Initial Testing on Solar Fingerprinting

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The key process in the climate change fingerprinting is to attribute the large spatiotemporal averaged spectral variation to different climate variables. This attribution can be expressed as a multivariable linear regression problem:

$$\Delta R = K \Delta X + e \qquad (1a)$$

$$\Delta R_i = \sum_{j=1}^{n_x} K_{ij} \Delta X_j + e_j \qquad (1b)$$

$$K_{ij} = \frac{\partial R_i}{\partial x_j}; \qquad i=1,2,\ldots,n_w;\ j=1,2,\ldots,n_x \qquad (1c)$$

ΔR Reflectance change signal (spectral difference between two climate states)
K Kernel matrix (fingerprints)
ΔX Climate variable changes to be retrieved
e Errors or residuals that cannot be explained by fingerprints

K **cannot be measured directly, has to be generated from RT modeling.**
R **either from observation or model simulation.**

Without the error consideration, the solution of Equation (1) is simply

$$\Delta X = (K^T K)^{-1} K^T \Delta R$$

This is based on the ordinary least squares estimation (LSE). A small error in ***K*** or in ***ΔR*** could produce large error in the solution.

A common approach used to account the error is the so-called optimal detection:

$$\Delta X = (K^T E^{-1} K)^{-1} K^T E^{-1} \Delta R$$

where ***E*** is the covariance matrix of *e* in Equation (1).

The formulation for fingerprinting retrieval here is similar to those used in many conventional retrieval methods applied to instantaneous satellite data. However, the fingerprinting retrieval differs from the traditional remote sensing retrieval in that

1) It uses the average-then-retrieval approach and thus is associated with the averaged quantities over large spatiotemporal scales instead of the local or instantaneous values.
2) It is for the difference ($\boldsymbol{\Delta R}$ and $\boldsymbol{\Delta X}$) between two mean climate states instead of the absolute value ($\boldsymbol{R}$ and $\boldsymbol{X}$).

Here we use model-simulated data to test the concept of fingerprinting attribution. Model input parameters:

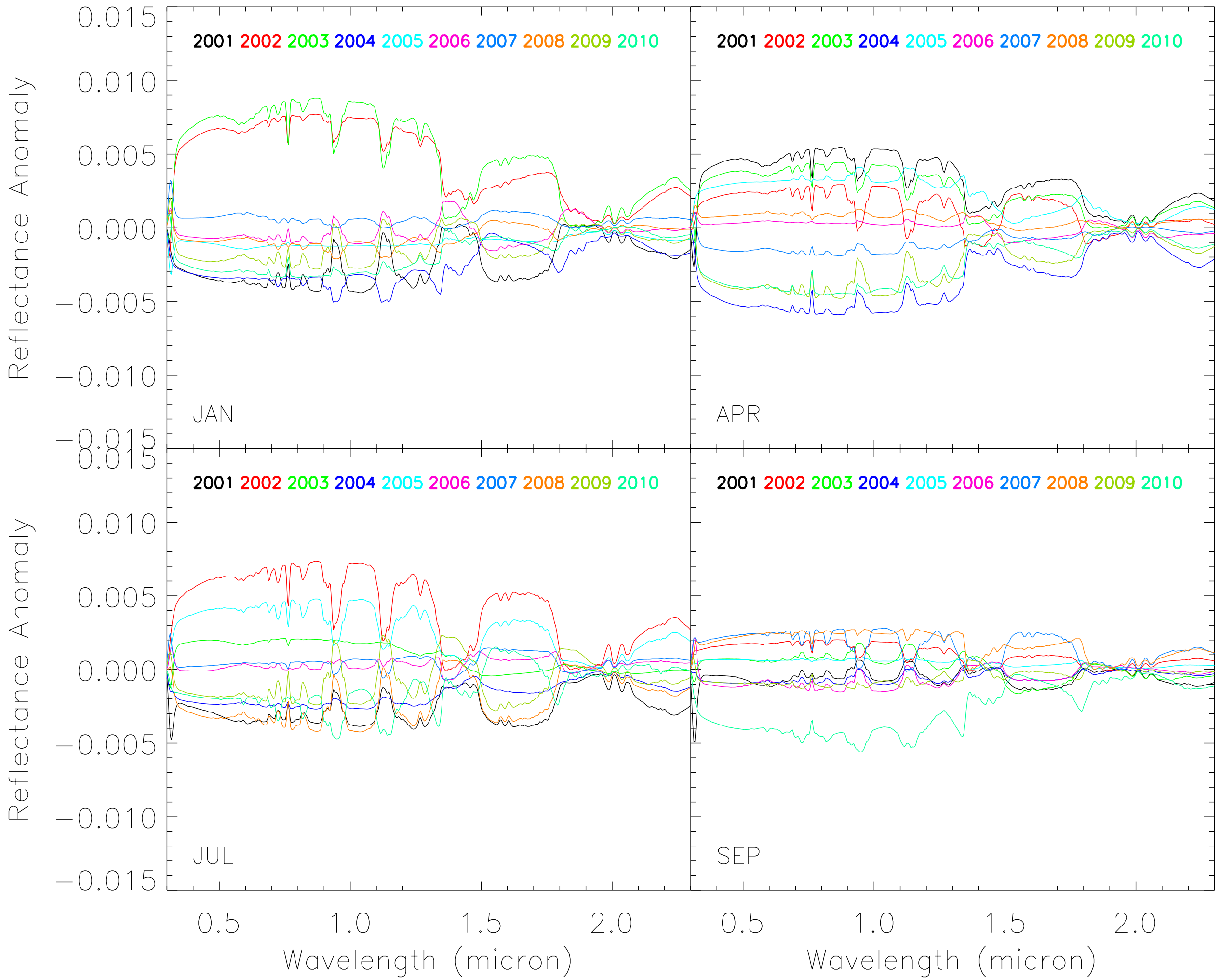
- ✓ **10 years (2001-2010) of CERES SSF data from NASA Terra satellite ;**
- ✓ **aerosol and cloud properties (optical depth, particle size, phase, and height) retrieved from MODIS;**
- ✓ **column water vapor and surface wind data from GEOS5-MERRA reanalysis;**
- ✓ **ozone data from SMOBA;**
- ✓ **ocean chlorophyll concentration from SeaWiFS.**

Using these input parameters in combination with COART-MODTRAN, we generate the spectral kernels and a time series (10 years) of monthly mean reflectance spectra (320-2300nm, 4nm resolution) to retrieve the interannual changes in the 11 relevant climate parameters:

PW, AOD, O3

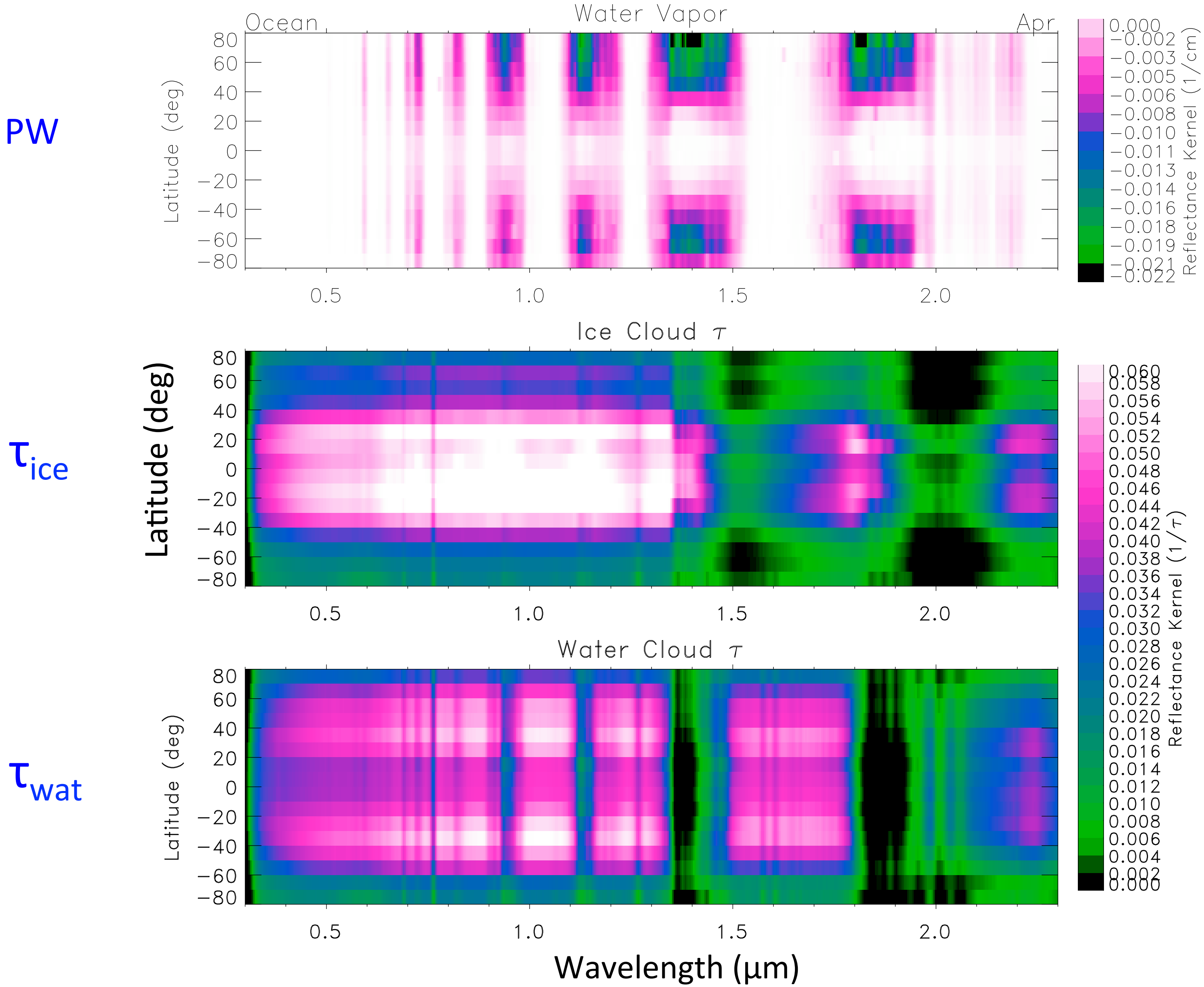
and

τ, Fc, Ht, Re for water and ice clouds, respectively.

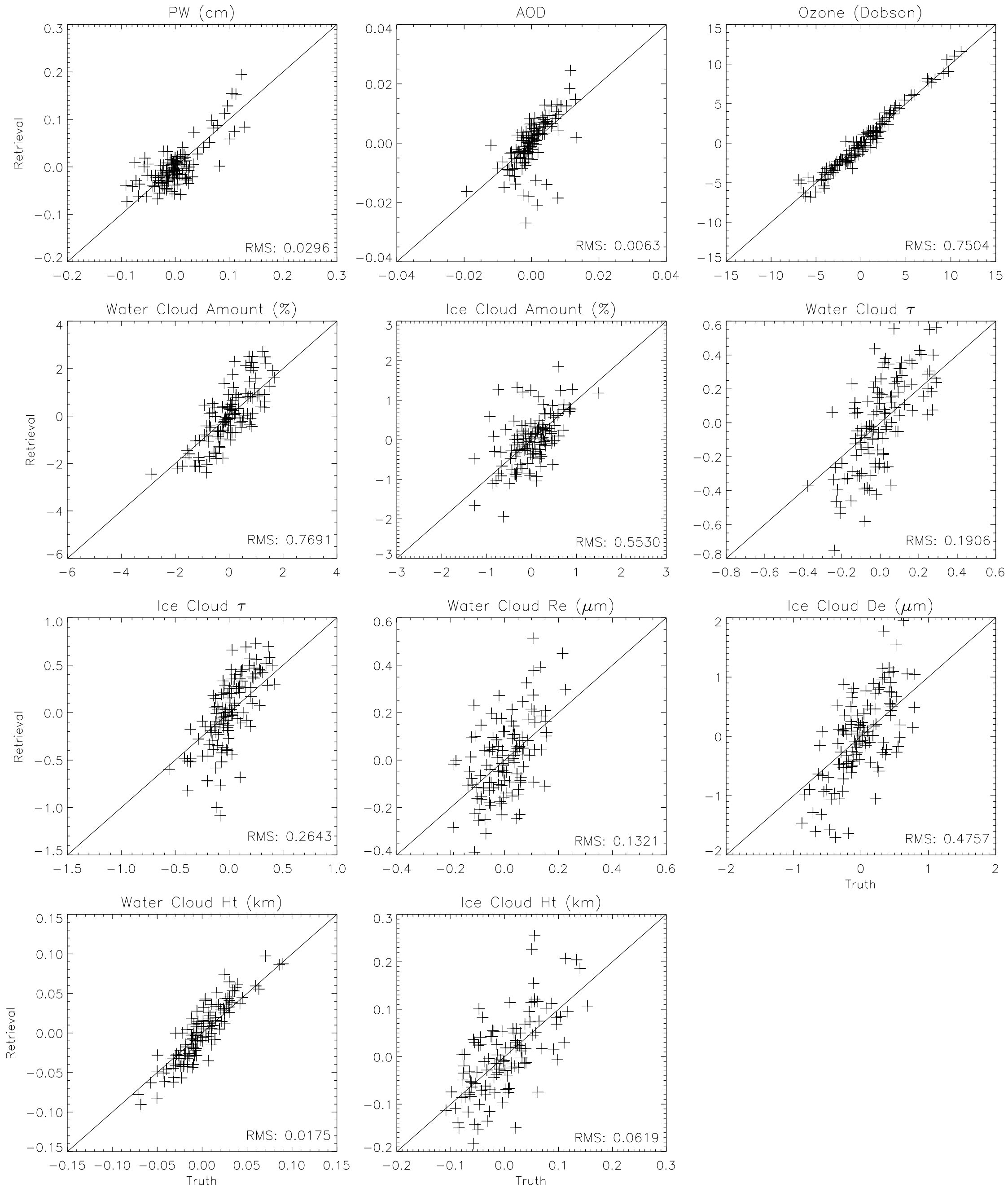


An example of the monthly and global mean reflectance anomalies (***ΔR***) in the four months. In each panel, each color is for a different year.

