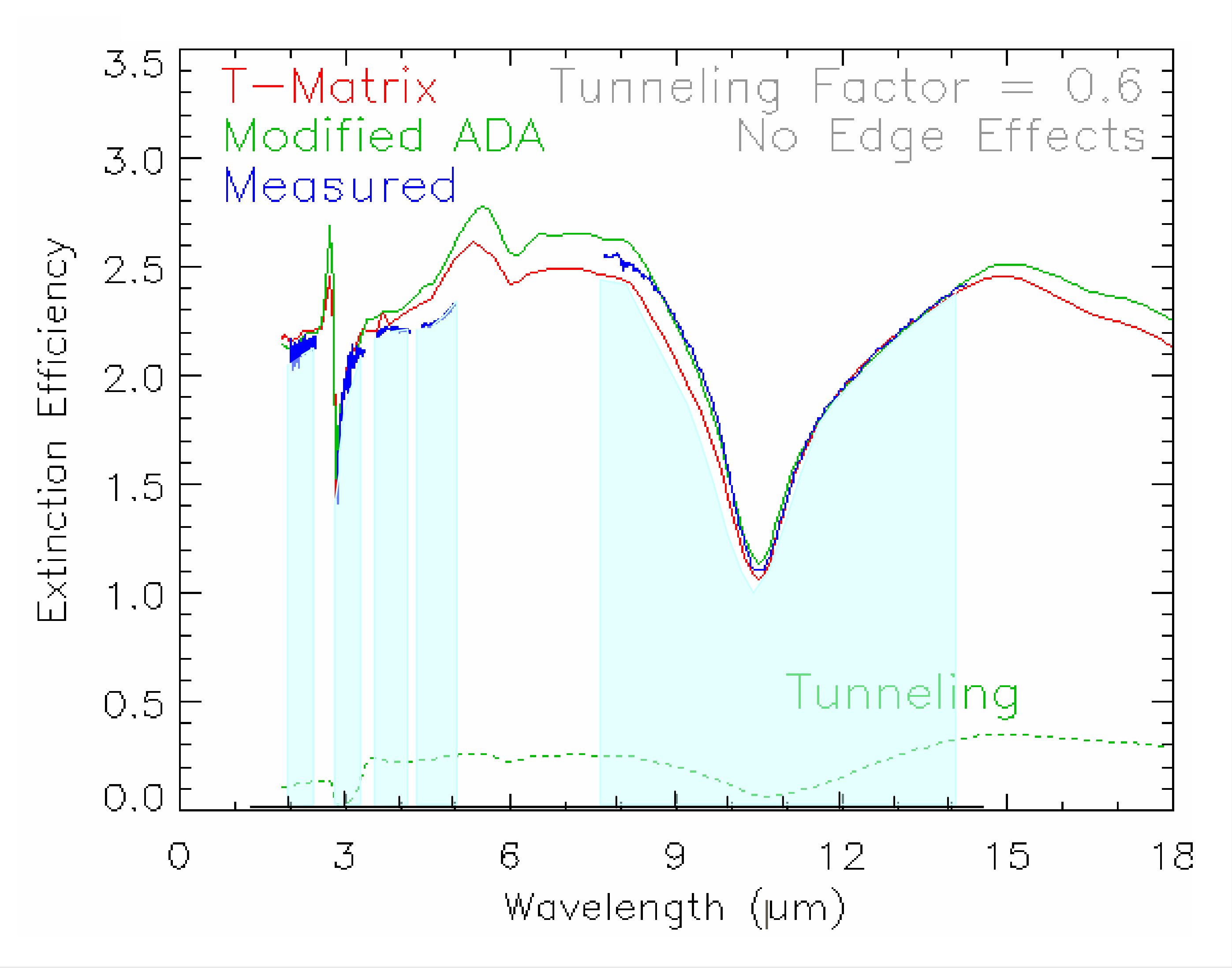


- Size distribution is strongly bi-modal
- Mid-latitude cirrus
  - Small mode:
    - fixed shape recipe (16% bullet-rosettes, 31% planar polycrystal / irregular – 53% quasi-spherical)
  - Large mode:
    - Temperature-dependent shape recipe
- Tropical cirrus
  - Small mode:
    - 40% planar polycrystals, 60% quasi-spherical
  - Large mode:
    - 30% hexagonal, 65% planar poly-crystals, 5% hexagonal plates
    - Strong temperature dependence of size distribution shape

