Toward detection of atmospheric changes in spatially and temporally averaged infrared spectra observed by CLARREO

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Outline of this talk

• CERES TOA deseasonalized anomalies (understanding natural variability)
• Nadir view spectral radiance simulation
• Cloud effect on non-linear term
• Relationship between atmospheric and cloud properties and spectral radiance change
• Retrieval simulation and error estimate
• Effect of small-scale variability on spectral radiance difference
• Future work
TOA flux anomalies from CERES

Blue line: global
Red line: tropics 30S to 30N
200801 – 200701 TOA Albedo and Longwave radiative flux and cloud fraction differences

Cloud fraction is computed for 200 m × 1° latitude grid boxes.
Spectral radiance computations

- MODIS (by Ed2 CERES cloud algorithm) derived cloud properties
- Temperature and humidity profiles are from GEOS-4 (reanalysis)
- Control (unperturbed) run is from 2003 and 2004
- Nadir view only
- Spectral radiance change is computed by perturbing 2003 and 2004 atmospheres
- TOA spectral radiances are computed with a 20 km spatial resolution for every CERES nadir view footprints
- Emphasis on understanding variability at a high temporal resolution
Mean spectral radiance

Spectral radiance averaged over Time Period 1 (reference)

\[ I_1(x_1) = I(x_1) + \sum_j \frac{1}{n_1} \sum_{i=1}^{n_1} \left[ \frac{\partial I(\bar{x}_1)}{\partial x_j} + \sum_k \frac{\partial^2 I(\bar{x}_1)}{\partial x_j \partial x_{ki}} \delta x_{1ki} \right] \delta x_{1ji}, \]

Time period 2, instantaneous

\[ \Delta x = \bar{\Delta x} + \bar{\delta x} \]

\[ I_2(x_2i) = I(\bar{x}_1) + \sum_j \left[ \frac{\partial I(\bar{x}_1)}{\partial x_j} + \sum_k \frac{\partial^2 I(\bar{x}_1)}{\partial x_j \partial x_{ki}} \Delta x_{ki} \right] \Delta x_{ji}, \]

Spectral radiance averaged over Time Period 2

\[ I_2(x_1 + \Delta x) = I(\bar{x}_1) + \sum_j \frac{1}{n_2} \sum_{i=1}^{n_2} \left[ \frac{\partial I(\bar{x}_1)}{\partial x_j} \Delta x_j + \sum_k \frac{\partial^2 I(\bar{x}_1)}{\partial x_j \partial x_{ki}} \Delta x_{ki} \Delta x_j + \frac{\partial I(x_2)}{\partial x_{ji}} \delta x_{2ji} \right] \]
Atmospheric and cloud property change retrieval

Spectral radiance difference, Time period 2 – Time period 2

\[ \Delta I = \sum_j \left\{ \frac{\partial I(x_1)}{\partial x_j} \Delta x_j + \frac{1}{n_1} \sum_{i=1}^{n_1} \sum_k \frac{\partial^2 I(x_1)}{\partial x_j \partial x_{ki}} \delta x_{ki} \Delta x_j + \sum_k \frac{\partial^2 I(x_1)}{\partial x_j \partial x_k} \Delta x_k \Delta x_j + \epsilon_{4j} + \epsilon_{5j} \right\} \]

where

\[ \epsilon_{4j} = \frac{1}{n_2} \sum_{i=1}^{n_2} \frac{\partial I(x_2)}{\partial x_{ji}} \delta x_{2ji} - \frac{1}{n_1} \sum_{i=1}^{n_1} \frac{\partial I(x_1)}{\partial x_{ji}} \delta x_{1ji} \]

(5)

and

\[ \epsilon_{5j} = \frac{1}{n_2} \sum_{i=1}^{n_2} \sum_k \frac{\partial^2 I(x_1)}{\partial x_j \partial x_{ki}} \delta x_{2ki} \Delta x_j - \frac{1}{n_1} \sum_{i=1}^{n_1} \sum_k \frac{\partial^2 I(x_1)}{\partial x_j \partial x_{ki}} \delta x_{1ki} \Delta x_j \]

Small scale variability difference

Kernel variability

Kernel to retrieve mean atmospheric and cloud changes is Term 1 + Term 2

Term 3 (non-linear term) can be included in the kernel.

