Band-by-band radiative flux and cloud radiative forcing: derivation and application in climate studies

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Huang, X.L, W.Z. Yang, N. G. Loeb, V. Ramaswamy., *Spectrally resolved fluxes derived from collocated AIRS and CERES measurements and their application in model evaluation, Part I: clear sky over the tropical oceans*, JGR, in press

Roadmap

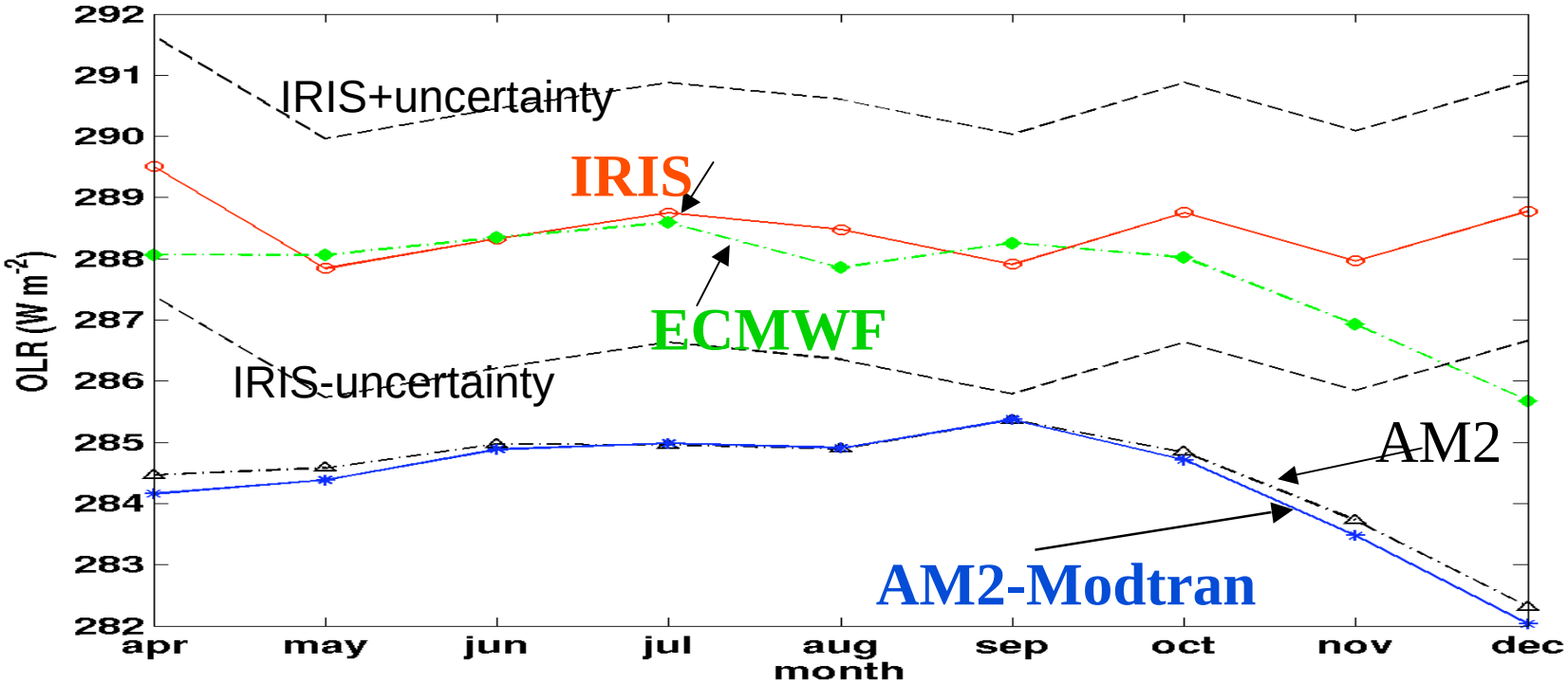
- Motivation
- Datasets and modeling tools
- Algorithm
- Validation
  - Theoretical validation
  - Comparison with the CERES OLR
- AIRS/CERES vs. GFDL AM2
- Conclusions

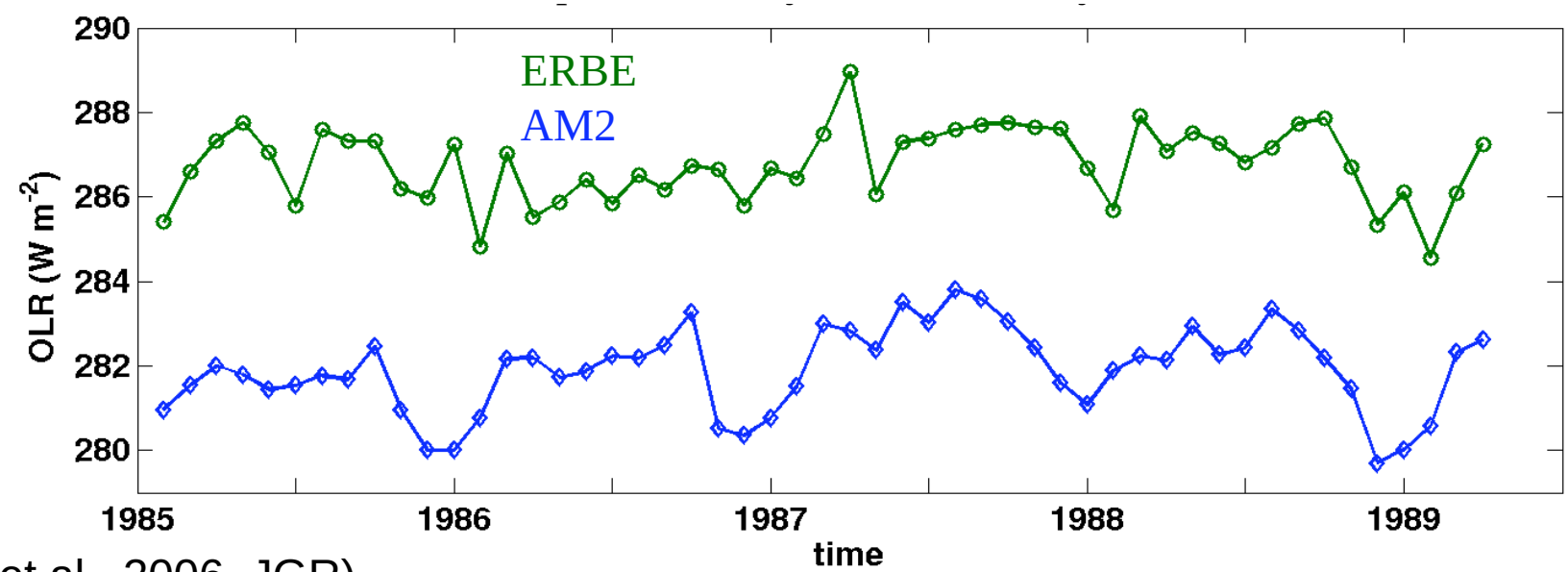
Objectives

1. Derive spectral fluxes at $10cm^{-1}$ intervals over the entire longwave spectrum from the AIRS radiance measurements with the help of collocated CERES scene type info.
2. Use such derived products to
   a. Directly evaluate the LW band-by-band flux and band-by-band CRF computed by the climate models.
   b. In the long run, the biases in the CRF and flux of each band → feedback to the simulated radiation and water substances interactions.

Motivations (I): modeling perspective

- Compensating biases from different spectral bands can make the understanding of the whole broadband deficiencies difficult

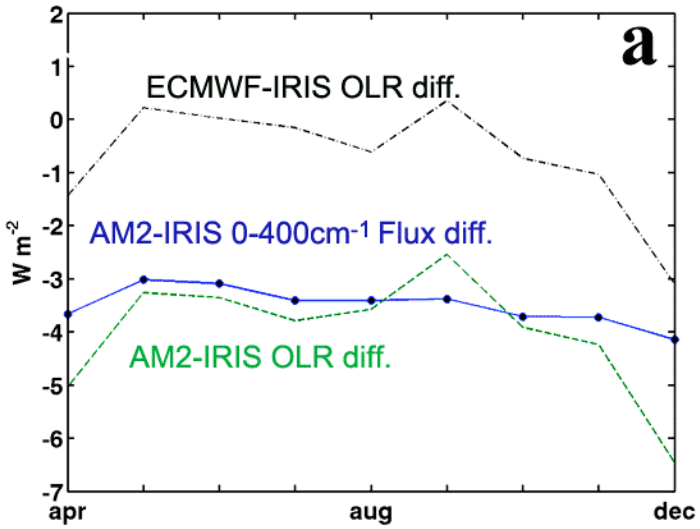


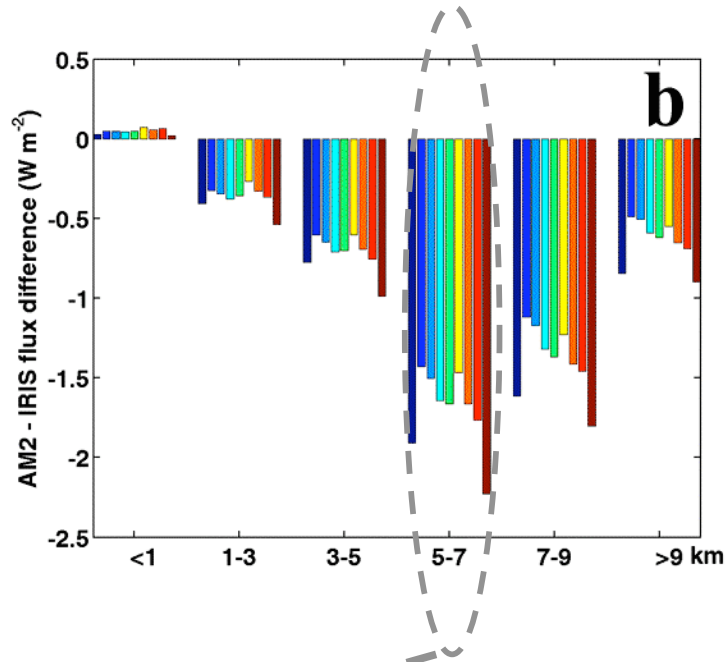


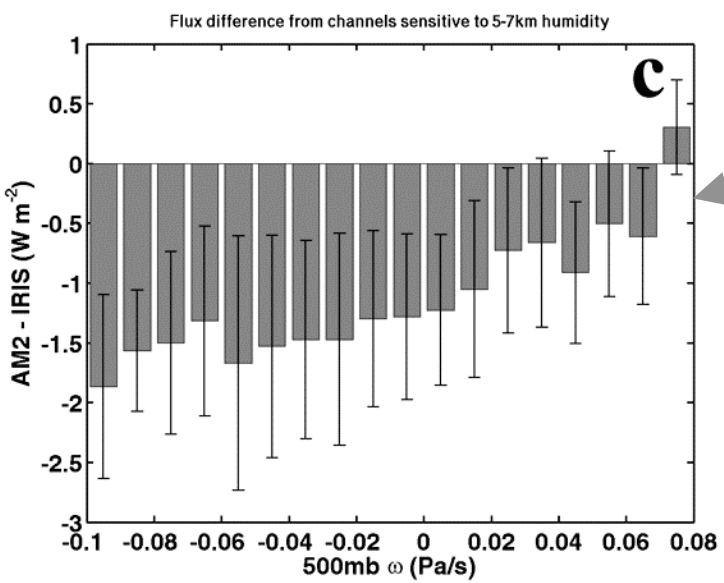
(Huang et al., 2006, JGR)

All-sky OLR are tuned to be with ERBE ~2Wm^{-2}

AM2-IRIS H_2O channels







radiance→ diagnose flux bias → link to dynamics

Huang et al, JGR 2006

Motivations (II): modeling perspective

- Band-by-band flux and CRF
  - Direct output from models
  - A more stringent metric in model evaluation and tuning practice

Motivations (II): observational perspective

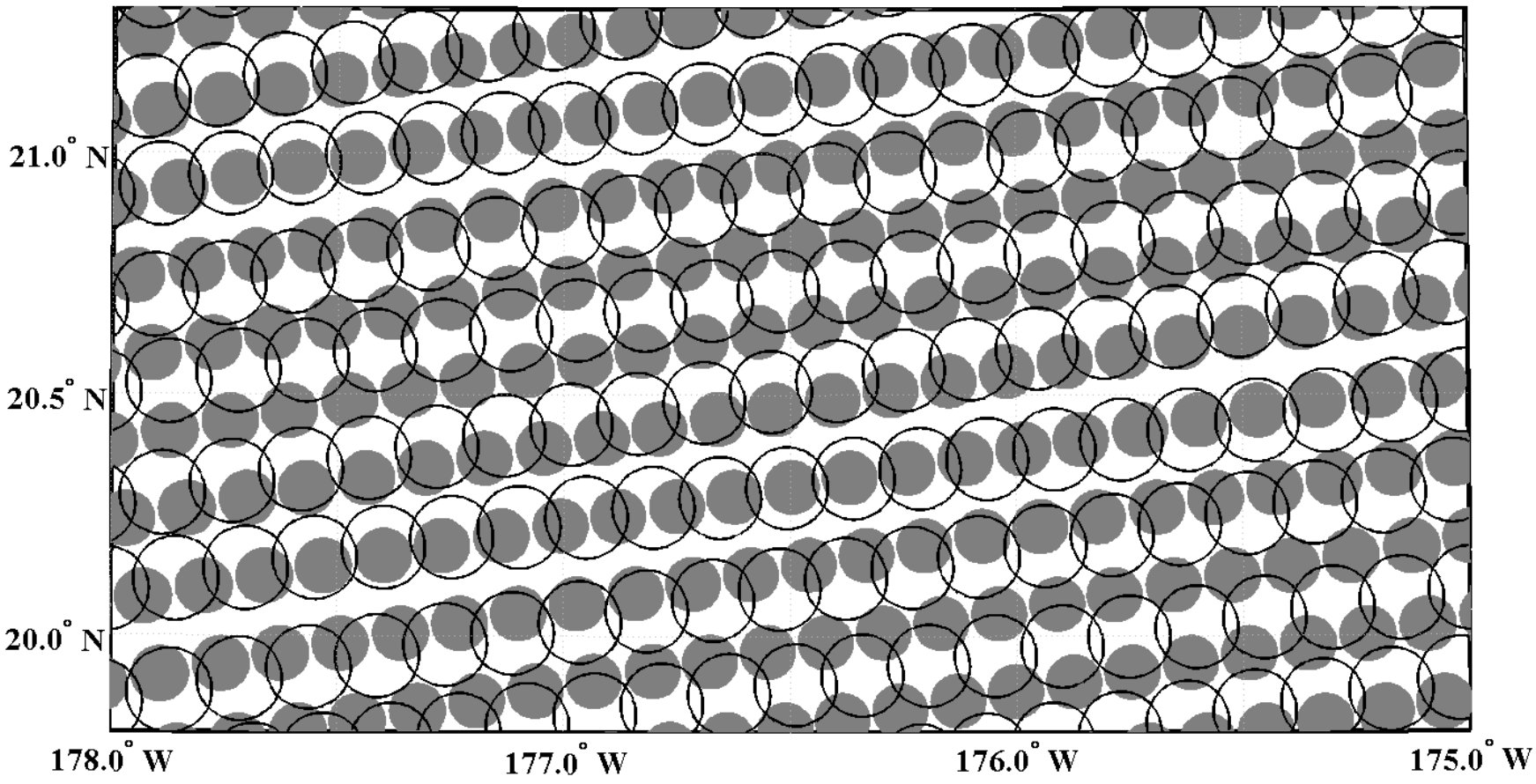
- AIRS and CERES on Aqua: a timely opportunity