Optical properties from Modified Anomalous Diffraction Approximation (MADA)

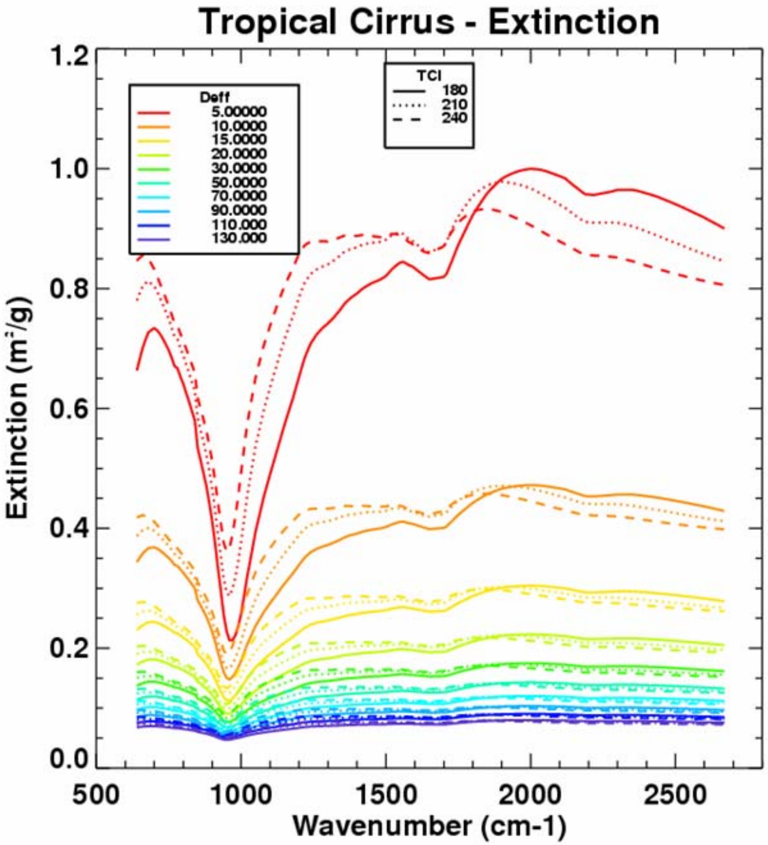
Comparing T-Matrix, MADA, and Measured Qext

