Fast Forward Modeling in Scattering Atmospheres with Optimum Spectral Sampling

Jean-Luc Moncet, Gennady Uymin, Alan Lipton, Ned Snell

Atmospheric and Environmental Research, Inc.

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Topics

- Optimal Spectral Sampling brief overview
- Global training
  - Application to AIRS and IASI
- Use of principal components of radiances
- Treatment of multiple scattering
  - Current training method
  - Minimizing the number of scattering RT operations
  - Application to AIRS and MODIS

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Review of the Basic OSS Method

- OSS channel radiances modeled as (Moncet et al. 2003, 2001, 2008)

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

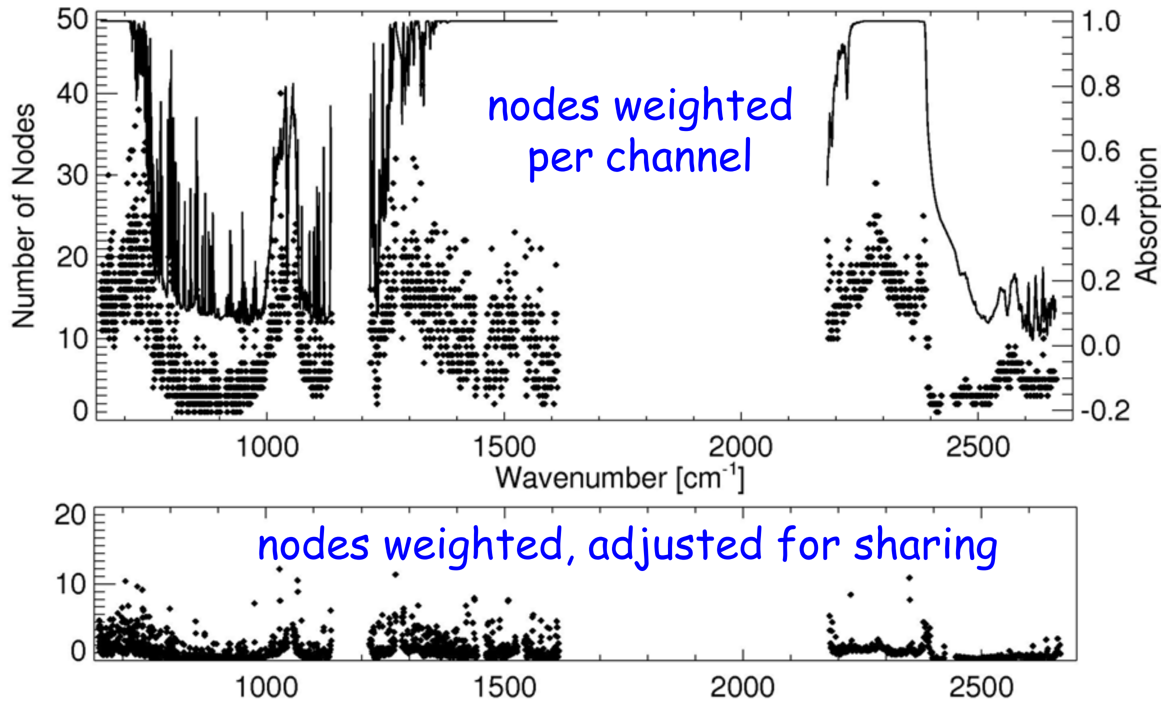
- Channel-average radiance is modeled as weighted average of monochromatic radiances
- Wavenumbers ν_i (nodes) and weights w_i are optimally selected to fit calculations from a reference line-by-line model for a globally representative set of profiles (training set)
- Monochromatic absorption coefficients from look-up tables
- Demonstrated to be generally faster and more accurate than methods that use regression to fit the space-to-level band transmittance (here called total path transmittance regression = TPTR methods)
  - For molecular absorption, non-scattering computations
  - Scattering case is discussed in this presentation

Training Approaches: 1) Local Training

- Operates on individual channels, one at a time
- Nodes for each channel required to be within spectral range of channel response
  - Nodes may be shared between channels with overlapping responses

