UNIVERSITY OF MICHIGAN

Multiple years of far-IR flux and cloud radiative forcing as inferred from the collocated AIRS-CERES observations and its application in GCM validation

Xianglei Huang
University of Michigan

Contributors: Norman Loeb (NASA Langley); Wenze Yang (Univ. of Maryland); V. Ramaswamy (Princeton/NOAA GFDL); Lazaros Oraiopoulos, Dongmin Lee, Max Suarez (NASA GSFC); Jerry Potter, Huiwen Chuang (Univ. of Michigan); Jason Cole (Enviromenta Canada)

Acknowledgements: GFDL HPCS, NSF, and NASA

Far-IR workshop, Madison, WI
November 9, 2011

Outline

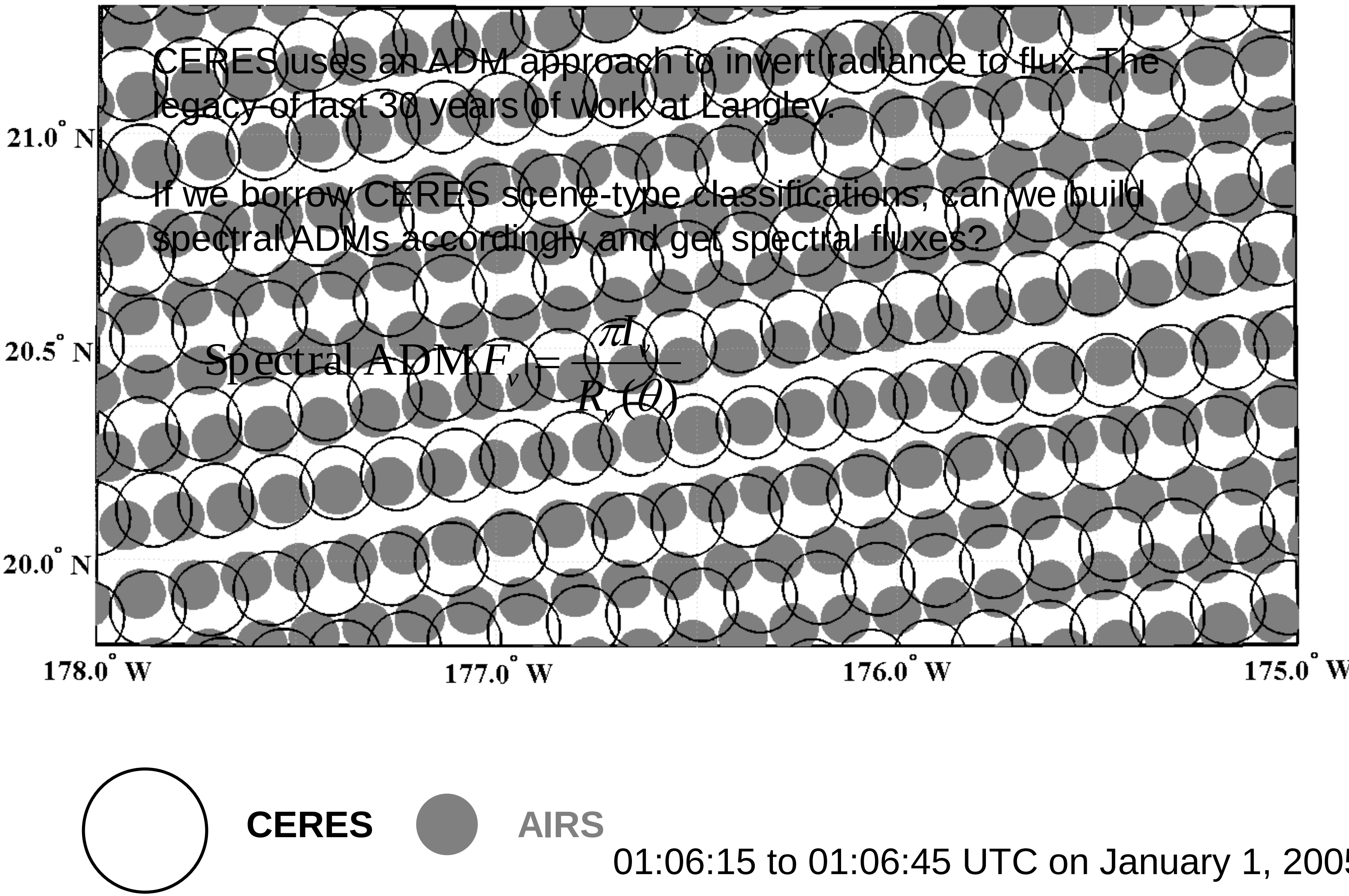
- Motivations
  - Broadband vs. band-by-band
    - Observations
    - Modeling
  - Band-by-band CRF: fraction also matters
- How to get it from observations?
  - Algorithm
  - Validation
- Case studies with GFDL AM2, NASA GEOS-5, and Canada CanAM4
  - Clear-sky band-by-band fluxes
  - Band-by-band cloud radiative forcings
- Further thoughts on the band-by-band CRFs
- Conclusions and discussions

Coincidental obs. Of CERES and AIRS

CERES uses an ADM approach to invert radiance to flux. The legacy of last 30 years of work at Langley.

If we borrow CERES scene-type classifications, can we build spectral ADMs accordingly and get spectral fluxes?

$$\text{Spectral ADM } F_v = \frac{\pi I_v}{R_v(\theta)}$$

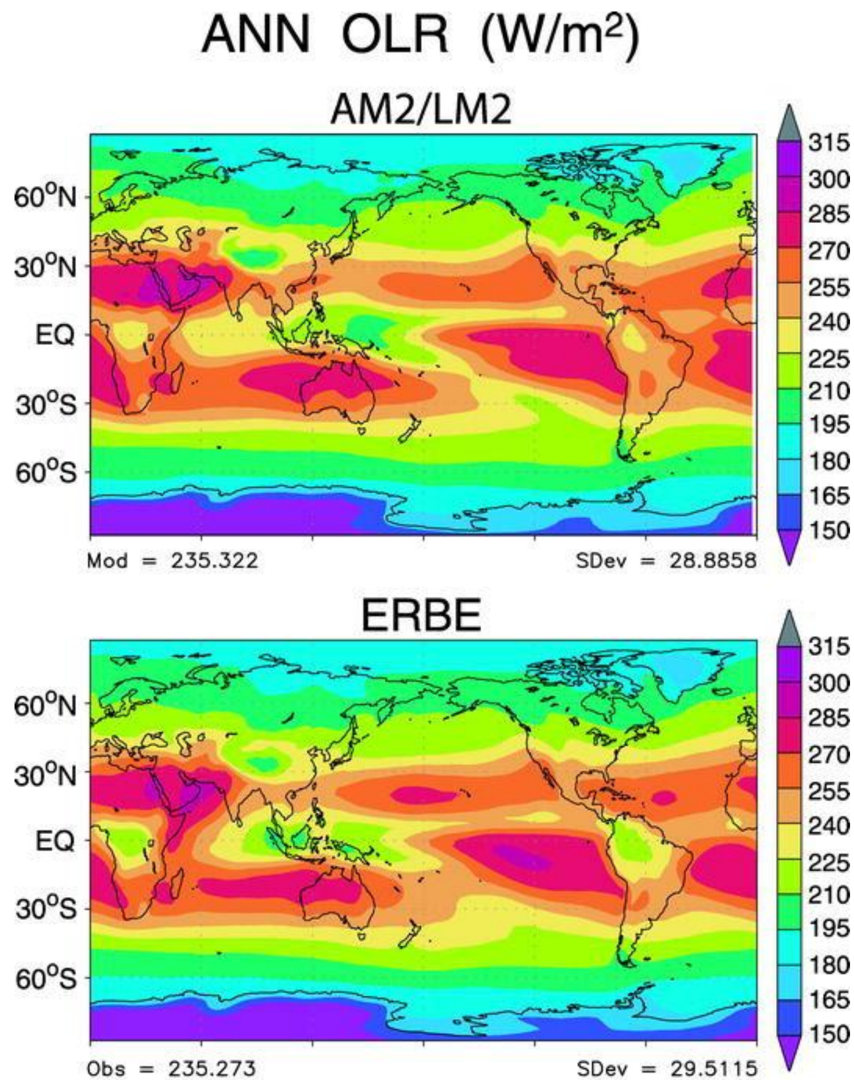


01:06:15 to 01:06:45 UTC on January 1, 2005

Motivations: every GCM center does this with OLR

- Tuning: to get TOA balance, to get numbers matched with ERBE's
  - Different centers have different (empirical) tuning strategies
- Consequence:
  - Compensating biases from different bands
    - E.g. $1Wm^{-2}$ bias in AM2 originated from stratosphere but tuned away with tropospheric cloud parameters
  - Seemingly right outcome but due to wrong results

  How much such compensation still holds for 2xCO2 run?



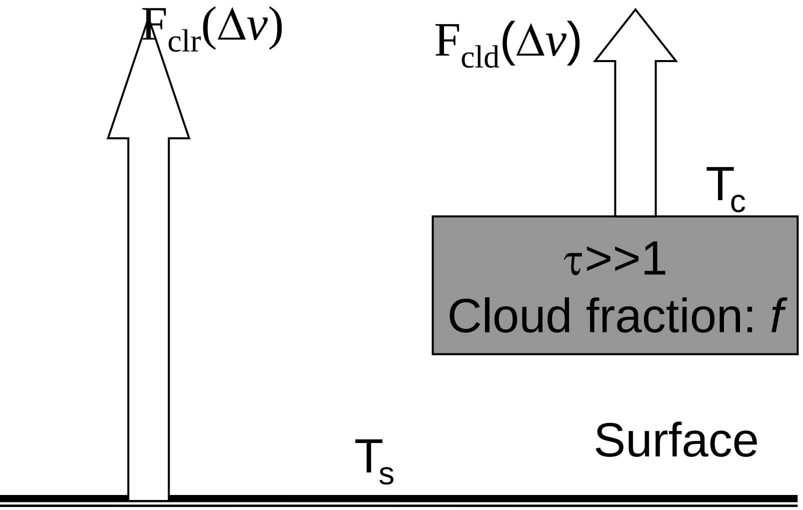
(GFDL GAMDT, 2004, J Clim)

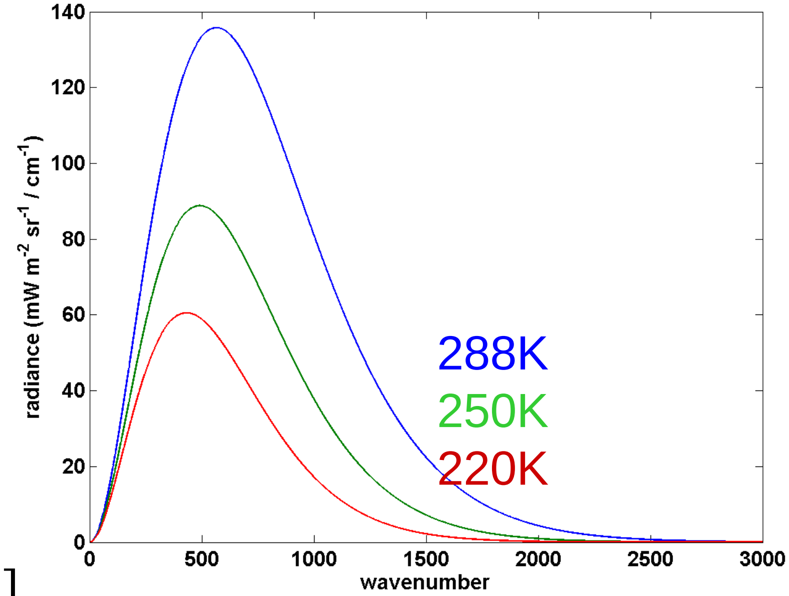
Why go band-by-band?

- Practical reasons (for model evaluation):
  - Compensating biases for simulated broadband CRF and fluxes
  - Band-by-band quantities are directly computed by each GCM
  - Observationally it is possible to derive them
- Also
  - Band-by-band CRFs provides more insights

Why go band-by-band: Toy model A

1. Blackbody cloud
2. Ignore atmospheric absorption

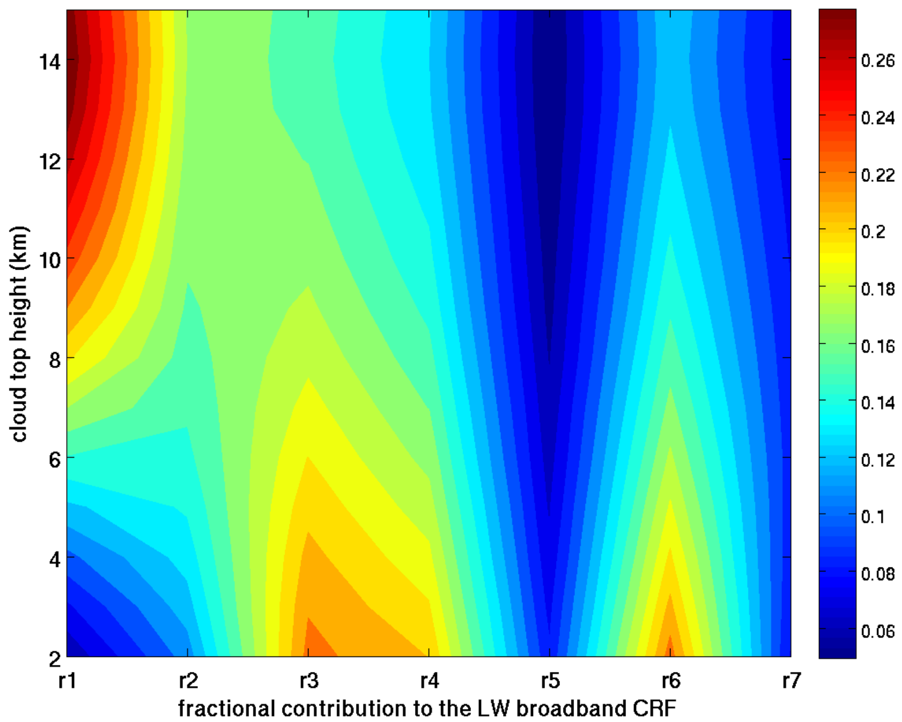




$$CRF_{LW} = \sigma T_s^4 - [f\sigma T_c^4 + (1-f)\sigma T_s^4] = f\left[\sigma T_s^4 - \sigma T_c^4\right]$$

CRF_{LW} sensitive to both f and T_c

Toy model B



- Typical tropical sounding profiles of T, q, O_3, etc ("*McClatchey*" profiles)
- Realistic one-layer cloud (τ>>1) with top varying from 2km to 15km
- 7 bands as used in the GFDL model

Band1: 0-560 and 1400-2500 cm^{-1} (H_2O)