ΔR is indeed small: typically less than ±3% of the mean reflectance



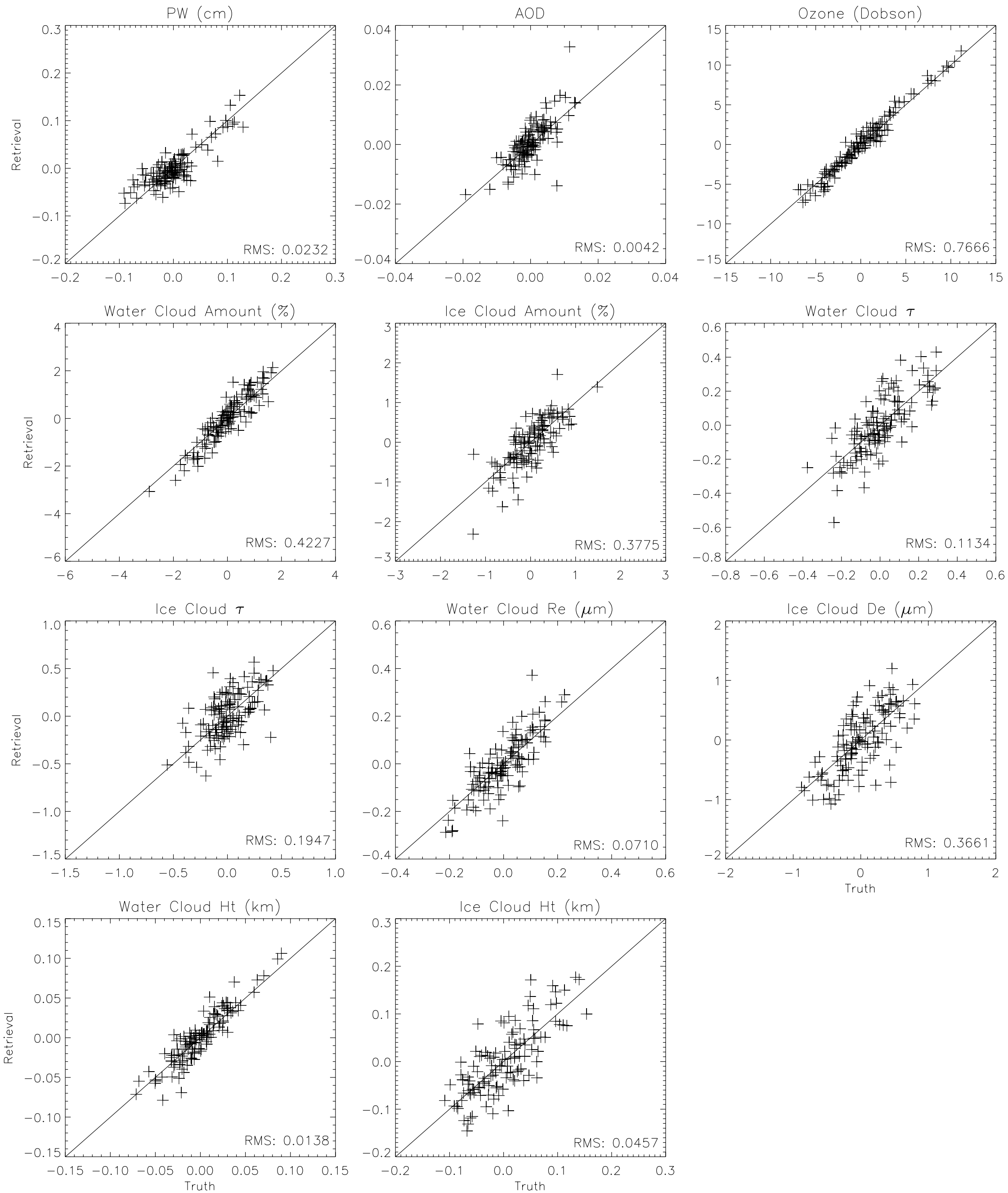
An example of solar spectral reflectance kernels.



Comparison between the fingerprinting retrieval and the observational truth for the monthly global mean anomaly.

Each panel is for a different climate parameter (11 total).

The nonlinear error in kernels is not considered in the retrieval.



Same retrieval as above, but the nonlinear error in kernels is considered.

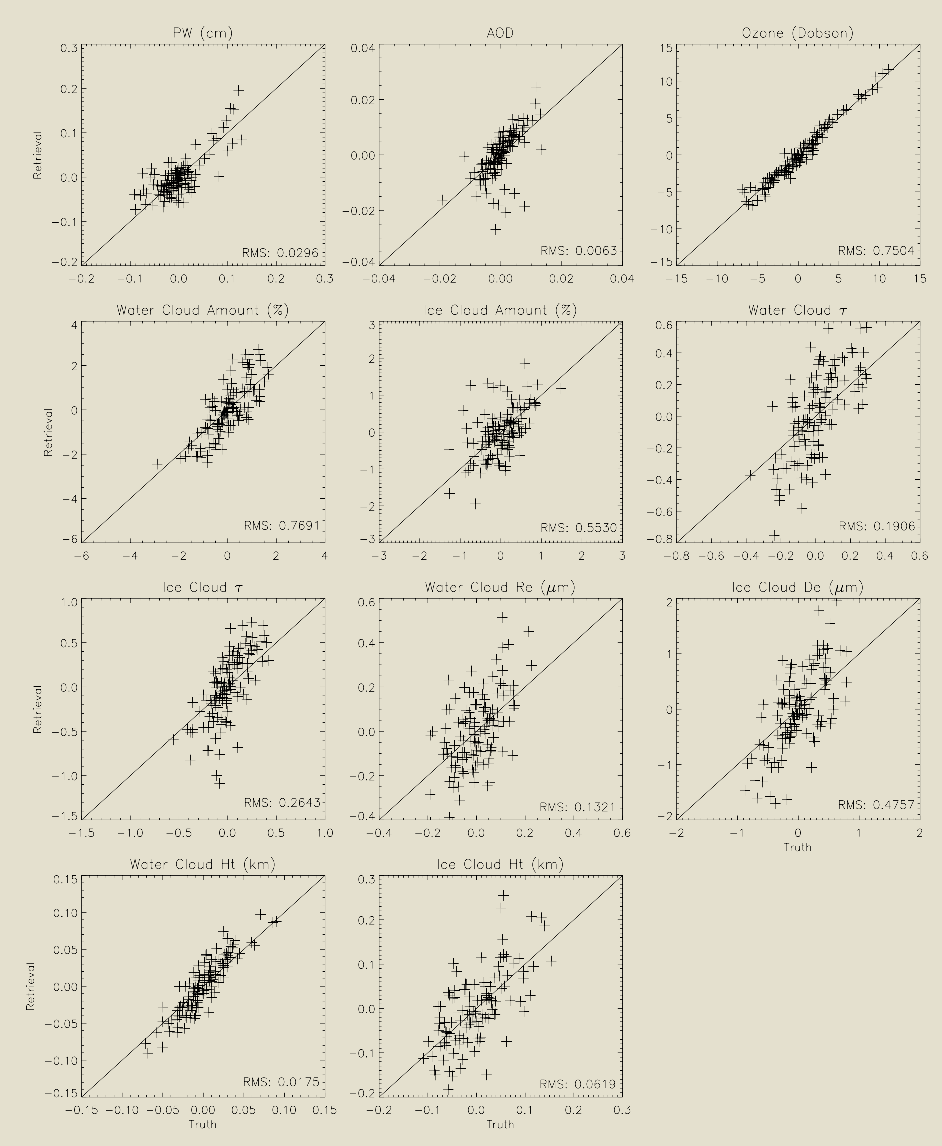
Two nonlinear error sources:

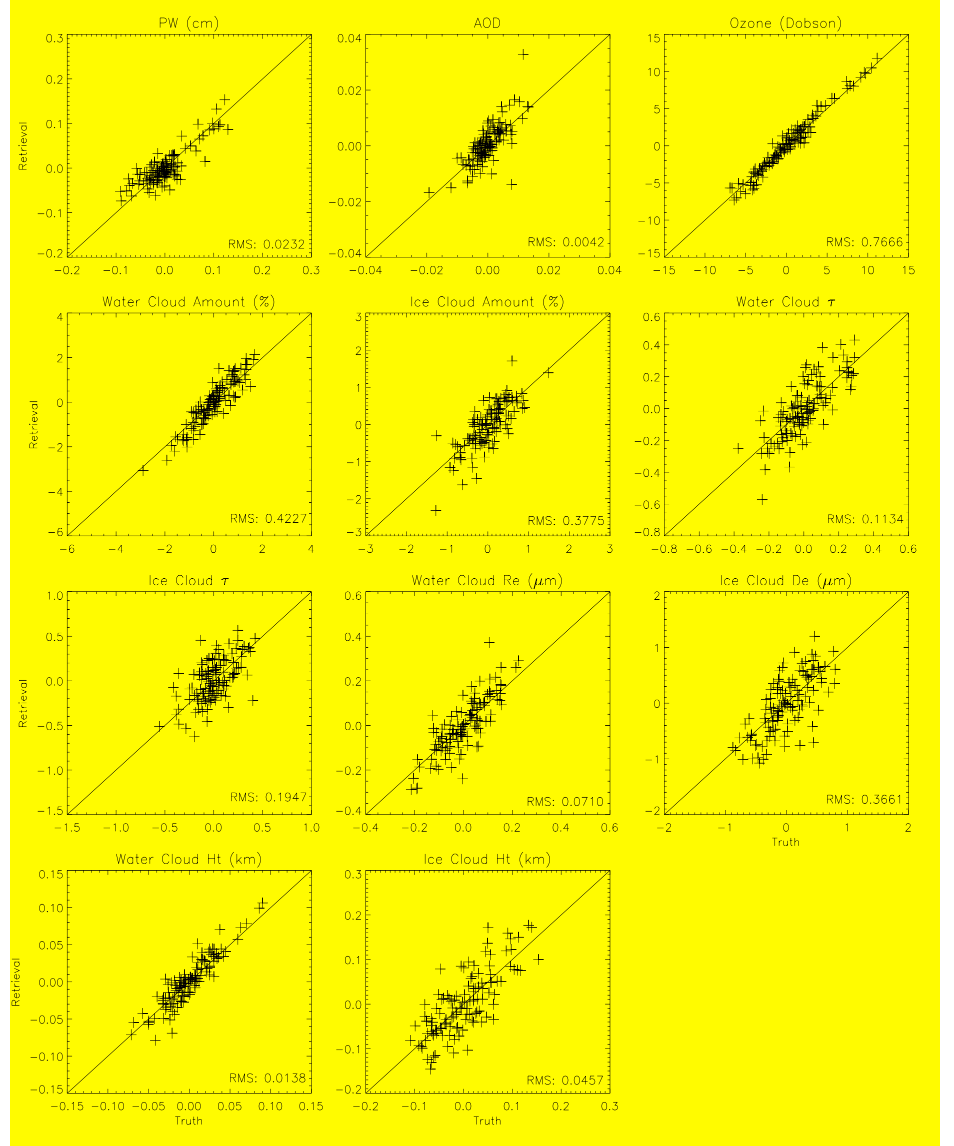
1). nonlinear radiative response :

$$\int_{x_0}^{x_0+\Delta x} K(x)\,dx \neq K(x_0)\Delta x$$

2). radiative interactions:

$$\Delta R \neq \Sigma_i \Delta R_i = \Sigma_i K \Delta X_i$$



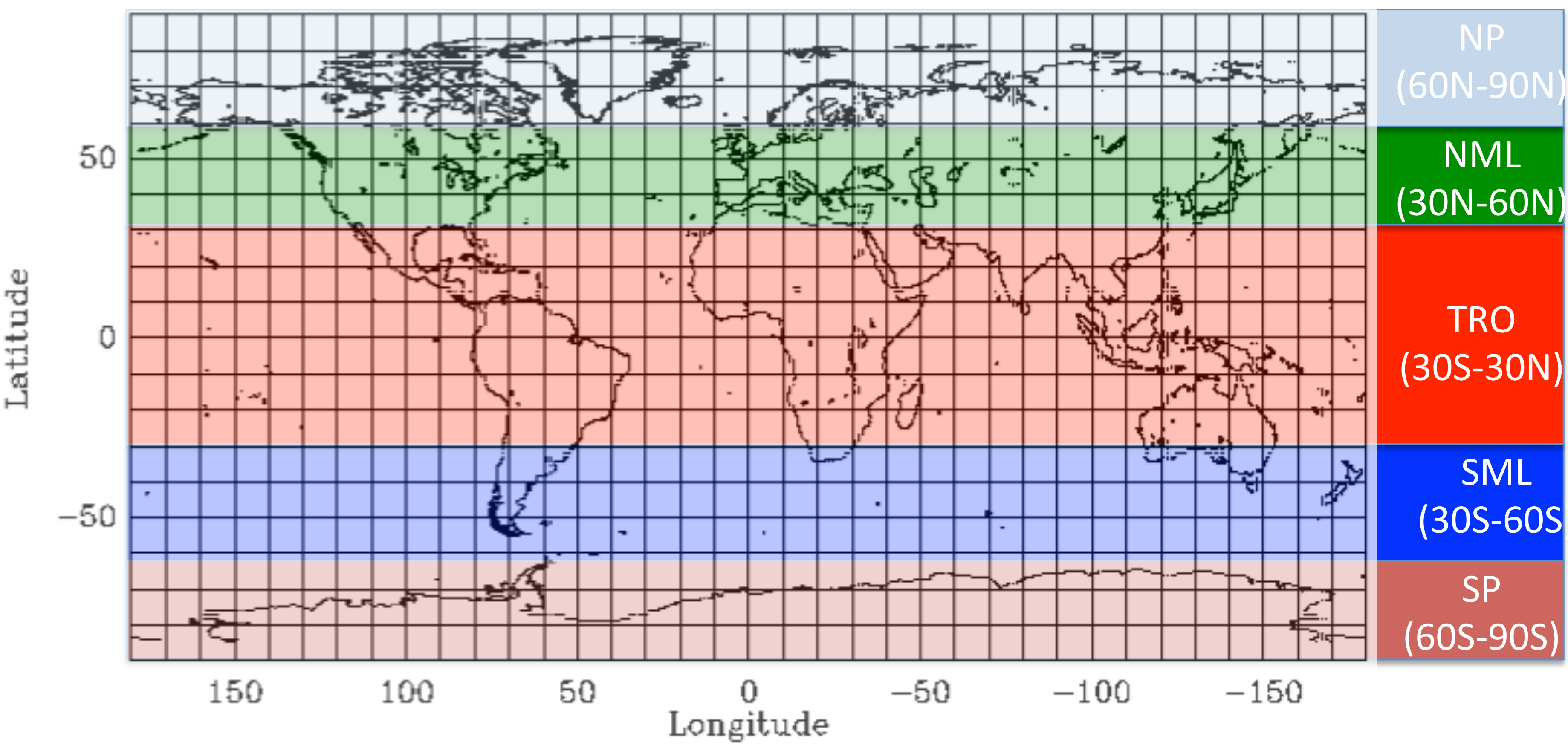


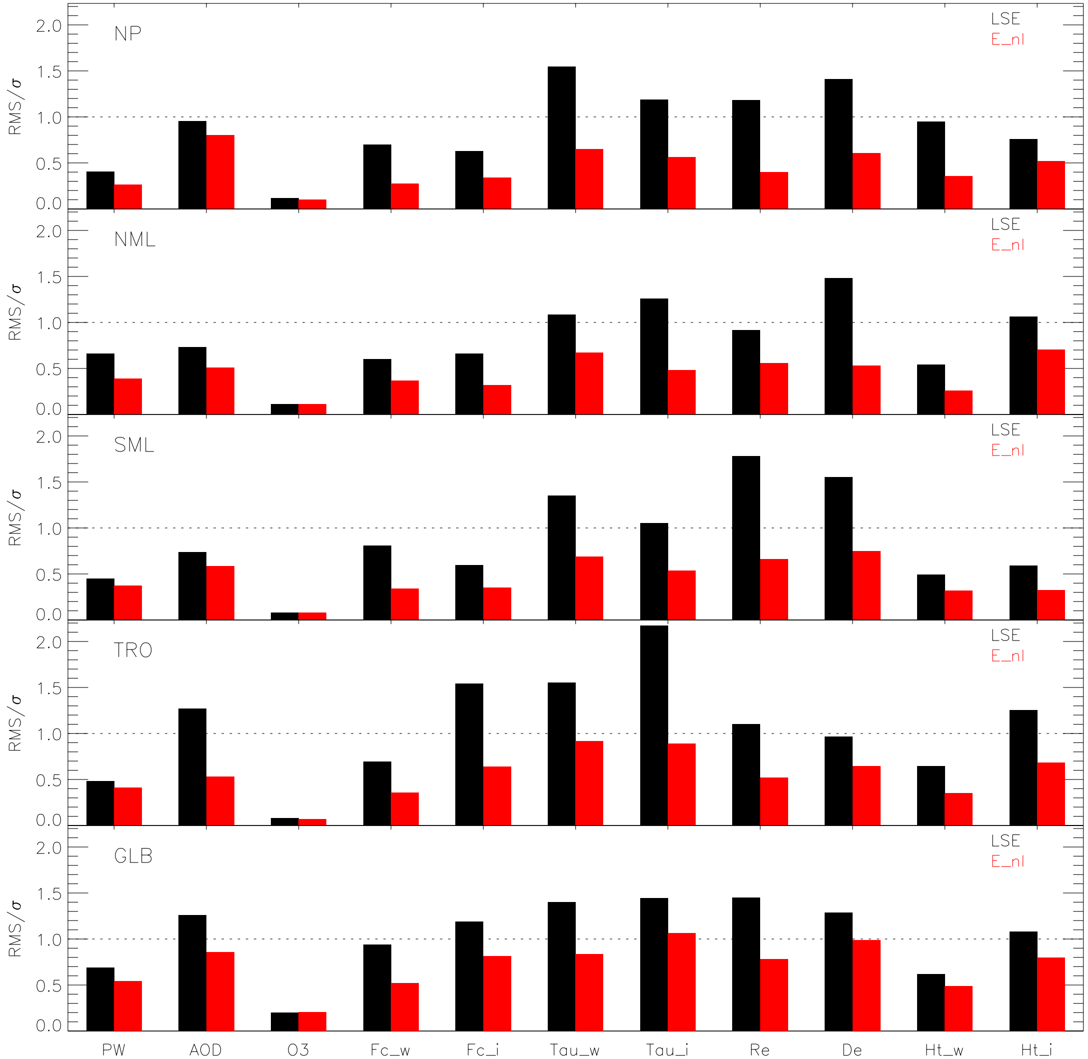
Without nonlinear errors considered

With nonlinear errors considered

With the averaged kernels and reflectance in the 5 large latitude regions, the fingerprinting retrieval as above is tested in these large regions and the results are similar as above.