AIRS (2378 channels):

- Average: 11 nodes weighted per channel
- Average: 1.3 nodes/channel overall (accounts for sharing)



Training Approaches: 2) Global Training

- Operates on groups of channels (up to the full channel set) simultaneously
- Uses clustering of nodes to efficiently account for spectral correlations
  - Condenses the information of the full channel set into a minimal number of nodes
- Monochromatic RT at a relatively few nodes determines radiances for full channel set
- Optionally, can be fit to channel subset, or first X principal components of channel set, or radiances filtered by PC transformation
  - Reduces information relative to full channel set

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AIRS Example

	AIRS - full channel set			AIRS - 281 channel subset		
	Local*	Global20	Global	Local	Global20	Global
# channels	2378	2378	2378	281	281	281
# nodes	5340	2323	507	1809	993	328
# nodes / # channels	**2.25**	**0.98**	**0.21**	**6.44**	**3.53**	**1.17**
N'	**9.84**	**35.60**	**203.63**	**11.75**	**30.53**	**238.43**

N' = number of nodes contributing to radiance computation in 1 channel (on average)

Training conditions:

- 0.05 K accuracy requirement
- Extra wide range of incidence angles (0°–70.5°)*
- Variable gases H_2O, O_3

*difference from data in chart 4

- Global20
  - Surface emissivity assumed linear over contiguous 20 cm-1 intervals (needs to be verified with real data)
  - Global training applied independently to each interval
  - Provides extra robustness by avoiding reliance on correlations from distant spectral points
    - Extra robustness for surfaces whose emissivity spectra are outliers

Application to IASI

- Global and local training results

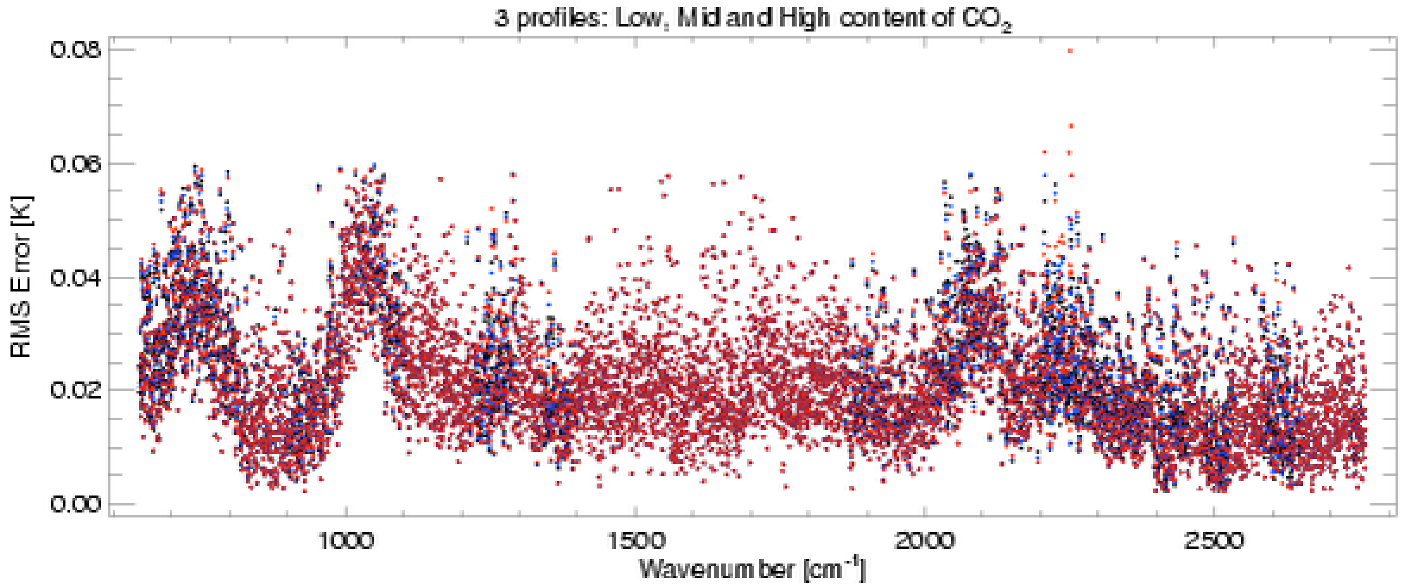
			Number of nodes		
IASI band	Spectral range (cm^{-1})	Number of channels	Local	Global	Global nodes/ channels
1	645–1210	2261	1855	220	0.097
2	1210–2000	3160	2927	281	0.089
3	2000–2760	3040	2639	321	0.11
Total		8461	7421	822	