  (a) good collocation

  (b) dense sampling patterns

  (c) CERES has well-developed angular distribution models (ADMs) and scene type classification schemes

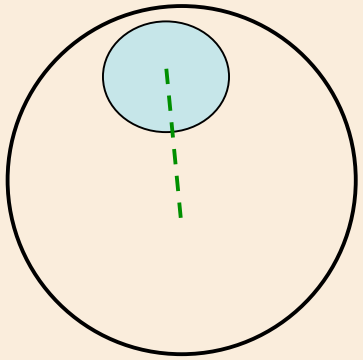
AIRS and CERES footprints



CERES AIRS

01:06:15 to 01:06:45 UTC on January 1, 2005

Datasets



- CERES SSF data product (edition 2A)
  - Cross-scanning mode only
  - CERES scene types and ADMs
- AIRS
  - 3.74-4.61μm (2169-2673 cm^{-1}) excluded
  - Quality control: filtering out bad channels
- Collocation criteria
  - Time separation ≤ 8 seconds
  - Spatial separation ≤ 3km
- Focus on measurements over the tropical oceans in 2004

Modeling tools

- Modtran™-5 for forward modeling of radiative transfer
  - Compute spectra at $0.1 cm^{-1}$ resolution
  - Good agreement with LBLRTM
  - AIRS SRF→ synthetic AIRS spectra
- GFDL AM2 (am2p14)
  - forced with observed SST and appropriate greenhouse gases (ozone fixed at 1990s)
  - 3-hourly output further sampled to satellite tracks

Algorithm (I): anisotropic factor

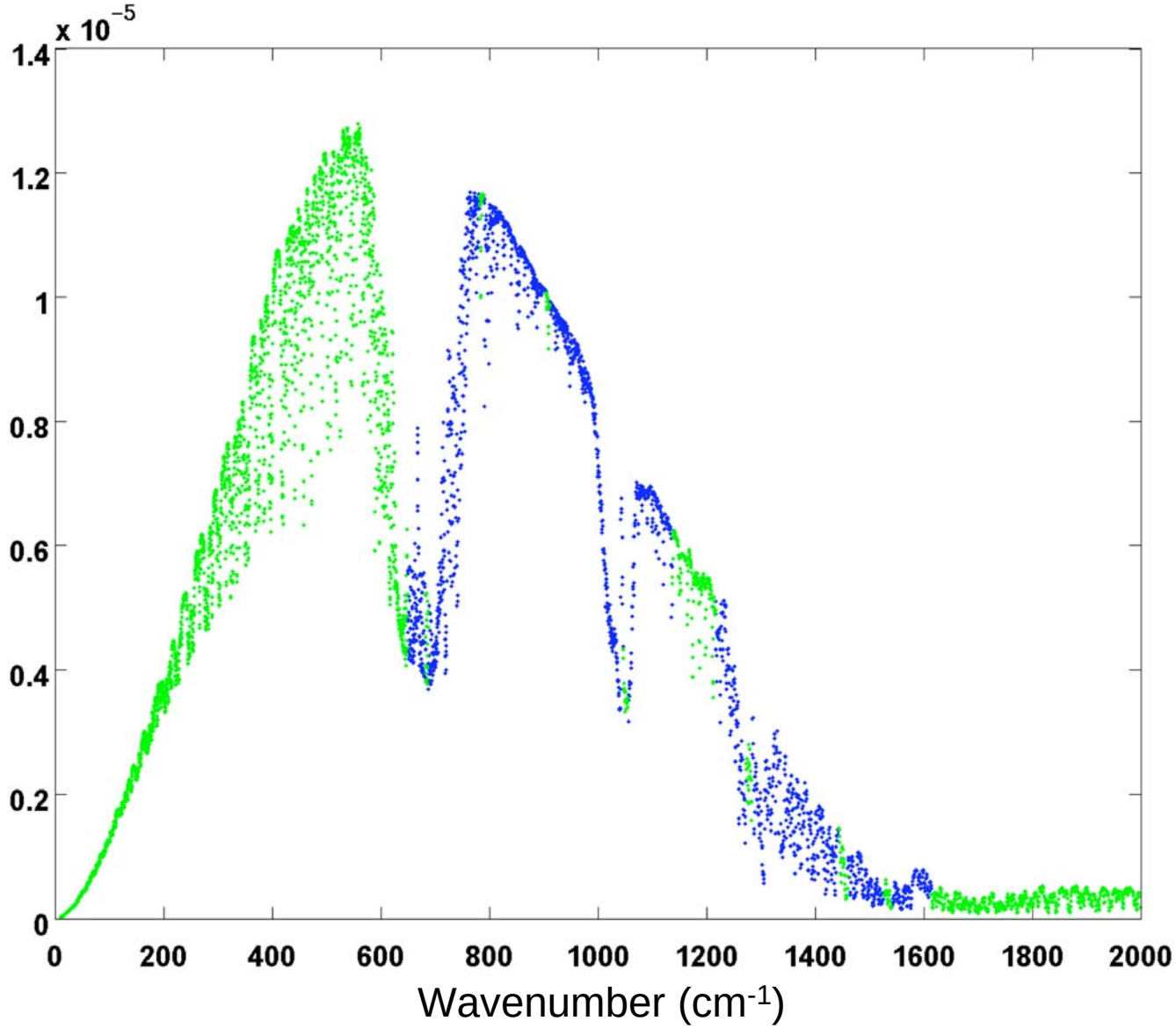
- For each predefined CERES scene subtype, construct corresponding anisotropic factor for each AIRS channel
- ECMWF 6-hourly reanalysis is used (~80,640 profiles) to construct the clear-sky spectral ADMs for AIRS channels
- Cloudy spectral ADMs are constructed in a similar way

$$R(\Delta\nu,\theta) = \frac{\pi I_{\Delta\nu}(\theta)}{F_{\Delta\nu}}$$

Algorithm (II): spectral regions with no AIRS coverage

- AIRS spectrum: varying resolution, no continuous coverage
- Spectral coverage
  - Single coverage by AIRS channels
  - Duplicated coverage by AIRS channels
    - Exclude the duplicated coverage
  - No coverage at all
    - Fill in channels with the same spectral resolution as the nearest AIRS channels
    - Estimate fluxes for all “filled-in” channels

- AIRS channels
- “filled-in” channels



An PCA-based scheme to estimate flux: basic idea

"Filled-in" channel

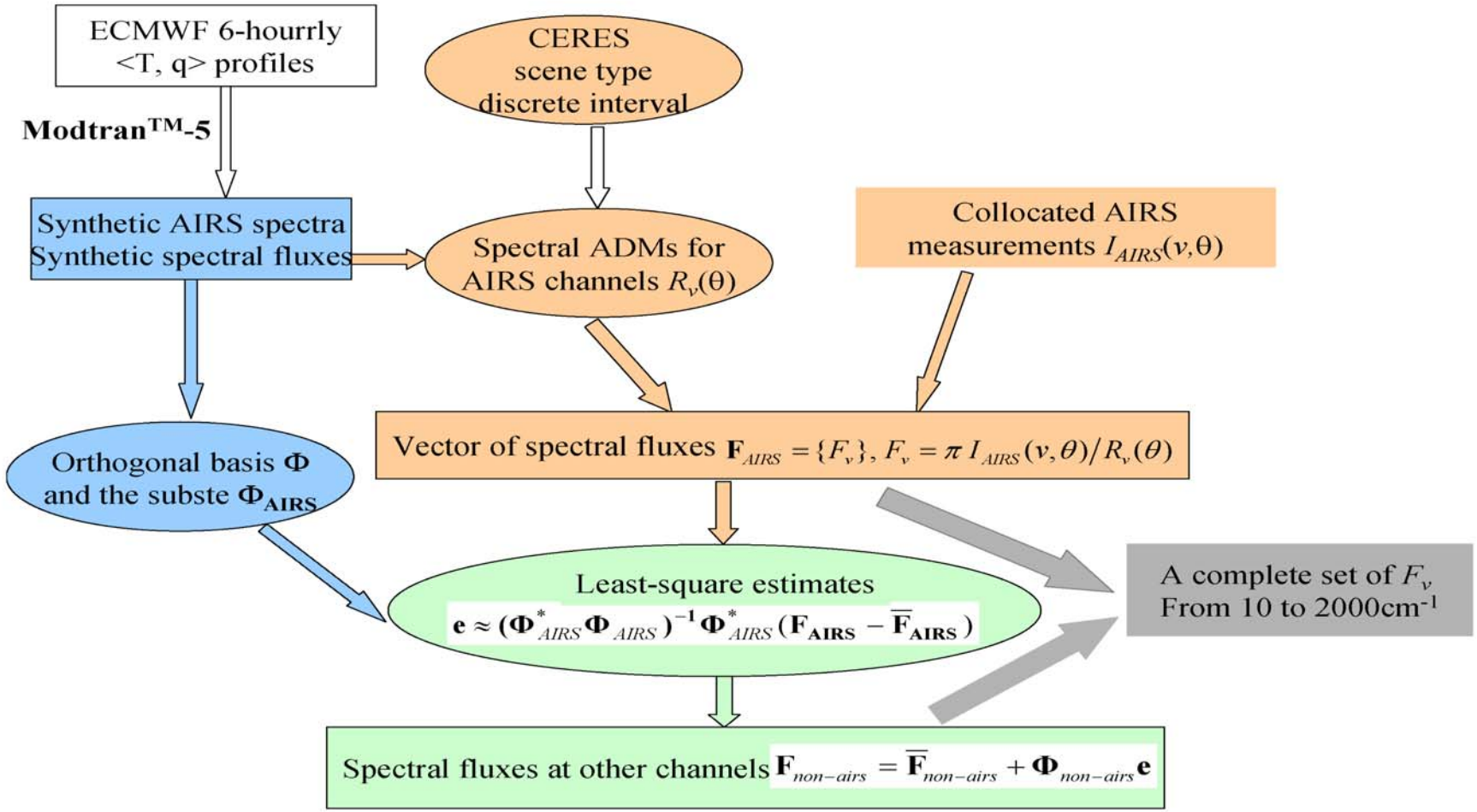
AIIRS channels

"Filled-in" channel

$$\begin{bmatrix} F_{v1} \\ F_{v2} \\ F_{v3} \\ F_{v4} \\ F_{v5} \\ F_{v6} \\ F_{v7} \\ \dots \end{bmatrix} = \begin{bmatrix} \overline{F}_{v1} \\ \overline{F}_{v2} \\ \overline{F}_{v3} \\ \overline{F}_{v4} \\ \overline{F}_{v5} \\ \overline{F}_{v6} \\ \overline{F}_{v7} \\ \dots \end{bmatrix} + e_1 \begin{bmatrix} \phi^1{}_{v1} \\ \phi^1{}_{v2} \\ \phi^1{}_{v3} \\ \phi^1{}_{v4} \\ \phi^1{}_{v5} \\ \phi^1{}_{v6} \\ \phi^1{}_{v7} \\ \dots \end{bmatrix} + e_2 \begin{bmatrix} \phi^2{}_{v1} \\ \phi^2{}_{v2} \\ \phi^2{}_{v3} \\ \phi^2{}_{v4} \\ \phi^2{}_{v5} \\ \phi^2{}_{v6} \\ \phi^2{}_{v7} \\ \dots \end{bmatrix} + e_3 \begin{bmatrix} \phi^3{}_{v1} \\ \phi^3{}_{v2} \\ \phi^3{}_{v3} \\ \phi^3{}_{v4} \\ \phi^3{}_{v5} \\ \phi^3{}_{v6} \\ \phi^3{}_{v7} \\ \dots \end{bmatrix} + O(F_v)$$

