Spectrum: An underutilized dimension in model validations and diagnostics

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Outline

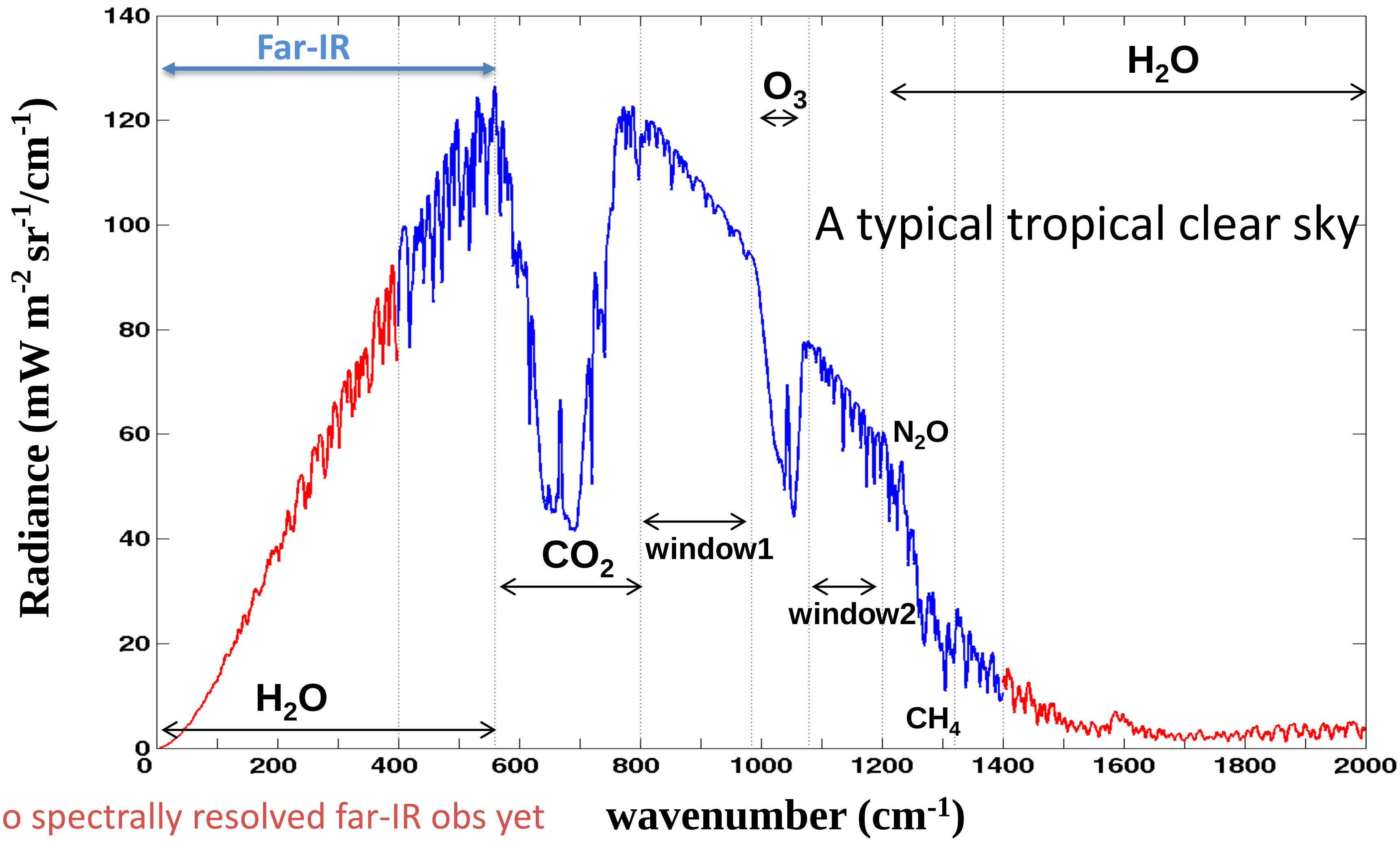
- Motivations
  - Why go from broadband to spectral (band-by-band)
- LW spectral flux from collocated AIRS&CERES observations
  - Derivation and validation
  - Applications
    - Spectral CRE
    - Trend of Arctic spectral OLR and greenhouse efficiency
- Spectral radiative feedbacks
  - Applications in the CMIP3 and CMIP5 diagnostics
  - Spectral cloud radiative feedbacks: short-term vs. long-term
- Conclusions

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

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

$$F = 2\pi \int_0^{\frac{\pi}{2}} I \cos\theta \sin\theta\, d\theta$$

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

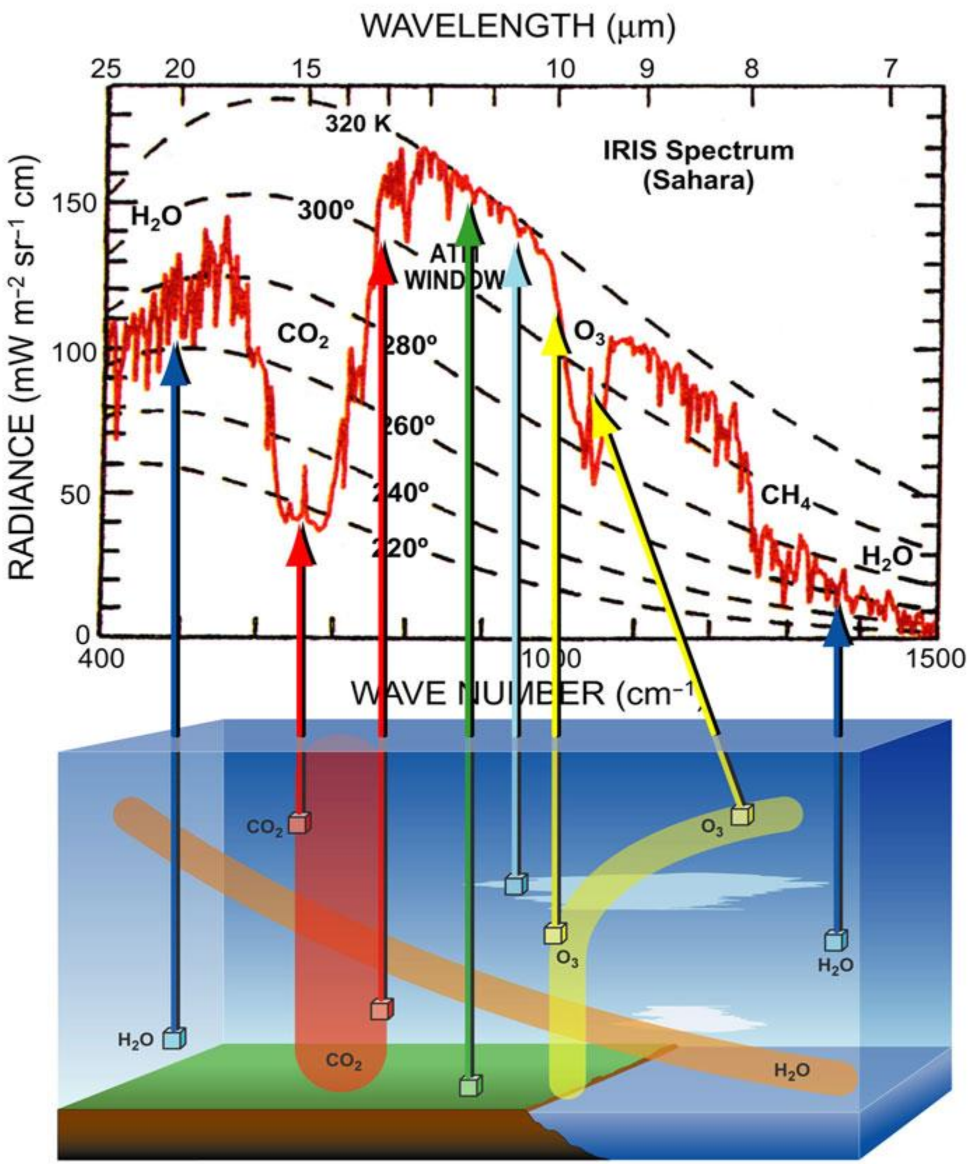


No spectrally resolved far-IR obs yet

The meaning of IR spectra

- Far-IR: upper and middle troposphere
- Window: PBL and surface
- CO_2 band:
  - Center: stratosphere
  - Wing: troposphere

Cloud complicates the scenario: “noise” and “signal”



(Courtesy of John Dykema)

What spectral dimension can offer?

Reveal compensating differences that cannot be revealed in broadband diagnostics alone.

I will use two examples to elaborate on this point.

Broadband Flux vs. Spectral flux vs. Spectral radiance

Energy budget ??? Retrievals/Sounding of (T, q, trace gases)

Example 1: clear-sky flux comparison

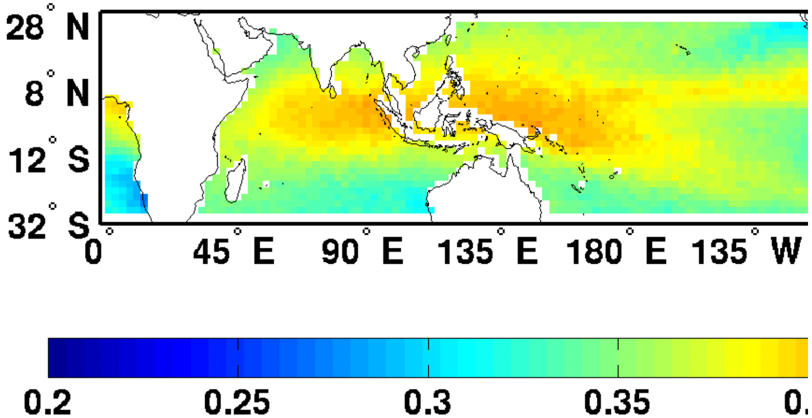
Using the green-house parameter to make the comparison.

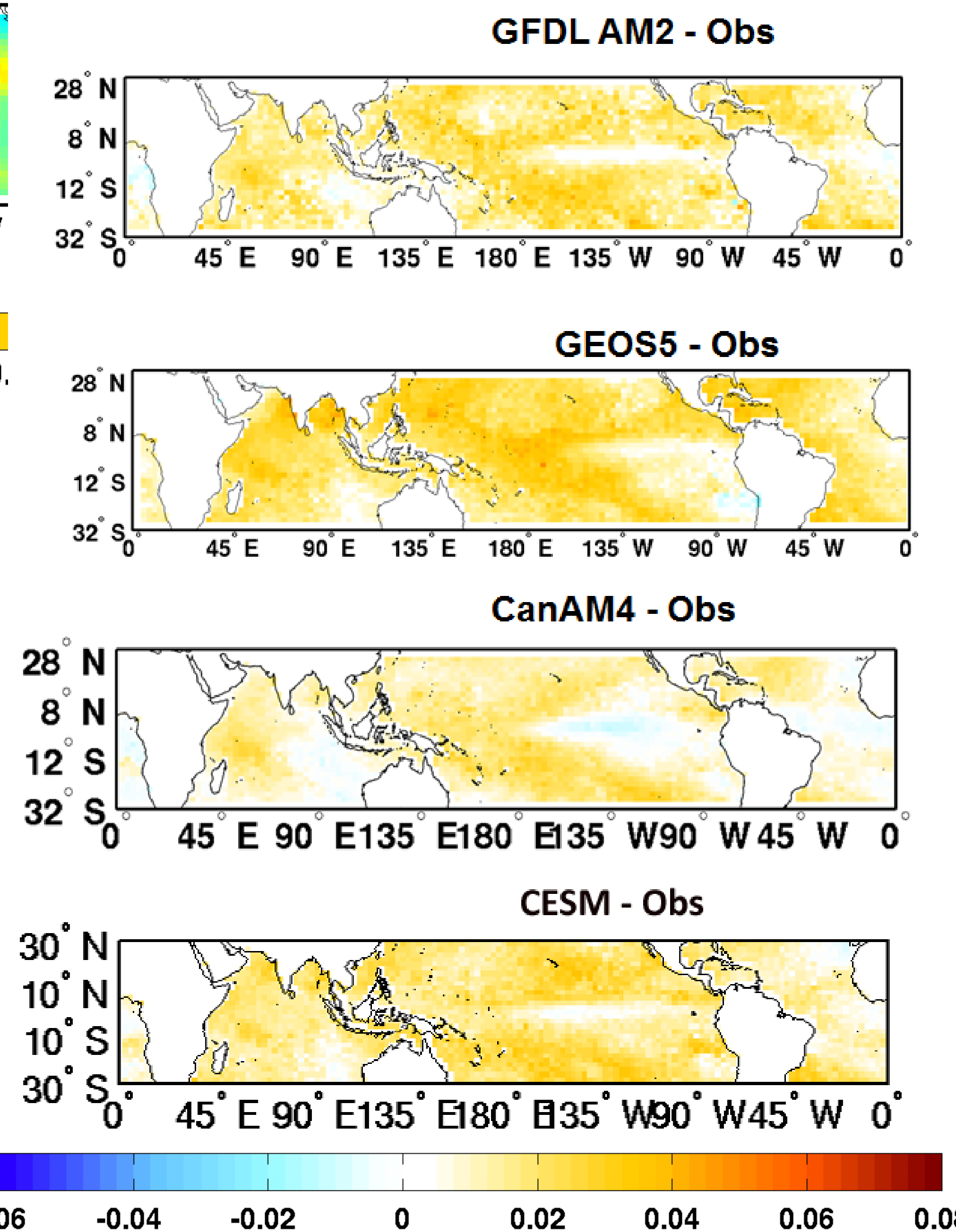
Green-house parameter (efficiency)