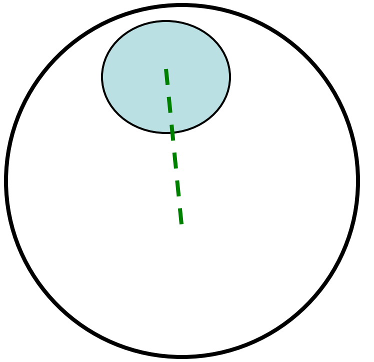
Band2: 560-800 cm^{-1} (CO_2, N_2O) Band5: 990-1070cm^{-1} (O_3)

Band3: 800-900 cm^{-1} (WN) Band6: 1070-1200cm^{-1} (WN)

Band4: 900-990 cm^{-1} (WN) Band7: 1200-1400cm^{-1} (N2O, CH_4)

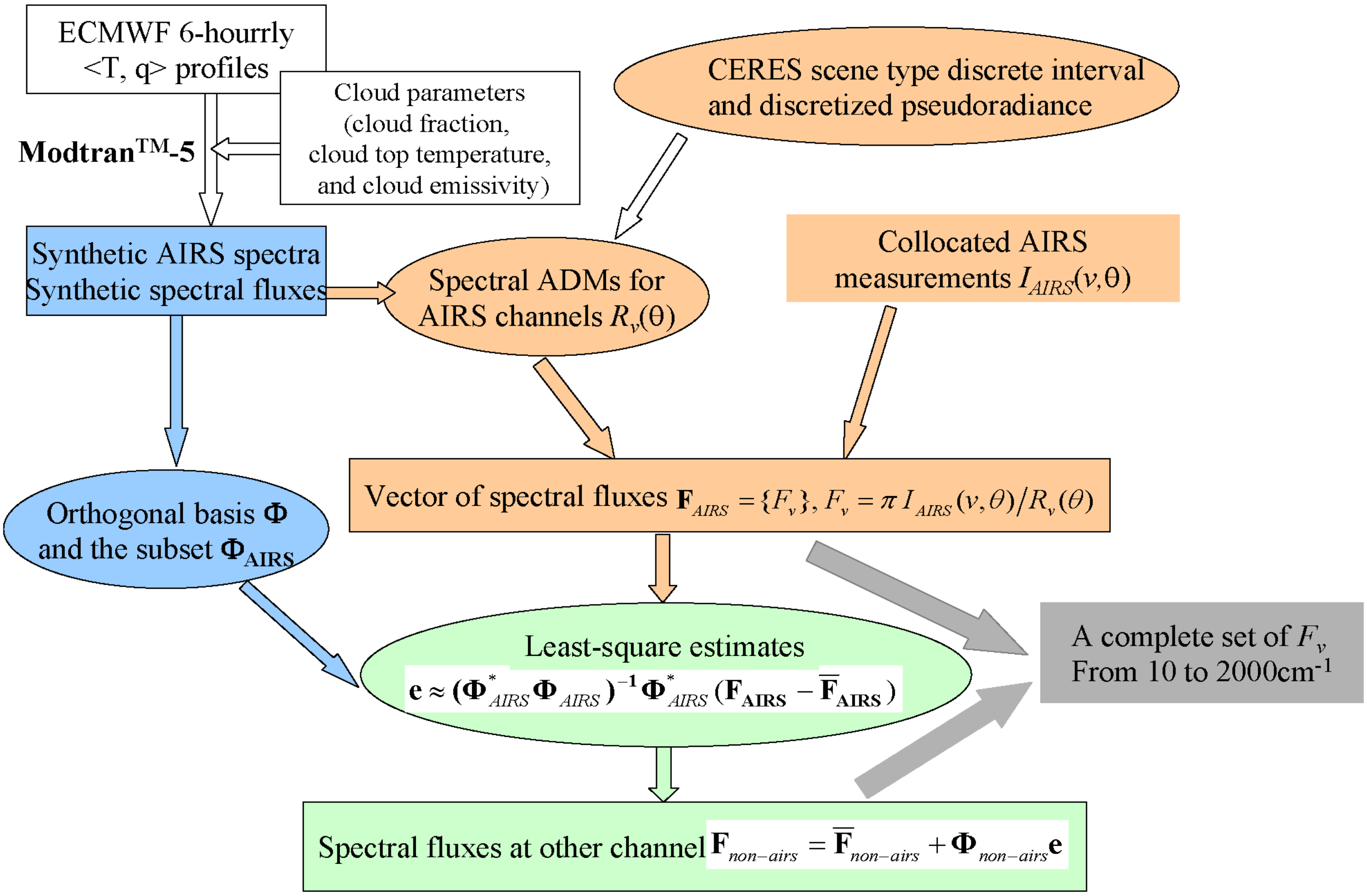
- Recap
  - Can we borrow CERES scene-type classification and get spectral fluxes from AIRS (for all-sky)
  - Can we show its merit in climate model evaluation and cloud feedback studies

Datasets



- CERES SSF data product (edition 2A)
  - Cross-scanning mode only
- AIRS
  - 3.74-4.61μm (2169-2673 cm^{-1}) excluded
  - Quality control: filtering out bad channels
- Collocation criteria strategy
  - Time separation ≤ 8 seconds
  - Spatial separation ≤ 3km
- Measurements over the tropical oceans: 2003-2007

Flowchart for the entire algorithm



Output: spectral flux at 10cm^{-1} intervals through the entire longwave spectral range

An PCA-based scheme to estimate flux: basic idea

"Filled-in" channel (row $\nu 1$); AIIRS channels (rows $\nu 2$ – $\nu 6$); "Filled-in" channel (row $\nu 7$)

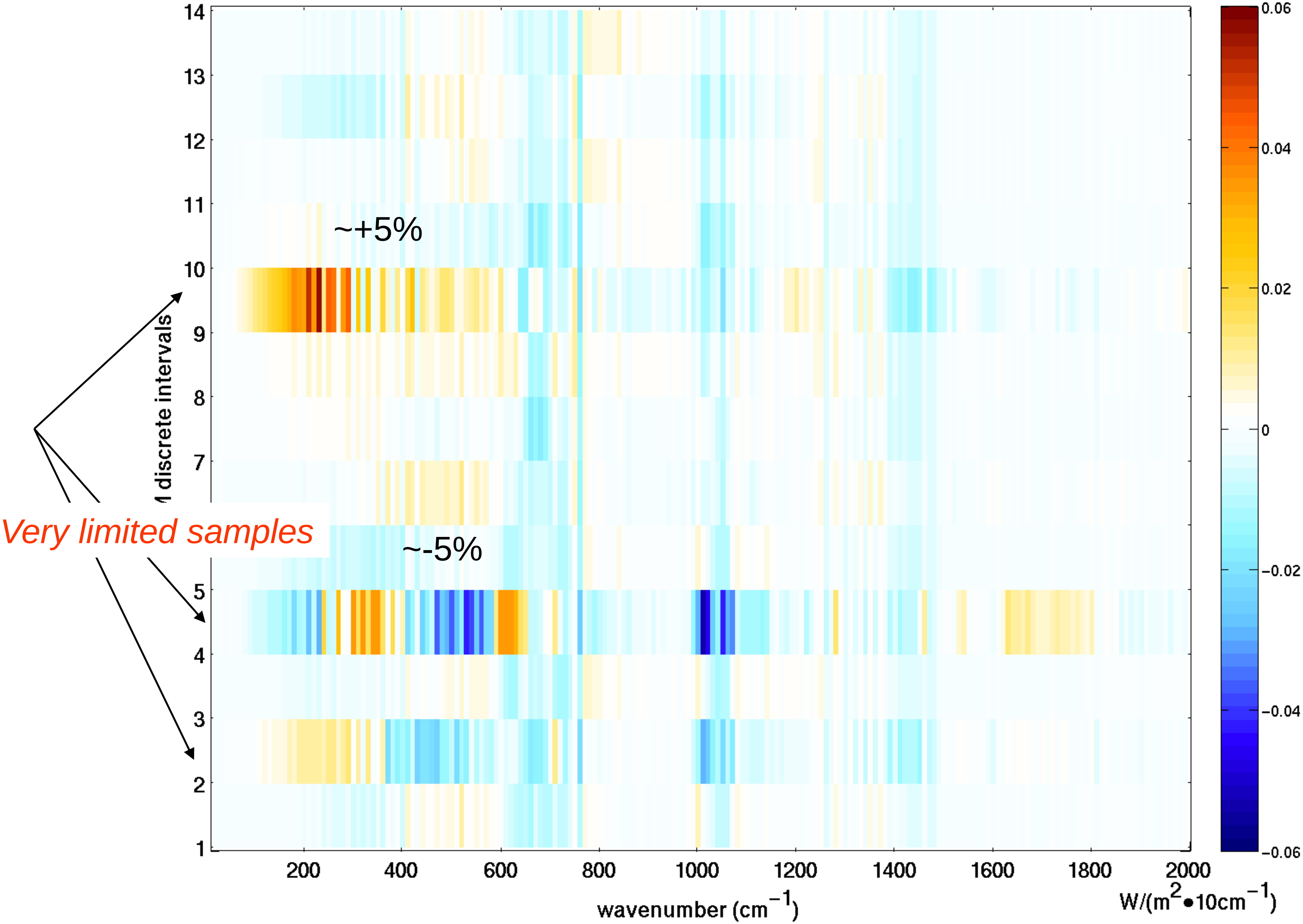
$$\begin{bmatrix} F_{\nu 1} \\ F_{\nu 2} \\ F_{\nu 3} \\ F_{\nu 4} \\ F_{\nu 5} \\ F_{\nu 6} \\ F_{\nu 7} \\ \cdots \end{bmatrix} = \begin{bmatrix} \overline{F}_{\nu 1} \\ \overline{F}_{\nu 2} \\ \overline{F}_{\nu 3} \\ \overline{F}_{\nu 4} \\ \overline{F}_{\nu 5} \\ \overline{F}_{\nu 6} \\ \overline{F}_{\nu 7} \\ \cdots \end{bmatrix} + e_1 \begin{bmatrix} \phi^1{}_{\nu 1} \\ \phi^1{}_{\nu 2} \\ \phi^1{}_{\nu 3} \\ \phi^1{}_{\nu 4} \\ \phi^1{}_{\nu 5} \\ \phi^1{}_{\nu 6} \\ \phi^1{}_{\nu 7} \\ \cdots \end{bmatrix} + e_2 \begin{bmatrix} \phi^2{}_{\nu 1} \\ \phi^2{}_{\nu 2} \\ \phi^2{}_{\nu 3} \\ \phi^2{}_{\nu 4} \\ \phi^2{}_{\nu 5} \\ \phi^2{}_{\nu 6} \\ \phi^2{}_{\nu 7} \\ \cdots \end{bmatrix} + e_3 \begin{bmatrix} \phi^3{}_{\nu 1} \\ \phi^3{}_{\nu 2} \\ \phi^3{}_{\nu 3} \\ \phi^3{}_{\nu 4} \\ \phi^3{}_{\nu 5} \\ \phi^3{}_{\nu 6} \\ \phi^3{}_{\nu 7} \\ \cdots \end{bmatrix} + O(F_\nu)$$

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

Validations

- Theoretical validation
  - $10cm^{-1}$ Fluxes estimated from synthetic AIRS spectra
  - Directly computed $10cm^{-1}$ fluxes
    - Largest difference < ±5% (clear-sky) < ±3.6% (cloudy)
- Comparing with collocated CERES OLR

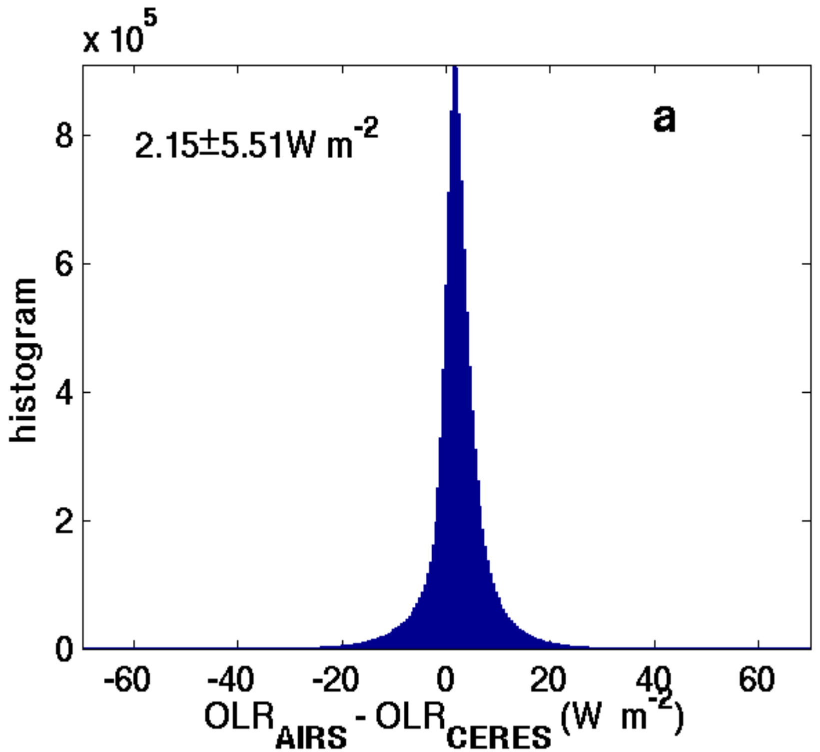
“predicted” – “directly computed” $10cm^{-1}$ clear-sky spectral flux