$$< \phi^i, \phi^j > = \begin{cases} 0 & i \neq j \\ 1 & i = j \end{cases}$$

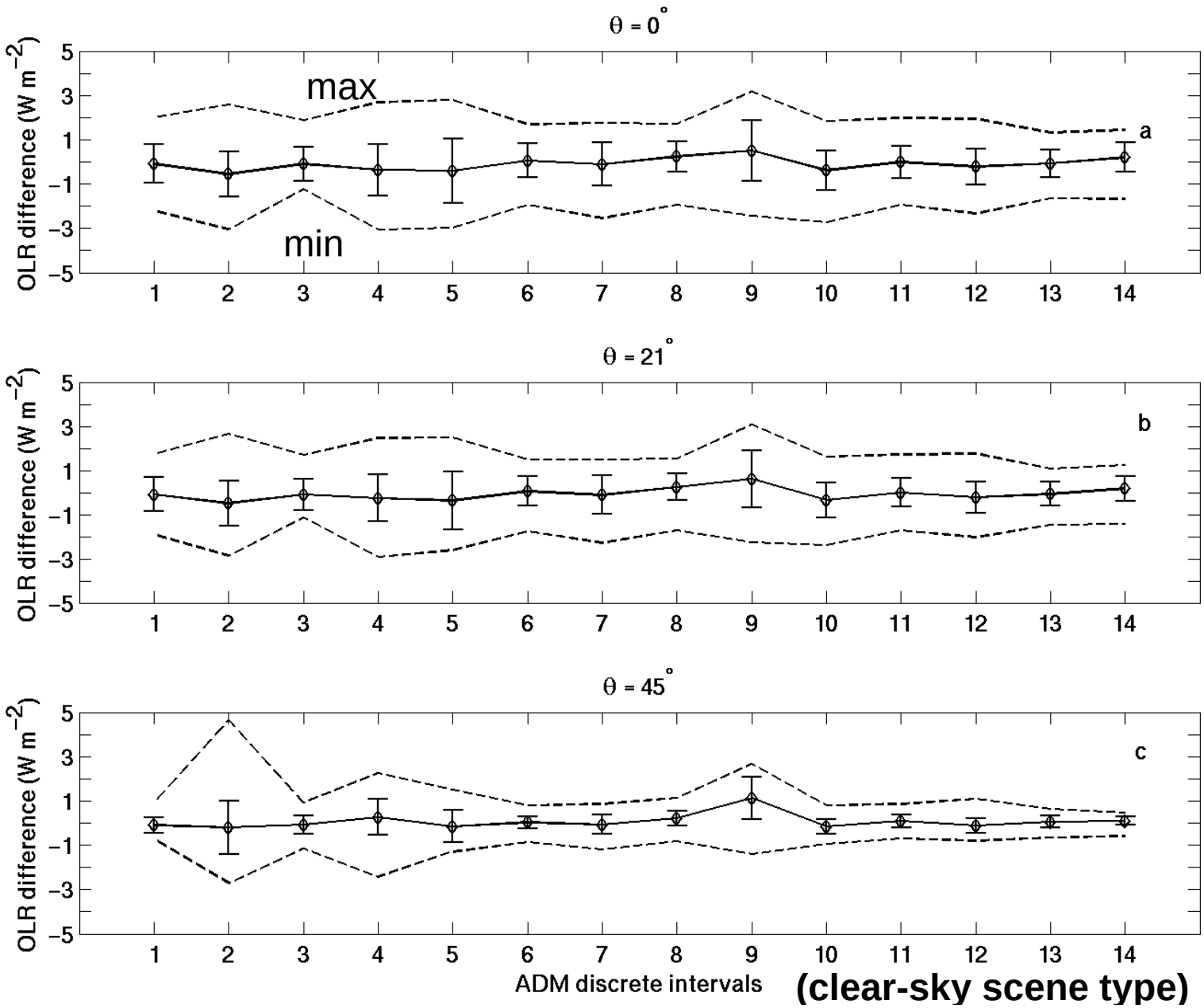
Flowchart for the entire algorithm



Validation (I): theoretical validation

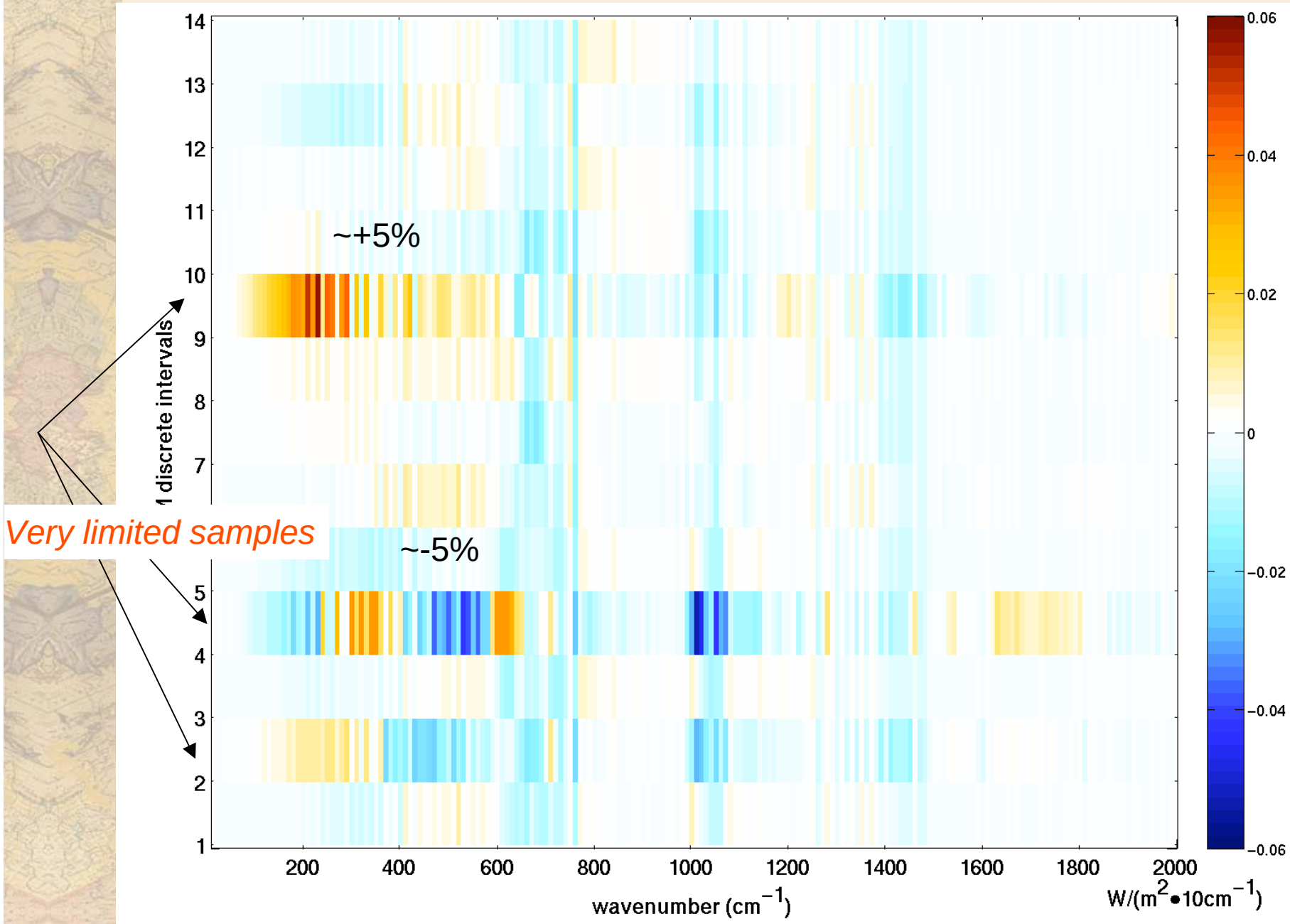
- Randomly chosen ECMWF and SHADOZ profiles for each predefined scene type
- "Predicted" 10cm^{-1} spectral fluxes and OLR from synthetic AIRS spectra
- "Directly-computed" 10cm^{-1} spectral fluxes and OLR from MODTRAN5
- "Predicted" – "Directly computed"

“predicted” – “directly computed” OLR

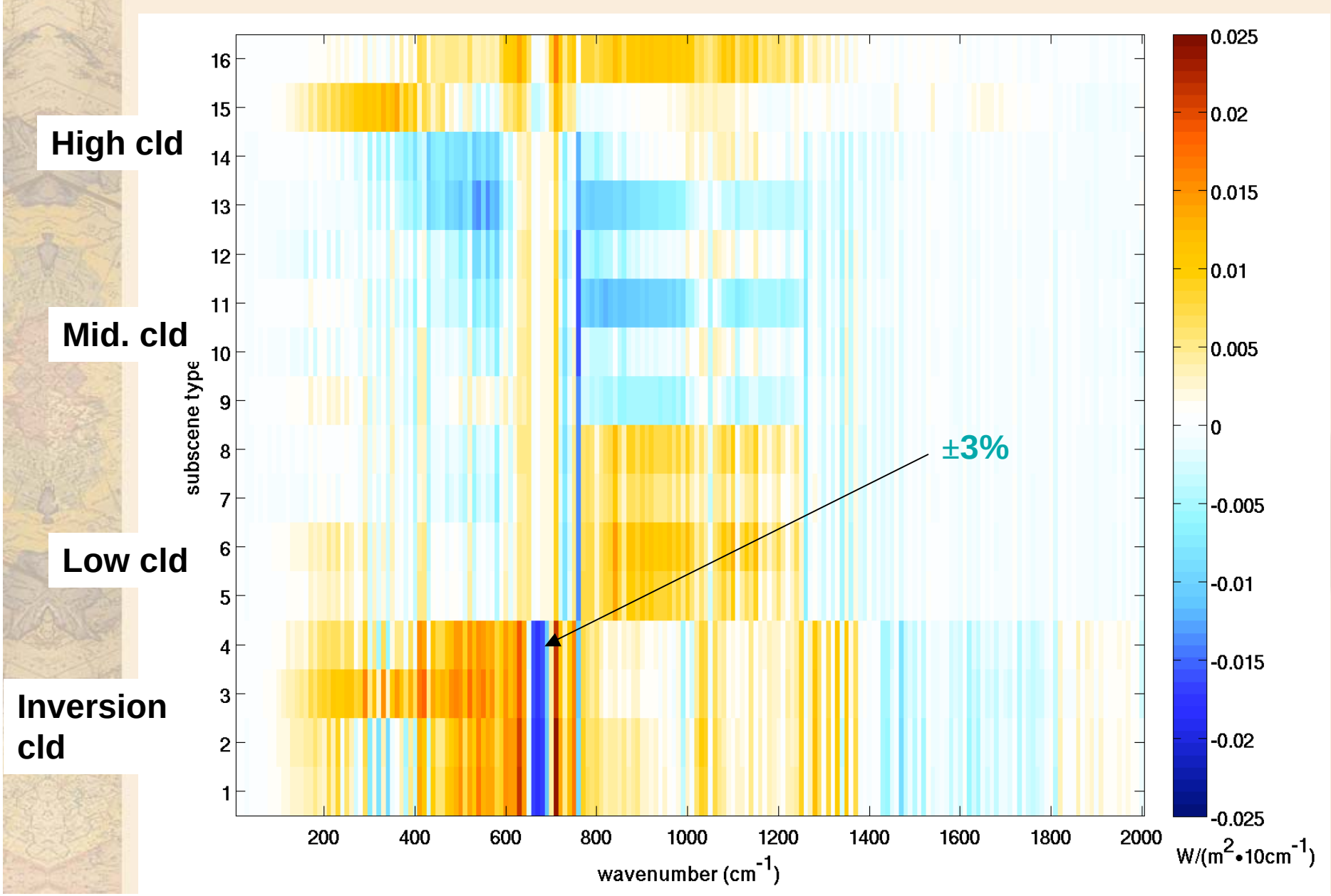


(clear-sky scene type)

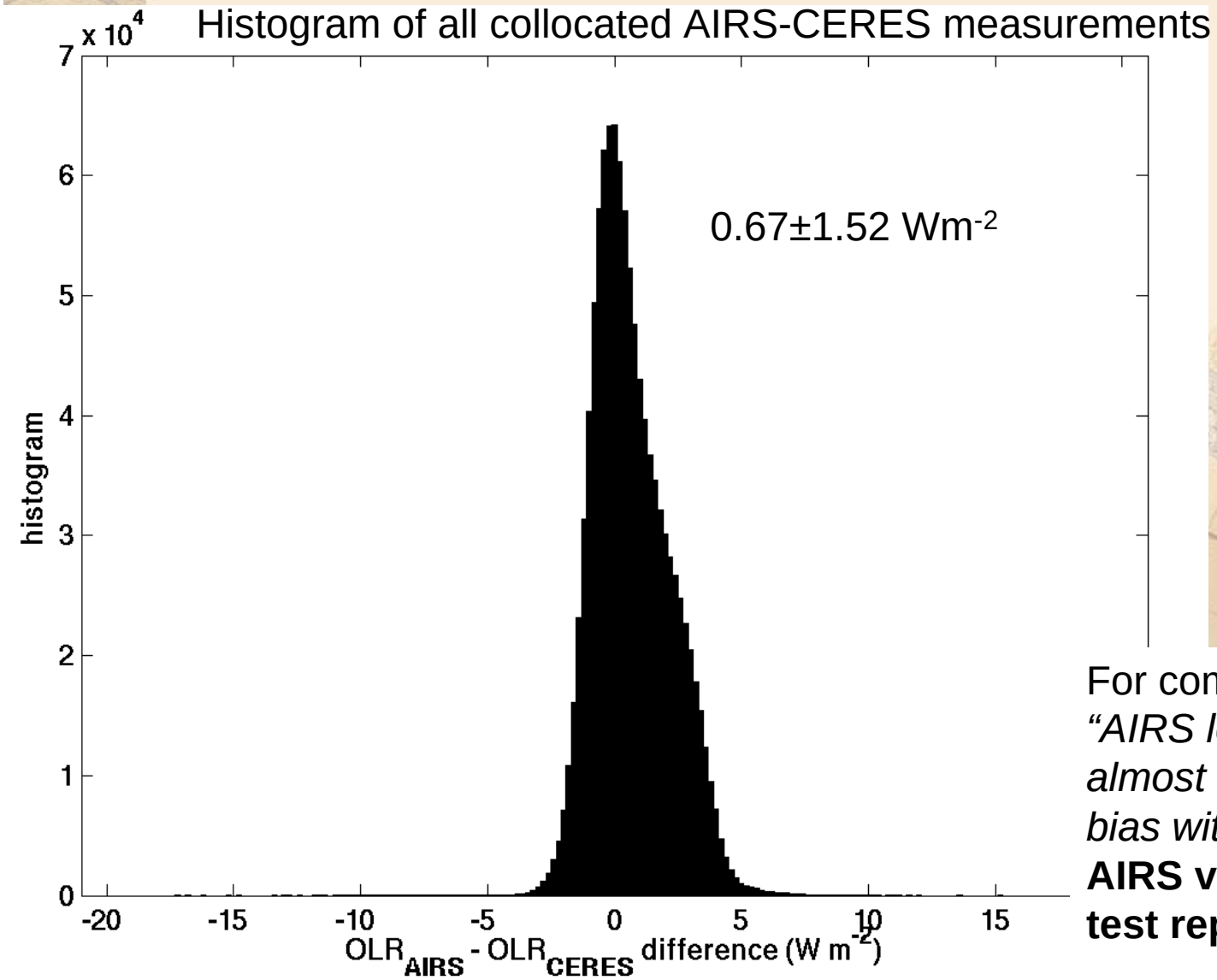
“predicted” – “directly computed” 10cm^{-1} clear-sky spectral flux