Term 4 and Term 5 are noise.
Non-linear term (annual global mean)

Cloud fraction change is included

Cloud fraction change is excluded

\[ \Delta I \left( \sum \Delta x \right) - \sum \Delta I(\Delta x) \]
Cloud fraction change significantly increases the non-linear term

\[
\frac{\Delta I(\sum \Delta x) - \sum \Delta I(\Delta x)}{\Delta I(\sum \Delta x)}
\]
Relationship between atmospheric and cloud changes and TOA spectral radiance change

\[ \frac{\Delta I(2\Delta x) - \Delta I(\Delta x)}{\Delta I(\Delta x)} \]

\(\Delta I\): 10° zonal monthly radiance change

Blue: mean of monthly 10°
Red: mean of annual 10°

Surface temp.: +0.2K
Sfc to 200 hPa Temp.: +0.2K
200 to 10 hPa Temp.: -0.2K

Sfc-500 hPa precip. water: +2.5%
500 to 200 hPa precip. water: +2.5%
Ice cloud OD: +30%

Low cloud height: +0.25km
Mid cloud height: +0.25km
High cloud height: +0.20km
Error \((\varepsilon_4 + \varepsilon_5)\) term estimate

\[
\Delta I = \sum_j \left\{ \frac{\partial I(\tilde{x}_1)}{\partial x_j} \Delta x_j + \frac{1}{n_1} \sum_{i=1}^{n_1} \sum_k \frac{\partial^2 I(\tilde{x}_1)}{\partial x_j \partial x_{ki}} \delta x_{ki} \Delta x_j + \sum_k \frac{\partial^2 I(\tilde{x}_1)}{\partial x_j \partial x_k} \Delta x_k \Delta x_j + \varepsilon_4 + \varepsilon_5 \right\}
\]

Term 1

Term 2

Term 3

Term 4

Term 5

Mean spectral radiance change computed with high temporal resolution (Terms 1, 2, 3, 4, and 5)
- Mean spectral change computed with annual mean atmospheres (Terms 1 and 3)
- Term 2 (estimated form perturbed run of the time period 1)

\[
a_c = \left( S^T S + \lambda H \right)^{-1} S^T \Delta I
\]

\[
Var(a_c) = \left( S^T S + \lambda H \right)^{-1} S^T (\varepsilon \varepsilon^T) S \left( S^T S + \lambda H \right)^{-1}
\]

When \(\lambda = 0\),

\[
\left[ S^T (\varepsilon \varepsilon^T)^{-1} S \right]^{-1}
\]
Temperature retrieval
(2003 2004 annual mean difference)

Retrieved from 10° zonal annual mean spectra

Red: true values
Blue open circles: retrieved values
Error bars: Uncertainty in retrieved values
Upper tropospheric water vapor
(2003 2004 annual mean difference)

Retrieved from 10° zonal annual mean spectra

Red: true values
Blue open circles: retrieved values
Cloud fraction retrieval
(2003 2004 annual mean difference)

The uncertainties averaged over 18 10° zones are:
Low cloud height:  ±2.0 km
Low cloud fraction: ±0.2
High cloud fraction: ±0.4
Because of Terms 4 and 5

Red: true values
Blue open circles: retrieved values
Effect of averaging atmospheric and cloud properties

Instantaneous spectrum computations: compute spectra for all 20 km footprints
Monthly mean: compute spectra with monthly mean atmospheric and cloud properties
Terms 2, 4, and 5 are not included
Modeled natural variability comparison

Global annual mean difference

Standard deviation ratio
Monthly 10° zonal: \( \frac{\sigma_{\text{Monthly}}}{\sigma_{\text{Inst.}}} \)

Correlation coefficient

Nadir view radiance difference, 2004 – 2003

Red: Computed with instantaneous 20 km footprints (high temporal resolution) \( \sigma_i \)

Blue: Computed with monthly mean atmospheric and cloud properties \( \sigma_m \)
Simulation with CALIPSO/CloudSat derived cloud properties

• Understand spectral shape and size of all terms (instantaneous spectrum computations & spectrum computations with mean atmospheric and cloud properties)

• 44 months of data (from July 2006 through Feb. 2010)

• Spectral radiative kernels
Comparison of LW broadband variability

Global Deseasoned LND

Closed circles: CERES
Open circles: Model

Global Deseasoned ICE

Closed circles: CERES
Open circles: Model

PCRTM -0.00 (0.38)
CERES 0.00 (0.32)
PCRTM-CERES 0.00 (0.14)

PCRTM -0.00 (2.80)
CERES -0.00 (2.55)
PCRTM-CERES 0.00 (1.00)

R^2 = 0.927
R^2 = 0.934
Variability comparison

Global Deseasoned ALL

Nadir Radiance [W/m^2/str-1]

Month (start Jul06)

PCRTM 0.00 (0.15)
CERES -0.00 (0.14)
PCRTM-CERES -0.00 (0.14)

R^2 = 0.562

Closed circles: CERES
Open circles: Model

Global Deseasoned OCE

Nadir Radiance [W/m^2/str-1]

Month (start Jul06)

PCRTM 0.00 (0.15)
CERES -0.00 (0.11)
PCRTM-CERES 0.00 (0.16)

R^2 = 0.282
Summary and future plan

• Demonstrated the importance of small scale variability in inferring atmospheric and cloud property changes from temporally and spatially averaged longwave spectral radiances.
• Use CALIPSO/CloudSat/MODIS derived cloud fields to model spectral radiances.
• Compare natural variability with AIRS observations.
• Reducing retrieval error by treating bias error terms (all-sky, clear-sky, subtracting bias etc.)
Back-ups