Training conditions:

- 0.05 K accuracy requirement
- 13 variable gases: H_2O, O_3, CO_2, CO, CH_4, N_2O, F11, F12, CCl_4, HNO_3, SO_2, OCS, CF_4
- 5 fixed gases: O_2, NO, NO_2, NH_3, N_2
- Sources: ECMWF for H_2O, O_3; Global Modeling Initiative chem model for CO_2, CO, CH_4, N_2O, F11,
  M. Matricardi for F12, CCl_4, HNO_3
- 2002-2012 secular trends added for CO_2 and CH_4
- Randomization was applied to all species for robust training
- Emissivity spectra for global training is random walk, with 20-cm^{-1} steps

IASI Validation

- Validation with 48 independent UMBC profiles
- Each profile assigned 3 CO_2 profiles:
  - Minimum (•), mean (•), maximum (•)
- Validates robustness of training over CO_2 trends



From local training

OSS with Principal Components

- Option may be useful when some information loss is accepted as trade-off for speed
  - When eigenvector truncation goes beyond eliminating redundancy
- Can be done without significant revision to OSS training
  - Filter training-profile radiances with truncated eigenvectors
    - Convert to PCs, then use reverse transformation to recover physical-space radiances
  - OSS training achieves required accuracy for every channel (PC filtered)
  - OSS coefficients project only on retained PCs (within training accuracy)
- Forward model output in terms of PCs efficiently done by combining eigenvectors with OSS coefficients in advance

$$\mathbf{R}_{chan} = \mathbf{W}\,\mathbf{R}_{node} \qquad \mathbf{PC} = \mathbf{U}_m\,\mathbf{R}_{chan} \quad \text{with } m \text{ retained PCs}$$

$$\mathbf{PC} = \mathbf{U}_m\,\mathbf{W}\,\mathbf{R}_{node} = \mathbf{W}_m\,\mathbf{R}_{node} \quad \text{where} \quad \mathbf{U}_m\,\mathbf{W} \equiv \mathbf{W}_m$$

Scattering Forward Model

- OSSSCAT is single-wavelength version of CHARTS adding-doubling RTM
  - Uses same molecular absorption and weighted monochromatic radiances as non-scattering RTM
  - Cloud module converts from physical properties (e.g., IWP, LWP, D_{eff}, top, thickness, T(p)) to optical properties (absorption and scattering optical depths, asymmetry parameter)
    - Look-up table
      - Size distributions based on in-situ aircraft measurements
      - Mie for liquid
      - MADA for ice – with temperature-dependent shape recipes
  - Optical properties linearly interpolated from hinge points to OSS nodes