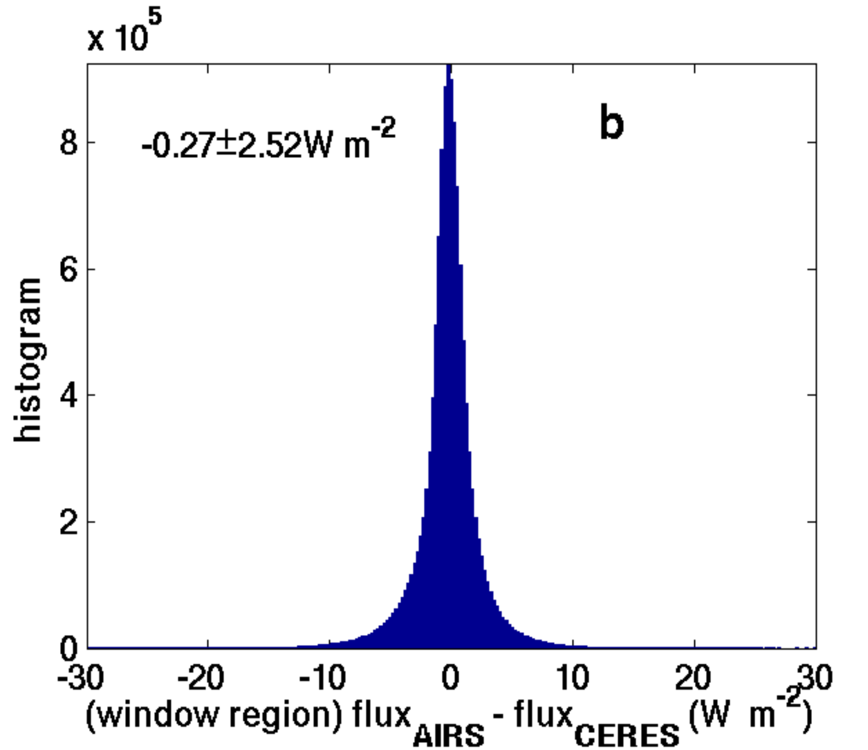


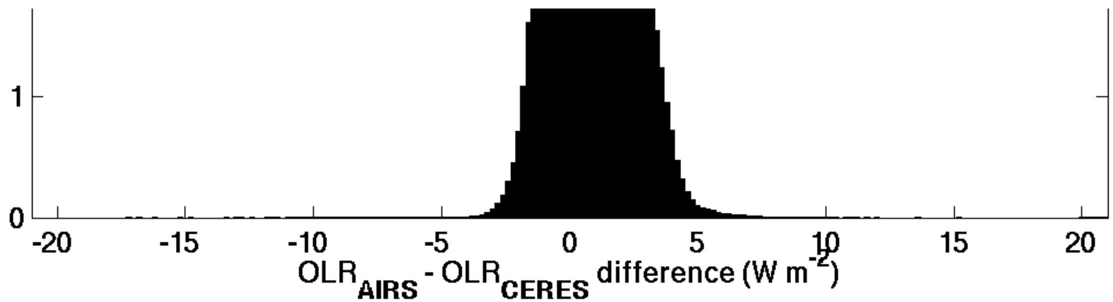
OLR_{AIRS}: OLR estimated from AIRS spectra with Huang's algorithm

OLR_{CERES}: OLR from collocated CERES observation

Cloudy-sky over the tropical ocean







CERES 2σ radiometric calibration uncertainty: 1% (i.e. ~ 2.5W m^{-2})

Stratifying $OLR_{AIRS\_huang\_algorithm}$-$OLR_{CERES}$ ($2.15\pm5.51\ Wm^{-2}$)

f \ ΔT_{sc}	<15K	15K-40K	>40K
0.001-0.5	$1.98\pm2.04Wm^{-2}$ (0.6%)	$3.93\pm3.53Wm^{-2}$ (1.4%)	$2.91\pm4.75Wm^{-2}$ (1.1%)
0.5-0.75	$2.32\pm3.36Wm^{-2}$ (0.8%)	$4.51\pm6.18Wm^{-2}$ (1.7%)	$2.18\pm8.80Wm^{-2}$ (0.9%)
0.75-0.999	$2.02\pm3.15Wm^{-2}$ (0.74%)	$4.10\pm6.89Wm^{-2}$ (1.7%)	$-0.12\pm10.40Wm^{-2}$ (-0.05%)
0.999-1.0	$2.00\pm2.49Wm^{-2}$ (0.74%)	$5.08\pm5.70Wm^{-2}$ (2.2%)	$1.58\pm7.99Wm^{-2}$ (0.9%)

OLR_{AIRS}-OLR_{CERES}: annual means and year to year changes

Clear sky over the ocean

	Nighttime (W m^{-2})	Daytime (W m^{-2})
2003	0.80	0.86
2004	0.52	0.79
2005	0.93	1.81
2006	0.86	2.10
2007	0.83	2.45

Cloudy sky over the ocean

	Nighttime (W m^{-2})	Daytime (W m^{-2})
2003	1.63	3.73
2004	1.33	3.00
2005	1.75	4.06
2006	1.58	4.35
2007	1.50	4.57

- Standard deviation changes little from year to year
- Spectral darkening in CERES FM3/FM4 SW channels
- This issue is being addressed now in CERES SSF V3 data

Over the land surface (ongoing)

2004 July OLR_{AIRS_huang}-OLR_{CERES}

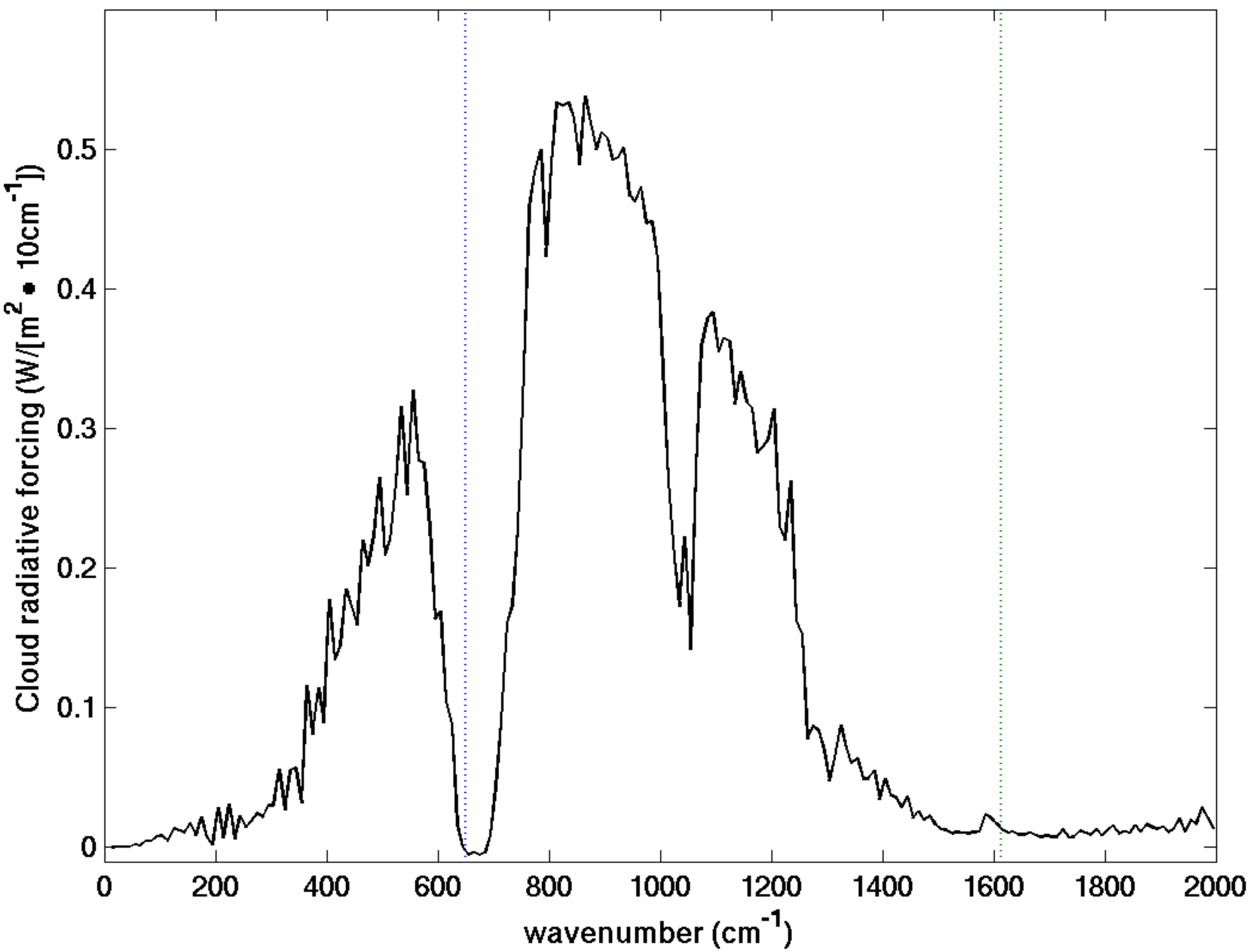
Surface Type	Daytime Difference (Wm^{-2})	Nighttime Difference (Wm^{-2})
Forest	0.53±1.26	-0.28±1.41
Savannas	-0.98±2.44	0.86±1.81
Grassland		
Dark Desert		
Bright Desert		

2004 January OLR_{AIRS_huang}-OLR_{CERES}

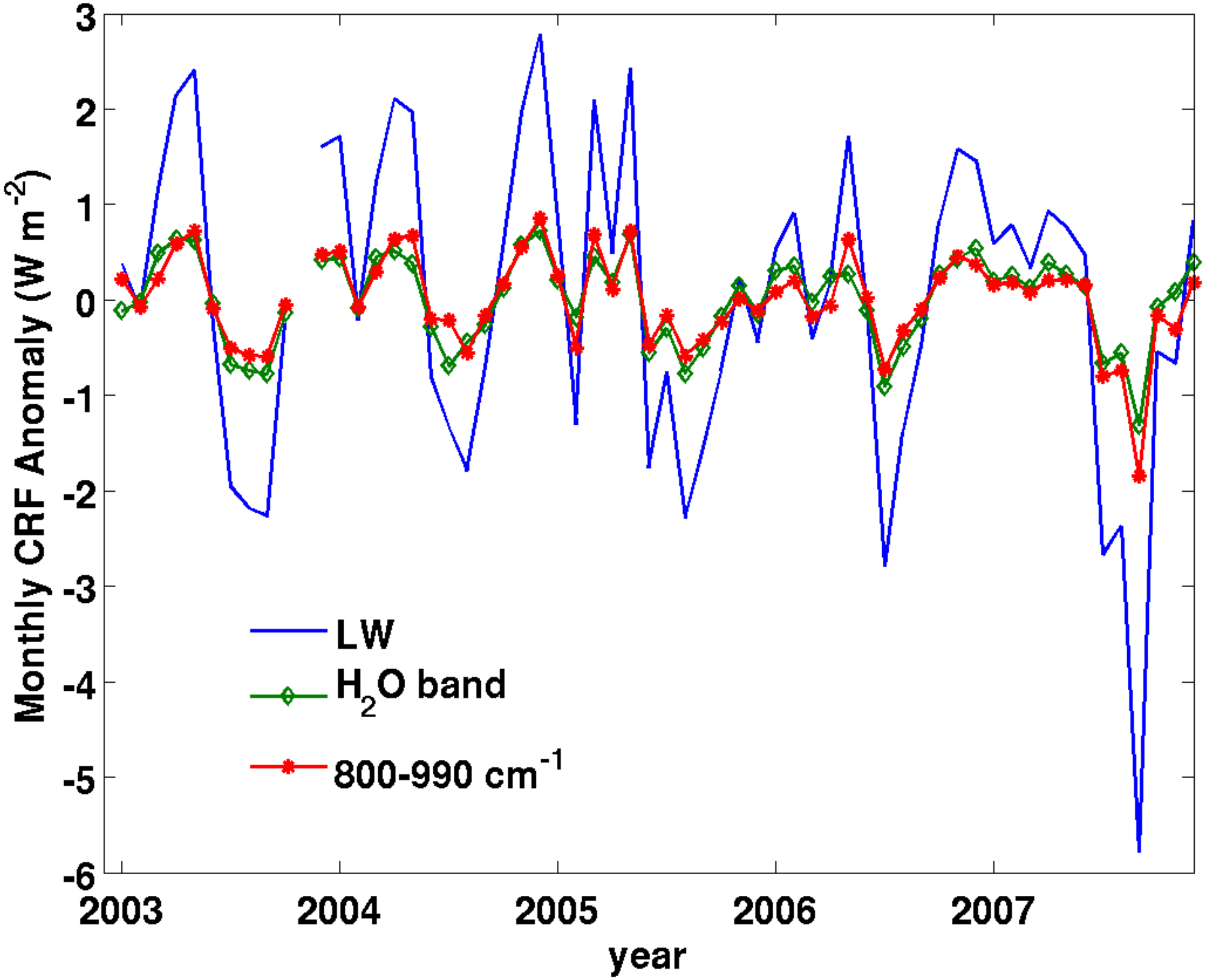
Surface Type	Daytime Difference (Wm^{-2})	Nighttime Difference (Wm^{-2})
Forest	0.45±1.63	-0.84±1.40
Savannas	0.24±2.3	0.08±1.17
Grassland	0.40±2.35	0.57±1.58
Dark Desert	-0.41±2.92	0.62±1.59
Bright Desert	2.87±2.89	2.93±1.70

Annual-mean Spectral CRF over tropical ocean in 2004 estimated from AIRS data

(Note: 1:30am/pm mean, no temporal interpolation)

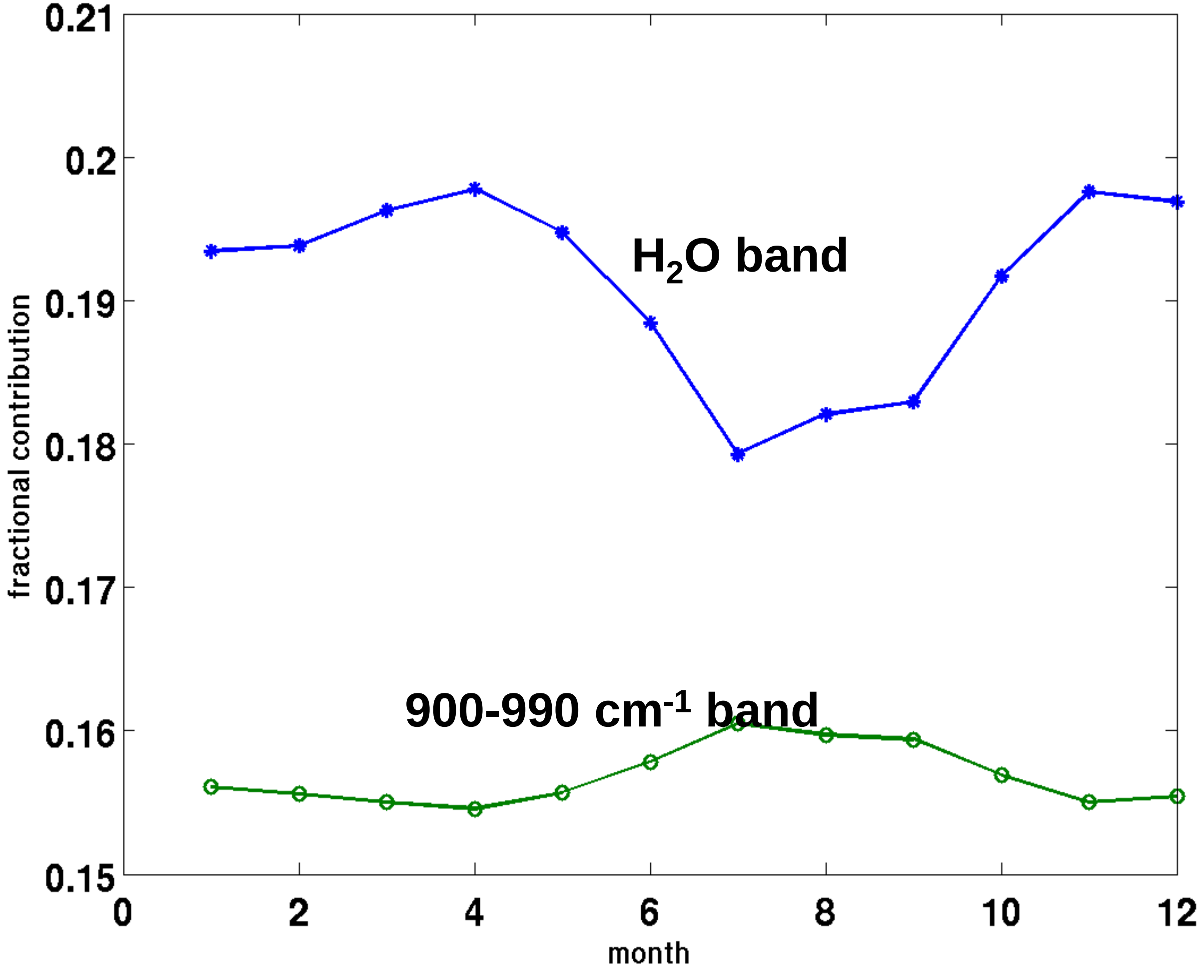


Time series of CRF anomaly (tropical ocean average)