“predicted” – “directly computed” 10cm^{-1} cloudy spectral flux



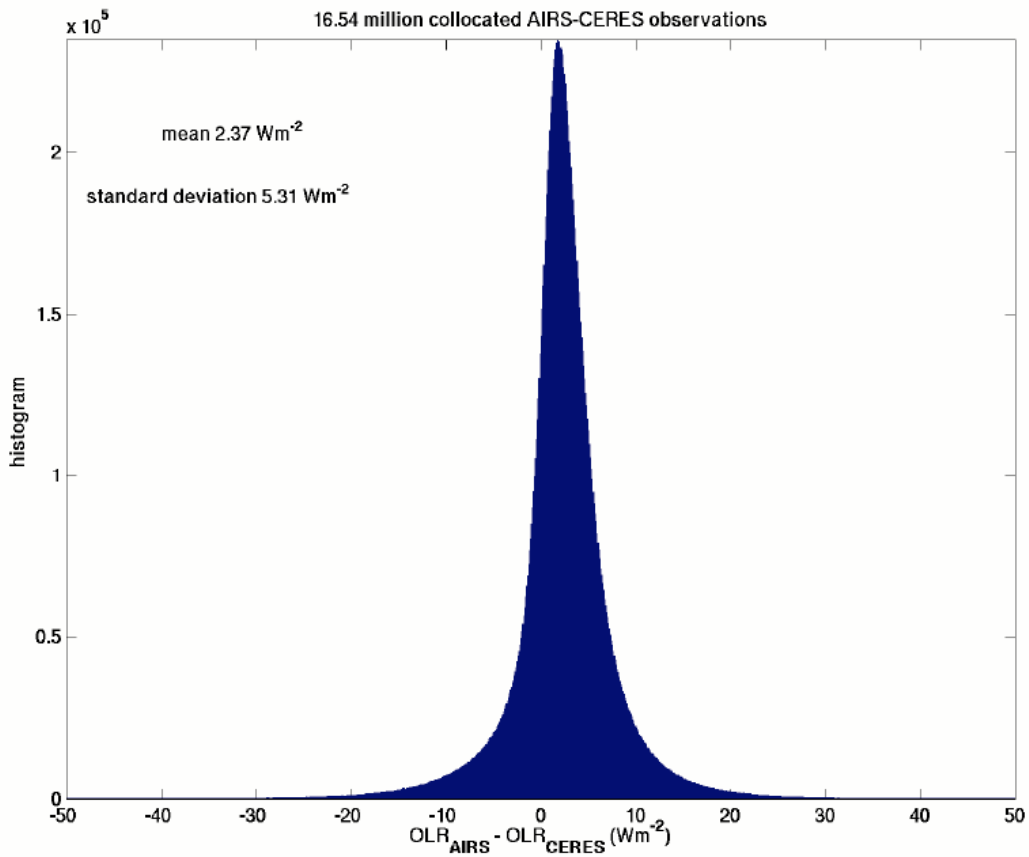
Validation (II): comparison with CERES clear-sky OLR



For comparison
"AIRS level-2 OLR has an almost constant 10 Wm^{-2} bias with respect to CERES"
AIRS v5 performance and test report

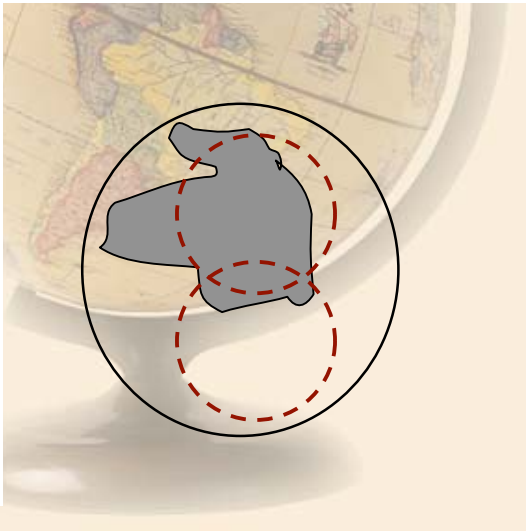
Validation (II): comparison with CERES cloudy OLR

Scene-50 (Cloud over the ocean), 40S-40N only



One caveat (stretch):
sub-pixel cloud inhomogeneity
could make diff very large (+/-), but in a random way

Quick estimation:
3-σ filtering: 97.2% retained
If normal distribution, 99.9% retained
~2.5% due to this stretch



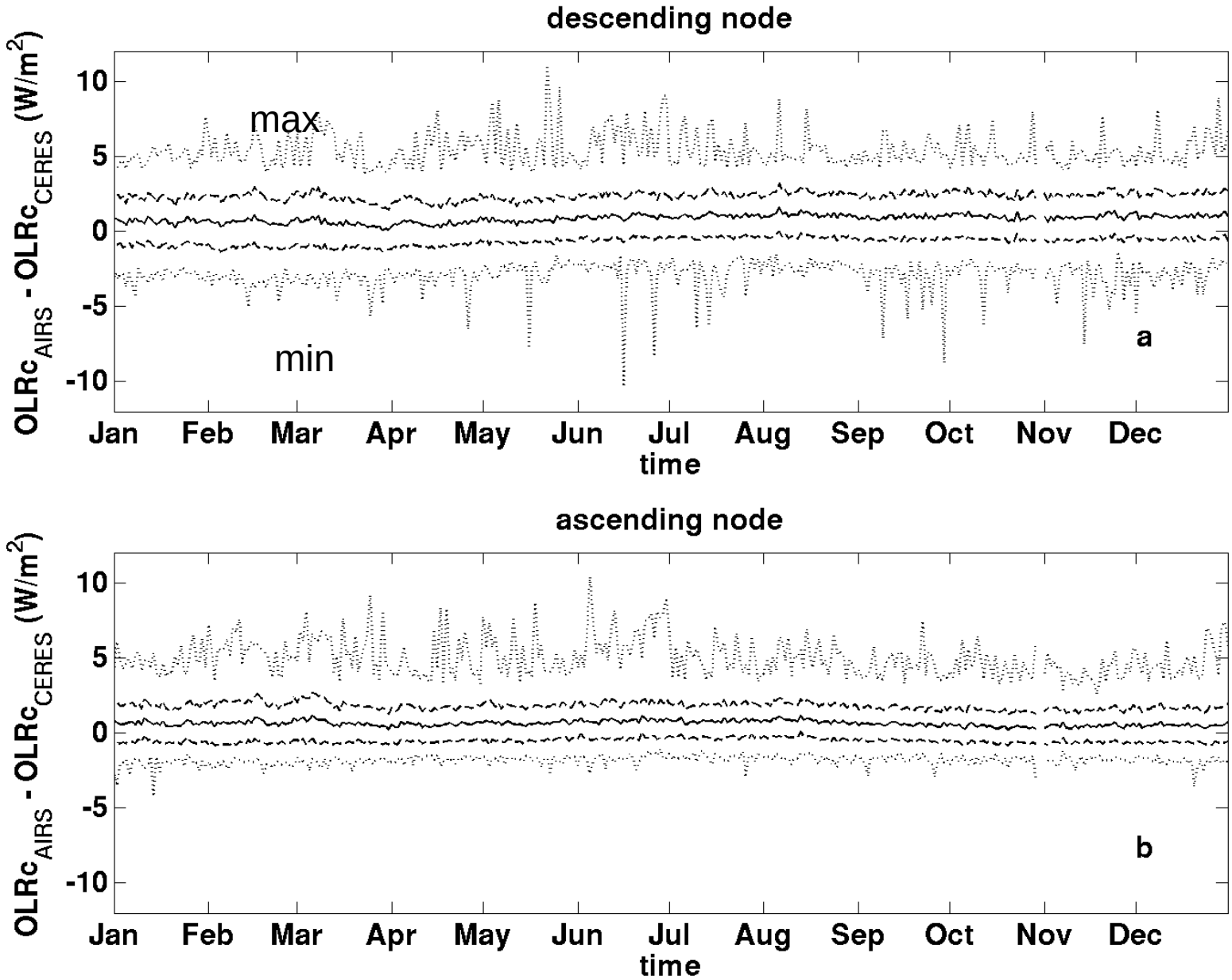
If nudging the ADMs to be fully consistent with CERES ADMs, mean difference is reduced1.27 Wm^{-2}, and the standard deviation is 5.21Wm^{-2}.

Dependences on cloud fraction, cloud temperature

	OLR_{AIRS}-OLR_{CERES} mean	OLR_{AIRS}-OLR_{CERES} Standard deviation
0.1%-50%	2.52	2.77
50%-75%	2.87	5.47
75%-99%	1.86	6.91
99%-100%	2.37	6.49

	OLR_{AIRS}-OLR_{CERES} Mean (wm^{-2})	OLR_{AIRS}-OLR_{CERES} Standard deviation (wm^{-2})
ΔT_{sc}<20K (~low cloud)	2.29	2.61
20K≤ΔT_{sc}<40K (~middle cloud, 2-layer cloud)	4.26	5.58
ΔT_{sc}≥40K (~high cloud)	1.54	8.03