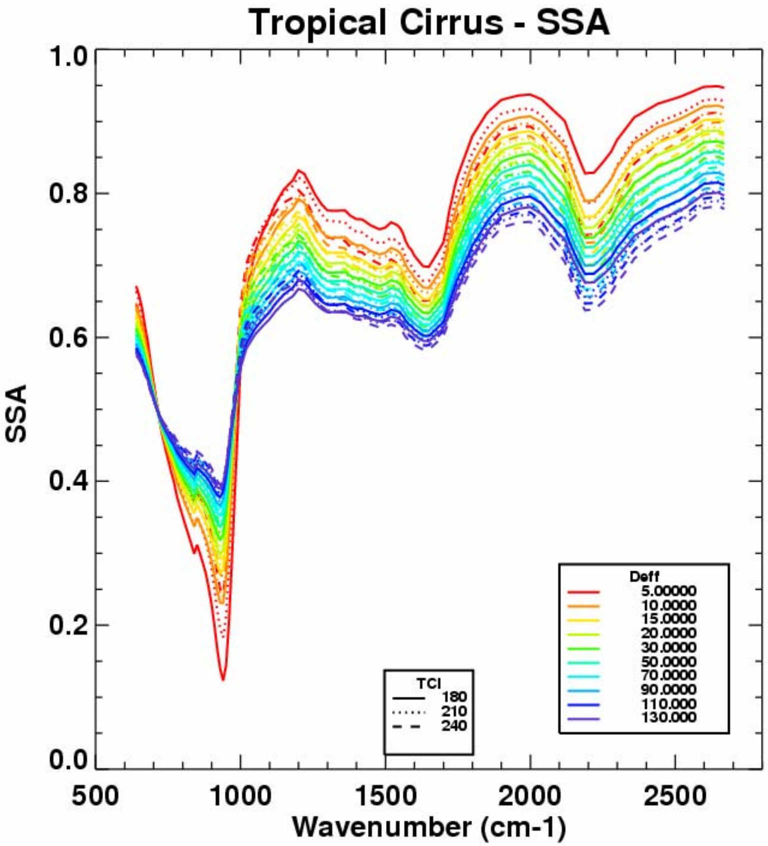
- Testing MADA against cloud chamber Q_{ext} measurements and against T-matrix theory using observed size distribution
- Effective diameter was 14 microns



References:* *(Mitchell, 2000, 2002)

MADA optical properties (tropical cirrus)

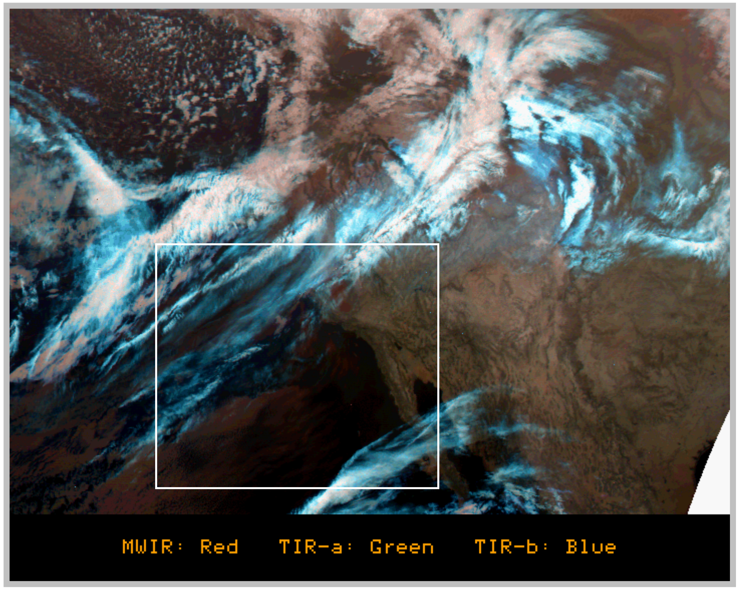




Application to AIRS

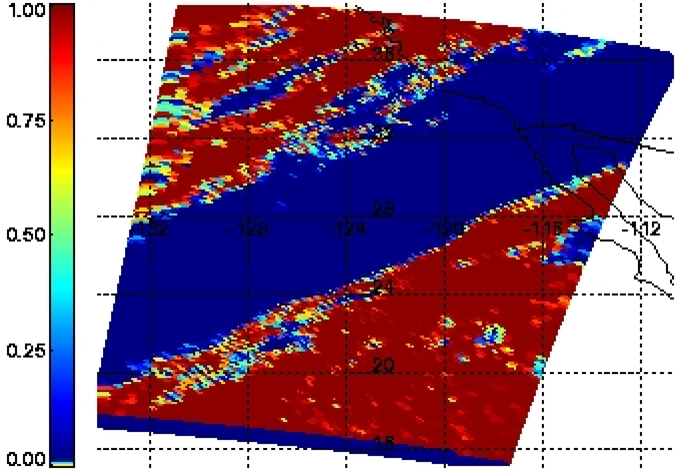
- Single FOV 1DVAR retrieval
  - Atmosphere/SST from NCEP/GDAS
  - Adjusted parameters:
    - Cloud top/thickness
    - Ice particles effective diameter (Deff)
    - IWP
    - Effective temperature
  - MODIS 1st guess
    - AER/SERCAA cloud algorithms
  - RTM:
    - OSSSCAT (100 layers)
    - 4-streams