As for the absolute value of CRF (W m^{-2}), all band closely tracks LW broadband

Seasonal Cycle of fractional contribution of each band CRF



In terms of fractional contribution, albeit its small variation with time

- **CO_2 band tracks H_2O band (r = 0.41)**
- **Window bands negatively correlation (r = -0.986 ~ -0.996)**
- **O_3 band positively correlates with window band (r ~ 0.72)**

For tropical mean: small variation at both seasonal and interannual timescale (H2O band, std ~ 3%; other bands, std < 1%)

Case studies with NOAA GFDL AM2 , NASA GEOS-5, and Canada CanAM4 GCMs

Rearrange of LW Bands for comparison

	New band	GFDL AM2 Band ID	GEOS-5 Band ID	CanAM4 Band ID	
1	0-560 and > 1400	Band 1 (0-560 and > 1400)	Band1-2 (0-540) Band8-9 (>1380)	Band 1-3 (>1400) Band 8-9 (0-540)	H_2O
2	560-800	Band 2 (560-800)	Band3&10 (540-800)	Band 7 (540-800)	CO_2
3	800-980	Band 3-4 (800-990)	Band4 (800-980)	Band 6 (800-980)	WN
4	980-1100	Band 5 (990-1070)	Band5 (980-1100)	Band 5 (980-1100)	O_3
5	1100-1400	Band 6 (1070-1200)	Band6 (1100-1215)	Band 4 (1100-1400)	WN + $N_2O/CH_4/H_2O$
		Band 7 (1200-1400)	Band7 (1215-1380)		

Slight differences in bandwidths of each GCM scheme lead to no more than 10% flux difference except for the ozone band (band4).

Clear-sky flux comparison

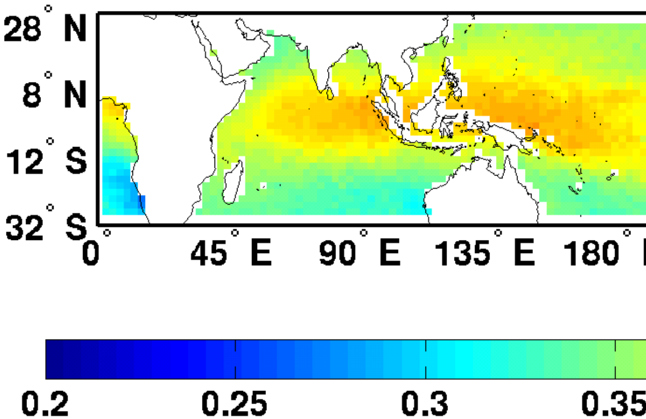
Using the green-house parameter to make the comparison.

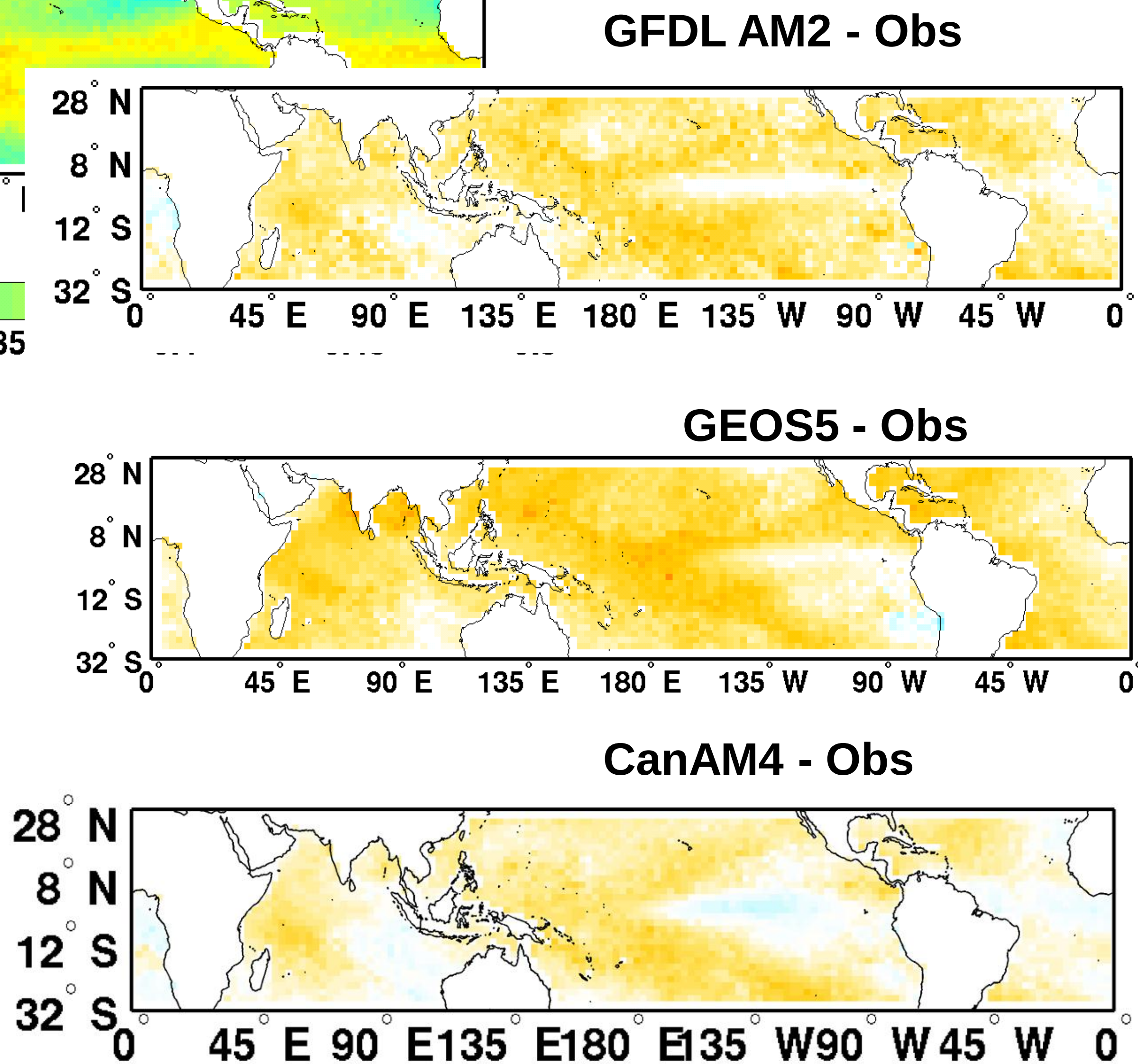
Green-house parameter (efficiency)

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

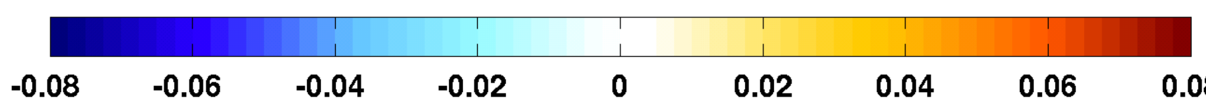
Physical Interpretation: Fraction of radiant energy over a given band that originates from surface but gets trapped within the atmosphere

Collocated AIRS & CERES obs. LW broadband *2004 Annual Mean*

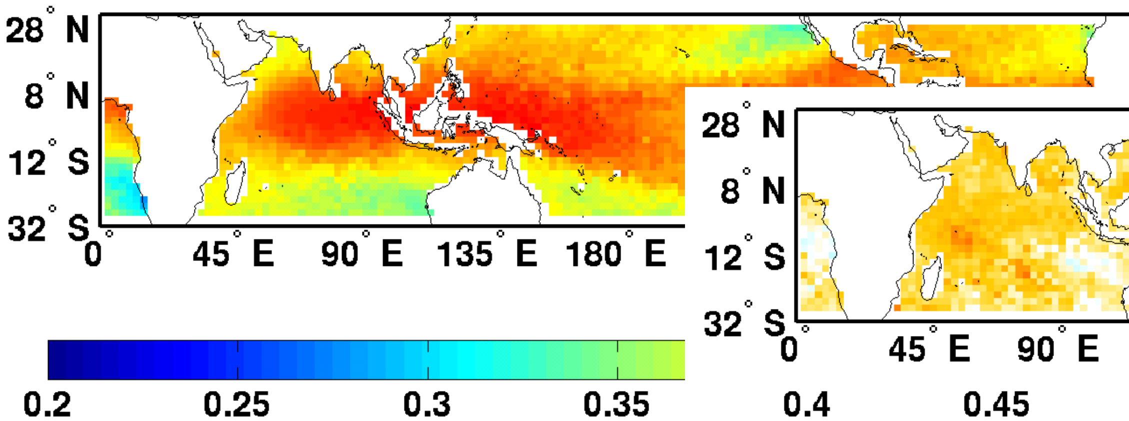




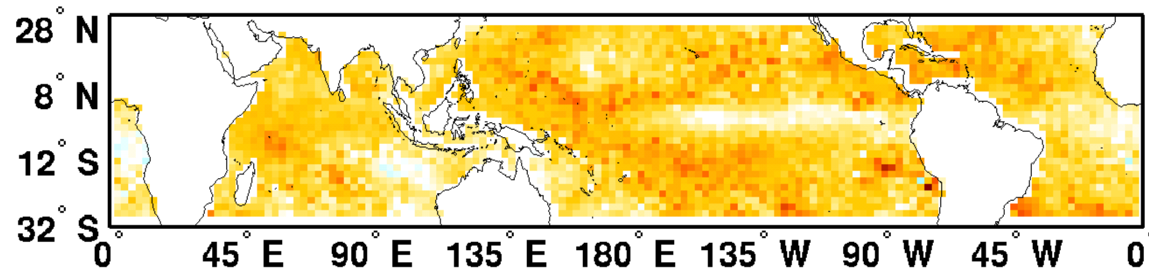
Obs	289.5 W m^{-2}
GFDL AM2	283.3 W m^{-2}
GEOS5	281.0 W m^{-2}
CGCM3.1	286.6 W m^{-2}



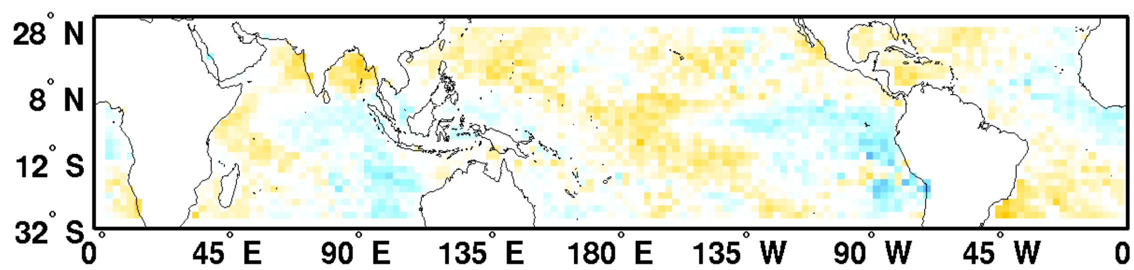
Collocated AIRS & CERES obs. H_2O bands (0-540cm^{-1}, >1400 cm^{-1})