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

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*

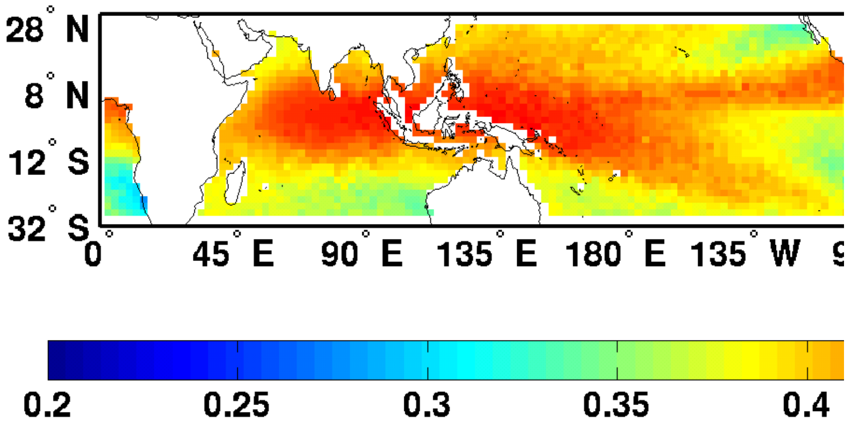


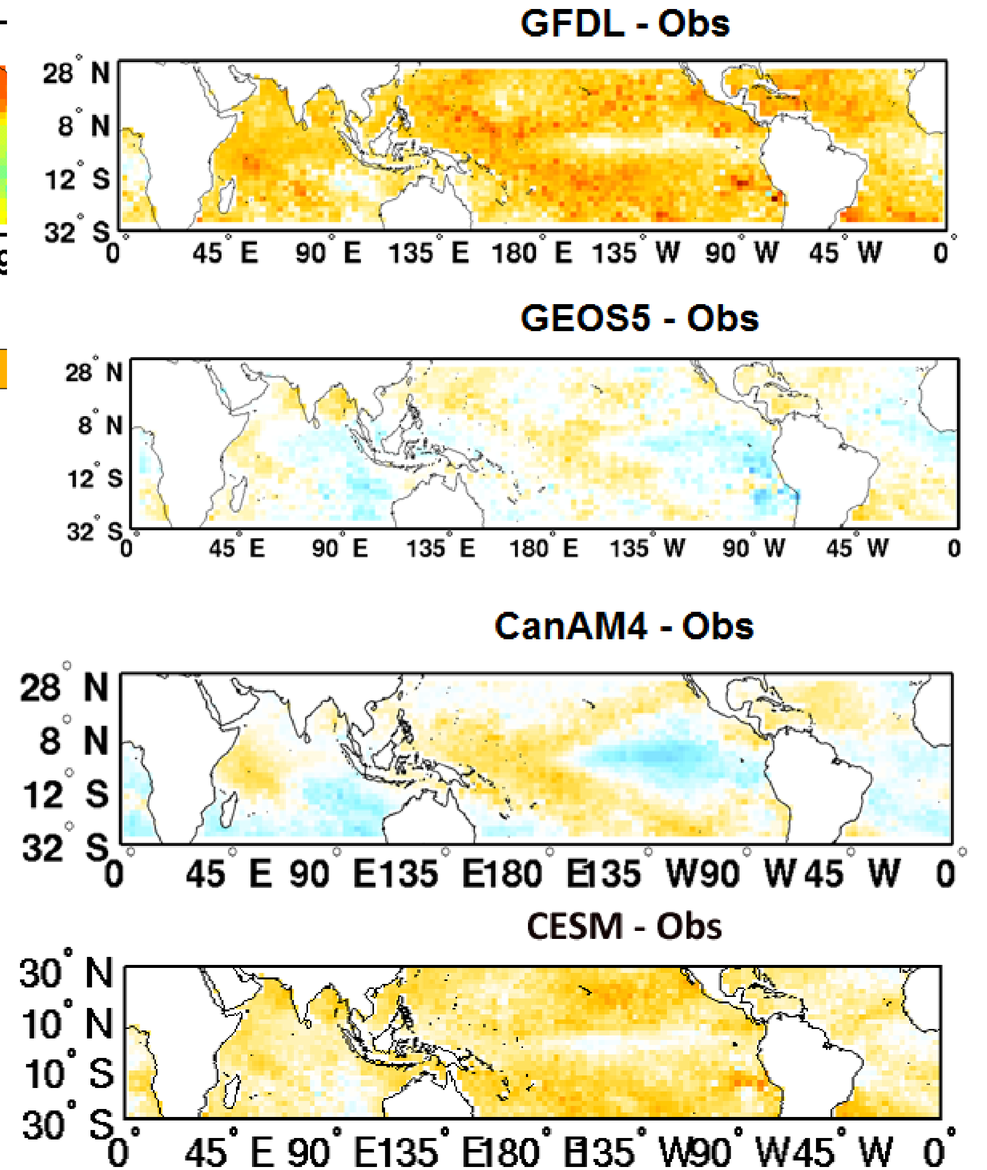


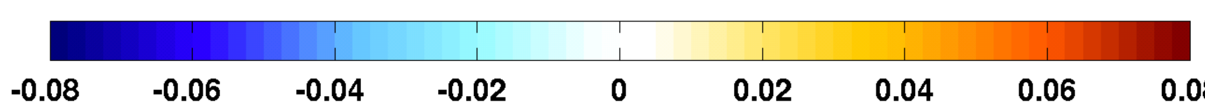
All AMIP runs

Obs	**289.5 W m^{-2}**
GFDL AM2	**283.3 W m^{-2}**
NASA GEOS5	**281.0 W m^{-2}**
Env. Canada CanAM4	**286.6 W m^{-2}**
NCAR CESM	**279.3W m^{-2}**