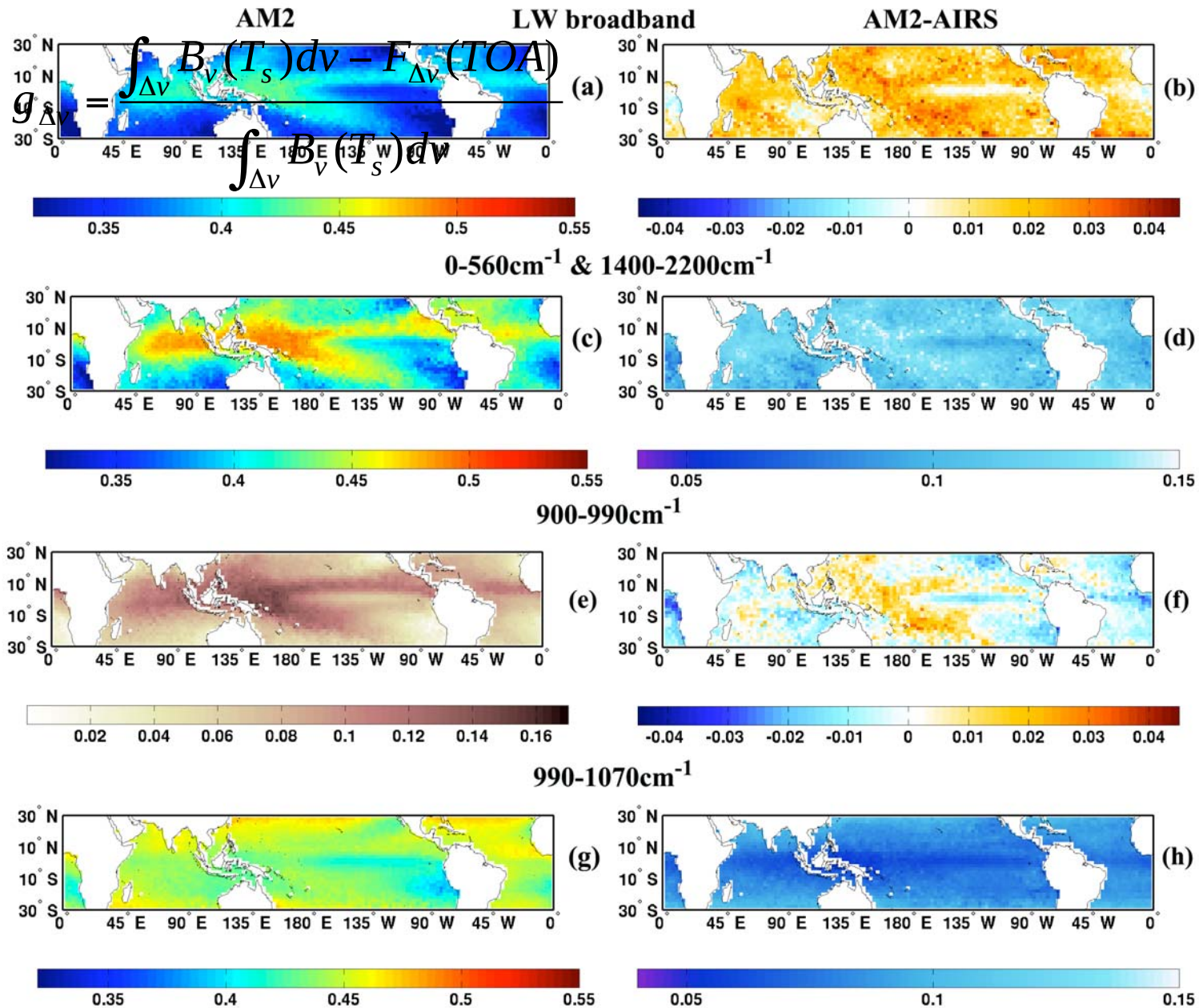
Daily gridded products



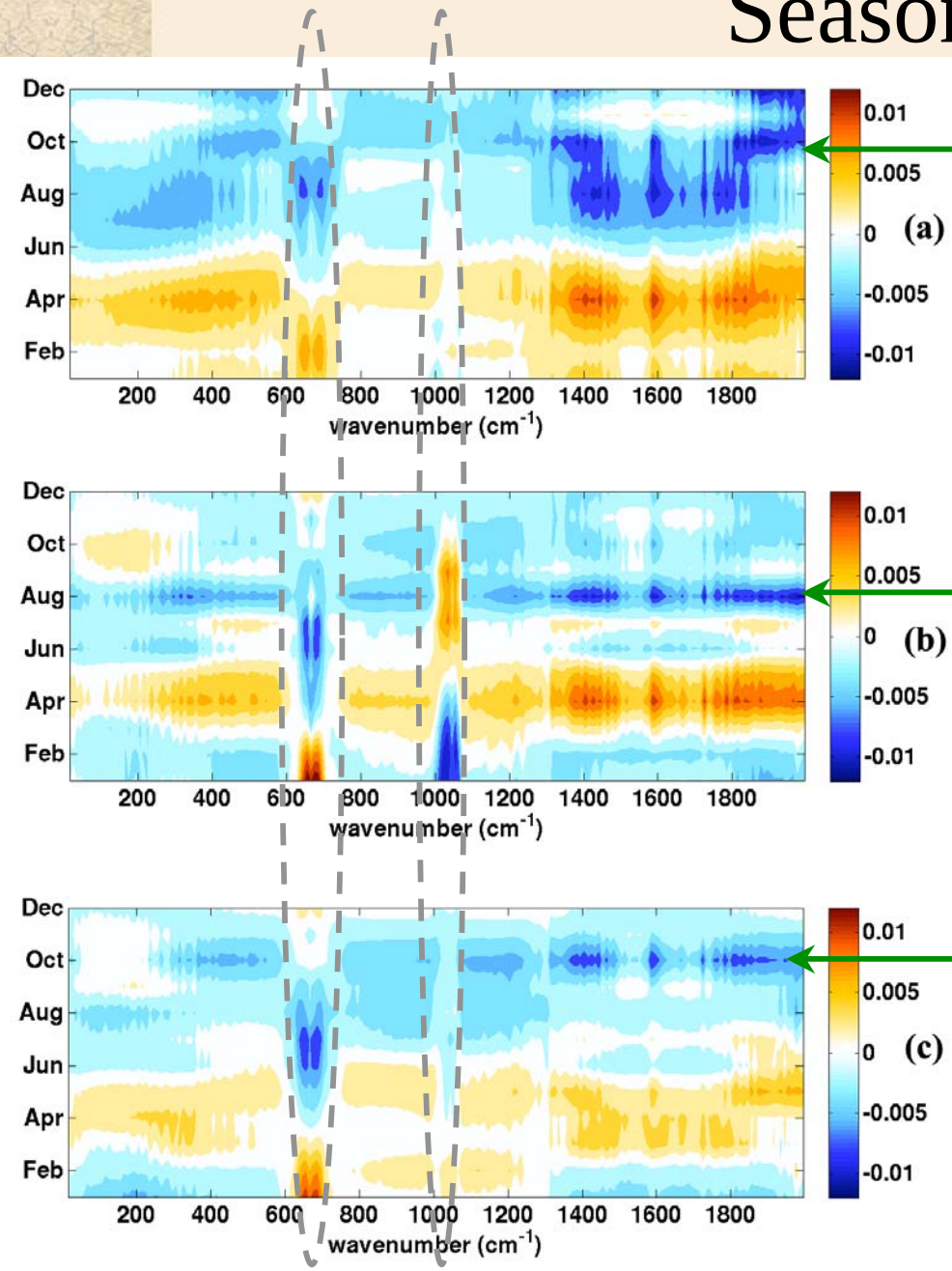
Application in model evaluation (I): clear-sky

$$g_{\Delta\nu} = \frac{\int_{\Delta\nu} B_\nu(T_s)d\nu - F_{\Delta\nu}(TOA)}{\int_{\Delta\nu} B_\nu(T_s)d\nu}$$

Spectral Greenhouse Parameter



Seasonal Cycle

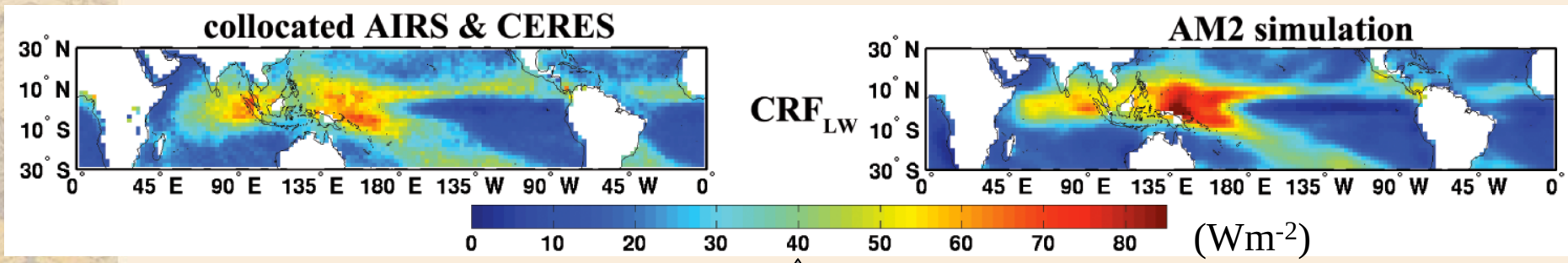


AM2

AIRS

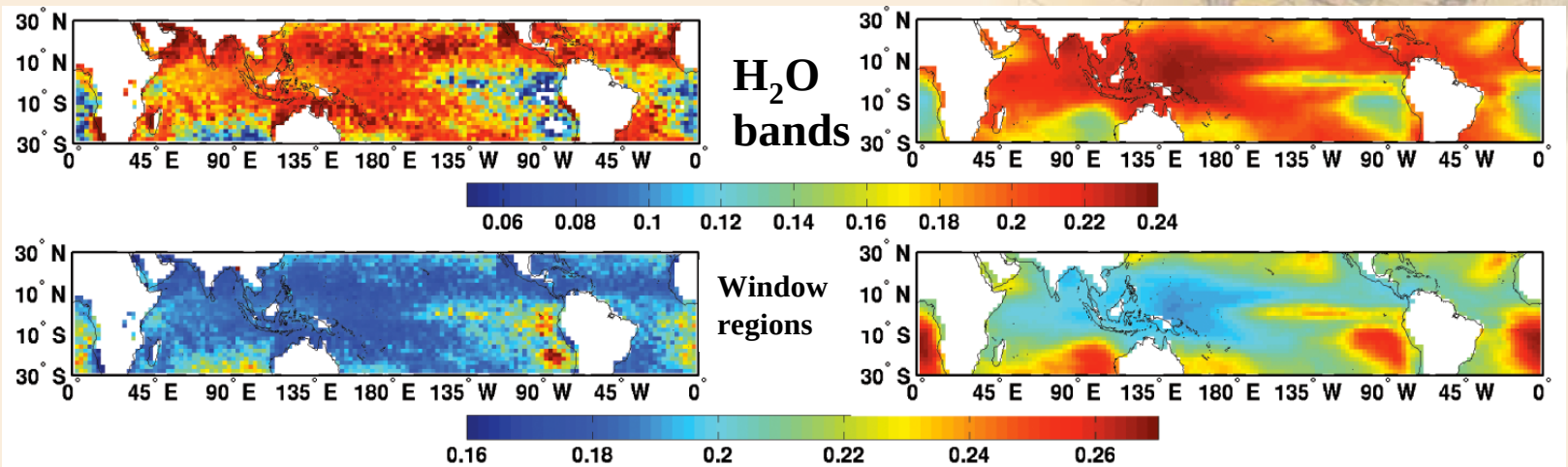
NCEP-II

Application in model evaluation(II): cloud CRF



The simulated broadband longwave CRF agrees well with observed.
But simulated fractional contribution from each band is different, especially in the window region