GFDL - Obs

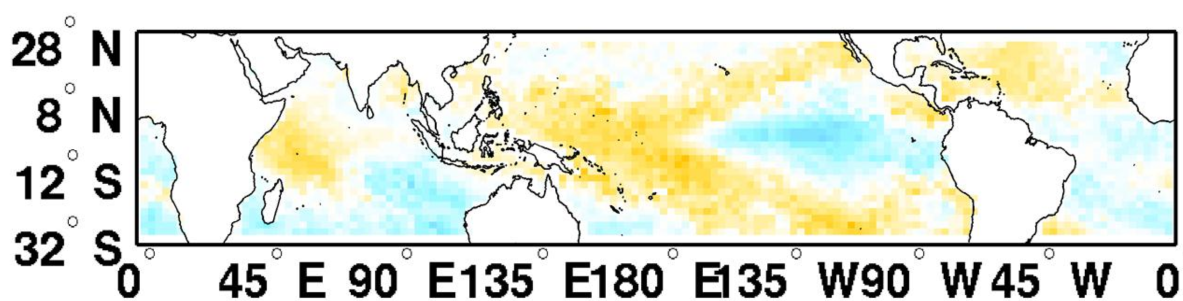


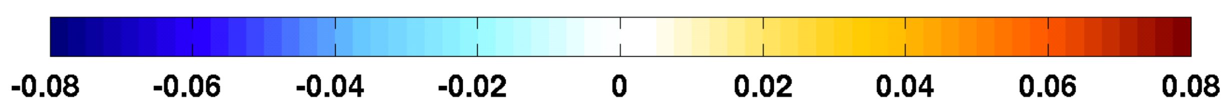
GEOS5 - Obs



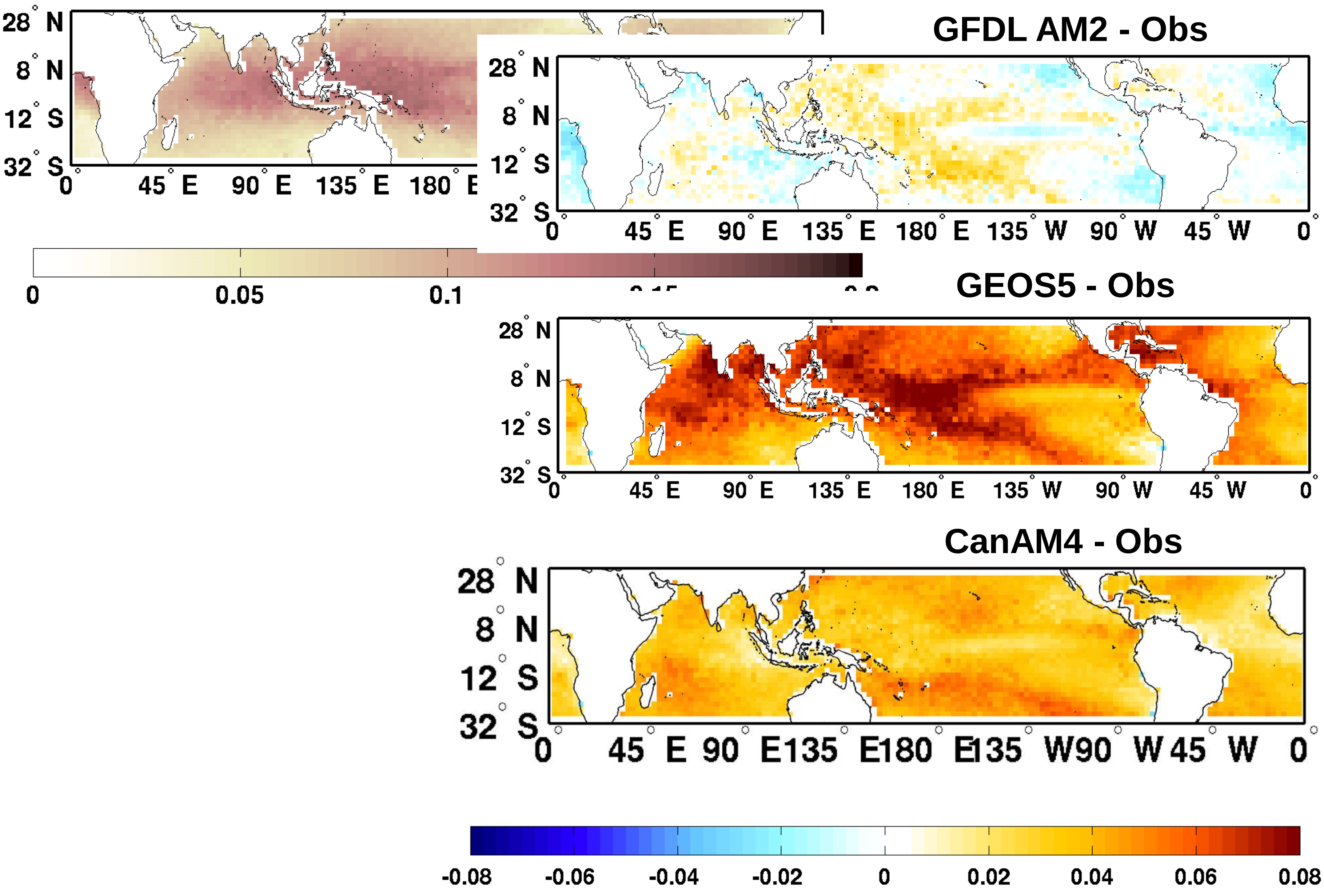
CanAM4 - Obs

0.02 in fraction ~ 2.7 Wm^{-2}





Collocated AIRS & CERES obs., window region (800-980cm^{-1})

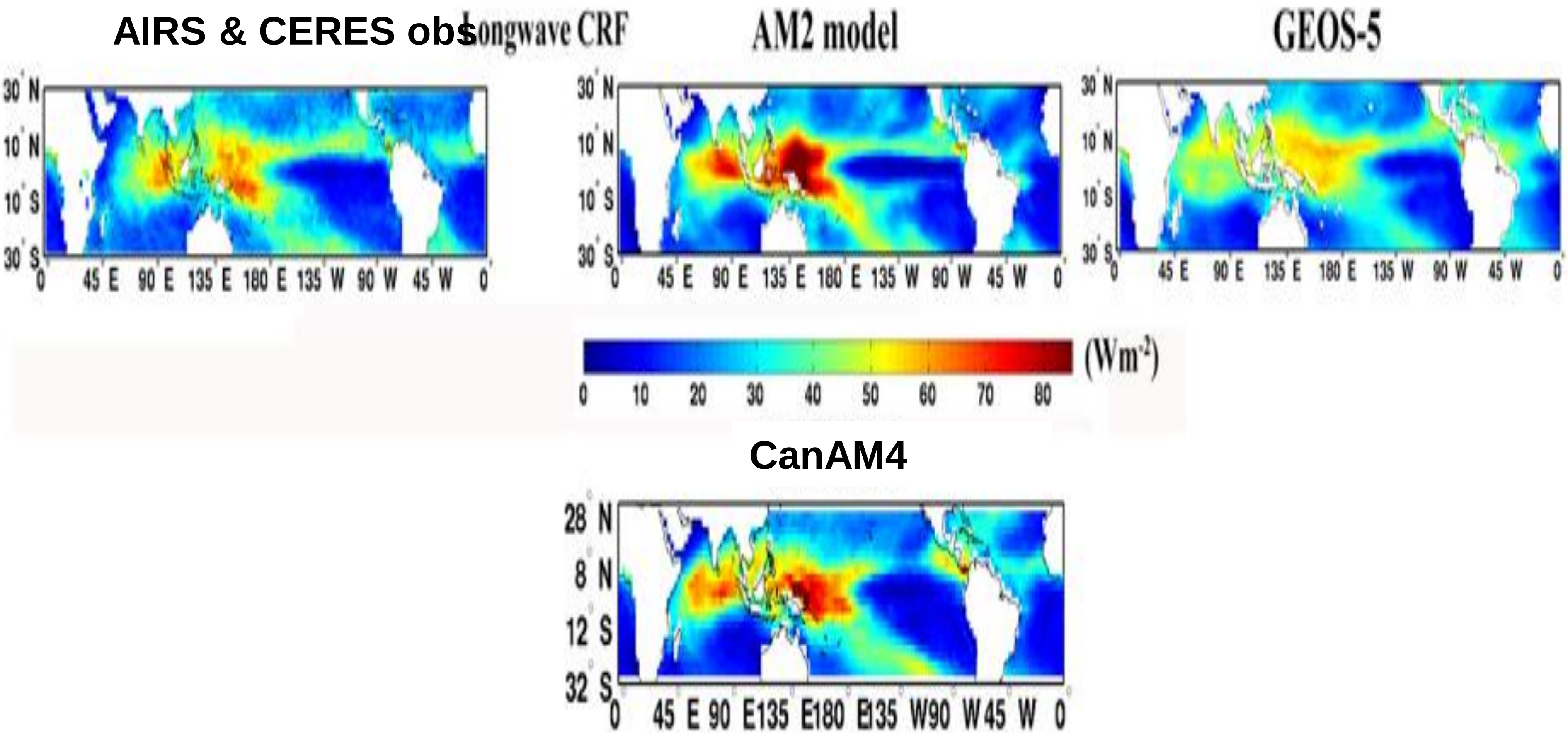


Annual-mean CRF in 2004 (Tropical oceans)

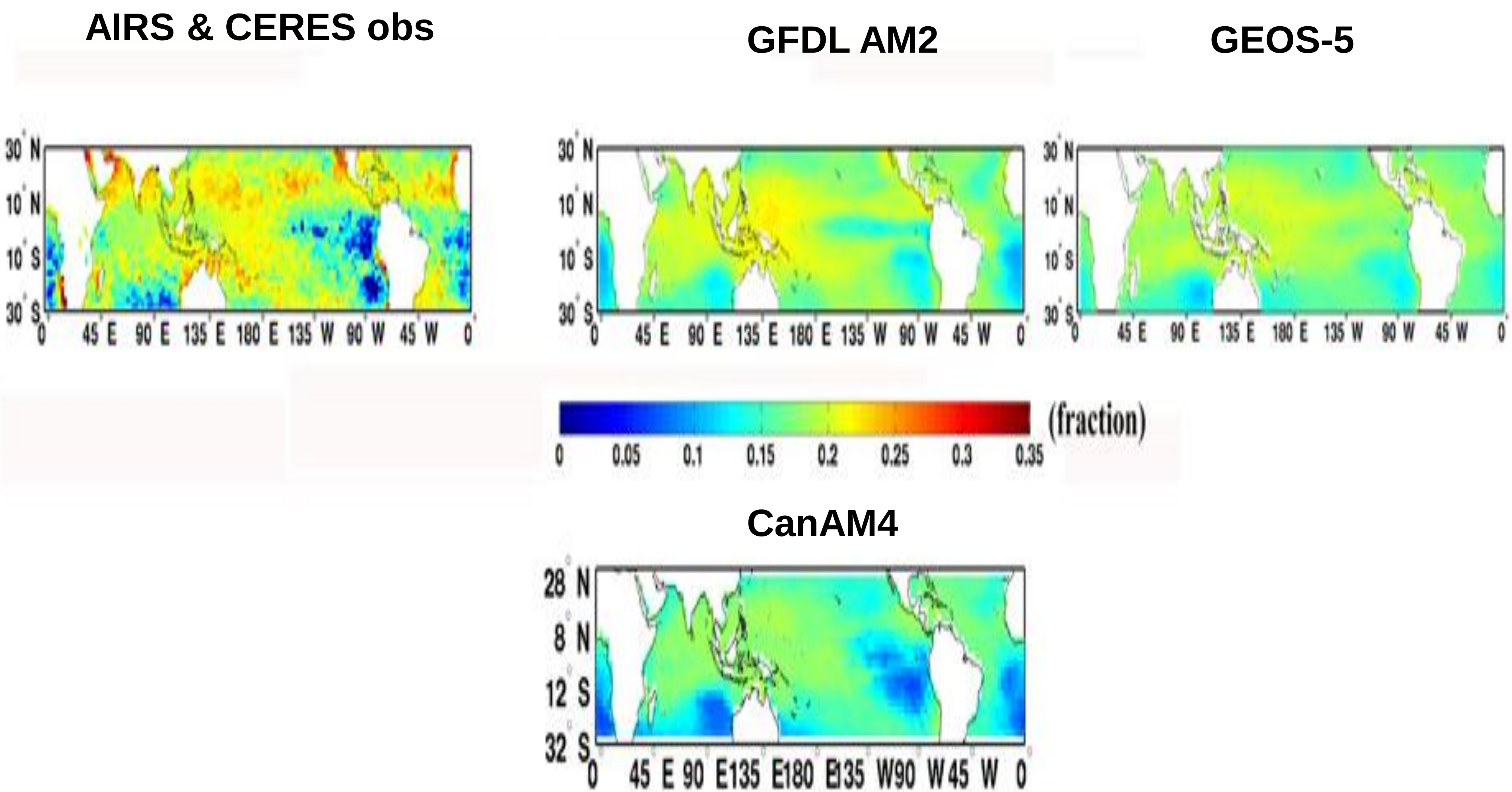
		AIRS&CERES observed CRF (Wm^{-2})	AM2 simulated CRF (Wm^{-2})	GEOS-5 simulated CRF (Wm^{-2})	CanAM4 simulated CRF (Wm^{-2})
	LW broadband	27.45 (100%)	28.13 (100%)	28.30 (100%)	27.27 (100%)
H_2O	0-560cm^{-1}; >1400cm^{-1}	5.36 (19.5%)	5.33 (19.0%)	5.08 (17.9%)	4.45 (16.3%)
CO_2	560-800cm^{-1}	4.18 (15.2%)	3.74 (13.3%)	5.15 (18.2%)	4.82 (17.7%)
WN	800-990cm^{-1}	9.35 (34.1%)	10.03 (35.6%)	9.06 (32.0%)	8.78 (32.2%)
O_3	990-1070cm^{-1}	2.02 (7.0%)	1.68 (6.0%)	3.62 (12.8%)	3.73 (13.7%)
WN H_2O NO_2 CH_4	1070-1400cm^{-1}	6.53(23.8%)	7.34 (26.1%)	5.43 (19.1%)	5.48 (20.1%)

- **LW CRF differs ~ 1 Wm^{-2}**
- **CRF of Individual band can have difference as large as that, or even larger**

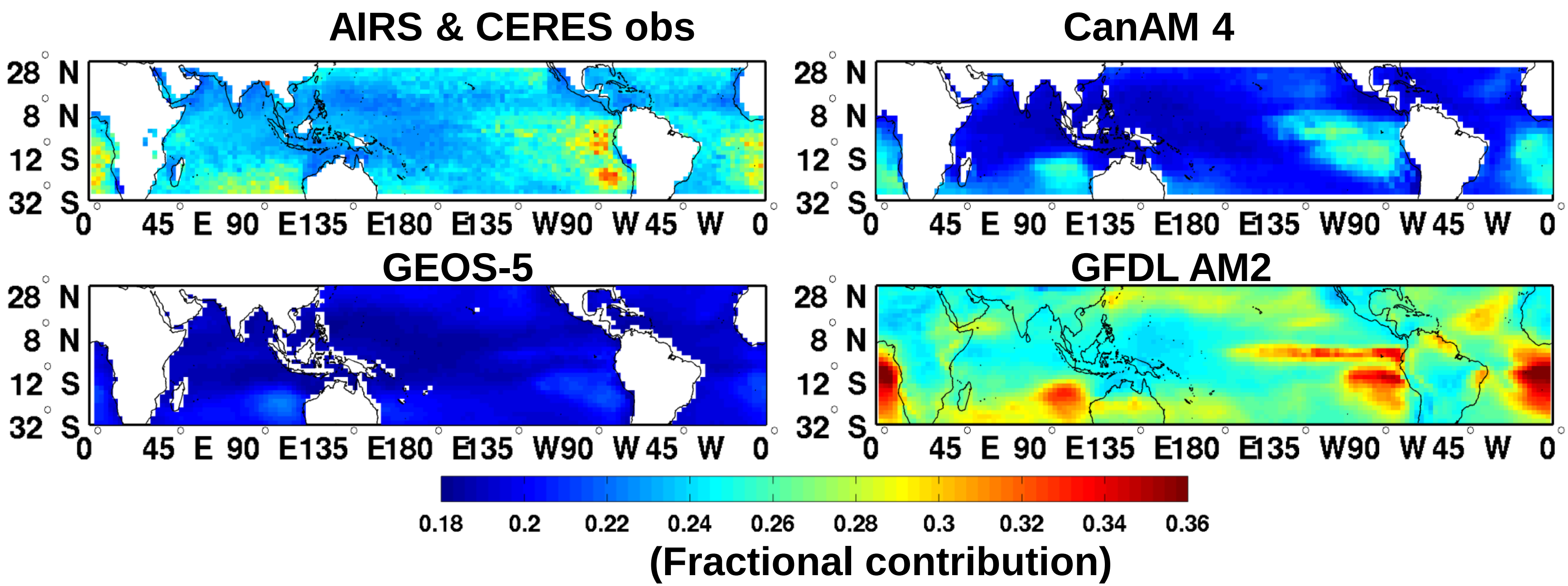
Annual-mean CRF map



Band 1: 0-560 cm^{-1} and > 1400 cm^{-1}



Annual-mean CRF map: 1070-1400 cm^{-1}



GEOS -5: lower than obs. and a narrow range: 0.18-0.22
GFDL AM2: higher than obs.