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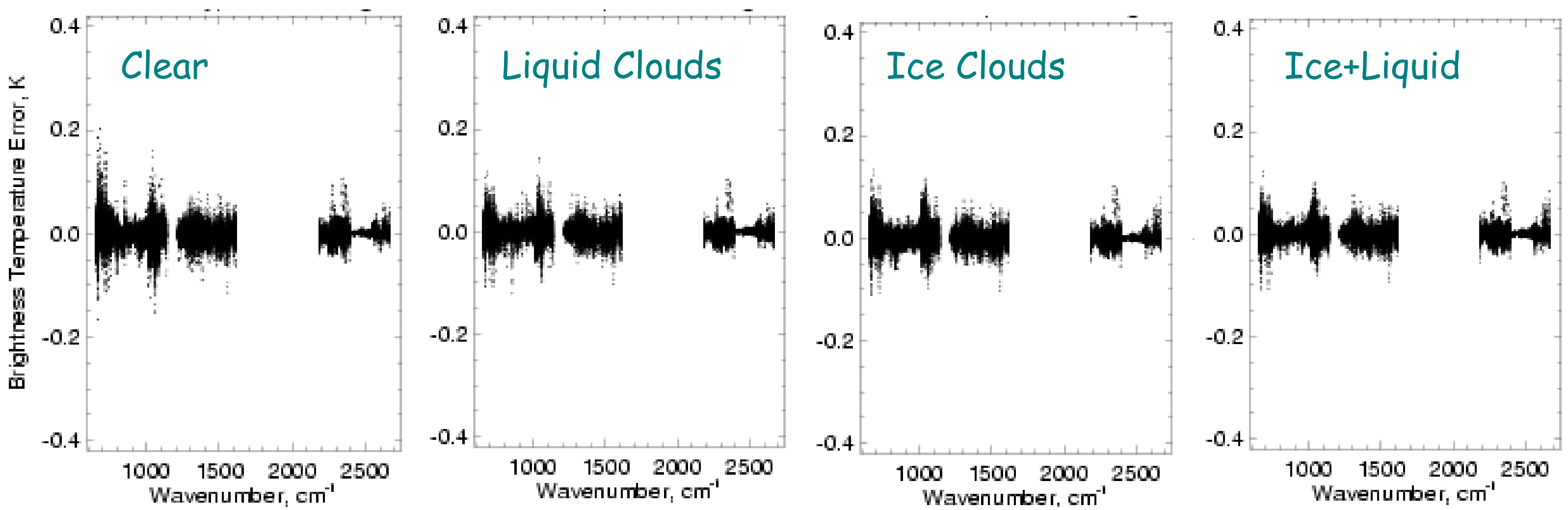
Cloudy Training

- Must include 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 robustnes
- Direct cloudy radiance training approach
  - Clouds tend to mask molecular structure, which makes training less demanding
  - If trained for mixture of clear and cloudy atmospheres in direct training, clear-sky performance degrades
  - Train with clear-sky and several clouds simultaneously, requiring all to meet the accuracy criterion

Cloudy and Clear Fit

- OSS selection requires accuracy threshold be met for each training set individually and simultaneously

AIRS Channel Set
Scattering included
Fit error -- all meet 0.05-K rms requirement
Nadir view shown



Multiple Scattering Acceleration

- With scattering, execution time is dominated by radiative transfer integration
  - Contrasts with non-scattering, where band transmittance calculation may be a bigger factor
  - OSS RT timing ~proportional to number of nodes
  - TPTR RT timing ~proportional to number of channels
  - OSS is faster than TPTR methods only when the number of nodes / number of channels <~1
- Scattering calculations do not have to be performed for each node
  - Scattering correction may be predicted based on a few nodes only:

$$\overline{R} \cong \sum_{i=1}^{N} w_i R^{ns}(\nu_i) + \sum_{k\in S} C_k \left[R(\nu_k) - R^{ns}(\nu_k) \right]$$

    - R is radiance from scattering model
    - R^{ns} is radiance from non-scattering model
    - w are the ordinary OSS weights
    - k are a subset of the set of the OSS nodes (S) for the channel
    - C are regression coefficients
- Number of predictors can be tuned to control balance between cloudy radiance accuracy and computation speed
  - Some relaxation of accuracy may be tolerable in clouds with high optical depth, in proportion to uncertainties in optical properties

In thermal regime

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Scattering Prediction Performance for MODIS

MODIS Channel #	Bandpass (μm)	Number of nodes*	Number of predictor nodes†
20	3.660 - 3.840	10	4
21	3.929 - 3.989	5	2
22	3.929 - 3.989	3	2
24	4.433 - 4.498	19	2
25	4.482 - 4.549	18	2
27	6.535 - 6.895	14	1
28	7.175 - 7.475	15	2
29	8.400 - 8.700	14	3
31	10.780 - 11.280	4	1
32	11.770 - 12.270	4	1
33	13.185 - 13.485	18	1
34	13.485 - 13.785	21	1
35	13.785 - 14.085	24	1
36	14.085 - 14.385	21	1
Average		13.6	1.7