Five latitude regions





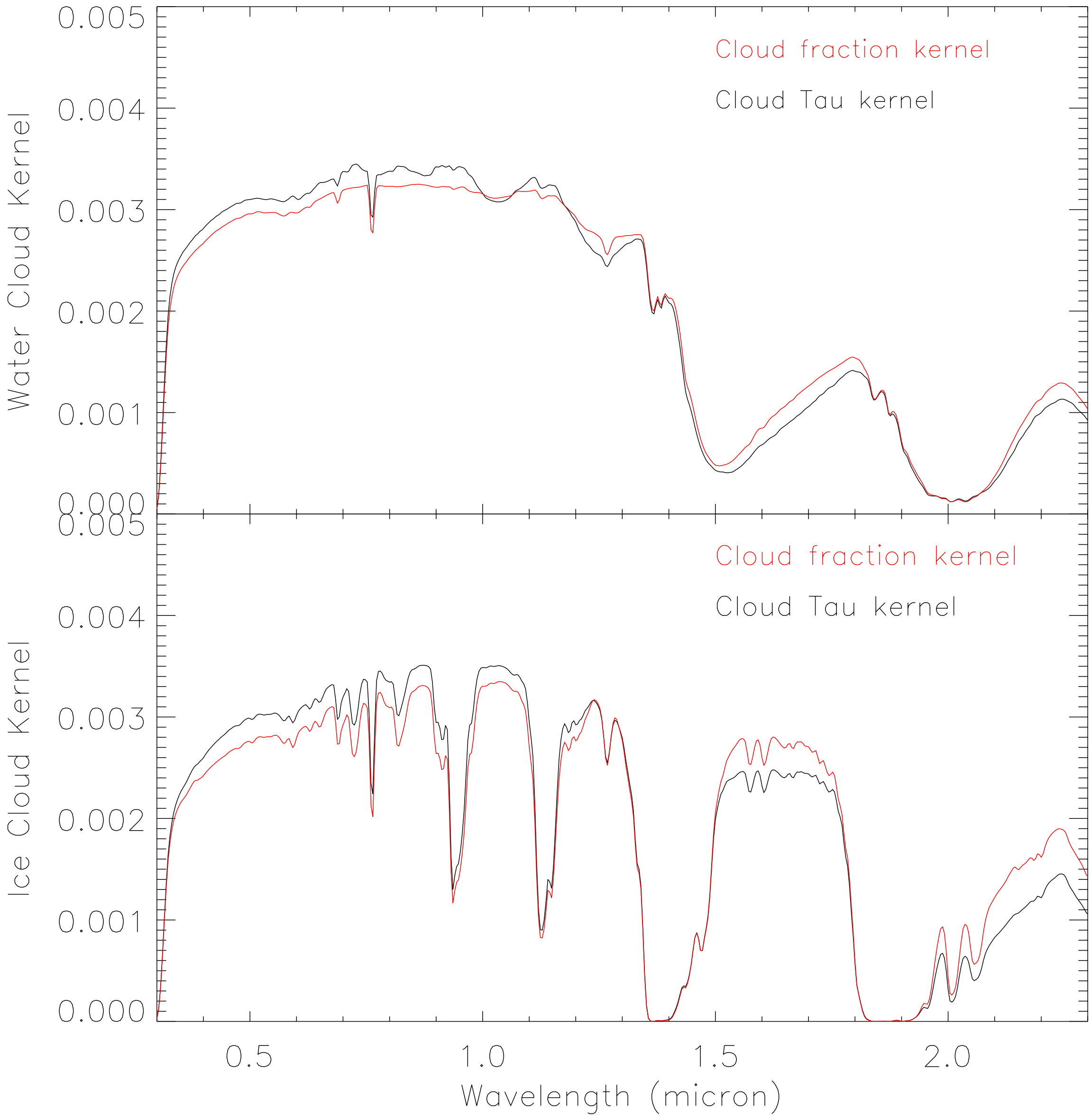
Without nonlinear error considered (LSE)

With nonlinear error considered (optimal detection)

RMS comparison in all regions fro all 11 parameters.

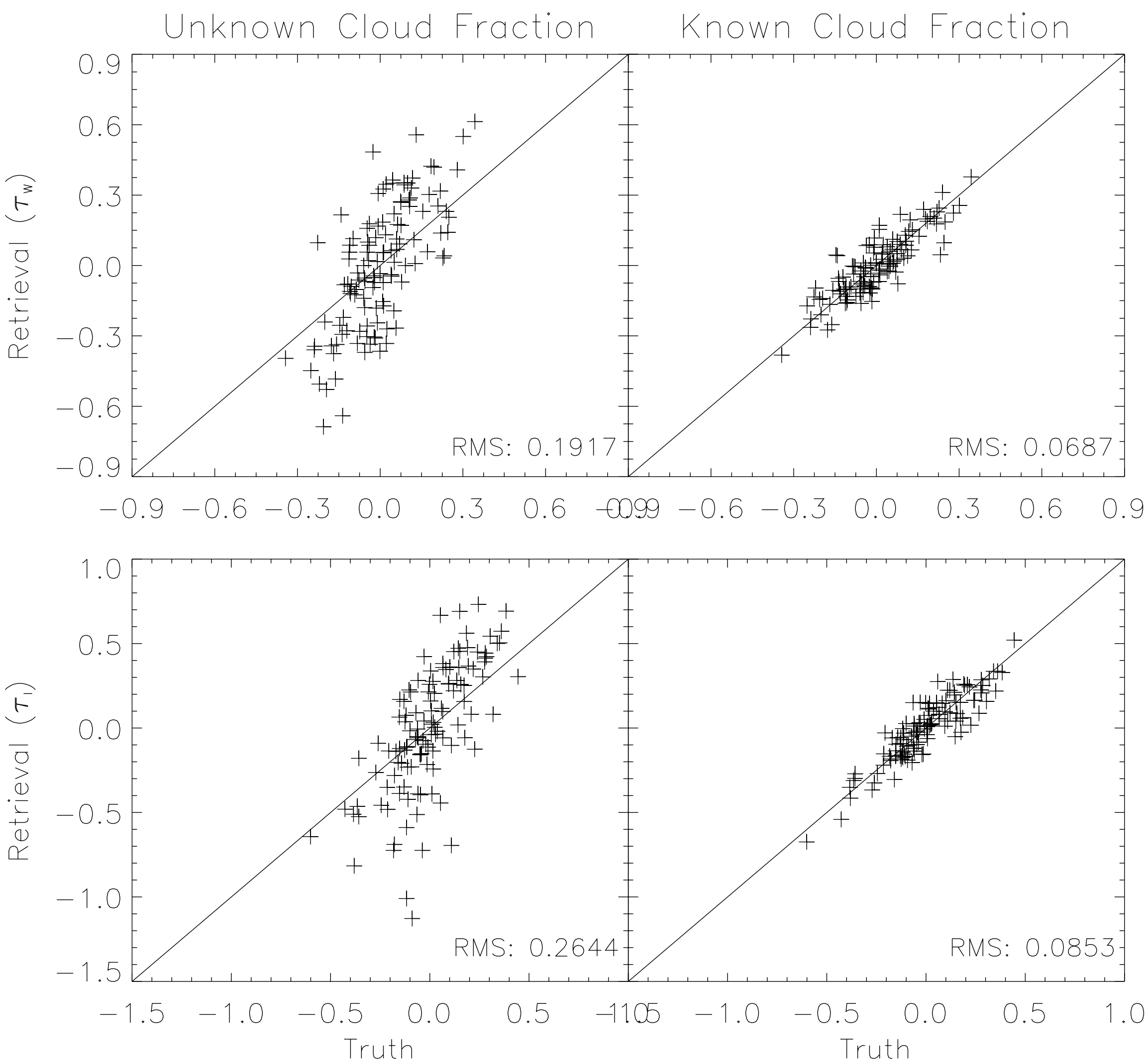
Each panel represents a different region.