Conclusions

- Using CERES scene-type classification, spectral fluxes can be derived from AIRS spectra with good agreements with CERES OLR
- Band-by-band CRF fractional contribution is more sensitive to cloud height, less sensitive to cloud fraction
- Band-by-band flux and CRF consist more rigorous test for climate model
  - Compensating biases: bias in each band could be as large as the broadband bias
  - What's the implication for climate changes?
- Perspectives
  - The overkill of CERES scene-type for spectra
    - Scene type should be able to inferred from spectrum alone
  - How band-by-band CRF changes in future climate

"…understanding cloud feedback will be gleaned neither from observations nor proved from simple theoretical argument alone. The blueprint for progress must follow a more arduous path that requires a carefully orchestrated and systematic combination of model and observations." **Stephens (2005 J Clim)**

Thank You

References:

- Huang, X.L., V. Ramaswamy, and M. Daniel Schwarzkopf, 2006: Quantification of the source of errors in AM2 simulated tropical clear-sky outgoing longwave radiation, *JGR–Atmospheres*, 111, D14107, doi:10.1029/2005JD006576.
- Huang, X.L., W.Z. Yang, N.G. Loeb, and V. Ramaswamy, 2008: 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-Atmospheres*, 113, D09110, doi:10.1029/2007JD009219.
- Huang, X.L., N.G. Loeb, and W.Z. Yang, 2010: Spectrally resolved fluxes derived from collocated AIRS and CERES measurements and their application in model evaluation, Part II: cloudy sky and band-by-band cloud radiative forcing over the tropical oceans over the tropical oceans, *JGR-Atmospheres,* 115, D21101, doi:10.1029/2010JD013932.

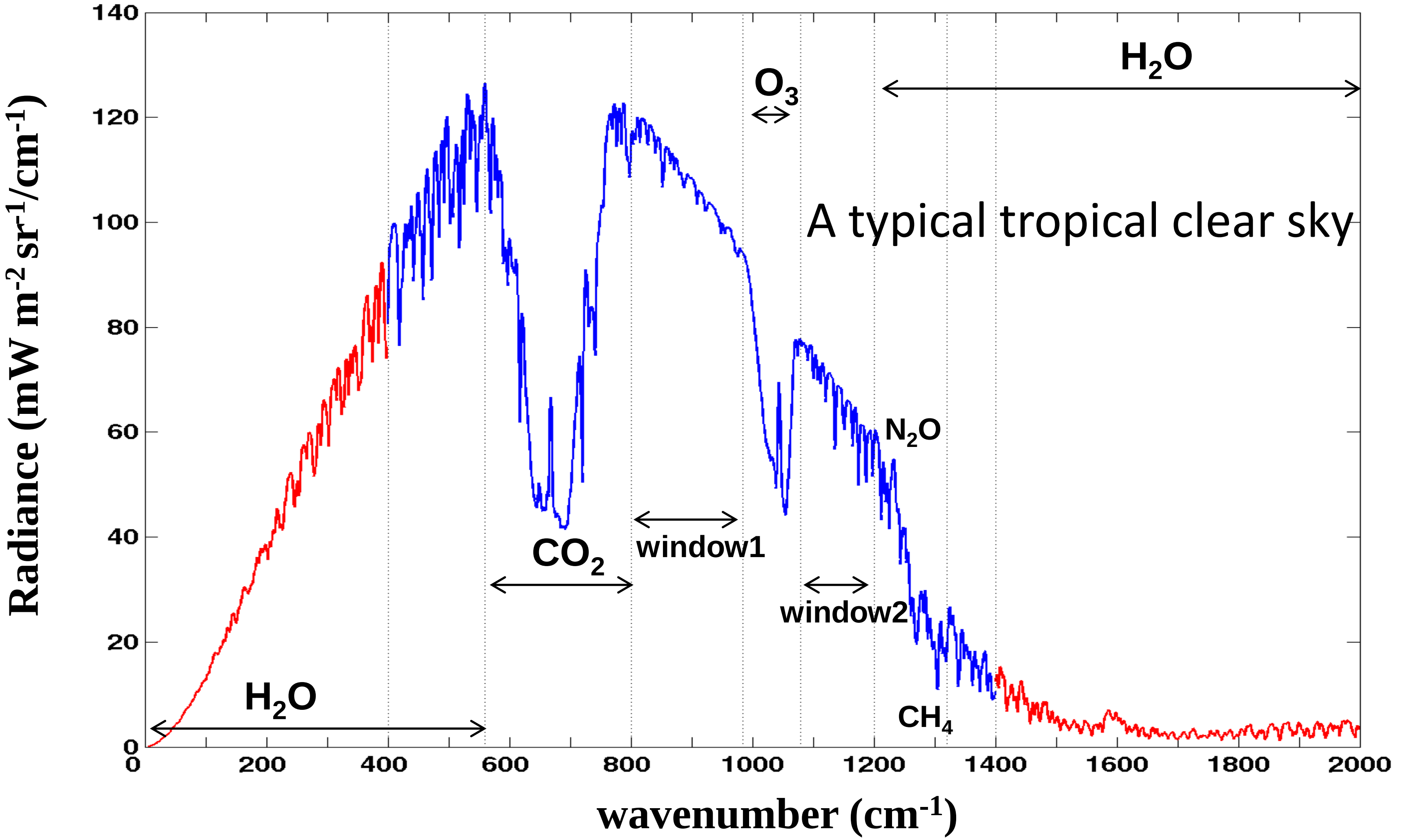
Backup Slides

OLR: important player in radiation budget, CRF, radiative forcings, and thus in climate change

$$F = 2\pi \int_{\Delta\nu} d\nu \int_0^1 I(\nu,\mu)\,\mu\, d\mu \quad (\mu = \cos\theta)$$

$$F = 2\pi \int_{\Delta\nu} d\nu \int_0^{\frac{\pi}{2}} I(\nu,\theta) \cos\theta \sin\theta\, d\theta$$

Total flux (wm^{-2}) 52.5 52.2 58.0 59.7 18.0 23.5 12.4 4.5 7.7 =288.5



Measuring broadband flux: ERBE/CERES approach

Digital Count → $I_{filter}(\Delta v;\theta) = I(v;\theta) \otimes SRF(v)$ → unfiltering → $I_{unfilter}(\Delta v;\theta) = \int_{\Delta v} I(v;\theta)dv$

LW=TOT (N)

LW=TOT-SW (D)

↓

$$F = \pi I_{unfilter}(\Delta v;\theta) / R_{\Delta v}(\theta)$$

$R_{\Delta V}(\theta)$ from Anisotropic Distribution Model (ADM)

1. Function of scene type
2. Scene-type classification: ERBE vs. CERES
   - ERBE ~15 scene types
   - CERES-SSF 14 sub scene types for clear-sky ocean; 2008 sub scene types for cloudy ocean (making use of MODIS and other info)

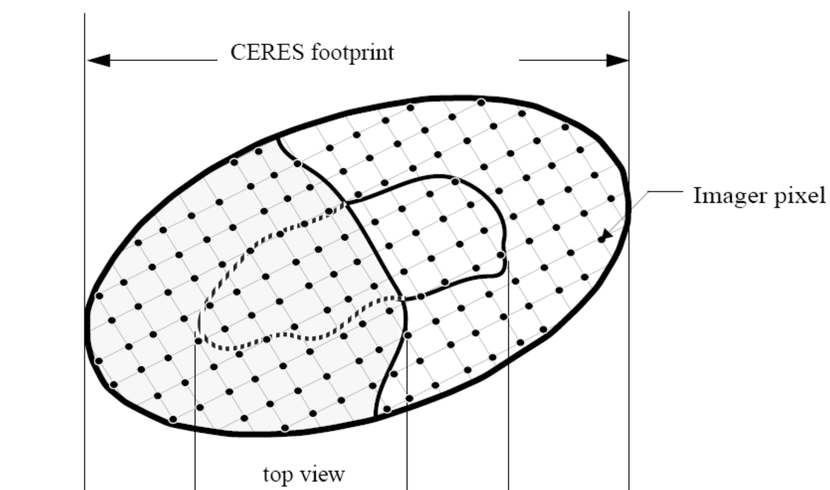


TABLE 3. Precipitable water (w), lapse rate (ΔT), and surface skin temperature (T_s) intervals used to determine LW and WN ADMs under clear-sky conditions over the ocean, land, and desert.

w (cm)	ΔT (K)	T_s (K)
0–1	<15	<270
1–3	15–30	270–290
3–5	30–45	290–310
>5	>45	310–330
		>330

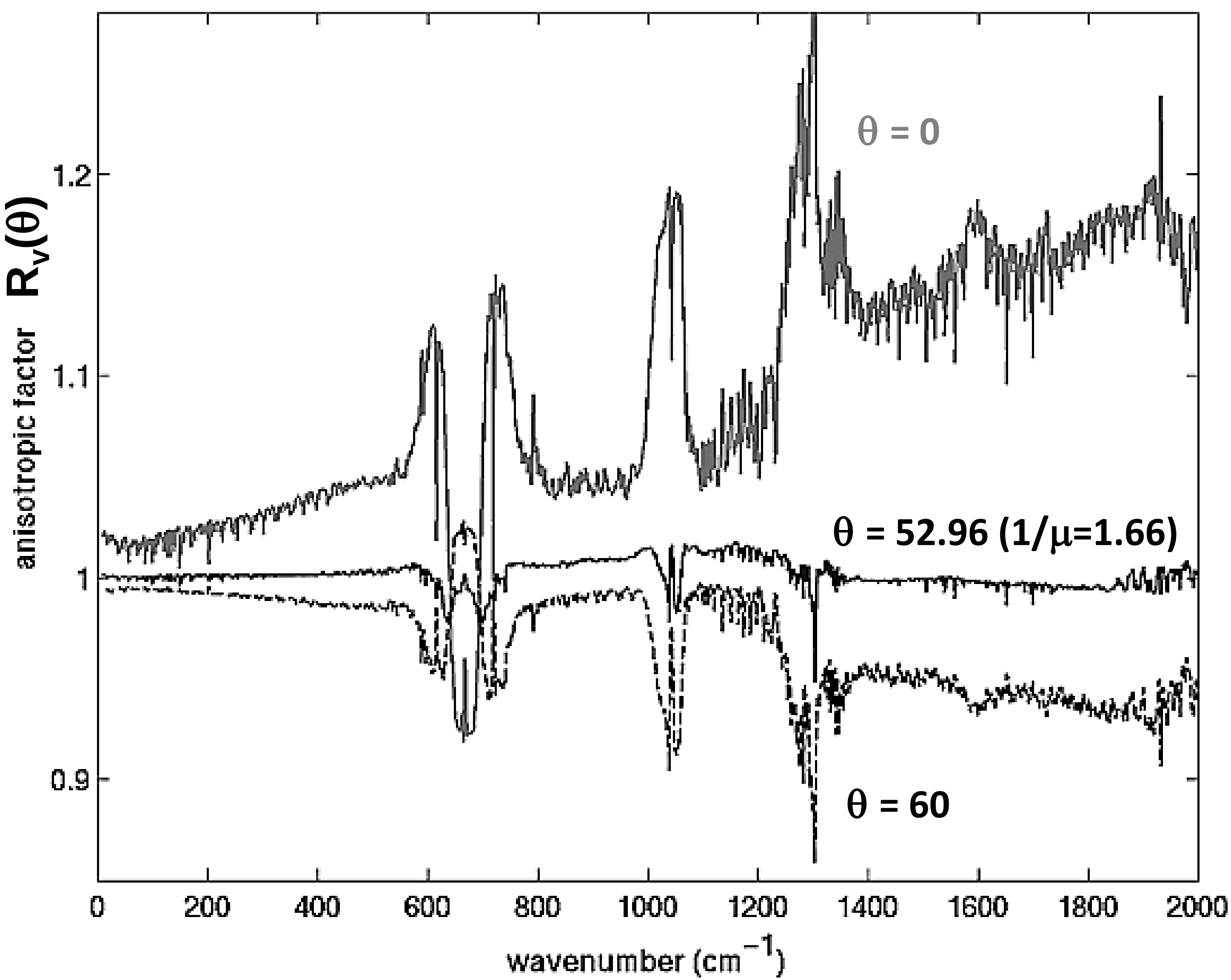
TABLE 4. Surface type, precipitable water (w), cloud fraction (f), surface–cloud temperature difference (ΔT_{sc}), and surface skin temperature (T_s) intervals used to determine LW and WN ADMs under cloudy conditions over the ocean, land, and desert.

Surface type	w (cm)	f	ΔT_{sc} (K)	T_s (K)
Ocean	0–1	0.001–0.5	<−15; −15 to 85 every 5 K; −10–>85	<275; 275 to 320 every 5 K >320
Land	1–3	0.5–0.75		
Desert	3–5	0.75–0.999		
	>5	0.999–1.0		

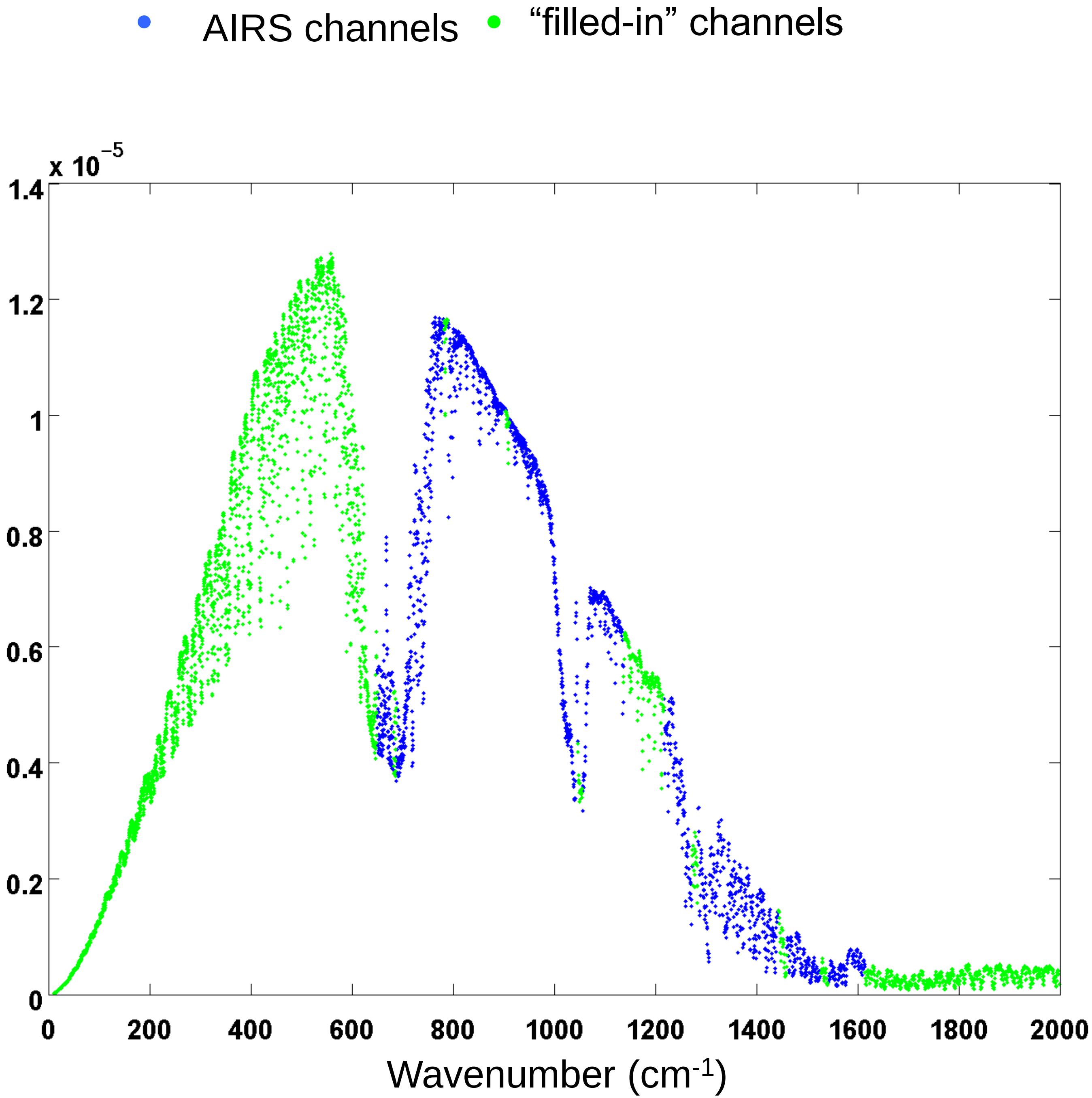
(Loeb et al., 2005)

$$F_\nu = \frac{\pi I_\nu}{R_\nu(\theta)} \text{ or } R_\nu(\theta) = \frac{\pi I_\nu}{F_\nu}$$