Fractional contribution

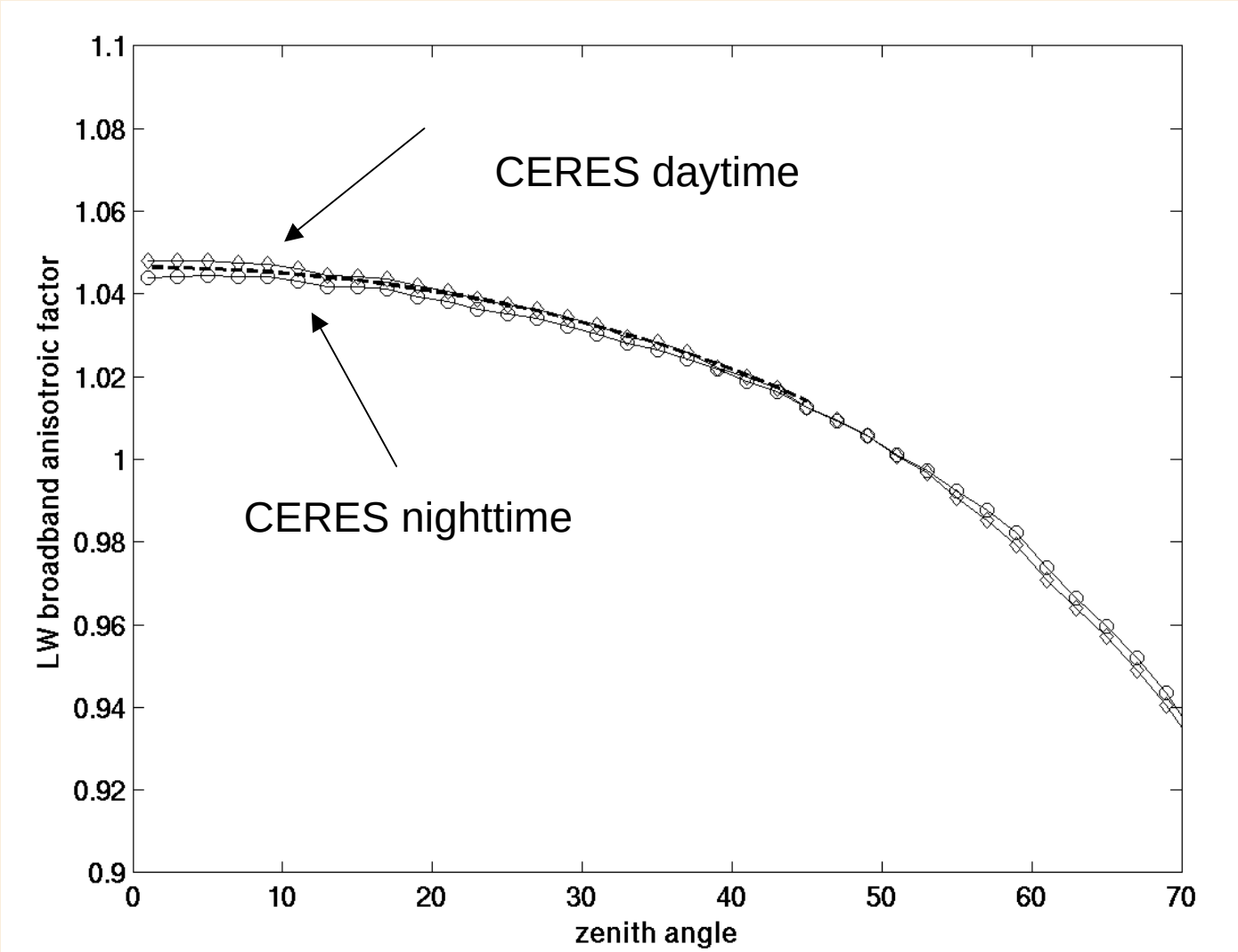


Conclusions

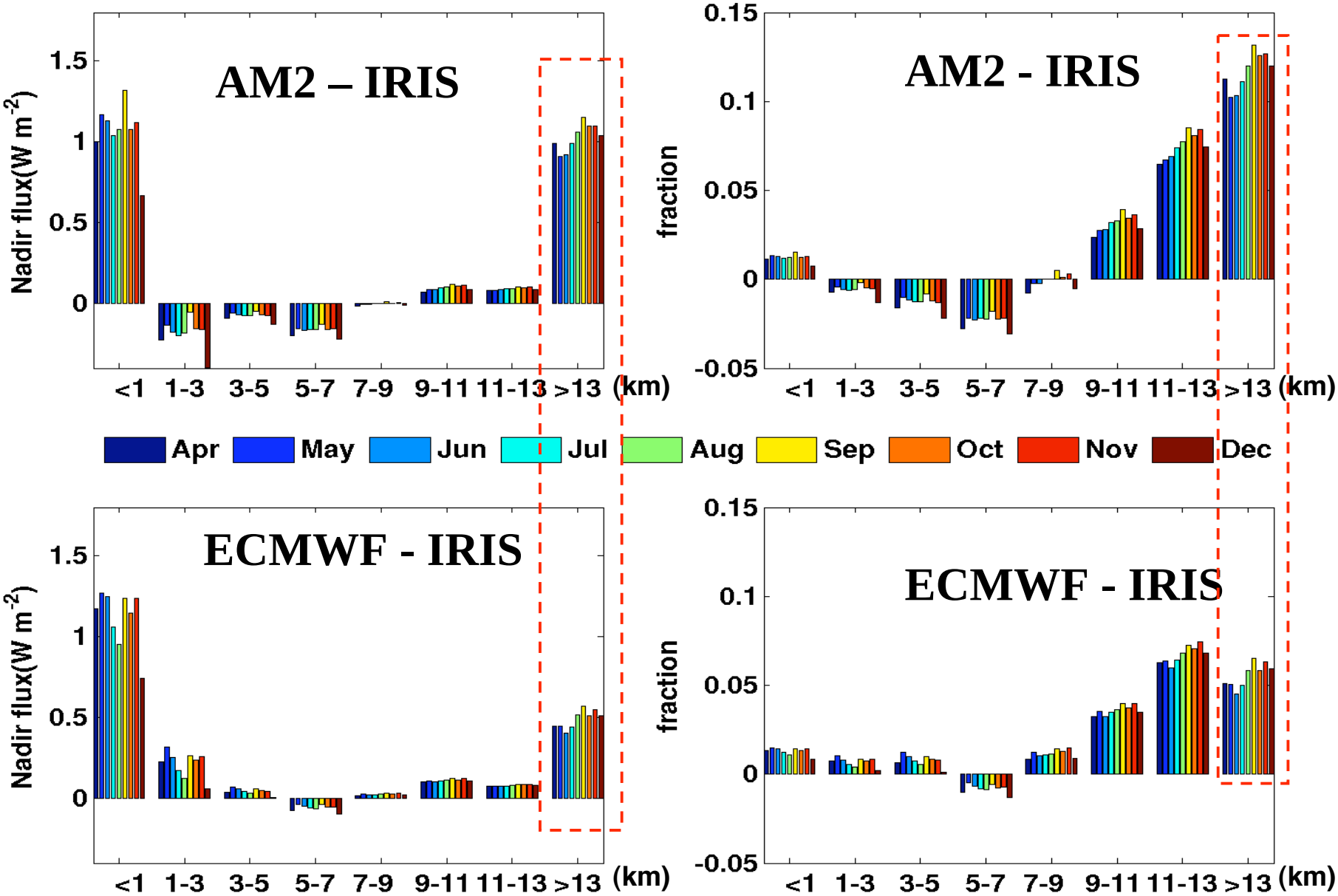
- For collocated AIRS-CERES measurements, band-by-band fluxes can be derived directly from radiance by borrowing CERES scene types.
- The comparisons with CERES and theoretical validation indicate the robustness of this approach
- 3 years of data has been analyzed and used in evaluating band-by-band performance of GFDL AM2 simulations.
- Future work
  - Algorithm
  - Model evaluation

Thank You!

Consistency with CERES ADMs

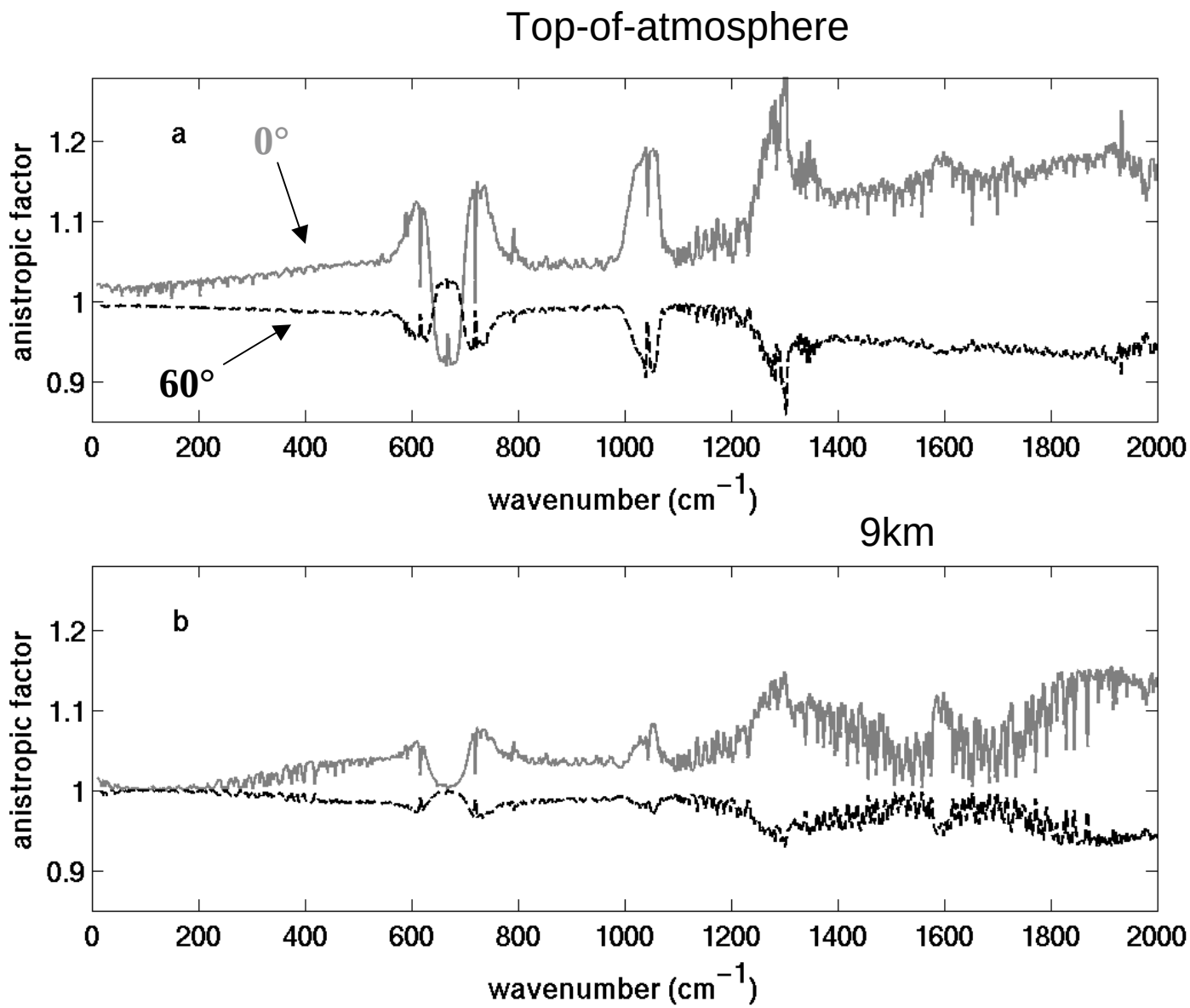


Differences in T-sensitive channels



OLR_{AIRS}-OLR_{CERES} Mean (wm^{-2})	cloud fraction 0.1%-50%	cloud fraction 50%-75%	cloud fraction 75%-99%	cloud fraction 99%-100%
ΔT_{sc}<20K (~low cloud)	2.25	2.61	2.28	2.19
20K≤ΔT_{sc}<40K (~middle cloud or 2-layer cloud)	4.15	4.48	3.77	4.78
ΔT_{sc}≥40K (~high cloud)	2.92	2.11	-0.20	1.79

US1976 standard atmosphere, 2cm^{-1} FWHM



An PCA-based scheme to estimate flux: in practice

Number of total channels N

Number of the AIRS subset channels N_{AIRS}

If only keep first M principal components ($N, N_{AIRS} >> M$)

$$\mathbf{F}_{N\times 1} - \overline{\mathbf{F}}_{N\times 1} \approx \ddot{\mathbf{O}}_{N\times M}\mathbf{e}_{M\times 1}$$

A subset of it

$$\mathbf{F}_{N_{AIRS}\times 1} - \overline{\mathbf{F}}_{N_{AIRS}\times 1} \approx \ddot{\mathbf{O}}_{N_{AIRS}\times M}\mathbf{e}_{M\times 1}$$

Least-square-fit for $\mathbf{e}_{M\times 1}$

$$\mathbf{e} = \left(\ddot{\mathbf{O}}^{*}_{M\times N_{AIRS}}\ddot{\mathbf{O}}_{N_{AIRS}\times M}\right)^{-1}\ddot{\mathbf{O}}^{*}_{M\times N_{AIRS}}\left(\mathbf{F}_{N_{AIRS}\times 1} - \overline{\mathbf{F}}_{N_{AIRS}\times 1}\right)$$

Note $\ddot{\mathbf{O}}^{*}_{M\times N_{AIRS}}\ddot{\mathbf{O}}_{N_{AIRS}\times M}$ is not a diagnoal matrix. $N_{AIRS} >> M$, which makes the inversion of matrix numerically stable.

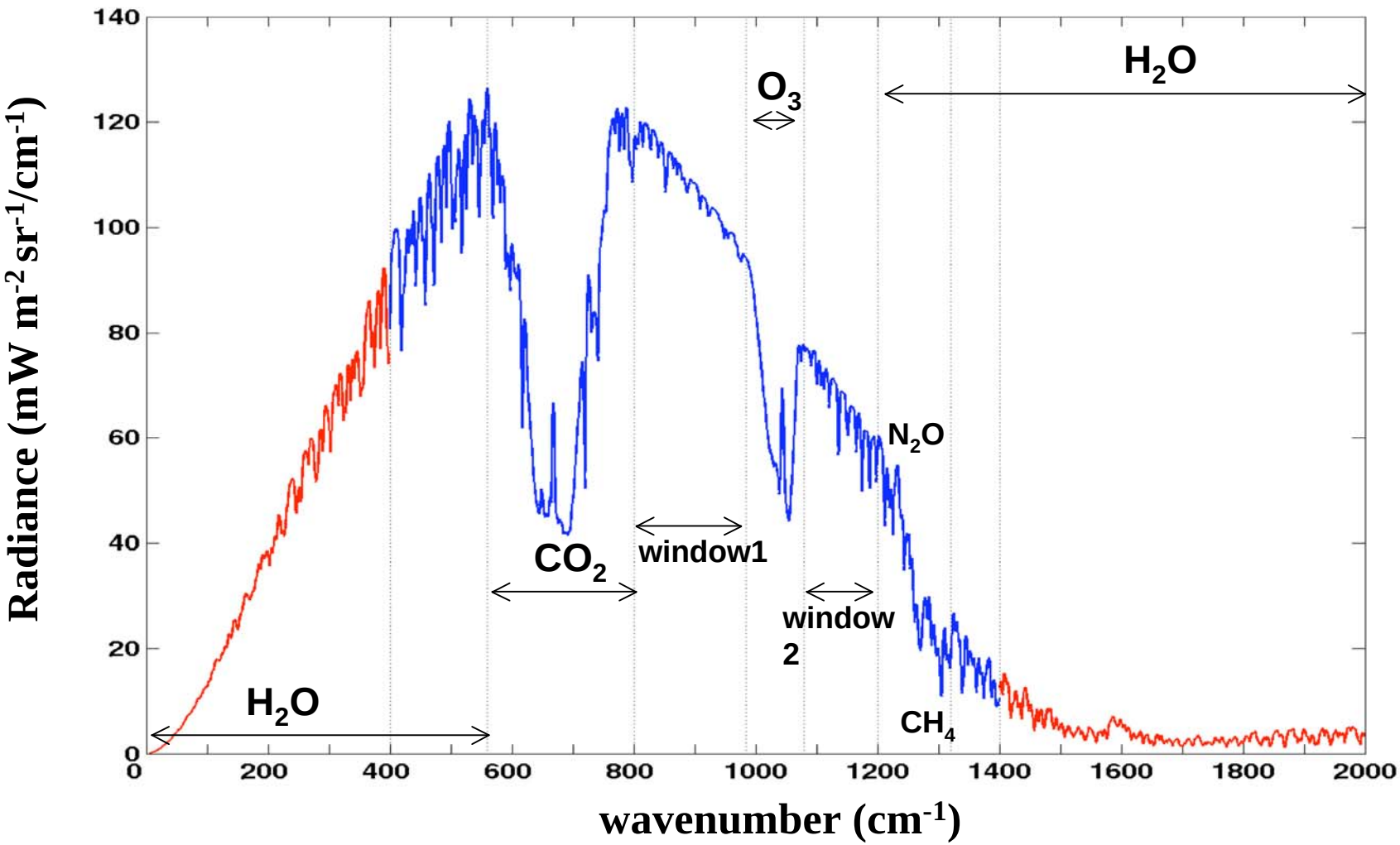
AIRS L2 clear-sky OLR vs collocated clear-sky OLR

- Different footprint, L2 OLR on 3x3 footprints (other footprints might be cloudy)
- L2OLR tends to be higher than CERES OLR and AIRS-inferred OLR here