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

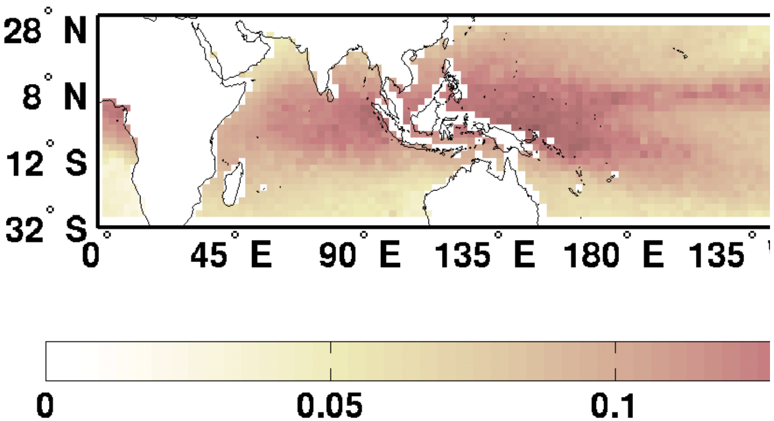


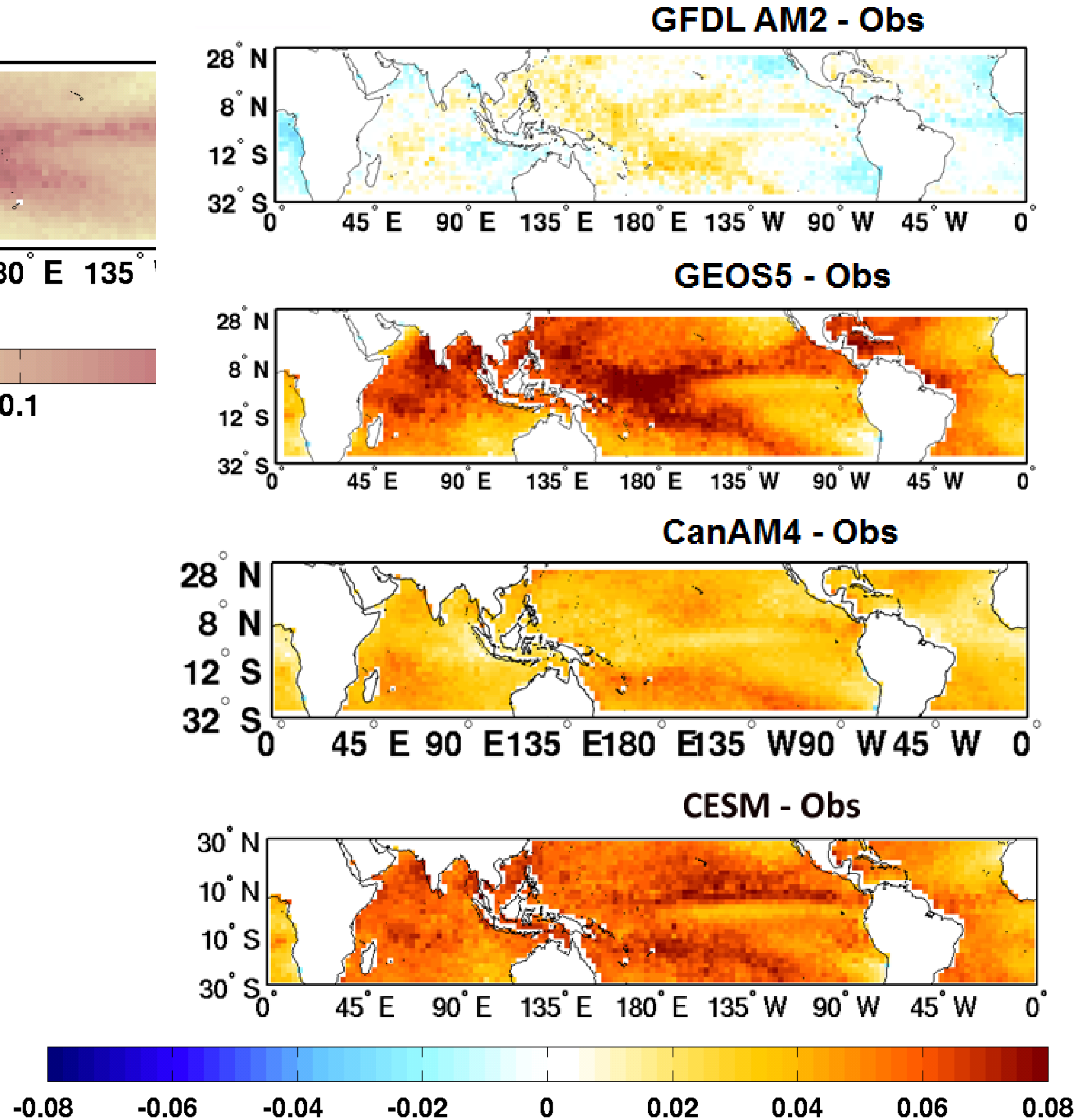




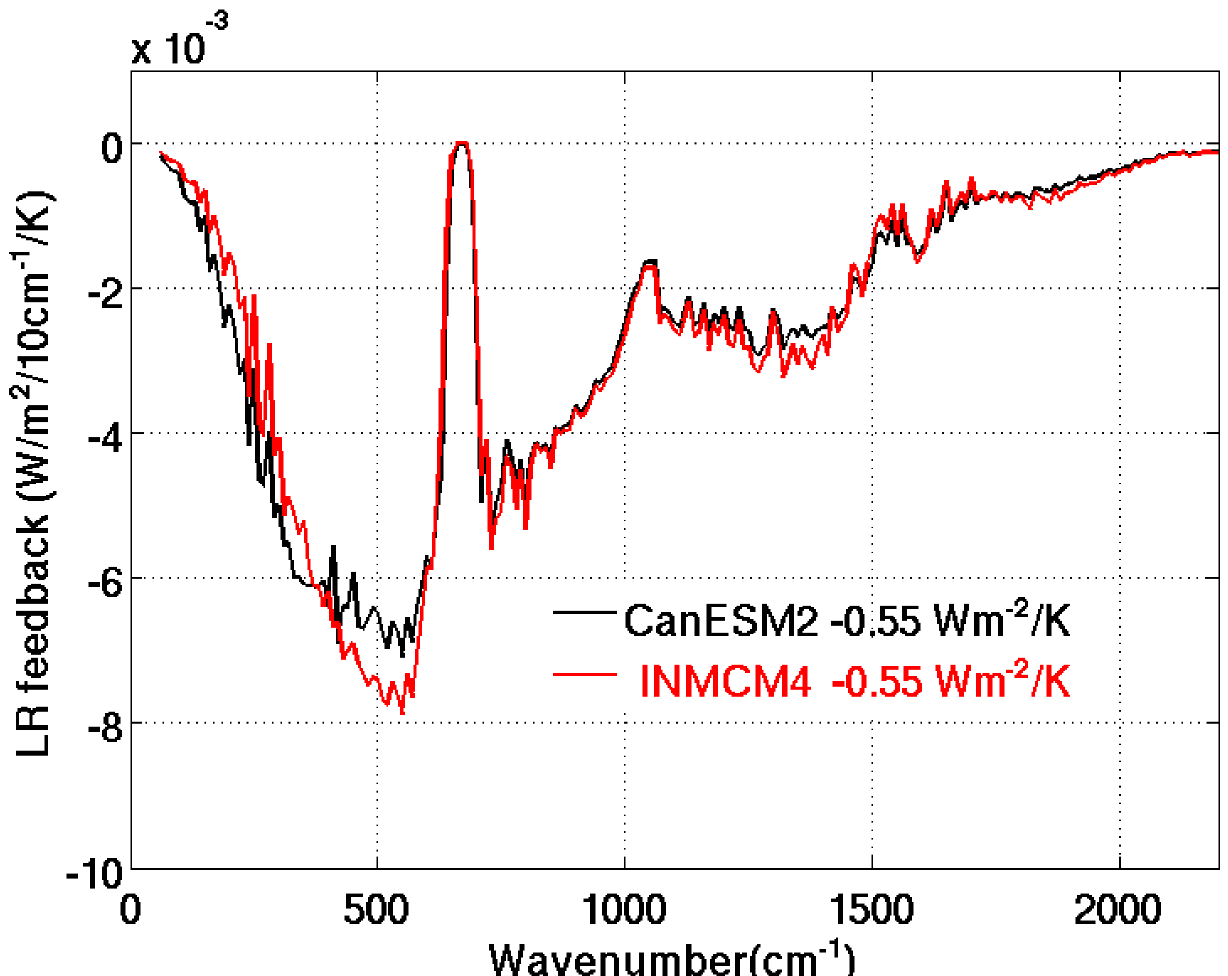
0.02 in fraction ~ 2.7 Wm^{-2}

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





Example 2: Spectral decomposition of broadband lapse-rate feedback



(Huang et al, 2014)

Can we get spectral flux from the observations?

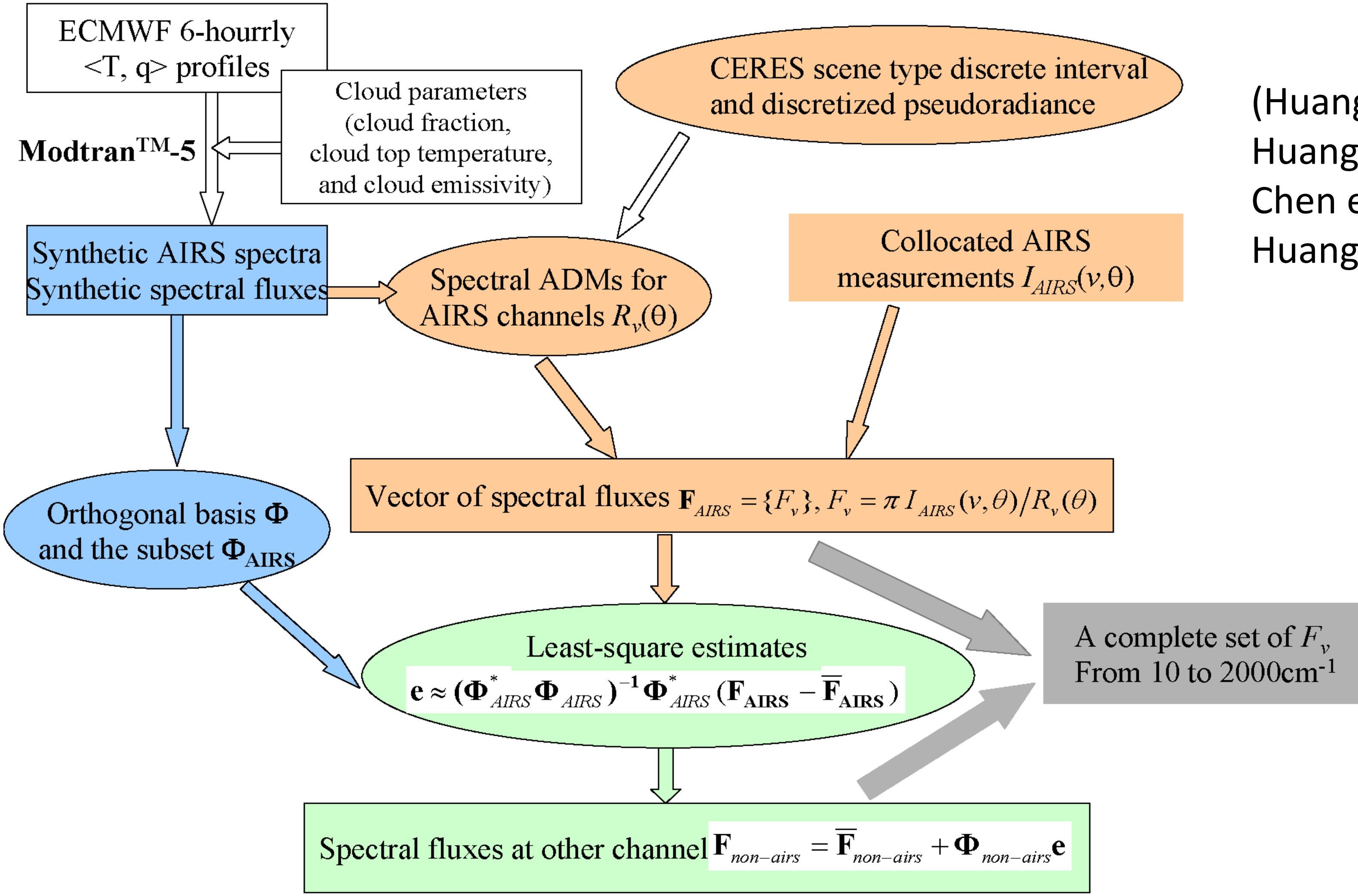
$$F = 2\pi \int_{\Delta v} dv \int_0^1 I(v;\mu)\mu d\mu \quad (\mu = \cos\theta)$$

1. What ERBE/CERES really measured was broadband radiance, not flux.
2. It was then converted to flux using anisotropic distribution model (ADM)

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

3. AIRS/CrIS/IASI measures spectral radiance. If we can have a spectral ADM, then we can have spectral flux
4. Scene type classification is the key to the use of ADM

Obtain spectral flux from observations



(Huang et al., 2008;
Huang et al., 2010;
Chen et al., 2013;
Huang et al., 2014);

CERES flux and radiance are never used. Only ancillary info in the CERES datasets.

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

All collocated clear-sky observations in 2004 (80° S-80° N)

Surface Type	Daytime	Nighttime
	OLR_{AIRS_Huang}-OLR_{CERES} (Wm^{-2})	OLR_{AIRS_Huang}-OLR_{CERES} (Wm^{-2})
Forest	0.58±1.43	-0.42±1.41
Savannas	-0.03±2.52	0.68±1.50
Grasslands	0.19±2.61	0.63±1.65
Dark Desert	-0.71±2.85	0.36±1.74
Bright Desert	1.67±2.62	1.42±2.28
Ocean	1.09±1.55	0.90±1.26

(Chen et al., J Climate, 2013)

Statistics of single footprint comparisons

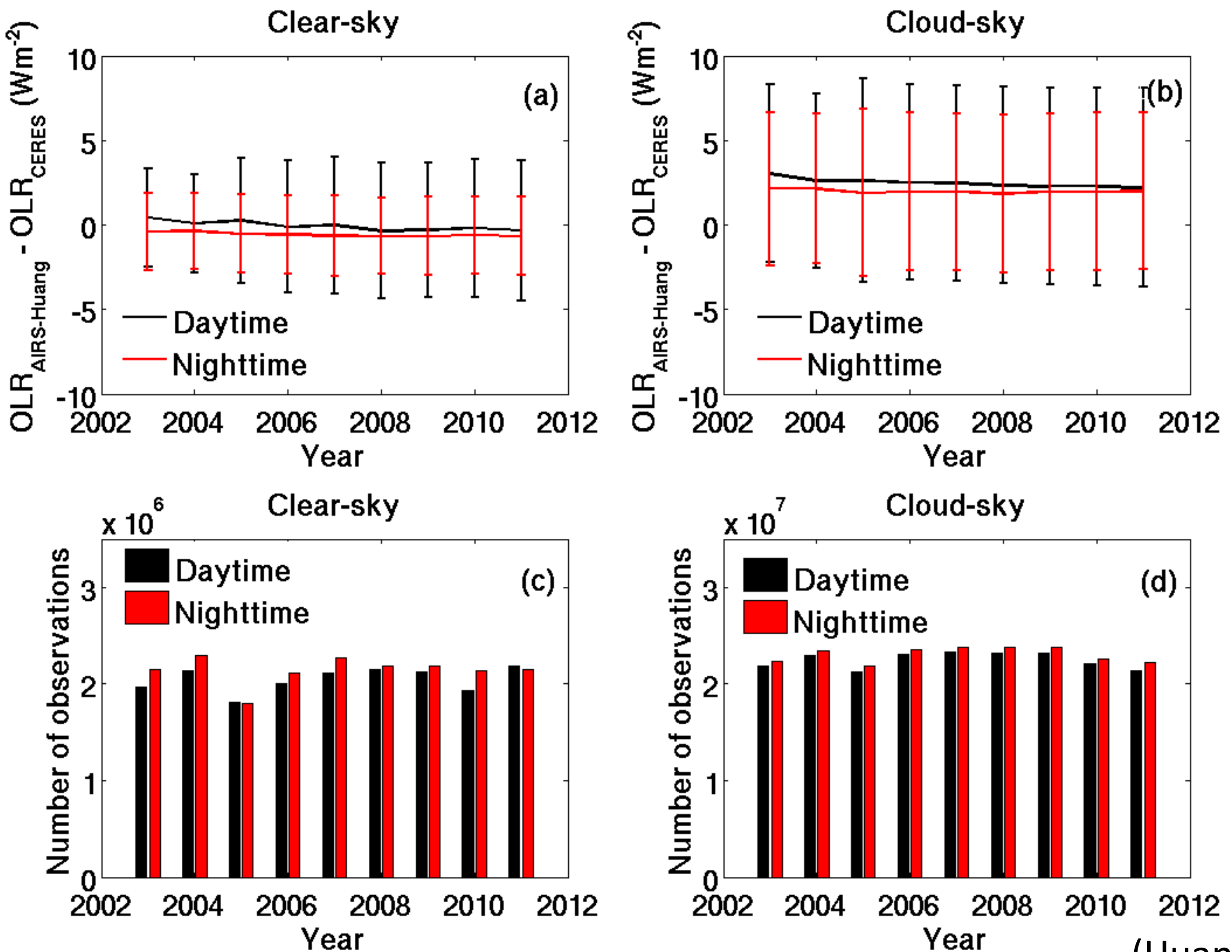
CERES 2σ radiometric calibration uncertainty: 1% (i.e. ~ 2.5W m^{-2})