GOES imagery

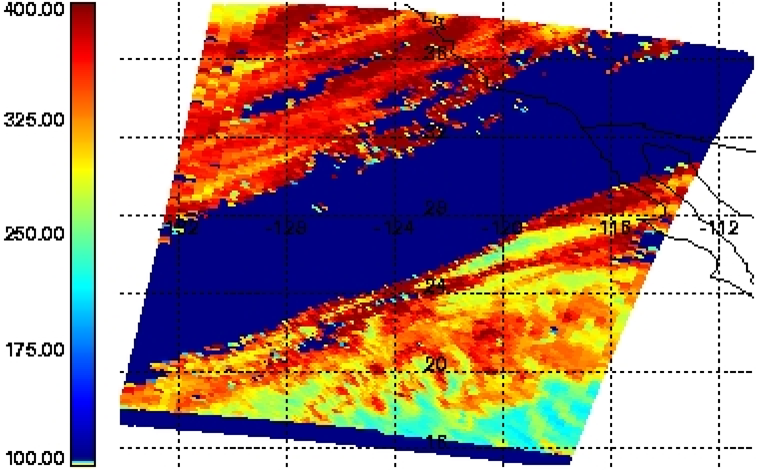


Retrieved cloud product

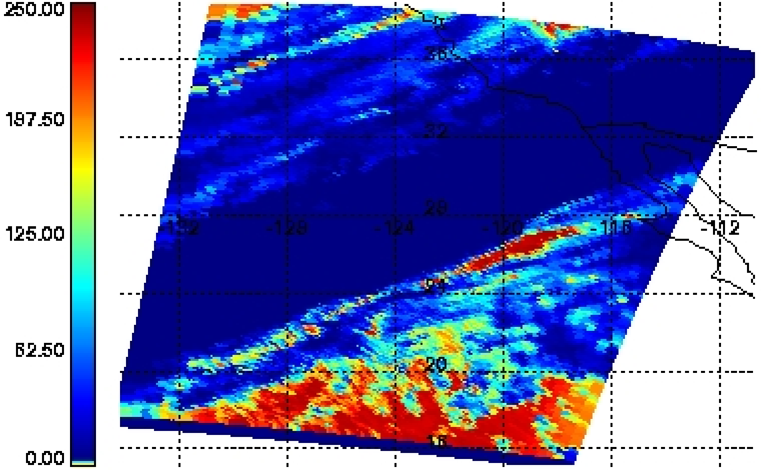
Ice Cloud Fraction – MODIS on AIRS.2006.01.11.100



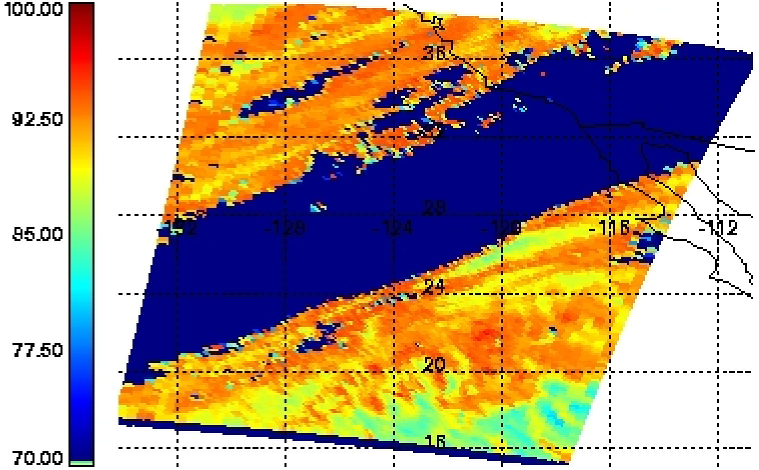
Cloud Top Pressure – MODIS on AIRS.2006.01.11.100 (mb)