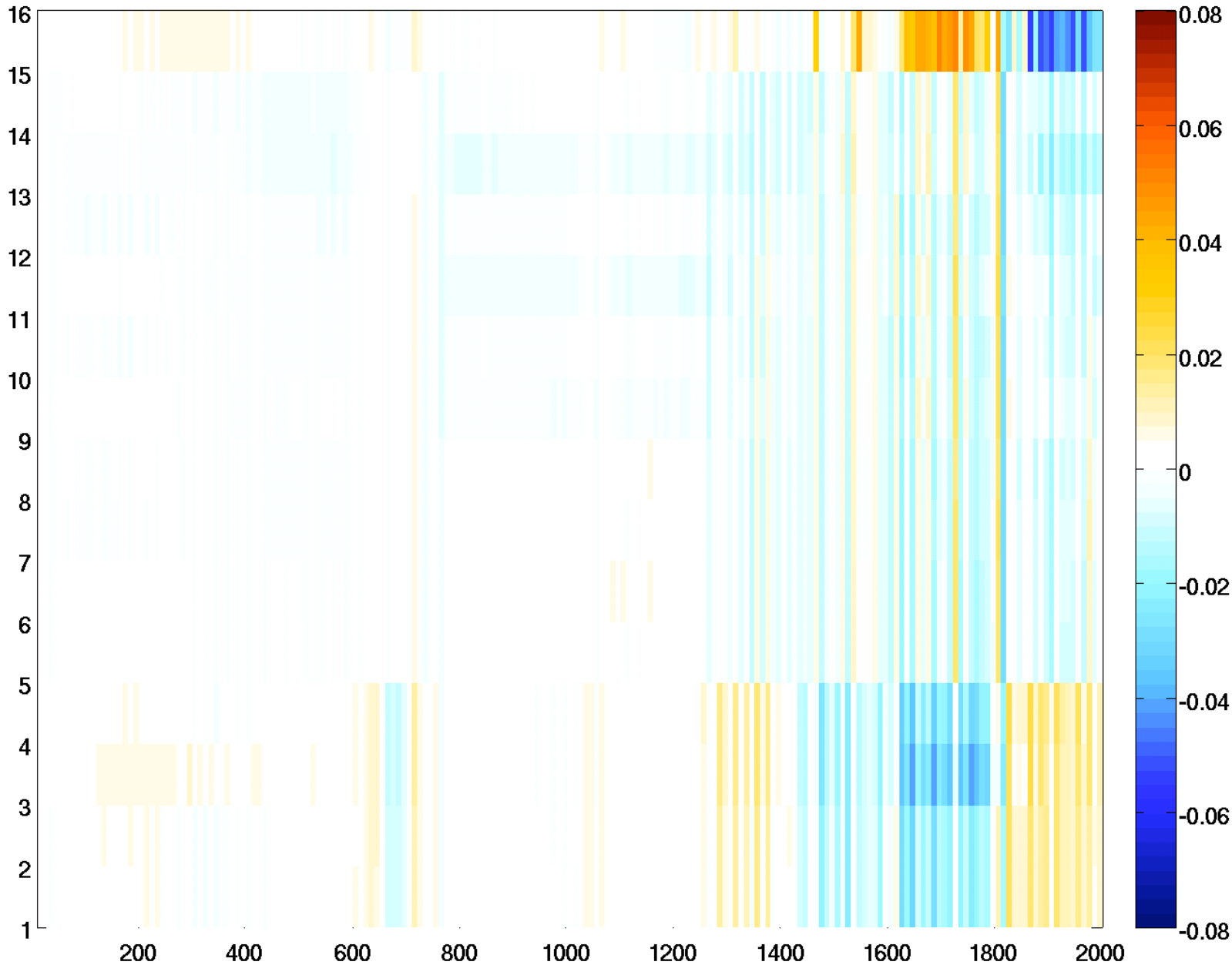
		AIRS L2 clear-sky OLR(Wm^{-2})	CERES OLR (Wm^{-2})
AIRS.2005.01.01.058.1190	313	302.1227	289.0183
AIRS.2005.01.01.058.0309	313	304.5234	292.3293
AIRS.2005.01.01.058.0354	313	304.5669	293.0906
AIRS.2005.01.01.058.0222	313	305.2441	294.4597
AIRS.2005.01.01.058.0494	313	307.071	294.5067
AIRS.2005.01.01.058.0225	313	306.144	295.2206
AIRS.2005.01.01.058.1152	313	300.6914	289.4892
AIRS.2005.01.01.058.1065	313	304.0598	293.0943
AIRS.2005.01.01.058.0395	313	303.1129	297.6411
AIRS.2005.01.01.058.0308	323	305.3004	297.1643
AIRS.2005.01.01.058.0713	313	313.4364	299.3801

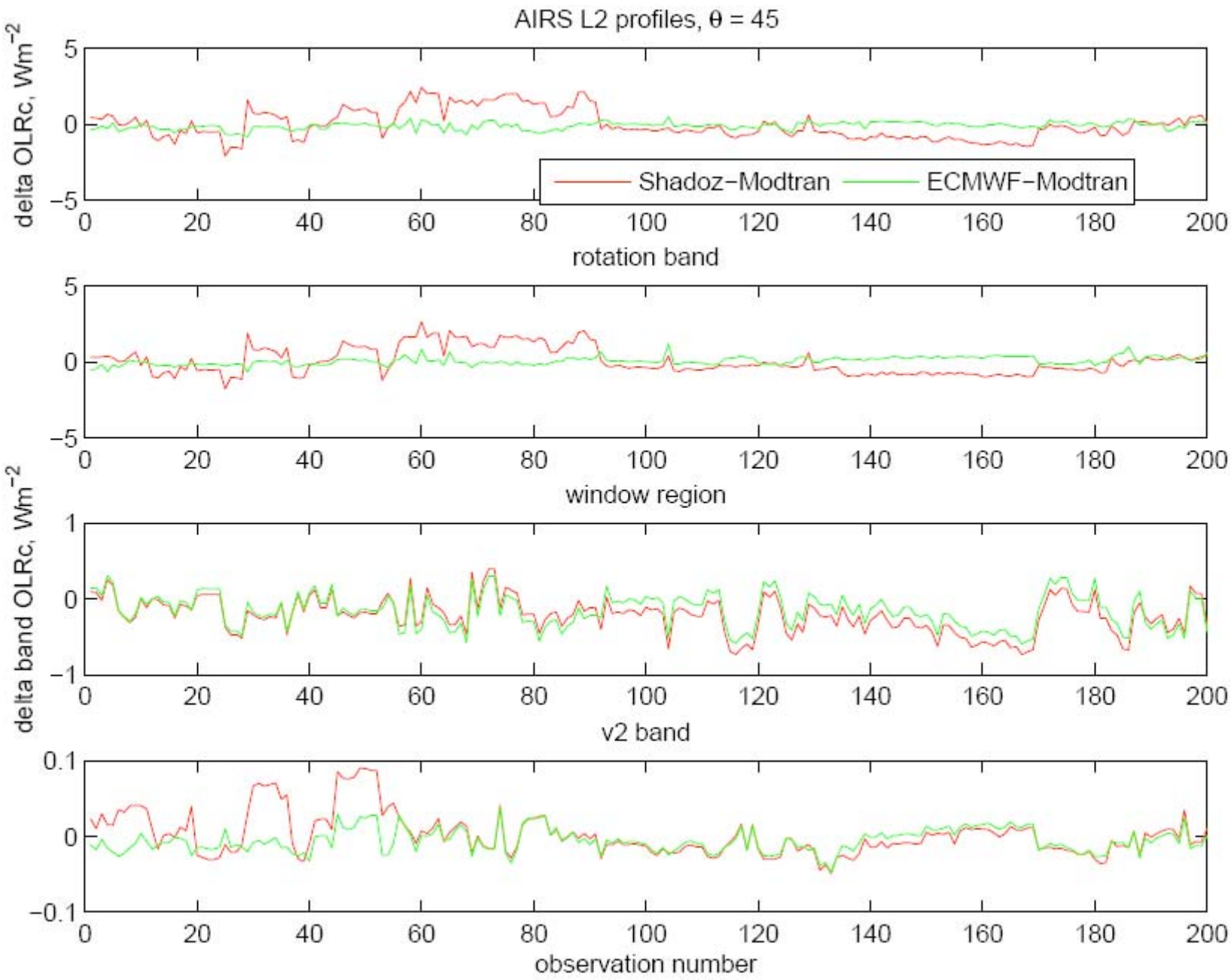
Decomposition (I): different absorption bands

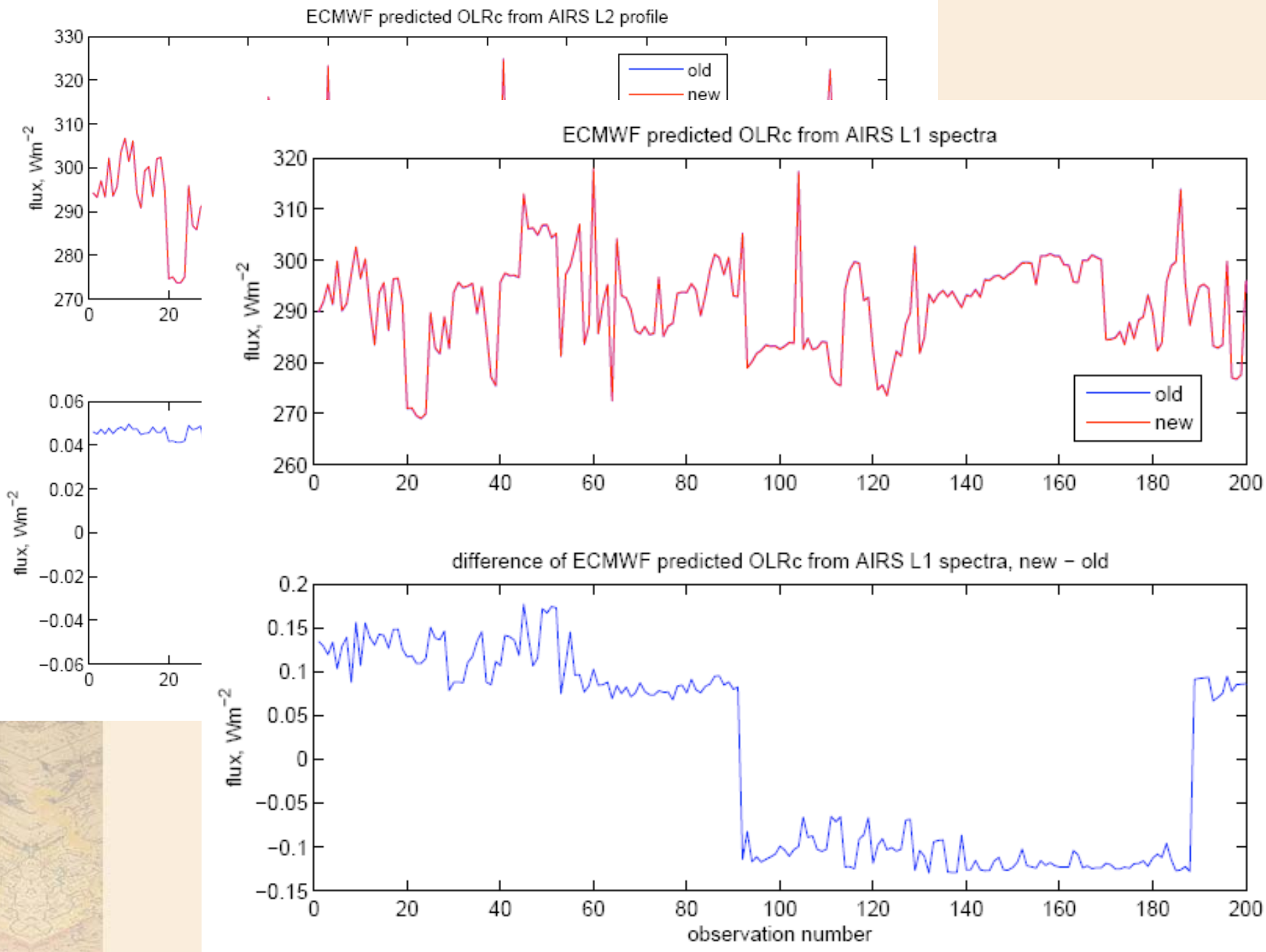
Total flux (wm^{-2}) 52.5 52.2 58.0 59.7 18.0 23.5 12.4 4.5 7.7



Difference in fraction (cloudy sOLR)




AIRS L2 profiles, θ = 45
delta OLRc, Wm^{-2}
Shadoz−Modtran
ECMWF−Modtran
rotation band
window region
delta band OLRc, Wm^{-2}
v2 band
observation number


ECMWF predicted OLRc from AIRS L2 profile
old
new
flux, Wm^{-2}
ECMWF predicted OLRc from AIRS L1 spectra
old
new
flux, Wm^{-2}
difference of ECMWF predicted OLRc from AIRS L1 spectra, new − old
flux, Wm^{-2}
observation number

Spectral bands used in the GFDL longwave radiation scheme

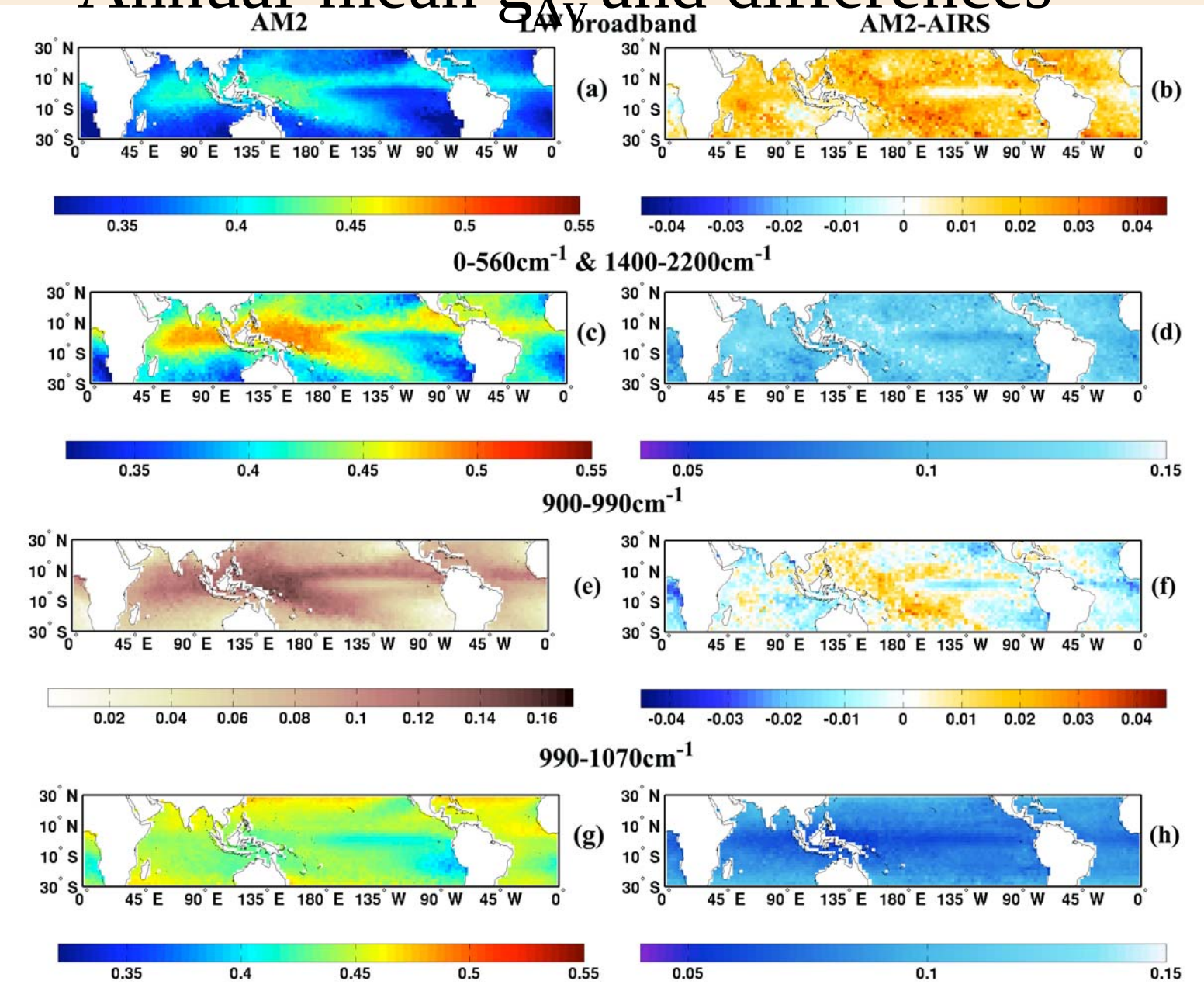
	Spectral Range (cm^{-1})	Primary absorbers
1*	0-560	H_2O
2	560-800	CO_2, N_2O
3	800-900	H_2O continuum
4	900-990	H_2O continuum
5	990-1070	O_3
6	1070-1200	H_2O continuum
7	1200-1400	H_2O, CH_4, N_2O
8*	1400-2200	H_2O