Selected IR channels

Localized training used
Generalized may require fewer predictors

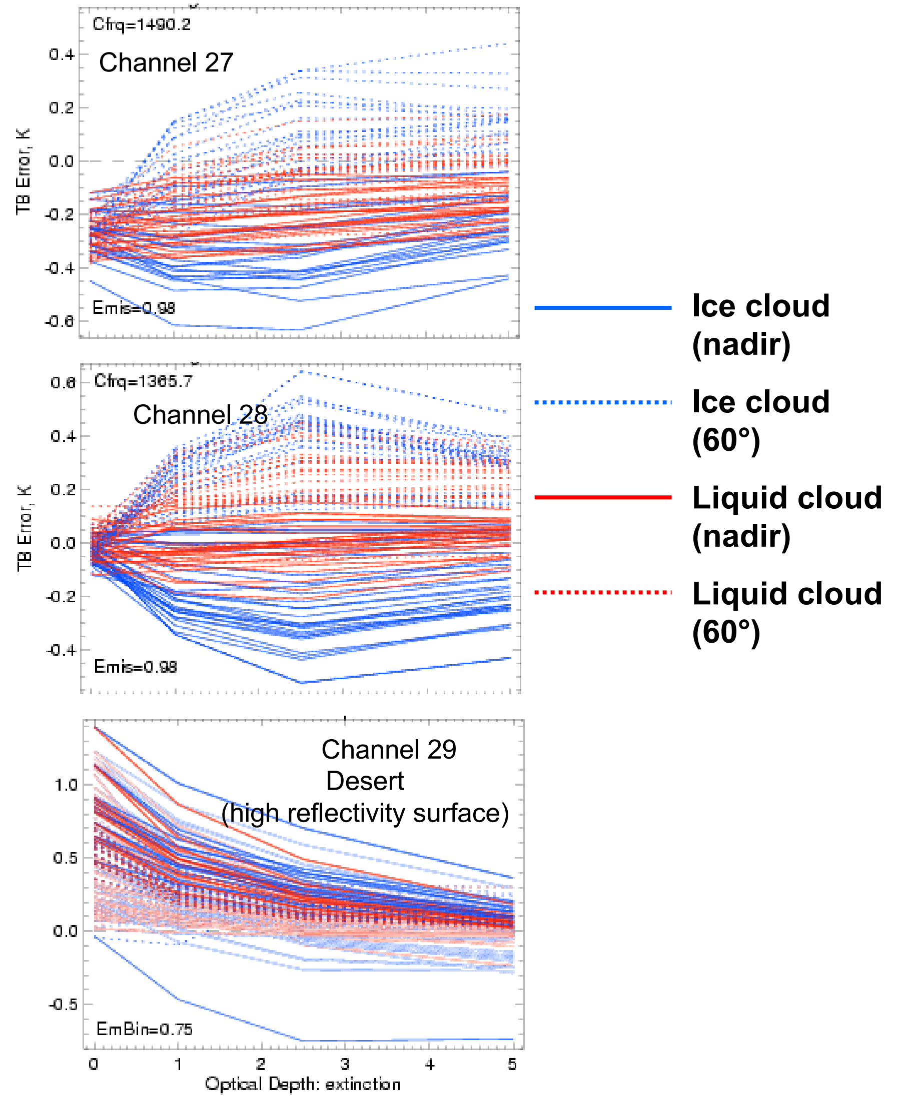
* for error threshold 0.05 K, clear and cloudy training
† for scattering prediction error threshold 0.2 K

Reference for Performance: TPTR Method for MODIS

- Simulated TPTR method
  - Ideal case of no error in transmittance regression
  - Effectively approximates reflected component as product of band-averages

$$\overline{R}_{refl} \approx \overline{r}\,\overline{T}\,\overline{R}^{\downarrow}$$

neglects in-band correlations
biggest impact is with low emissivity = high reflectivity r