The RMS is normalized by the variation **σ** for each parameter.



The kernel spectral shapes for the cloud fraction and the cloud σ are similar in many cases!

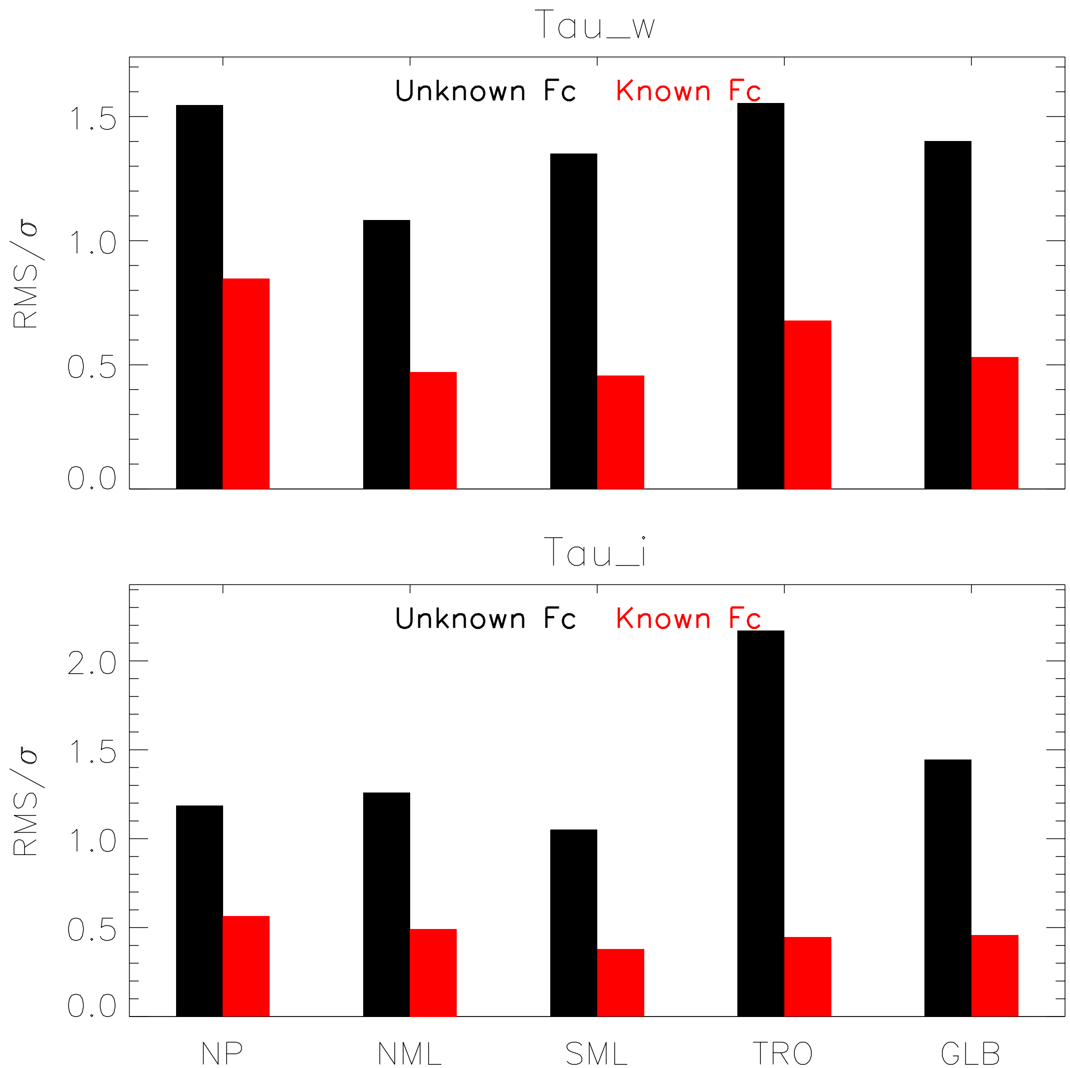
The upper panel is for water cloud and the lower panel is for ice cloud.
This example is for a zonal mean in the tropic (0N-10N).



A comparison of the cloud τ retrievals between two cases:

1) the cloud fraction is unknown and is also retrieved (the left panels);
2) the cloud fraction is known a priori in the retrieval (the right panels).

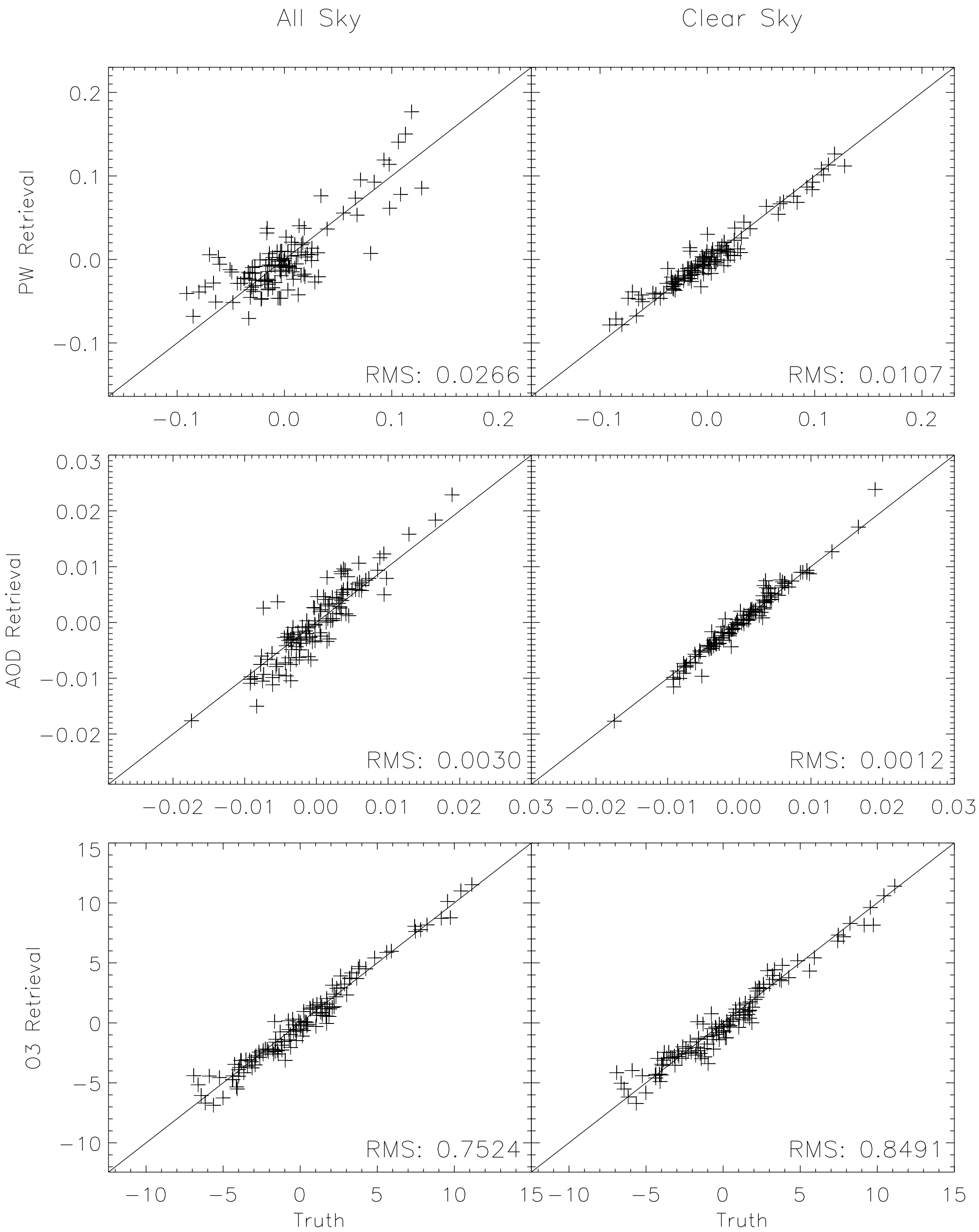
The upper panel is for water cloud and the lower panel is for ice cloud. This example is for the mean data between 60N to 60S in latitude.