IWP – MODIS on AIRS.2006.01.11.100 (g/m^2)

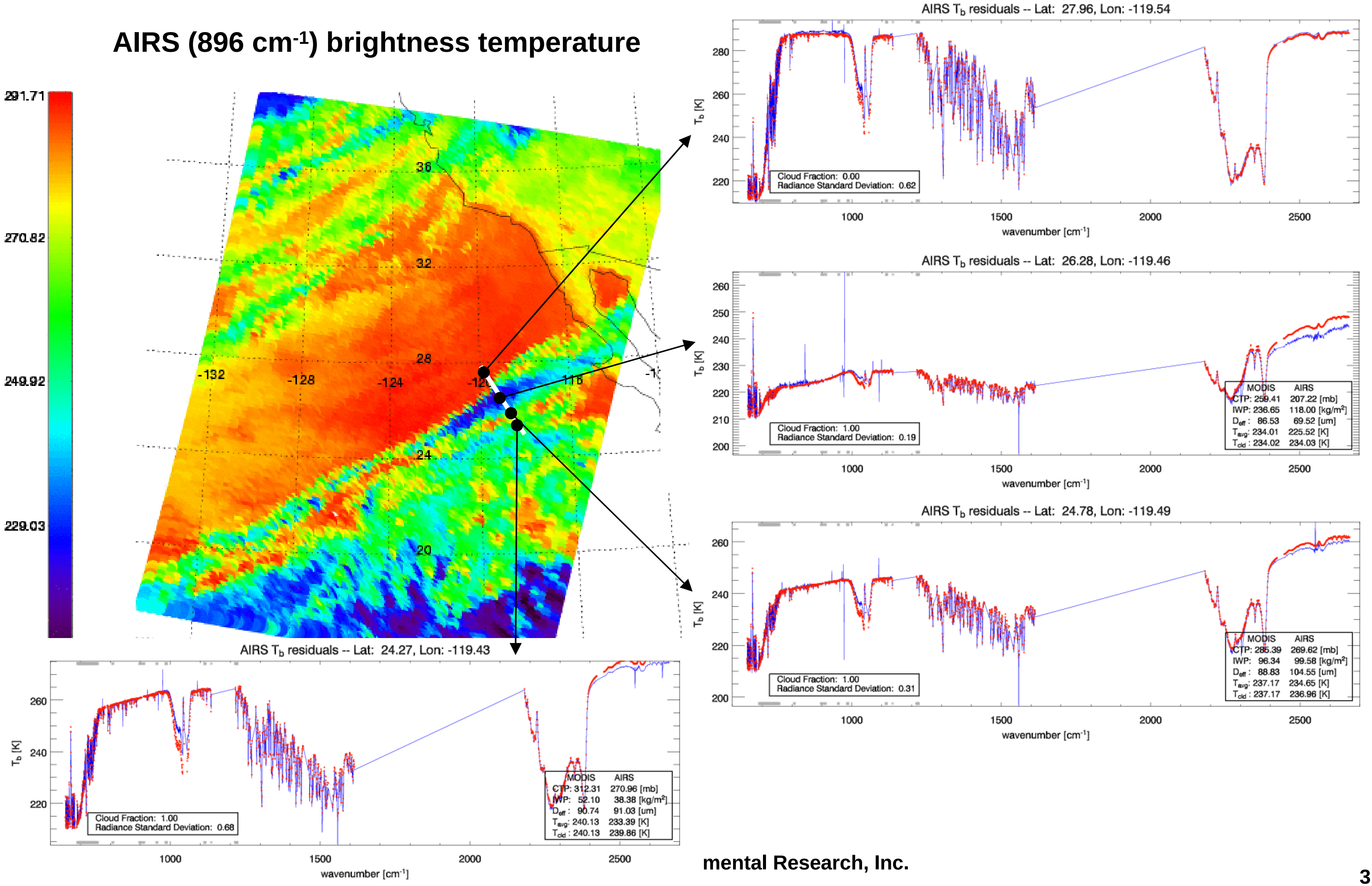


Deff – MODIS on AIRS.2006.01.11.100 (um)