OSS Performance for MODIS Accelerated with Scattering Selection

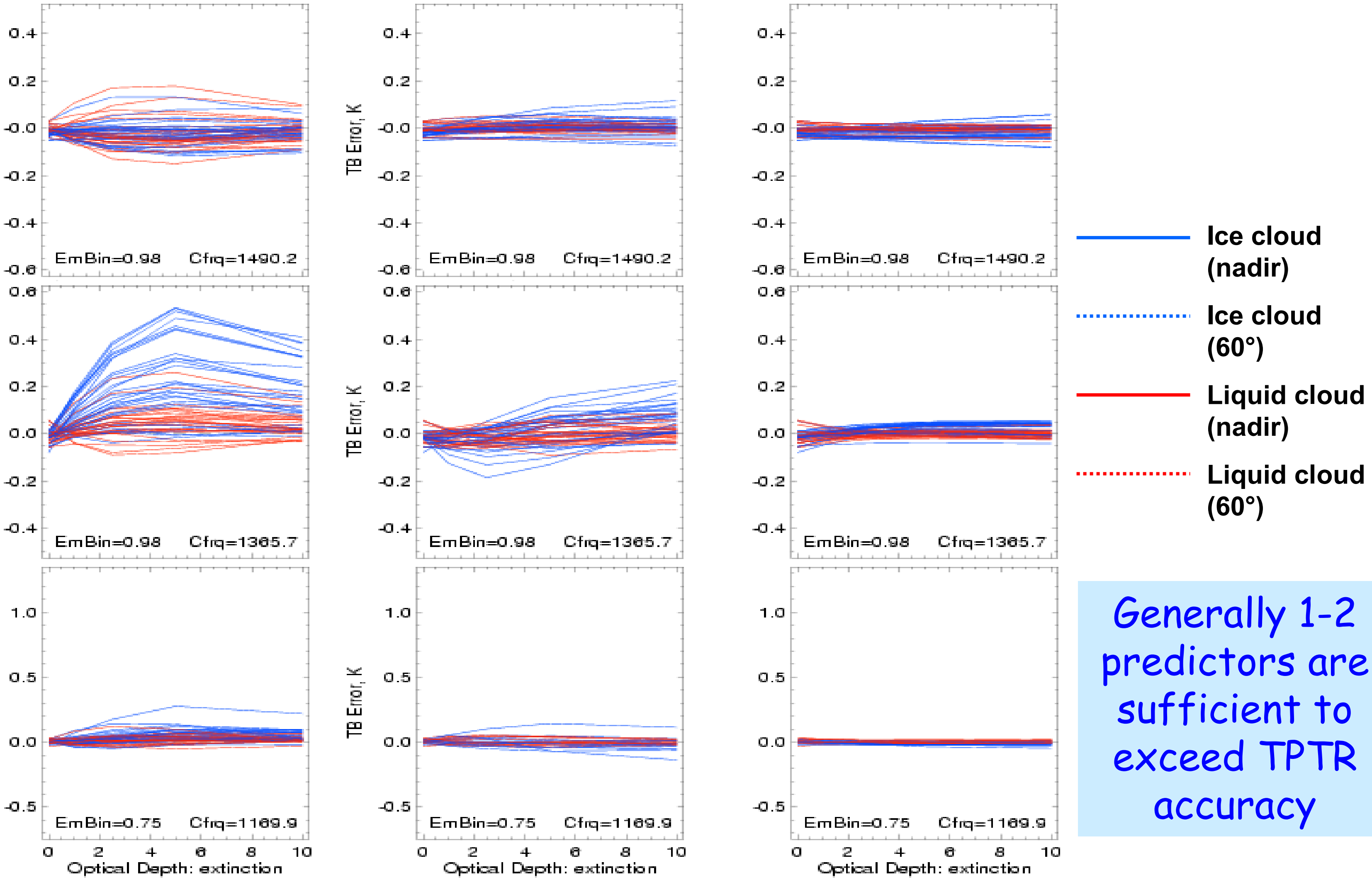
Scattering: 2 predictor nodes | 3 predictor nodes | all nodes

Channel 27

Channel 28

Channel 29

Desert (high reflectivity surface)