Stratifying OLR_{AIRS_Huang}-OLR_{CERES} (Wm^{-2}): cloudy observations over the lands

ΔT_{sc} / *f*	Over deserts			Over non-desert lands		
	<15k	15K-40K	>40K	<15k	15K-40K	>40K
0.001-0.5	**2.44±3.79 (0.9%)**	**3.25±5.12 (1.2%)**	**1.49±7.61 (0.5%)**	**2.34±2.86 (0.8%)**	**3.62±4.48 (1.3%)**	**2.84±5.94 (1.0%)**
0.5-0.75	**2.79±4.16 (1.1%)**	**3.34±7.80 (1.3%)**	**1.39±12.75 (0.5%)**	**2.90±3.86 (1.1%)**	**4.24±7.25 (1.7%)**	**2.61±11.38 (1.0%)**
0.75-0.999	**2.67±3.67 (1.1%)**	**1.45±6.47 (0.6%)**	**-1.17±10.97 (-0.5%)**	**2.81±3.56 (1.2%)**	**3.14±6.68 (1.4%)**	**0.47±11.45 (0.2%)**
0.999-1.0	**2.61±2.80 (1.2%)**	**3.15±4.00 (1.6%)**	**1.28±6.64 (0.7%)**	**2.86±2.83 (1.3%)**	**4.04±4.33 (2.0%)**	**2.48±7.16 (1.5%)**

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

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

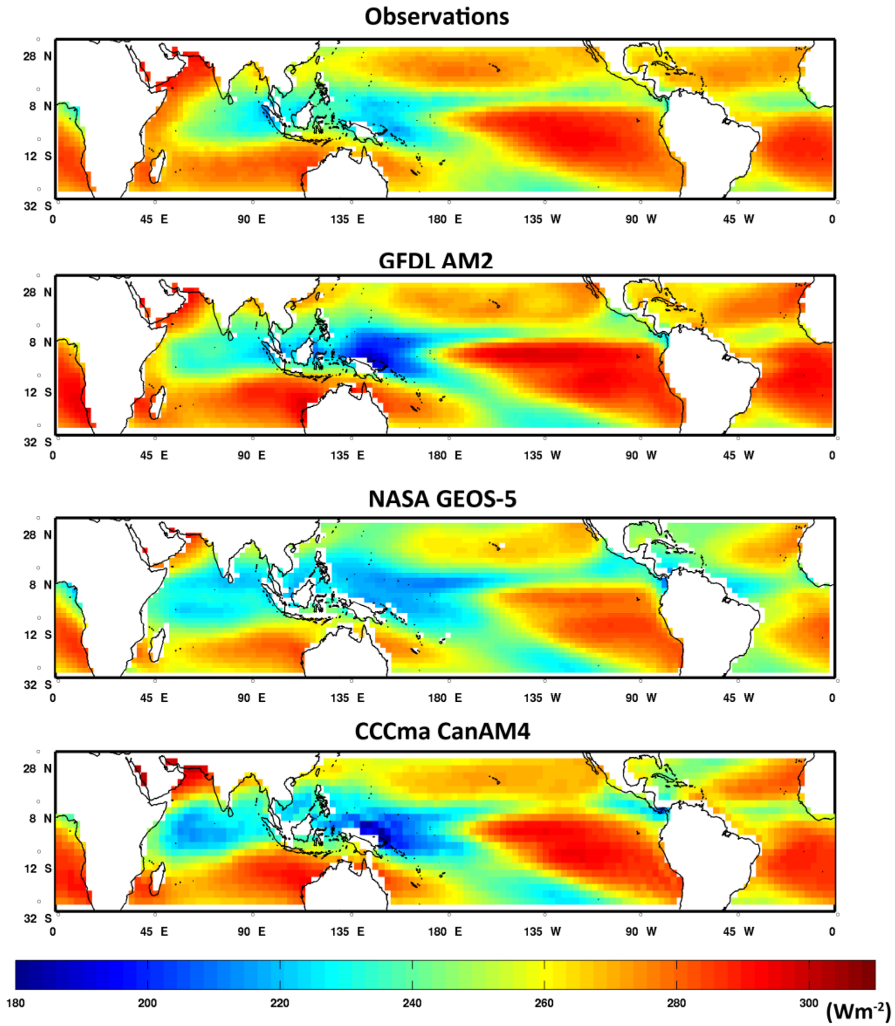


(Huang et al., 2014)

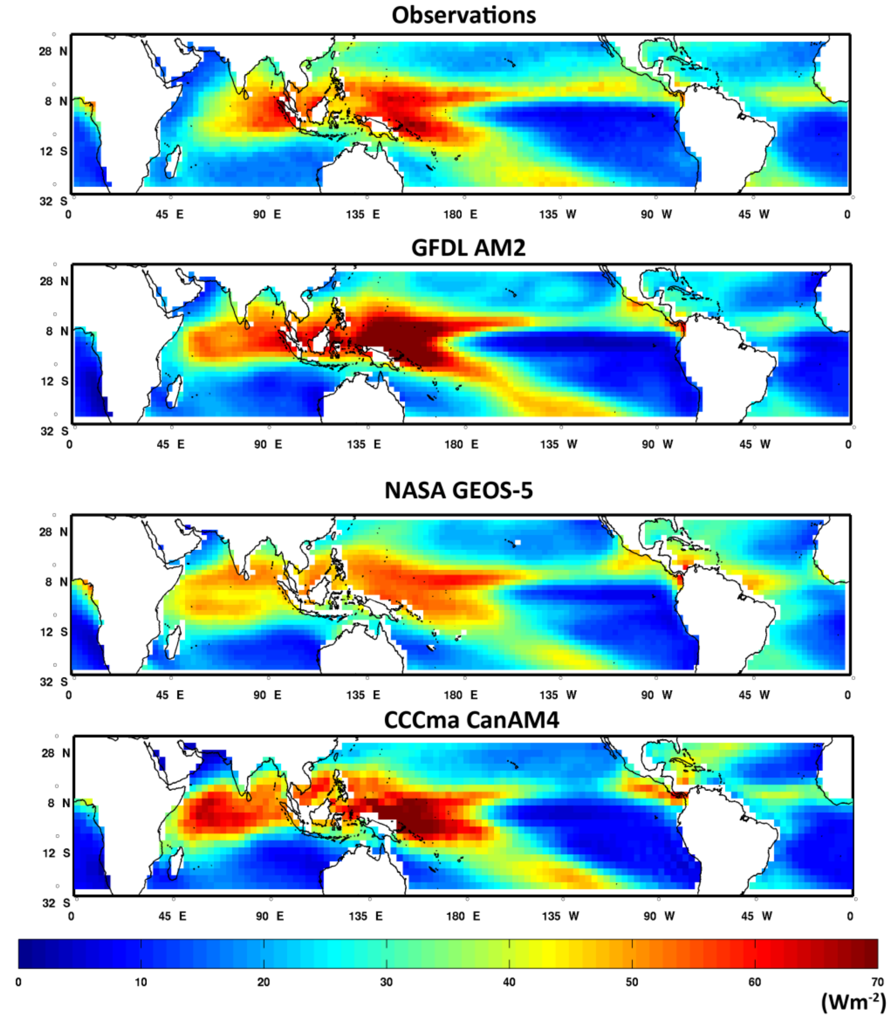
http://www.umich.edu/~xianglei/datasets.html

Multi-year averages

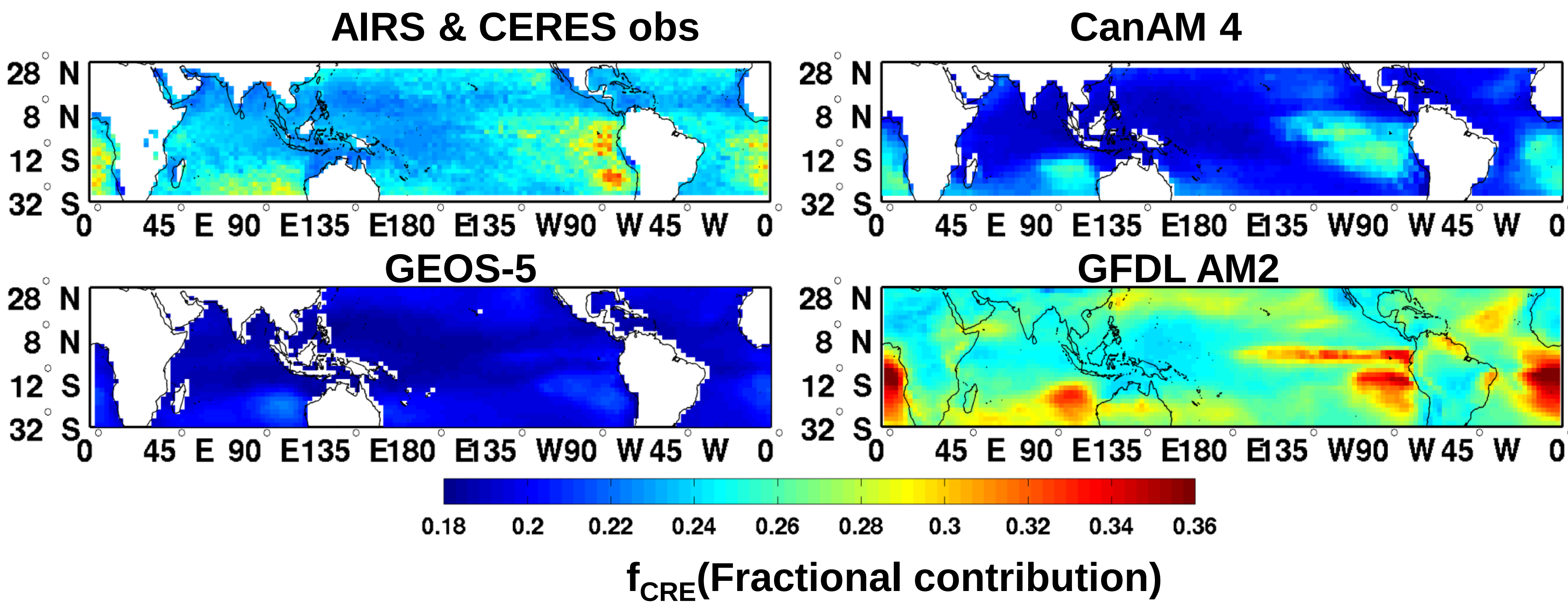
All-sky OLR



Longwave CRE



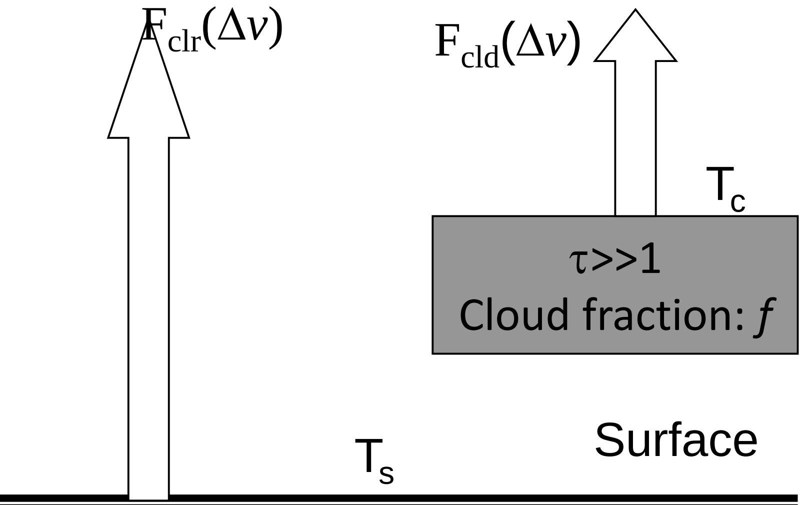
Band 5 (1070-1400 cm^{-1}): Long-term mean of fractional contribution to the LW CRE

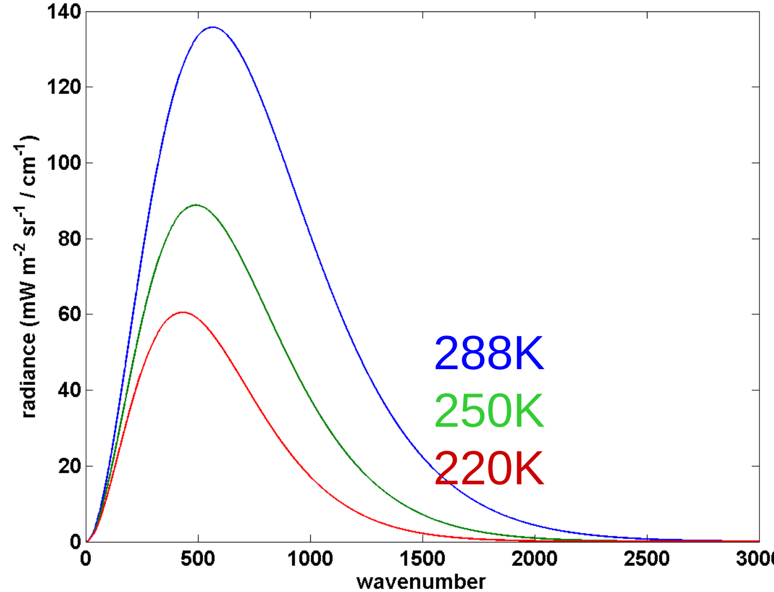


GEOS -5: lower than obs. and a narrow range: 0.18-0.22
GFDL AM2: higher than obs.
CanAM4: more similar to GEOS-5
Treatment of IR scattering matters here, but cannot explain the full discrepancies (only up to ~0.02-0.04 diff.)