Calculated vs. measured cloudy AIRS spectra

AIRS (896 cm^{-1}) brightness temperature



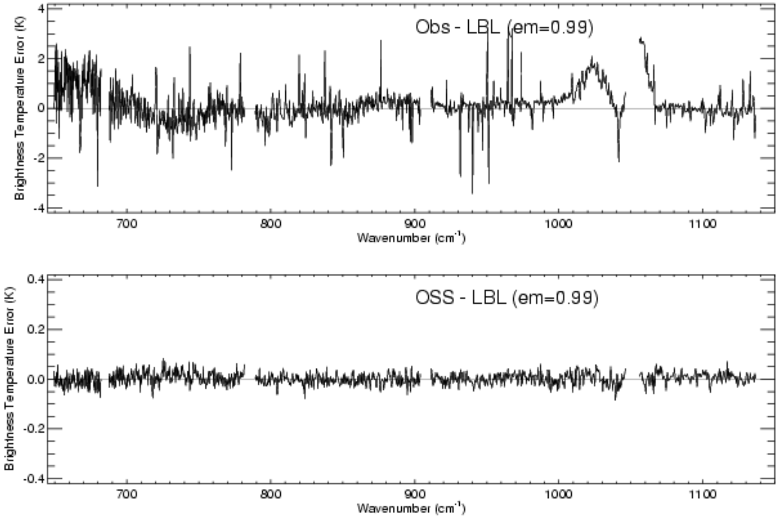
Summary/future work

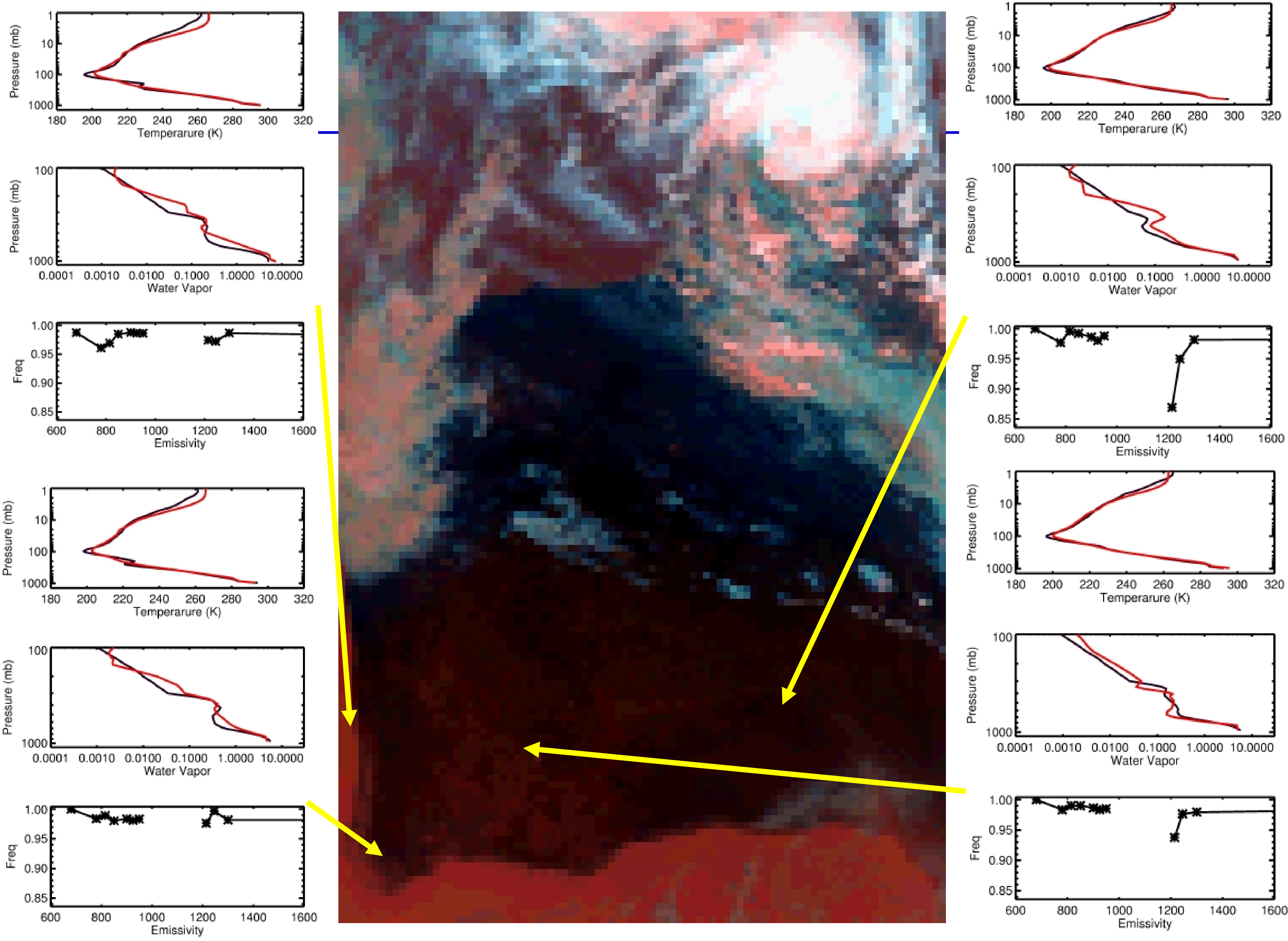
- **Localized training (reference):**
  - already offers higher numerical accuracy (both in clear and cloudy atmospheres) and significant speed gain over current OPTRAN based RT model
  - Used for NPOESS/ATMS CrIS (older version) and CMIS EDR algorithms
  - Considered for operations at NCEP for processing of current operational sensors (including AIRS)
- **Non-localized (generalized) training**:
  - Potential for high computational gains (over localized training) for high spectral resolution IR sounders
    - Forward model is only one component of inversion algorithm
    - Further work needed to improve overall inversion speed
  - Work on going for applications to land (spectrally variable surface emissivity) and cloudy atmosphere (spectrally variable cloud properties)
- **Cloud modeling/retrieval in cloudy conditions**
  - Applied to AIRS cloud property retrieval
  - Develop fast parameterizations for real-time application (already available for EO imaging instruments)
  - Extend validation of RT model/cloud property parameterization to microwave (NPOESS/CMIS) and near-IR/visible region (AFRL/MODTRAN and MODIS applications)
  - Collaboration with **NOAA-CU Center for Environmental Technology (CET) NOAA Earth System Research Laboratory** to include analytical Jacobians in scattering model
    - Goal: simultaneous retrieval of cloud and atmospheric composition

Summary/future work (cont.)

- Refine handling of solar source (clear/cloudy) in near-IR region
- Validate treatment of surface reflectivity over land
- Other focus areas:
  - improvement in molecular spectroscopy in both microwave and IR
  - Broadband flux/heating rate calculations

OSS vs. LBLRTM - AIRS clear-sky, ARM TWP site (08/12/08)

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Temperarure (K)
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Water Vapor
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Emissivity
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Summary/future work (cont.)

- Refine handling of solar source (clear/cloudy) in near-IR region
- Validate treatment of surface reflectivity over land
- Other focus areas:
    - improvement in molecular spectroscopy in both microwave and IR
    - Broadband flux/heating rate calculations

OSS vs. LBLRTM - AIRS clear-sky, ARM TWP site (08/12/08)