Generally 1-2 predictors are sufficient to exceed TPTR accuracy

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Summary

- Global training with correlated clustering minimizes number of nodes for channel set as a whole
- Flexibility – same monochromatic (physical, general) framework provides options to meet user requirements
  - Produce radiances for full channel set
  - Retrieve/assimilate at OSS nodes
    - Avoids computational cost of mapping from nodes to channels
    - Involves channel $\rightarrow$ node transformation of measurement error covariance
      - Treatment of scene-dependent noise depends on application
- Scattering version maintains accuracy in clear areas
- Scattering can be accelerated with process to select subset of nodes to do scattering
  - Requires testing with global training

Backup

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

$$\mathbf{y^m} = \mathbf{A}\tilde{\mathbf{y}}_0^{\mathbf{m}} \rightarrow \tilde{\mathbf{y}}_0^{\mathbf{m}} = \mathbf{H}\mathbf{y^m}$$

Avoids Jacobian transformation altogether and reduce K-matrix size (inversion speed up)

- for AIRS: 2378 channels -> 250 nodes

$$\delta x_{n+1} = \left(\mathbf{K_n^T S_\varepsilon^{-1} K_n} + \mathbf{S_x^{-1}}\right)^{-1} \mathbf{K_n^T S_\varepsilon^{-1}} \left[\left(y_n - y^m\right) + \mathbf{K_n}\delta x_n\right],$$

where,

$\mathbf{y} = \mathbf{A}\tilde{\mathbf{y}}_0$ and

$\mathbf{K} = \mathbf{A}\tilde{\mathbf{K}}_0$

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

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

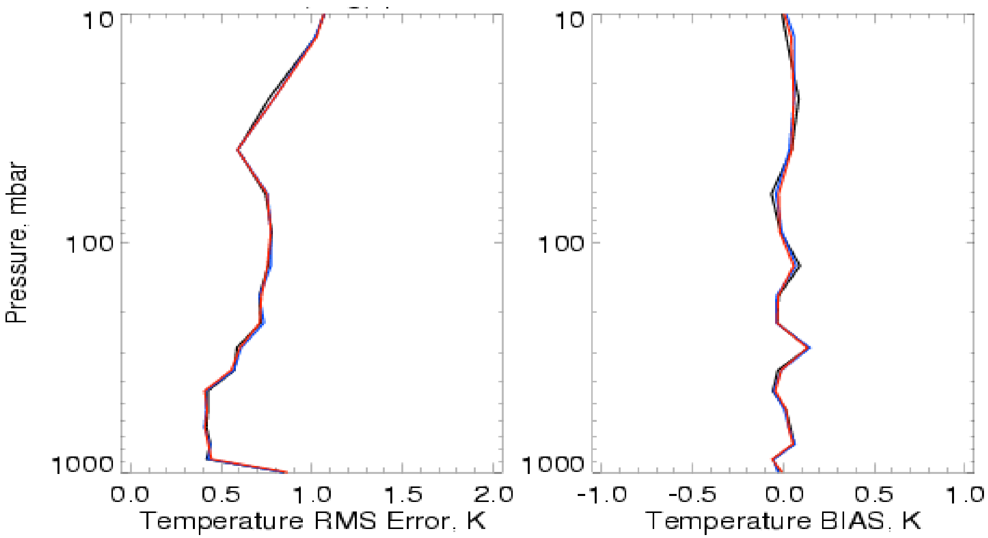
$$\delta\mathbf{x}_{n+1} = \left(\tilde{\mathbf{K}}_n^T \tilde{\mathbf{S}}_\varepsilon^{-1} \tilde{\mathbf{K}}_n + \mathbf{S}_x^{-1}\right)^{-1} \tilde{\mathbf{K}}_n^T \tilde{\mathbf{S}}_\varepsilon^{-1} \left[\left(\tilde{\mathbf{y}}_n - \tilde{\mathbf{y}}^m\right) + \tilde{\mathbf{K}}_n \delta\mathbf{x}_n\right]$$

**Equivalent to

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

Inversion (continued)

Retrieval performance – constant noise



Channel space retrieval
Node space retrieval

- 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