A trait of spectral (band-by-band) CRE

1. Blackbody cloud
2. Ignore atmospheric absorption





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

CRE_{LW} sensitive to both f and T_c

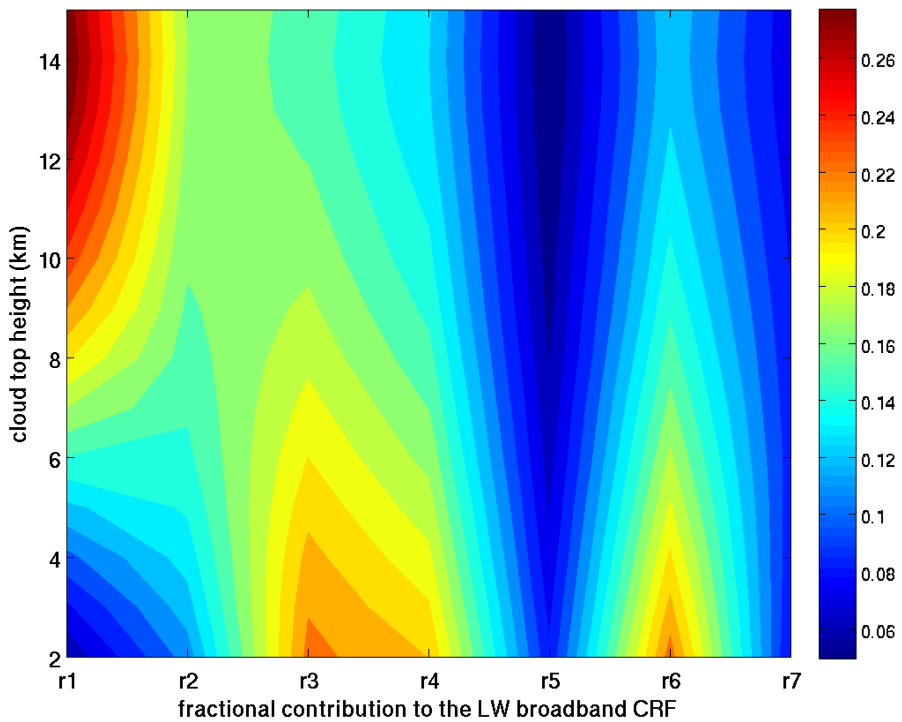
$$CRE(\Delta v) = f[F_{clr}(\Delta v) - F_{cld}(\Delta v)]$$

Fractional contribution

$$r(\Delta v) = \frac{CRE(\Delta v)}{CRE_{LW}} = \frac{F_{clr}(\Delta v) - F_{cld}(\Delta v)}{\left[\sigma T_s^4 - \sigma T_c^4\right]}$$

r(Δv) sensitive to T_c but not f

More realistic model of r(Δ*v*)



- 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)

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

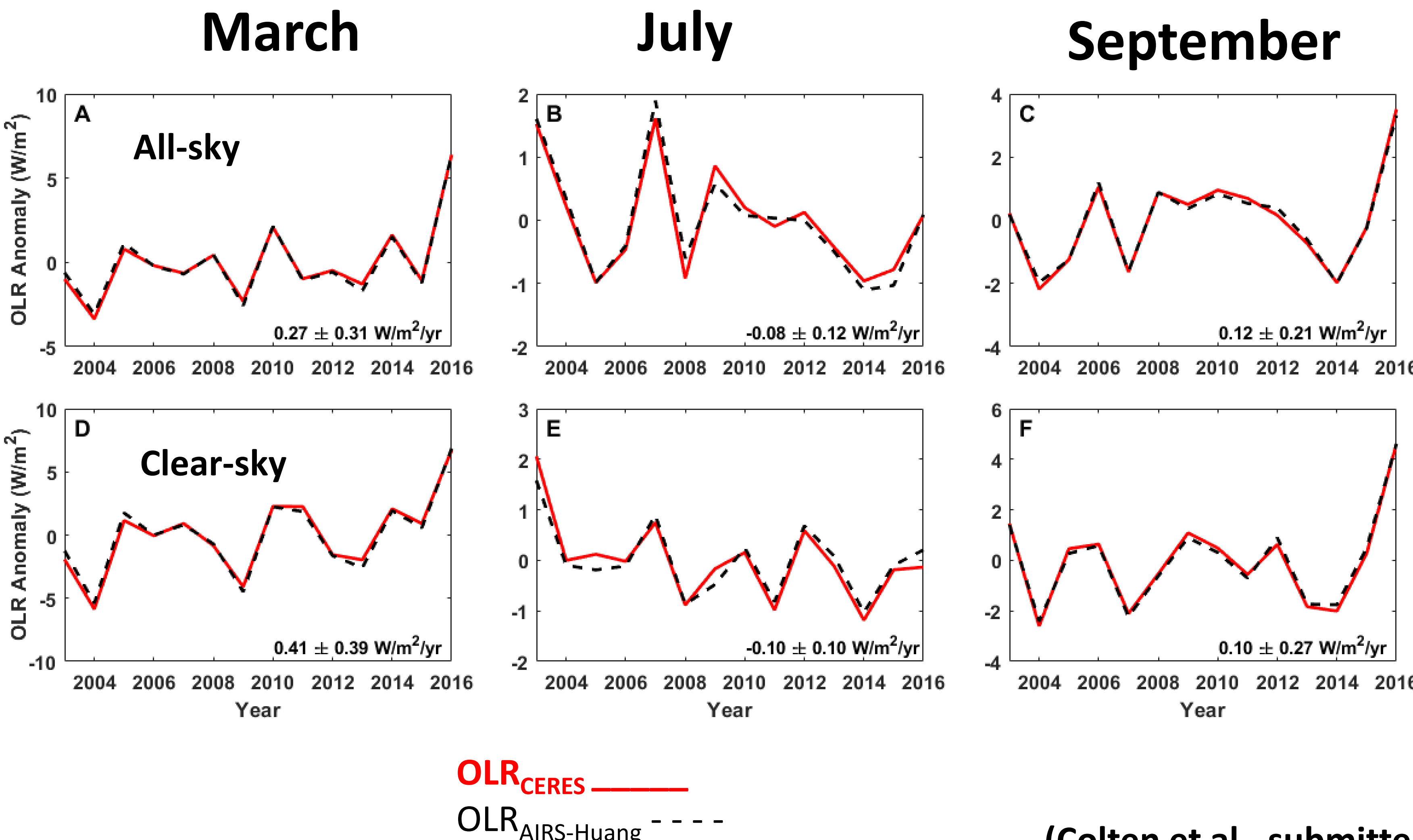
Band4: 900-990 cm^{-1} (WN)

Band5: 990-1070cm^{-1} (O_3)

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

Band7: 1200-1400cm^{-1} (N2O, CH_4)

Arctic OLR time series (2003-2016)



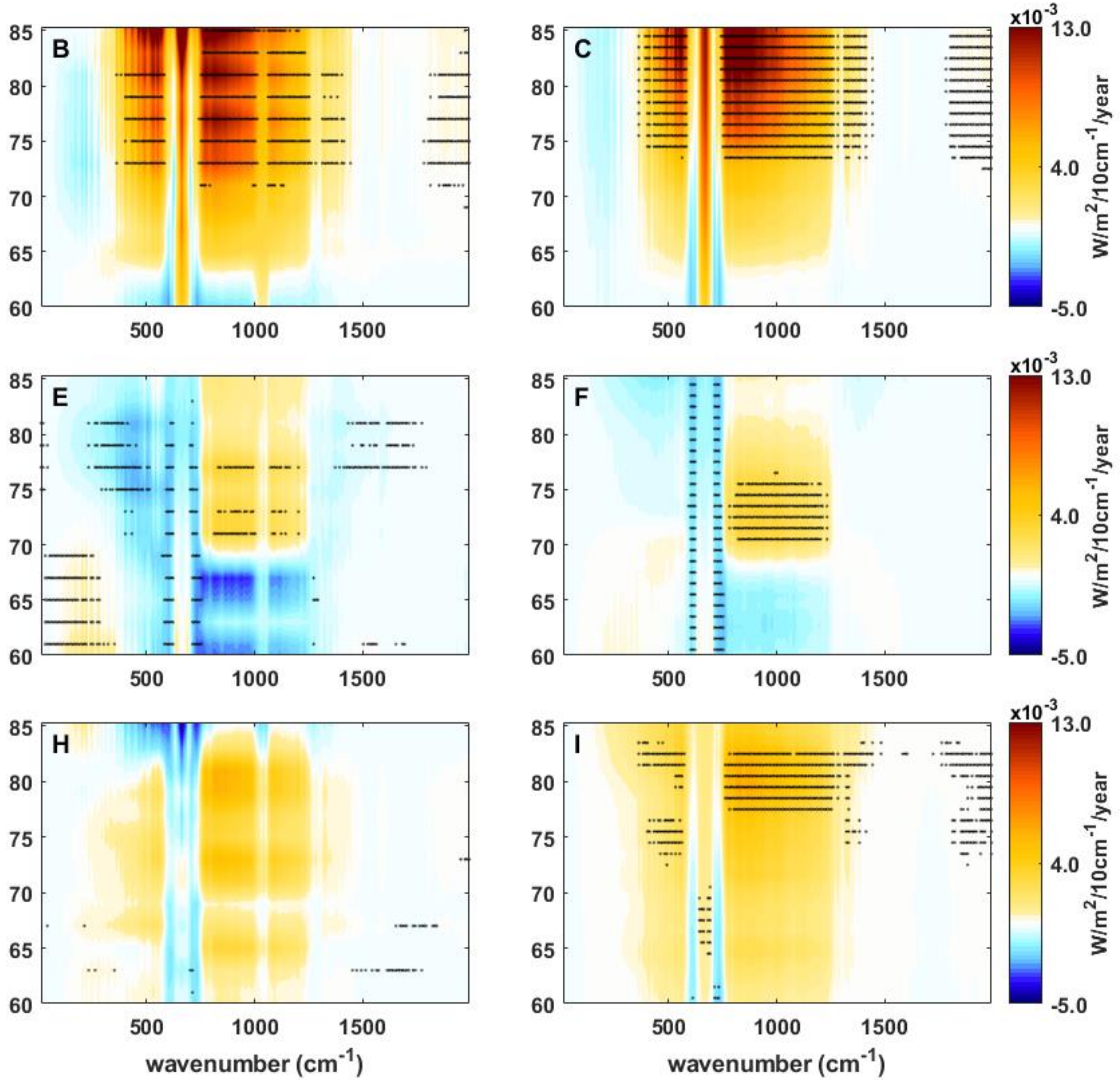
(Colten et al., submitted)