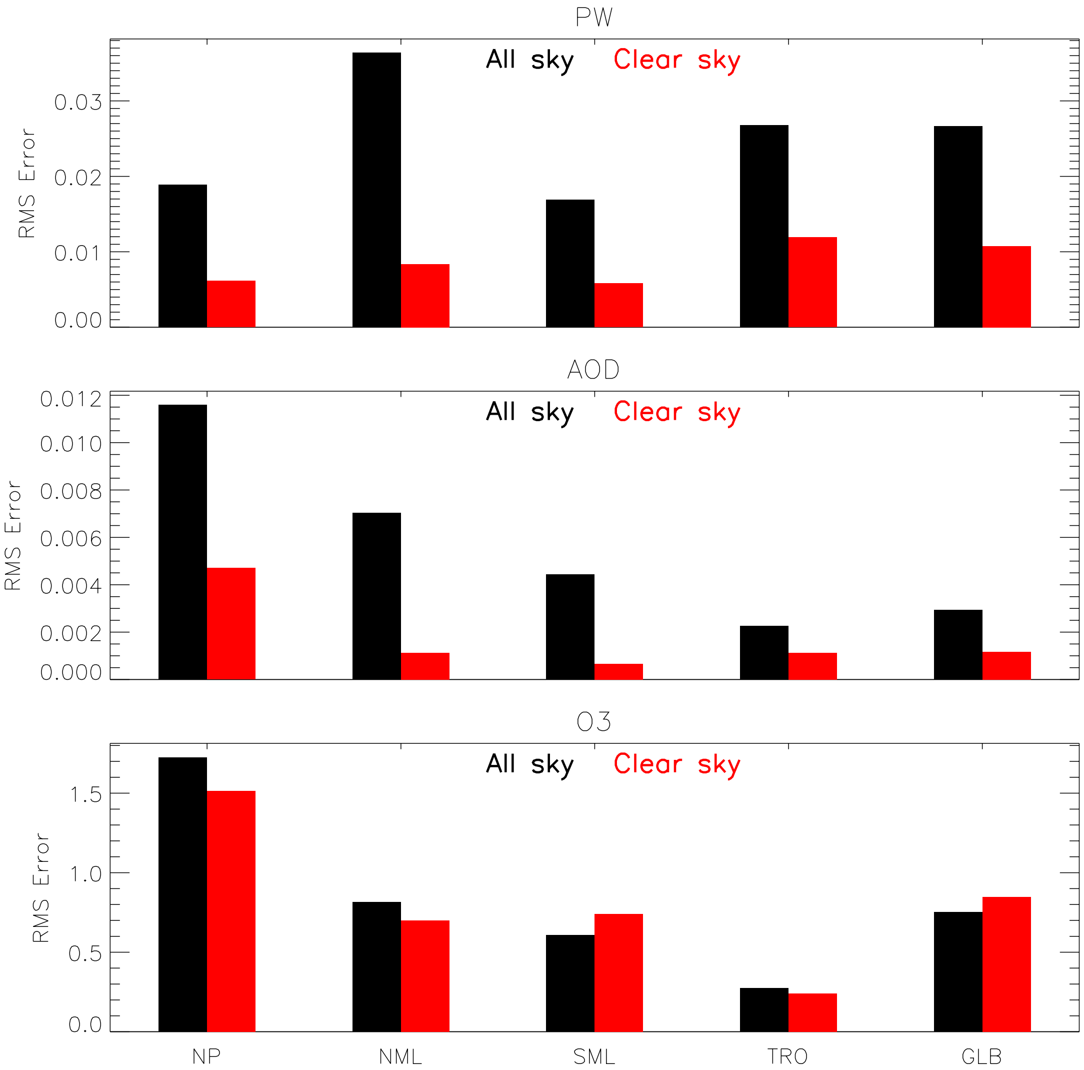
Comparison of the RMS errors in the retrieved cloud **τ** anomalies in the five climate regions between known and unknown cloud fraction. The upper panel is for water cloud and the lower panel is for ice cloud.

The improvement is general in all regions!

Suggesting a separate measure of cloud amount from CLARREO to unscramble cloud fraction and optical depth.



A retrieval comparison for the three atmospheric parameters (PW, AOD and ozone) between all sky and clear sky retrievals. Each row is for a different parameter.



Comparison of the retrieval RMS errors in the three parameters between clear sky and all sky retrievals in the five climate regions.

This example is for the mean data between 60N to 60S in latitude.

Conclusion

- ✓ Using ten years of satellite data, we tested the concept of using fingerprinting approach for climate change detection/attribution.
- ✓ Comparing the fingerprinting retrieval to the observational truth, the RMS differences are less than 2σ of the variance for all variables in all regions. A large error usually corresponds to the variables with large nonlinear radiative response, such as cloud **τ** and ice particle size.
- ✓ Using the optimal detection method to take into account the nonlinear radiative error in the kernels, the retrieval accuracy is significantly higher, so that the RMS errors are reduced to less than 1σ of the variance, indicating the profound impact of the nonlinear error on fingerprinting retrieval.
- ✓ Another important finding is that if the cloud fraction is known a priori, the retrieval accuracy in cloud **τ** would be improved substantially and generally; in addition, a better retrieval for the water vapor amount and aerosol optical depth can be achieved from the clear sky data only.
- ✓ This finding suggests a separate measure of cloud fraction by CLARREO to unscramble cloud fraction and optical depth variations.

- ✓ Ozone retrieval has the highest accuracy among all variables in all cases.
- ✓ The test results demonstrate that the concept of climate change fingerprinting based on the reflected solar benchmark spectra is viable.