US 1976 standard atmosphere

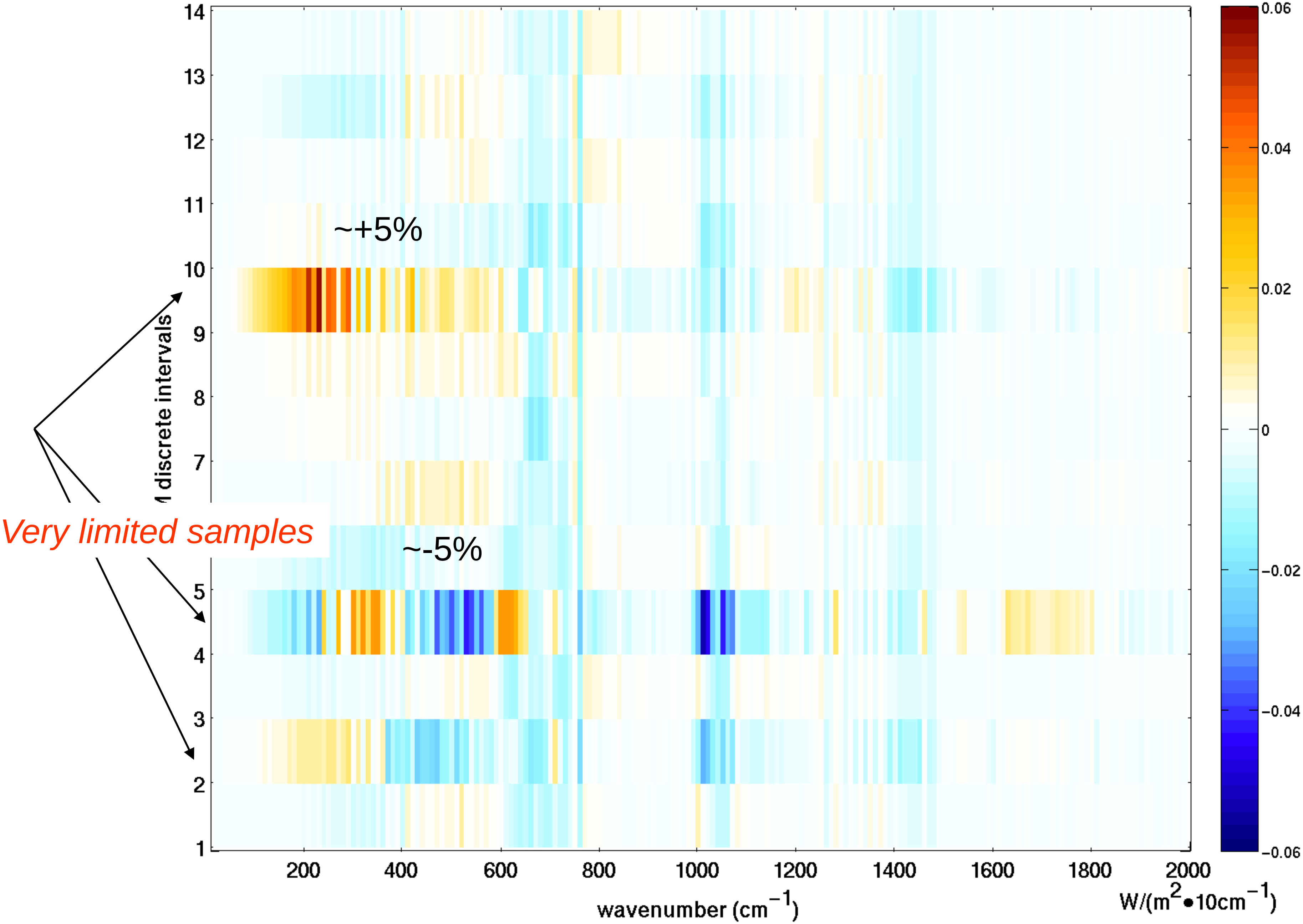


(Huang et al., JGR, 2008)

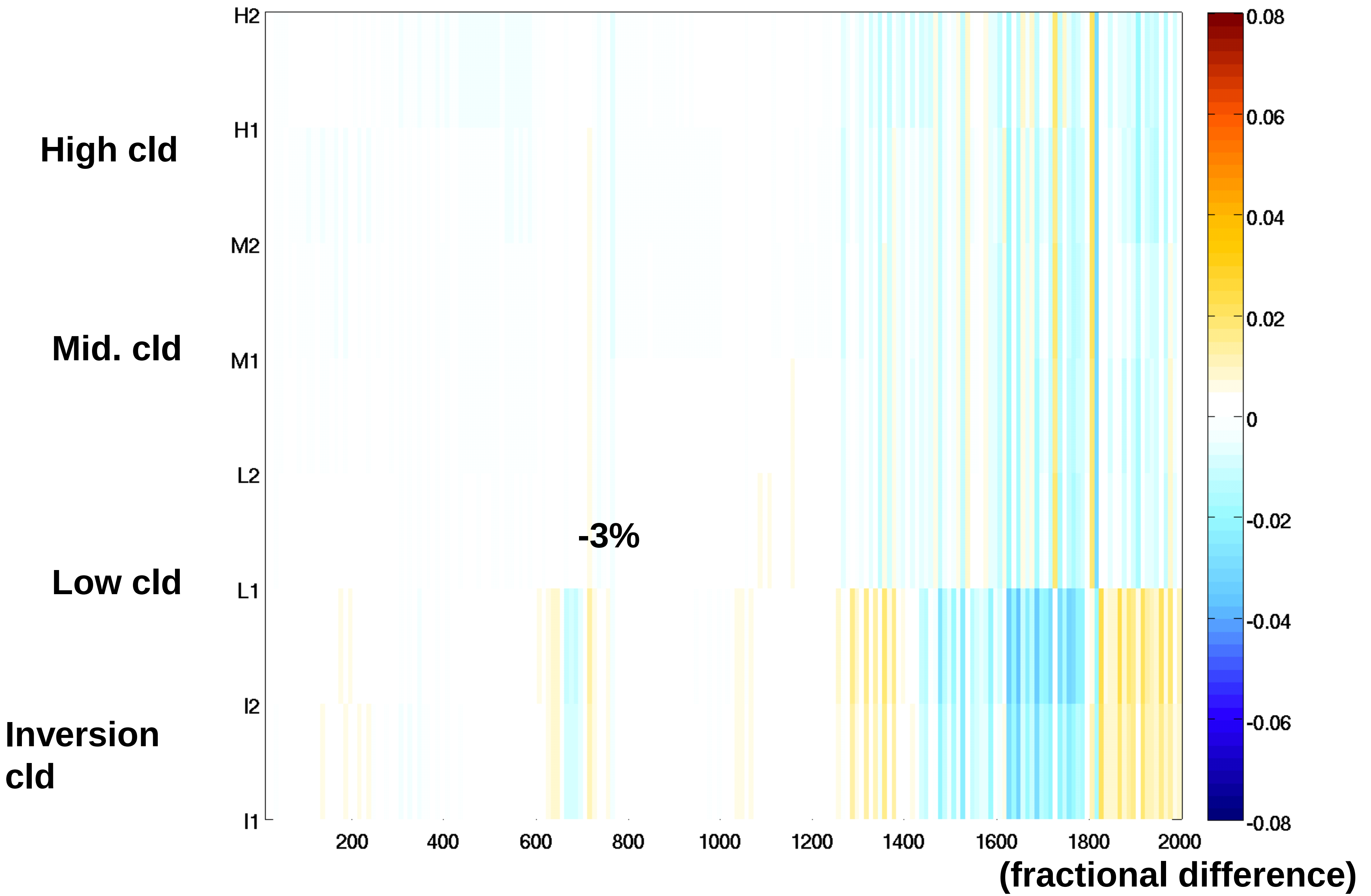


AIRS channels
"filled-in" channels
x 10^-5
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Wavenumber (cm-1)

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



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

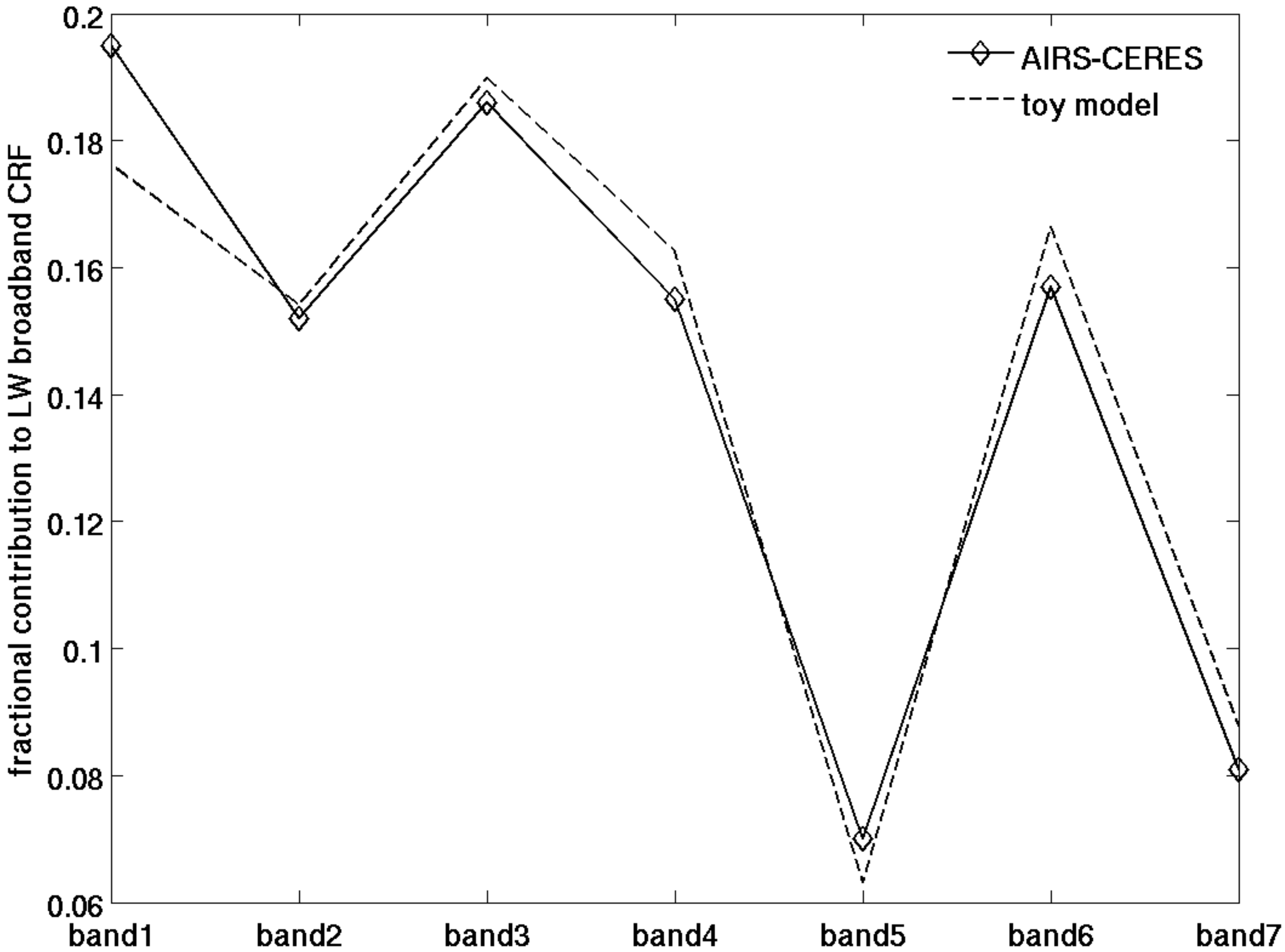


- A fit using Toy Model B (Typical Tropical profiles + a fractional thick cloud layer

Best fit: cloud top height at 9.3km, cloud fraction 23%

f=CRF/CRF(overcast)