Clear-sly Spectral OLR Trends

March

July

September



Observation: OLR_{AIRS_Huang}

Simulation:ERA-interim + retrievals

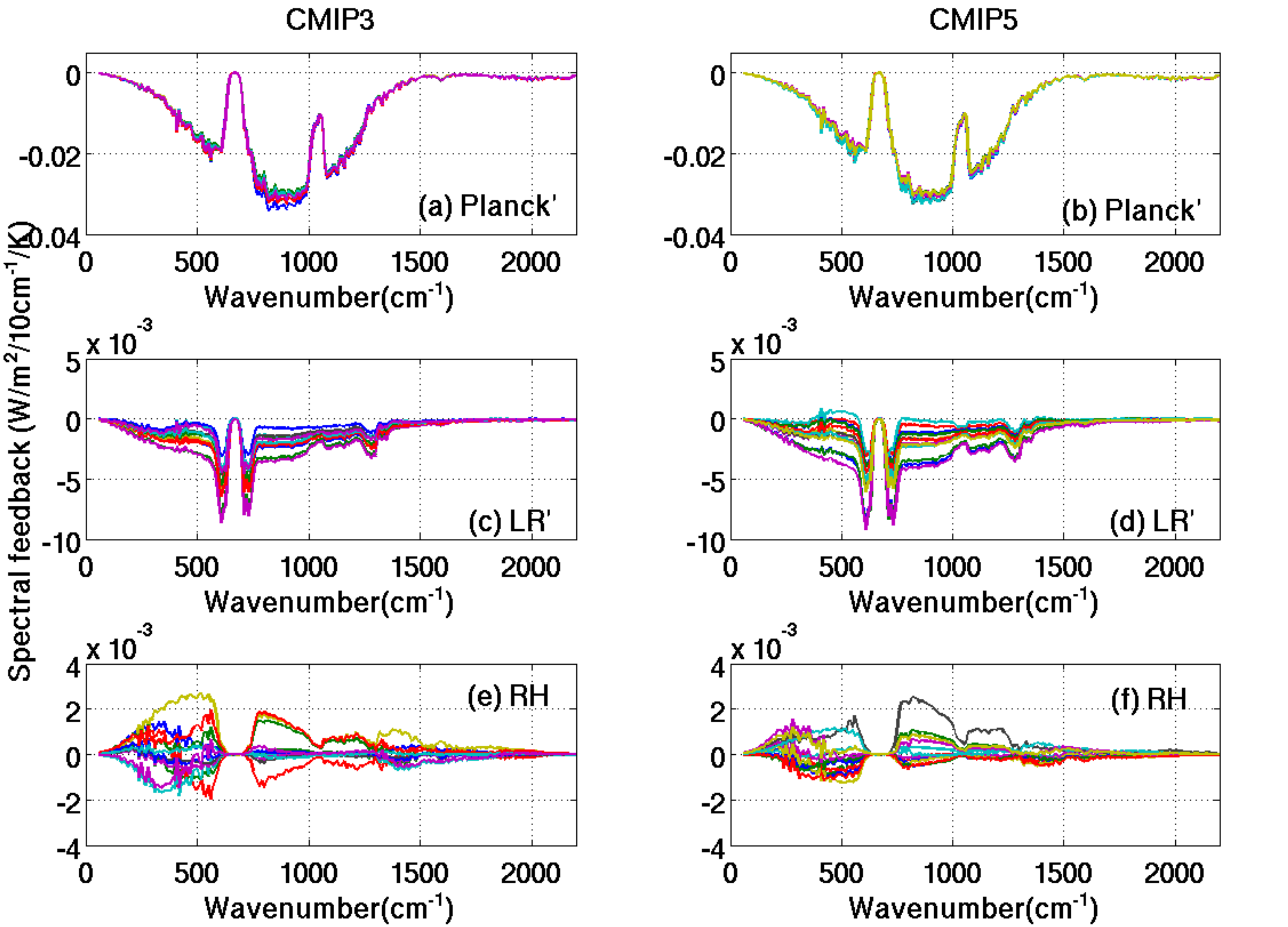
Spectral radiative feedbacks

- In addition to spectral flux climatology
- We also developed a set of spectral radiative kernels so CMIP-type output can be used to directly generate spectral radiative feedbacks (Huang et al., 2014b).
- Our recent work extended this to cloud feedbacks as well

Using RH as a state variable

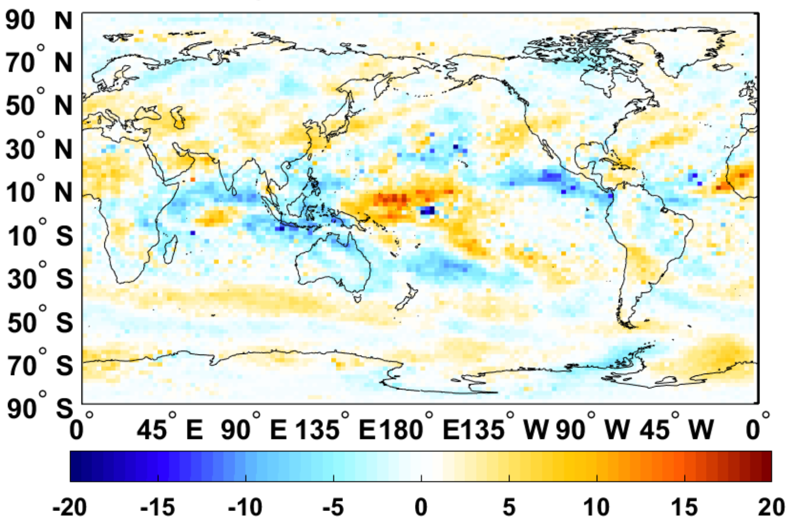
	Planck’	LR’	RH
gfdl cm2.0	-1.95	-0.26	0.05
giss er	-1.95	-0.36	-0.02
inmcm 3.0	-2.07	-0.25	-0.04
miroc3-2-medres	-2.02	-0.16	-0.07
mpi-echam5	-2.07	-0.38	-0.02
m-cgcm2-3-2a	-1.99	-0.25	0.17
ncar-ccsm3	-2.01	-0.18	-0.02
MPI-ESM-LR	-2.05	-0.40	-0.04
IPSL-CM5A-LR	-1.97	-0.39	0.01
CNRM-CM5	-2.05	-0.09	-0.02
BNU-ESM	-2.08	-0.05	0.01
HadGEM2-ES	-2.01	-0.23	-0.00
MRI-CGCM3	-1.96	-0.20	-0.05
FGOALS-s2	-2.06	-0.22	0.13

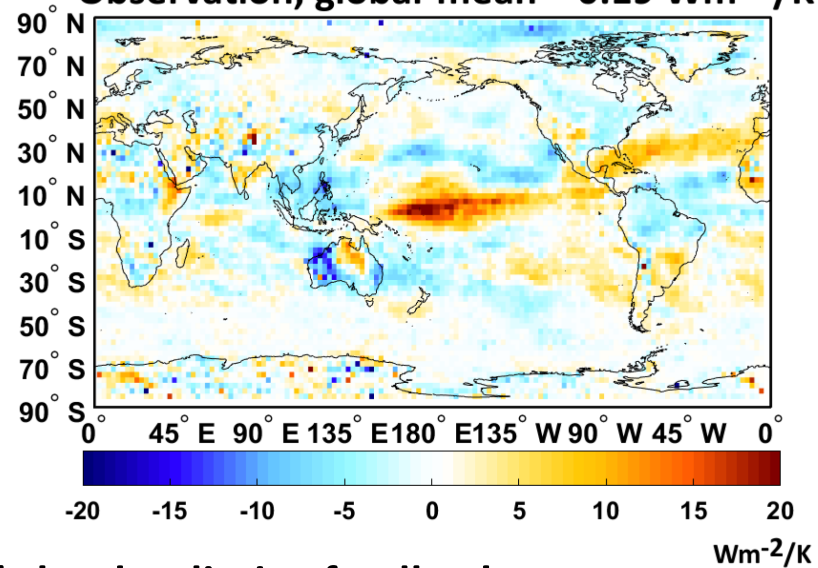
Using RH as a state variable



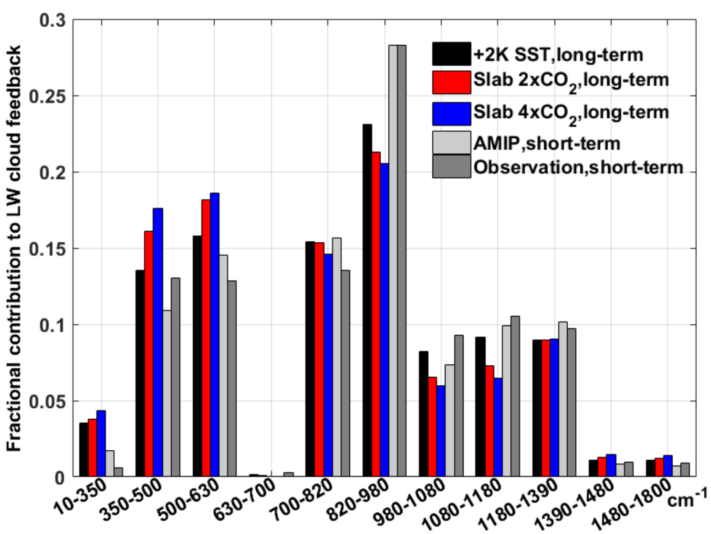
(Pan & Huang, 2018, J. Climate)

“short-term” cloud radiative feedback: CESM vs. observation (2003-2013)





Longterm vs. “short-term” cloud radiative feedback



	Total fractional contribution from 10-630 cm^{-1} (far-IR)	Total fractional contribution from 820-1180 cm^{-1} (window)
+2K SST	0.33	0.40
Slab $2xCO_2$	0.38	0.35
Slab $4xCO_2$	0.40	0.33
AMIP	0.27	0.45
Observation	0.26	0.48

CESM

A-Train

(Huang et al., under revision)

Conclusions and Discussions

- Spectral dimension has its potential in model evaluations and diagnostics
  - It can help expose offset biases
  - Available from observations
  - Computable from model archives (band-by-band output eve simpler)
- Spectral diagnostics: help bridging the understandings to biases in radiation budget and biases in geophysical variables
- How to best use of spectral flux info in model developments
  - One broadband OLR vs. 16 band-by-band OLRs
  - Suggestion: broadband OLR; H2O band/window OLRs

Data available at http://wwwl.umich.edu/~xianglei/datasets.html

Thank You!

References:

1. Huang et al., 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.
2. Huang, X.L., et al. 2010:Spectrally resolved fluxes derived from collocated AIRS and CERES measurements and their application in model evaluation: 2. cloudy sky and band-by-band cloud radiative forcing over the tropical oceans, JGR-Atmospheres, 115, D21101, doi:10.1029/2010JD013932.
3. Chen et al., 2013: Comparisons of clear-sky outgoing far-IR flux inferred from satellite observations and computed from three most recent reanalysis products, *Journal of Climate*, 26(2), 478-494, doi:10.1175/JCLI-D-12-00212.1.
4. Huang et al., 2014: A global climatology of outgoing longwave spectral cloud radiative effect and associated effective cloud properties, *Journal of Climate*, 27, 7475-7492, doi:10.1175/JCLI-D-13-00663.1.
5. Huang, X. L., X. H. Chen, B. J. Soden, X. Liu, 2014B: The spectral dimension of longwave feedbacks in the CMIP3 and CMIP5 experiments, *Geophysical Research Letters*, 41, doi:10.1002/2014GL061938.
6. Pan, F., X. L. Huang, The spectral dimension of modeled relative humidity feedbacks in the CMIP5 experiments, Journal of Climate, 31 (24), 10021-10038, 10.1175/JCLD-D-17-0491.1, 2018.