Application in model evaluation

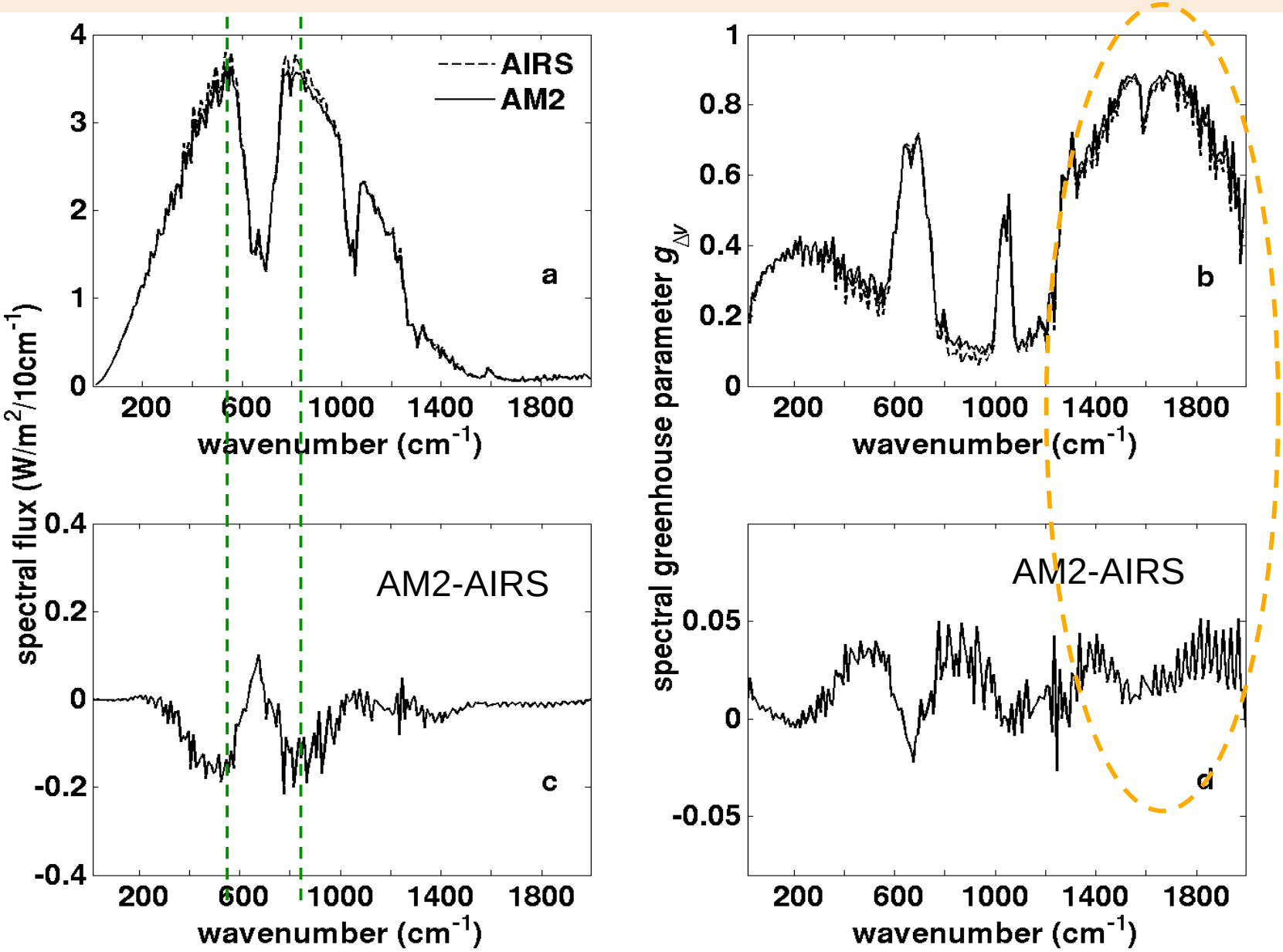
- Absolute flux could change by several factors from one band to another
- Spectral greenhouse parameters

$$g_{\Delta v} = \frac{\int_{\Delta v} B_v(T_s)dv - F_{\Delta v}(TOA)}{\int_{\Delta v} B_v(T_s)dv}$$

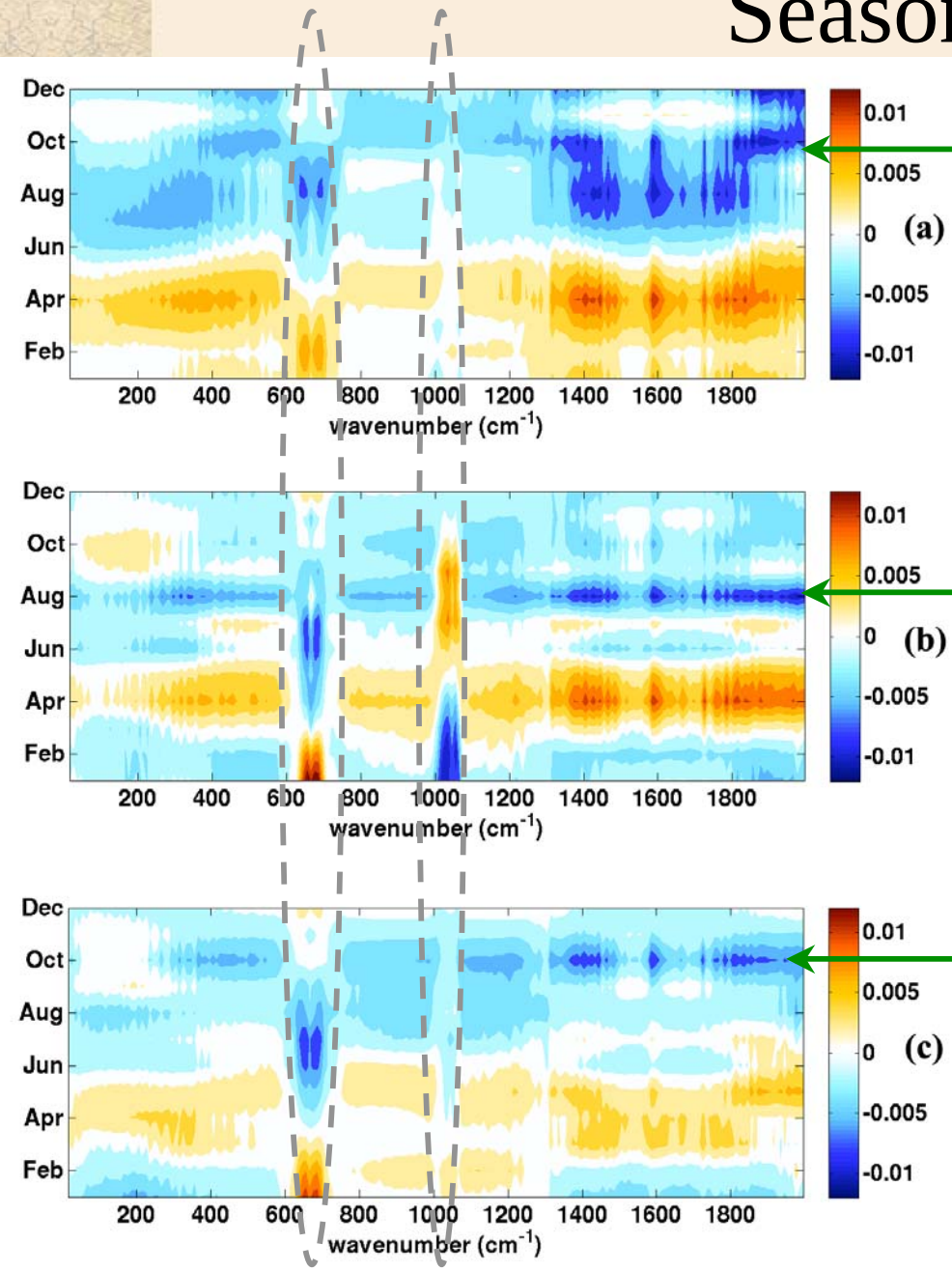
Annual-mean $g_{\Delta\nu}$ and differences



Annual-mean 10cm^{-1} spectral fluxes and $g_{\Delta v}$



Seasonal Cycle



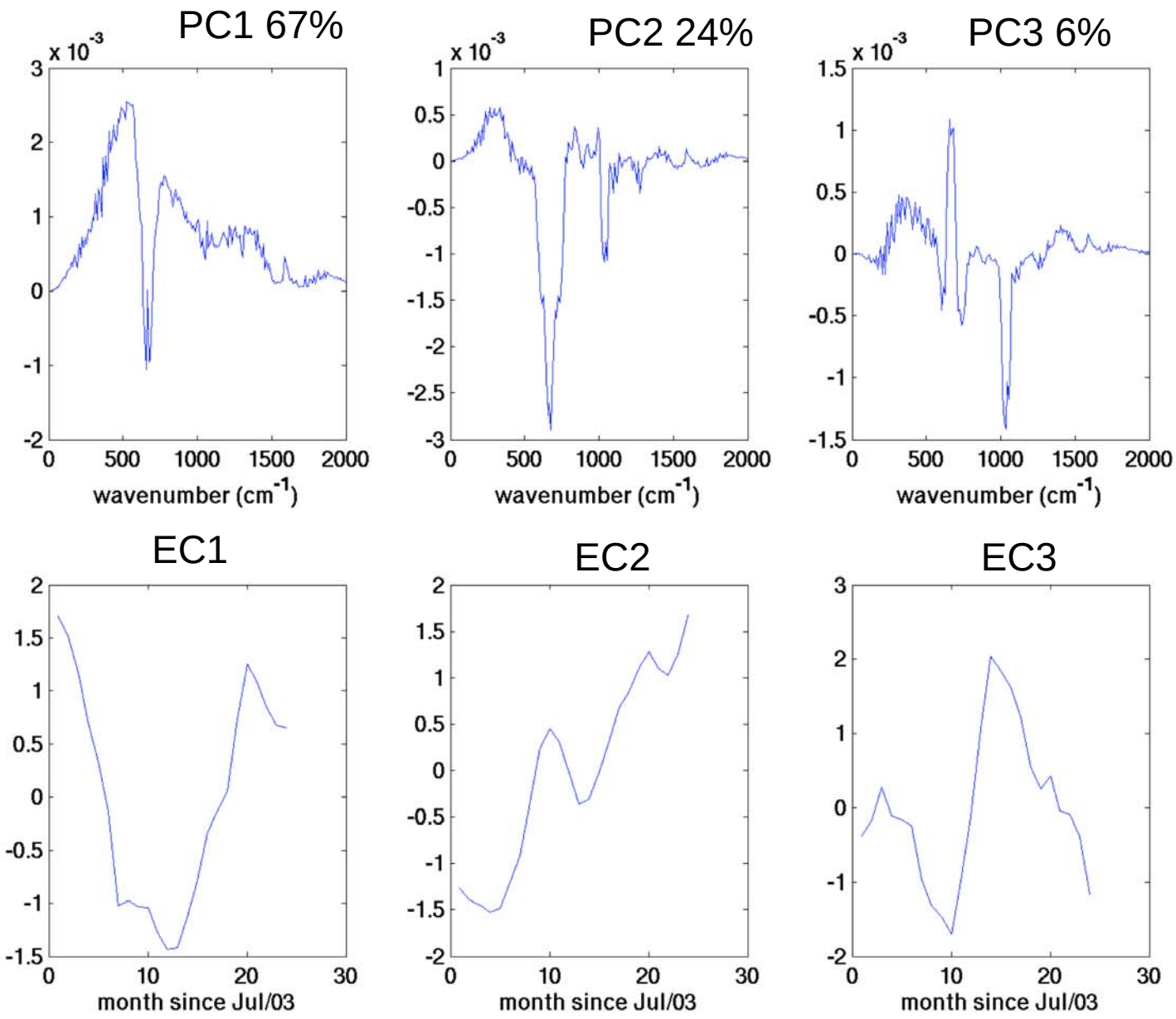
AM2

AIRS

NCEP-II

“Interannual variability” of spectral fluxes

- Processed 3 years of data, 2003-2005
- Mean seasonal cycle removed, 13-pt moving average (24 months left)
- PCA analysis


PC1 67%
x 10^-3
wavenumber (cm^-1)
PC2 24%
x 10^-3
wavenumber (cm^-1)
PC3 6%
x 10^-3
wavenumber (cm^-1)
EC1
month since Jul/03
EC2
month since Jul/03
EC3
month since Jul/03