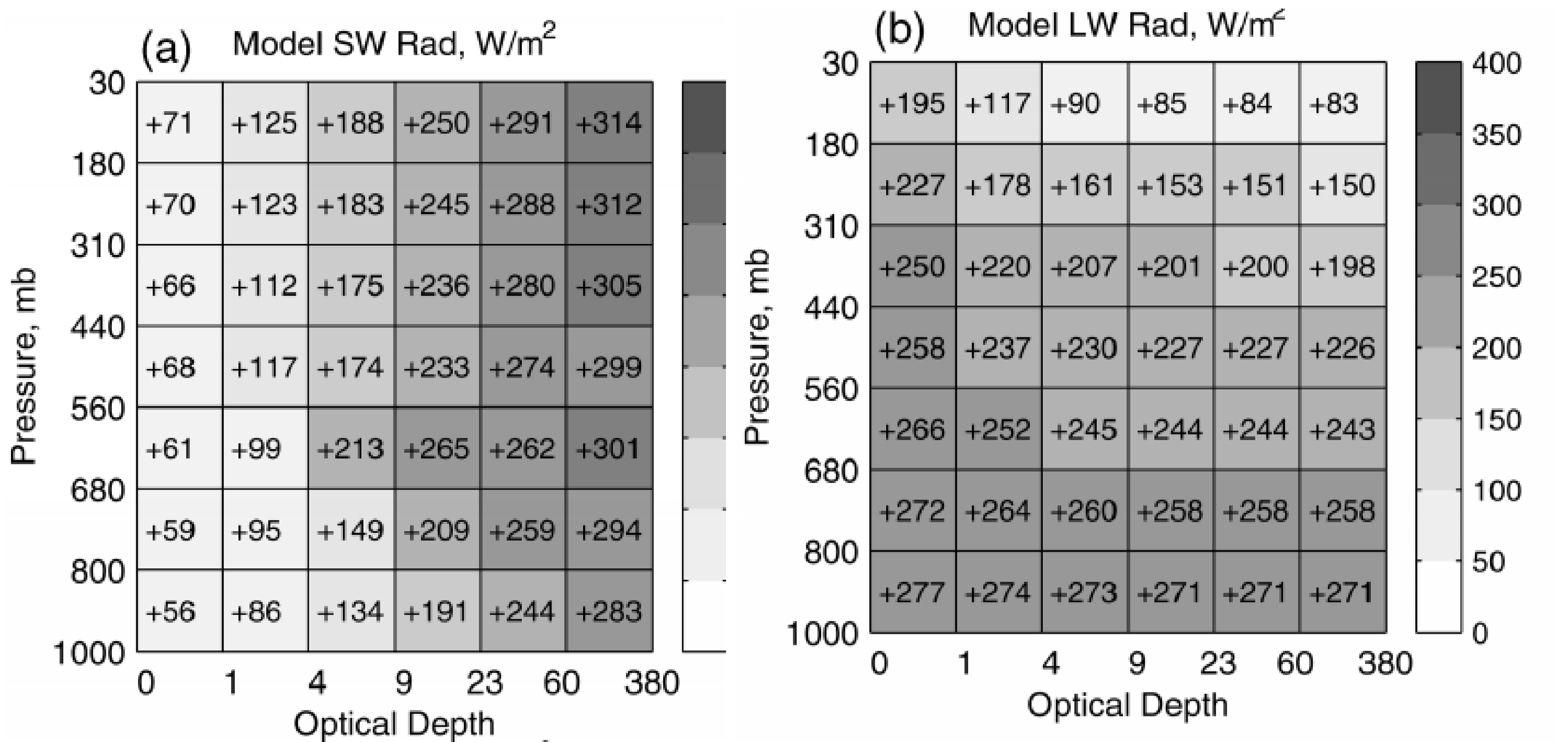
The deviation from usual climatology of *CTH* and *f*

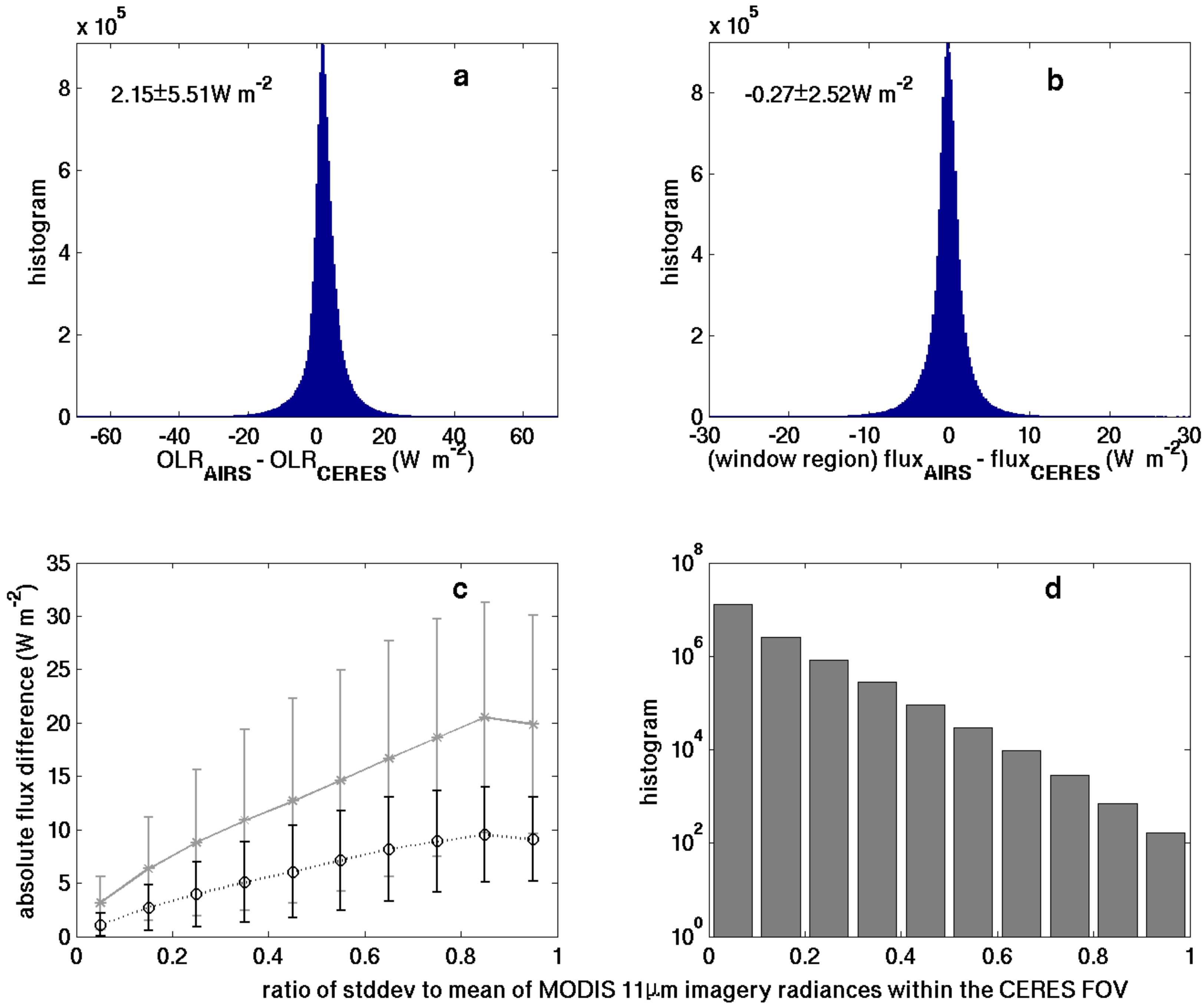


Low cloud amount and low cloud height

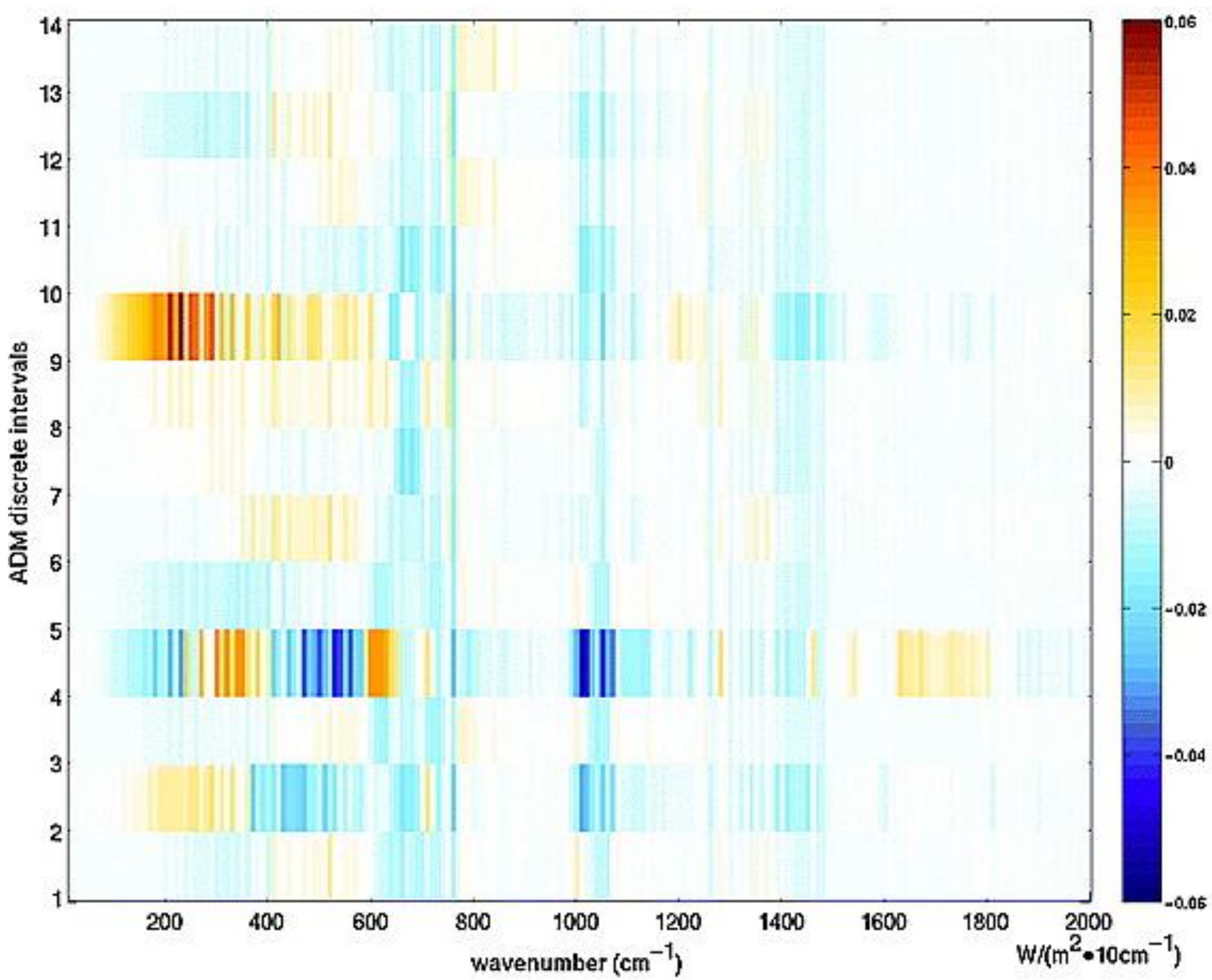
“Feedbacks involving low-level clouds remain a primary cause of uncertainty in global climate model projections.” (Clement et al., Science)

“The COSM4 still has significant biases, such as the mean precipitation distribution in the tropical Pacific Ocean, too much low cloud in the Arctic, and the latitudinal distributions of short-wave and long-wave cloud forcings.” (Gent et al., J Climate)

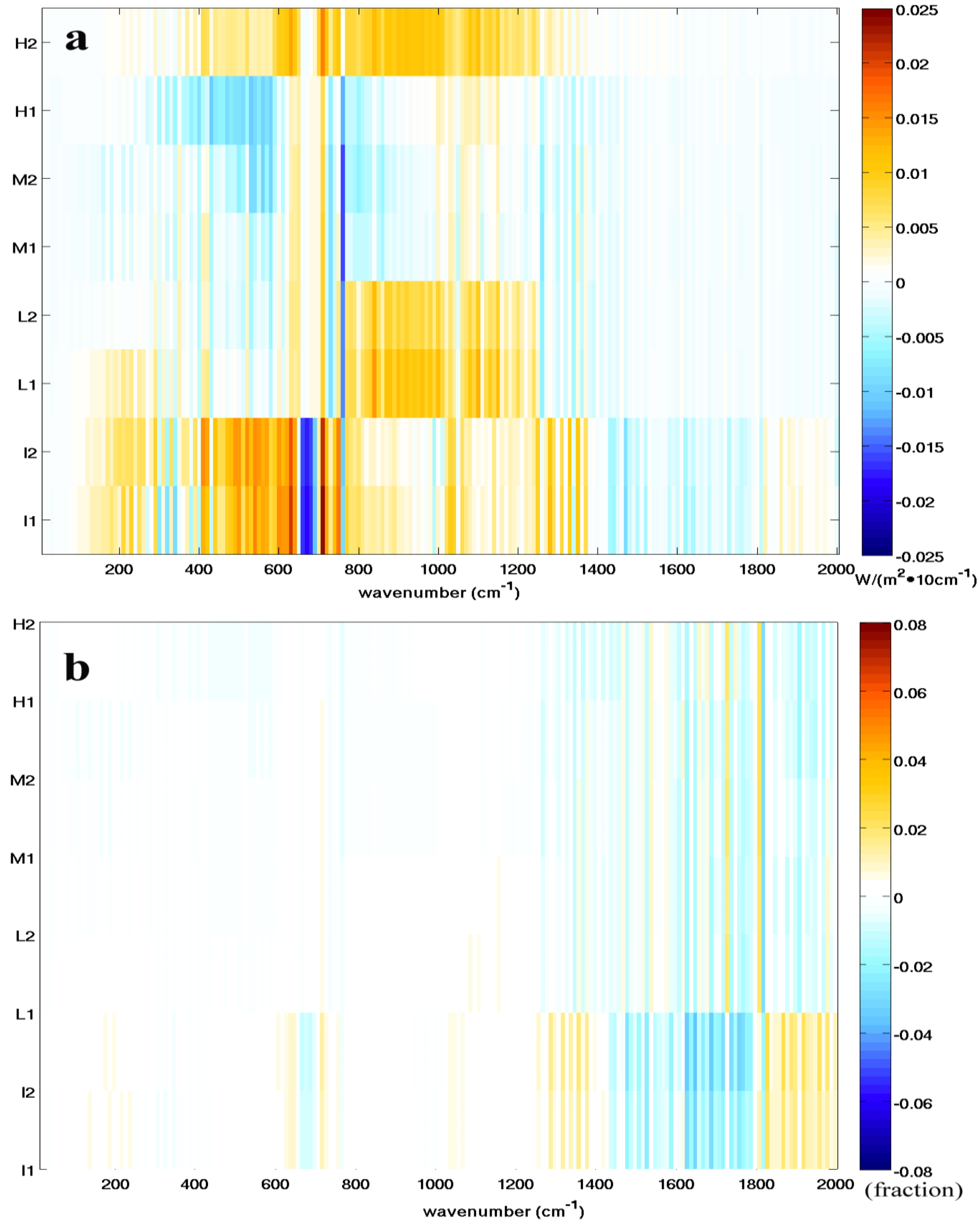




x 10^5
a
2.15±5.51W m^-2
histogram
OLR_AIRS - OLR_CERES (W m^-2)
x 10^5
b
-0.27±2.52W m^-2
histogram
(window region) flux_AIRS - flux_CERES (W m^-2)
c
absolute flux difference (W m^-2)
d
histogram
ratio of stddev to mean of MODIS 11μm imagery radiances within the CERES FOV



ADM discrete intervals
14
13
12
11
10
9
8
7
6
5
4
3
2
1
200
400
600
800
1000
1200
1400
1600
1800
2000
wavenumber (cm−1)
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
W/(m2•10cm−1)



a
H2
H1
M2
M1
L2
L1
I2
I1
200
400
600
800
1000
1200
1400
1600
1800
2000
wavenumber (cm-1)
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
W/(m2•10cm-1)
b
0.08
0.06
0.04
0.02
-0.02
-0.04
-0.06
-0.08
(fraction)