Averages of net TOA **broadband** flux R(x,y;t)

$$\lambda_X = -\frac{\delta_X \overline{R}}{\delta X}\frac{\delta X}{\delta T_s}$$

$Wm^{-2}\,K^{-1}$

Change of global-mean surface temperature

X : [Temp, WV, cloud, albedo]

(Soden et al., 2008)

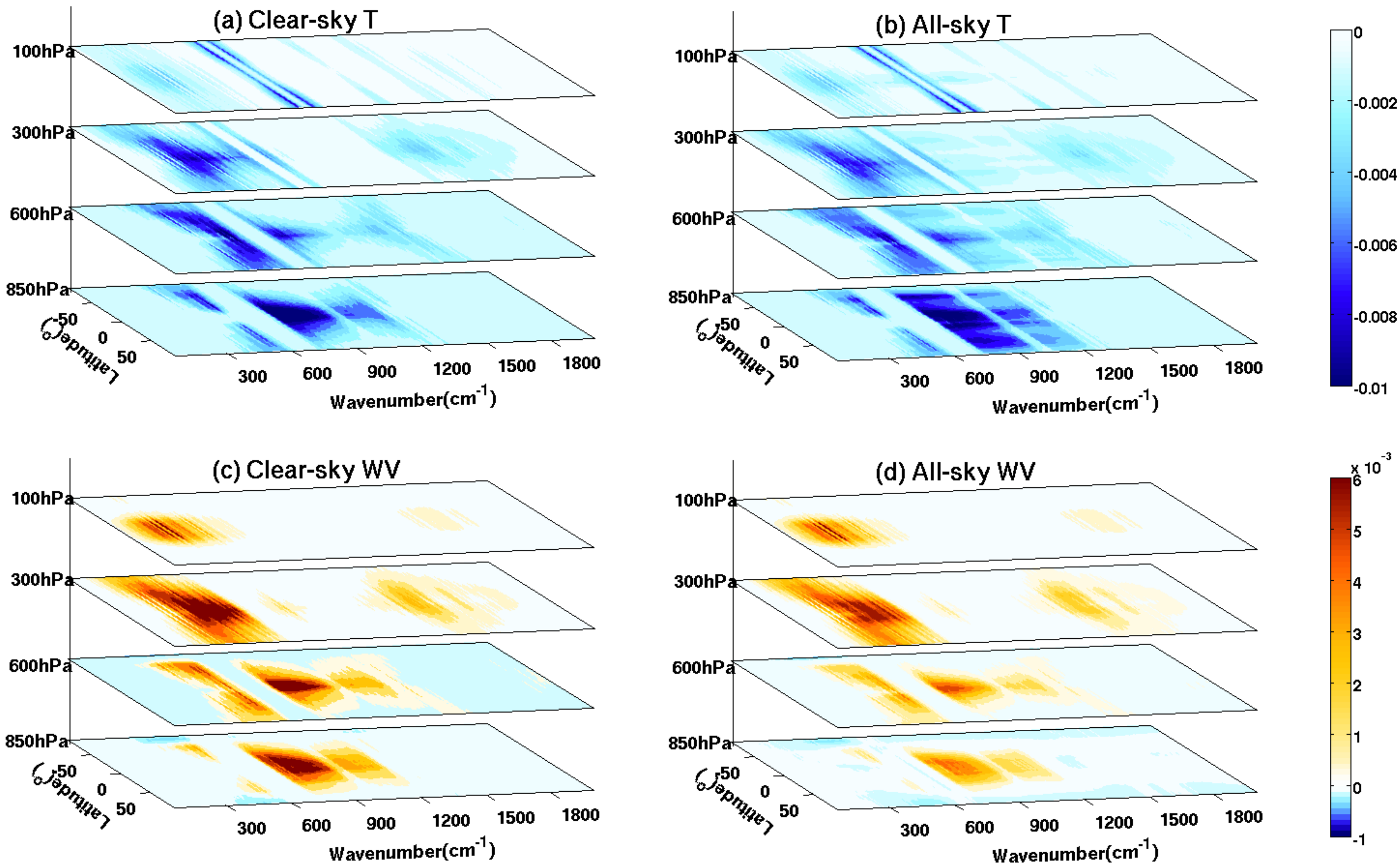
$\overline{R}$ has another dimension, the frequency v

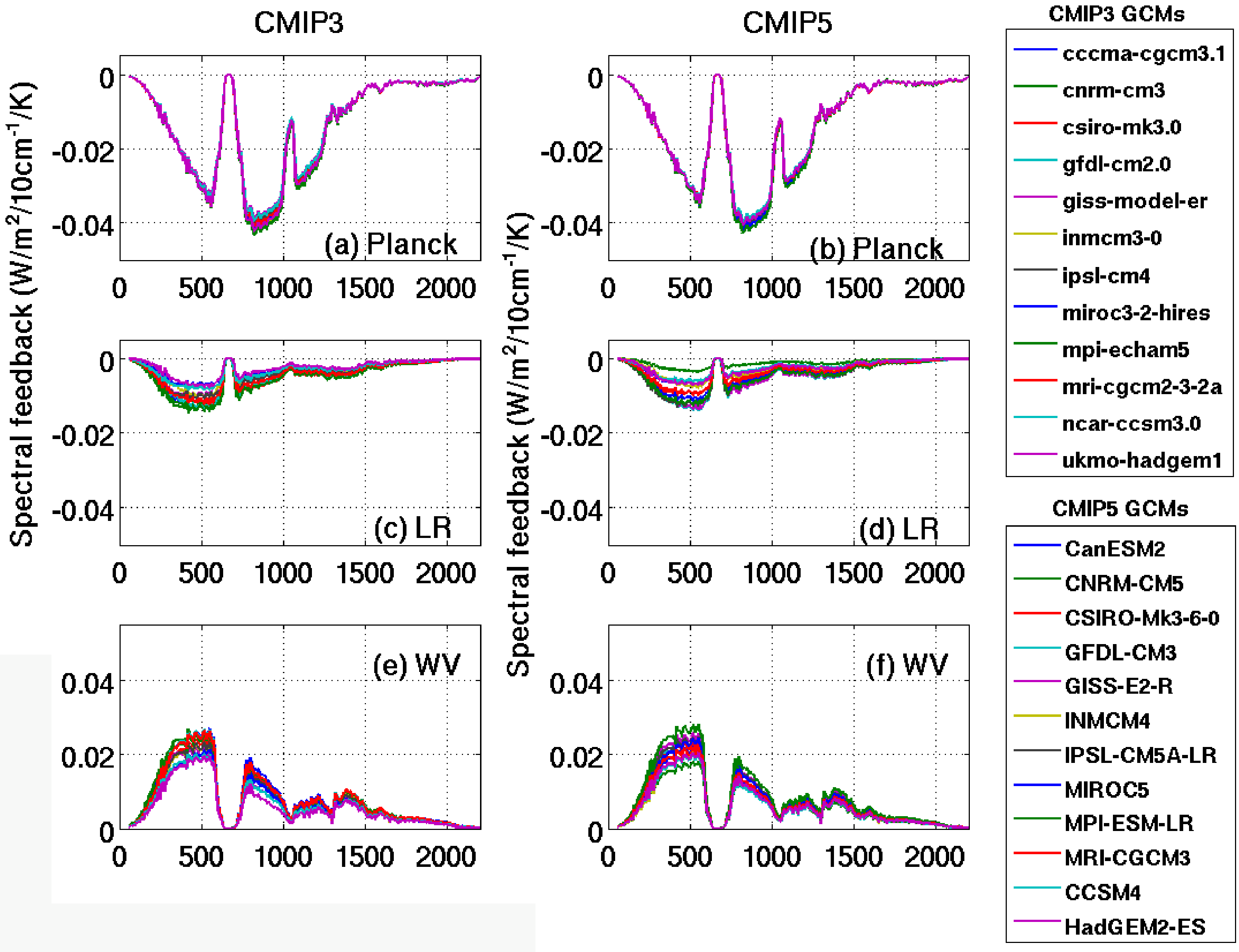
Spectral radiative feedbacks

$$\lambda_{x_v} = -\frac{\delta_x \overline{R_v}}{\delta X}\frac{\delta X}{\delta T_s}$$

$Wm^{-2}\,cm^{-1}\,K^{-1}$

Construction of the SRK



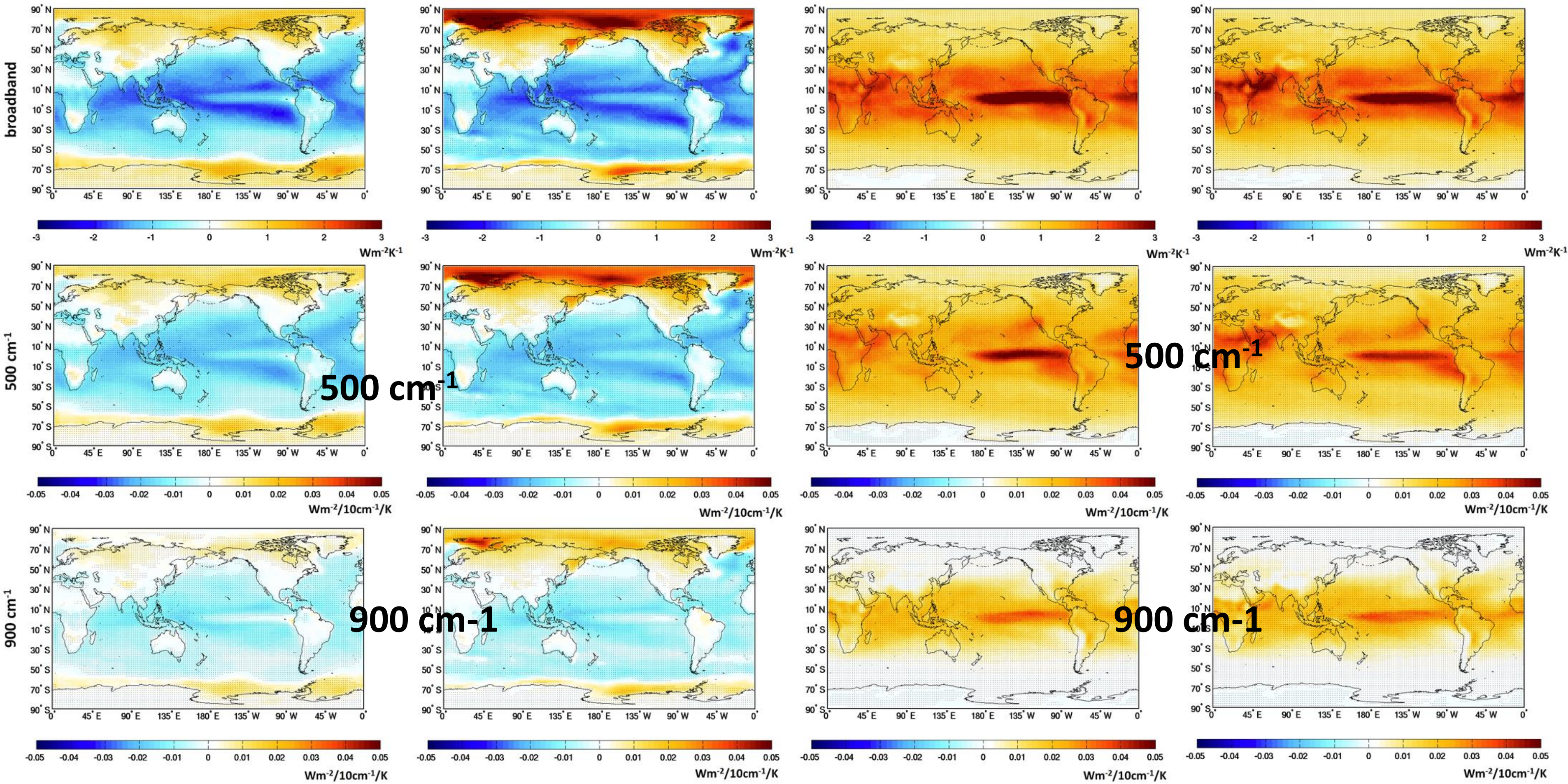


CMIP3
CMIP5
CMIP3 GCMs
cccma-cgcm3.1
cnrm-cm3
csiro-mk3.0
gfdl-cm2.0
giss-model-er
inmcm3-0
ipsl-cm4
miroc3-2-hires
mpi-echam5
mri-cgcm2-3-2a
ncar-ccsm3.0
ukmo-hadgem1
CMIP5 GCMs
CanESM2
CNRM-CM5
CSIRO-Mk3-6-0
GFDL-CM3
GISS-E2-R
INMCM4
IPSL-CM5A-LR
MIROC5
MPI-ESM-LR
MRI-CGCM3
CCSM4
HadGEM2-ES
Spectral feedback (W/m2/10cm-1/K)
(a) Planck
(b) Planck
(c) LR
(d) LR
(e) WV
(f) WV
0
-0.02
-0.04
0.04
0.02
500
1000
1500
2000

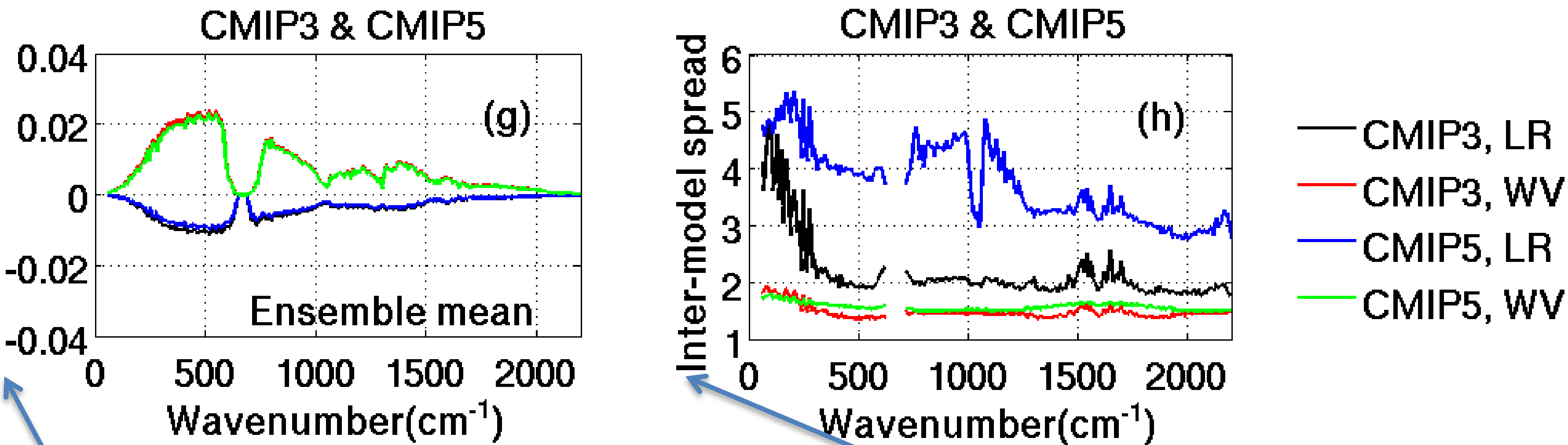
Spatial distribution of the all-sky spectral feedback: deciphering the broadband feedback

Lapser-rate feedback | **LW Water-vapor feedback**

CMIP3 **Broadband** **CMIP5** | **CMIP3** **Broadband** **CMIP5**



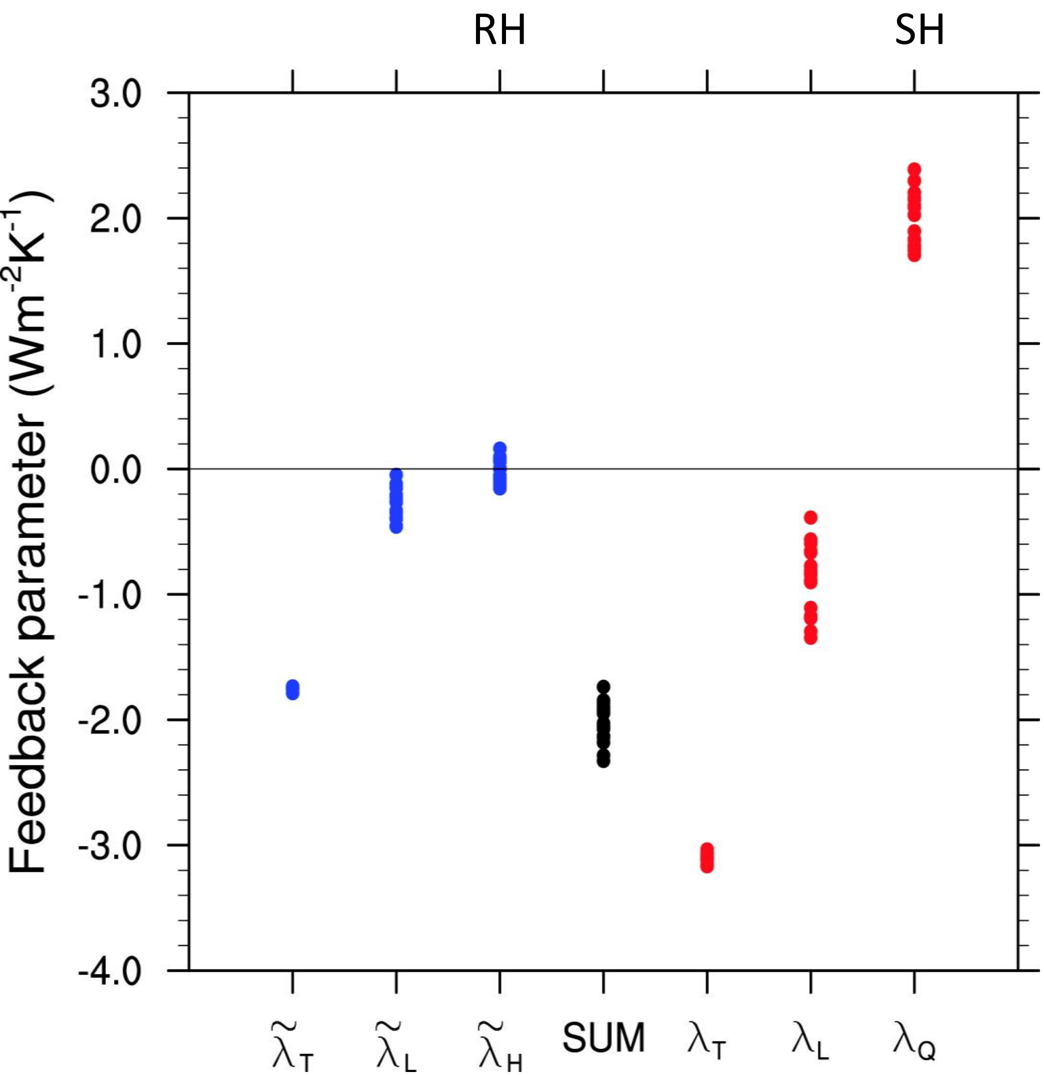
Maps of clear-sky feedbacks are similar



Intermodel Spectral = Max/Min

Unit: Spectral Radiative Feedback
(Wm^{-2} per $10cm^{-1}$ per K)

Broadband Radiative Feedbacks: choices of state variables



(Held and Shell, 2012)

"Relative humidity seems to change little at low latitudes under a global warming scenario, even in models of very high vertical resolution, suggesting this may be a robust 'emergent constraint' "
(Myles et al., 2002)

Spectral cloud radiative feedbacks

- Cloud radiative kernel is ill-defined w.r.t. (x, y, z), but well-defined for (τ, CTP) dimensions
- Yue et al. (2016; J Climate) constructed a set of cloud radiative kernels w.r.t. (x, y; τ, CTP) based on A-Train statistics
- Similar methodology can be applied to any GCMs as well
  - No need of off-line R.T. calculation
  - Use GCM its own statistics: ensure consistency
- AIRS/CERES spectral flux + other A-train data: spectral LW cloud radiative kernel
- CESM 3-hourly output for 15 years: spectral LW cloud radiative kernel at RRTMG bandwidths

Measuring broadband flux: ERBE/CERES approach

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

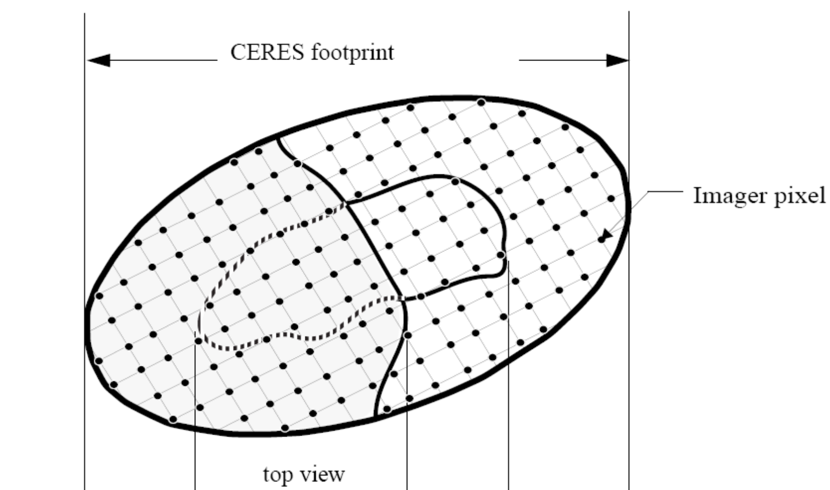
LW=TOT (N)

LW=TOT-SW (D)

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

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

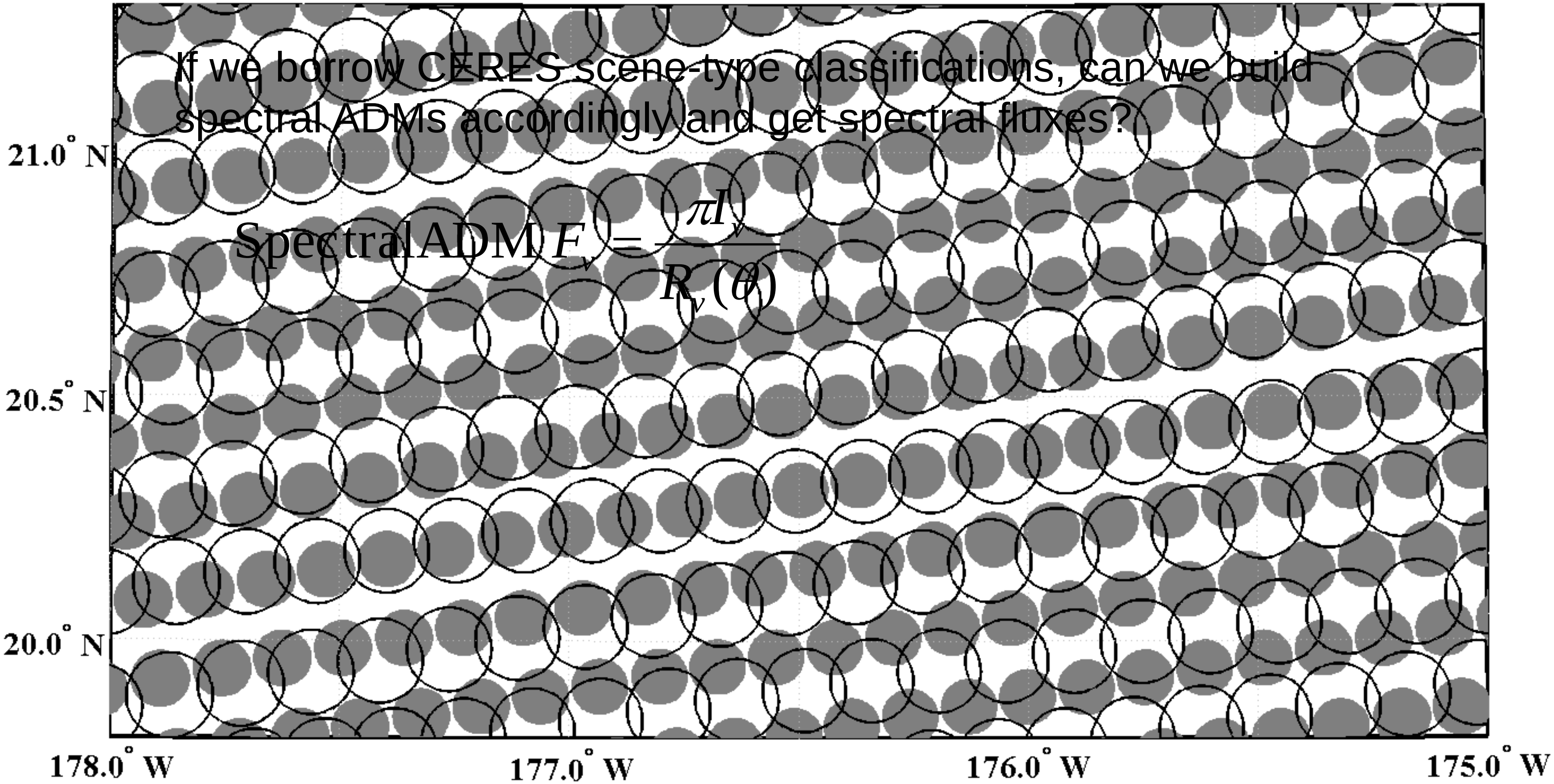
1. Function of scene type
2. Scene-type classification: ERBE vs. CERES
   - ERBE ~15 scene types
   - CERES-SSF 14 sub scene types for clear-sky ocean; 2008 sub scene types for cloudy ocean (making use of MODIS and other info)



Coincidental obs. Of CERES and AIRS

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

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



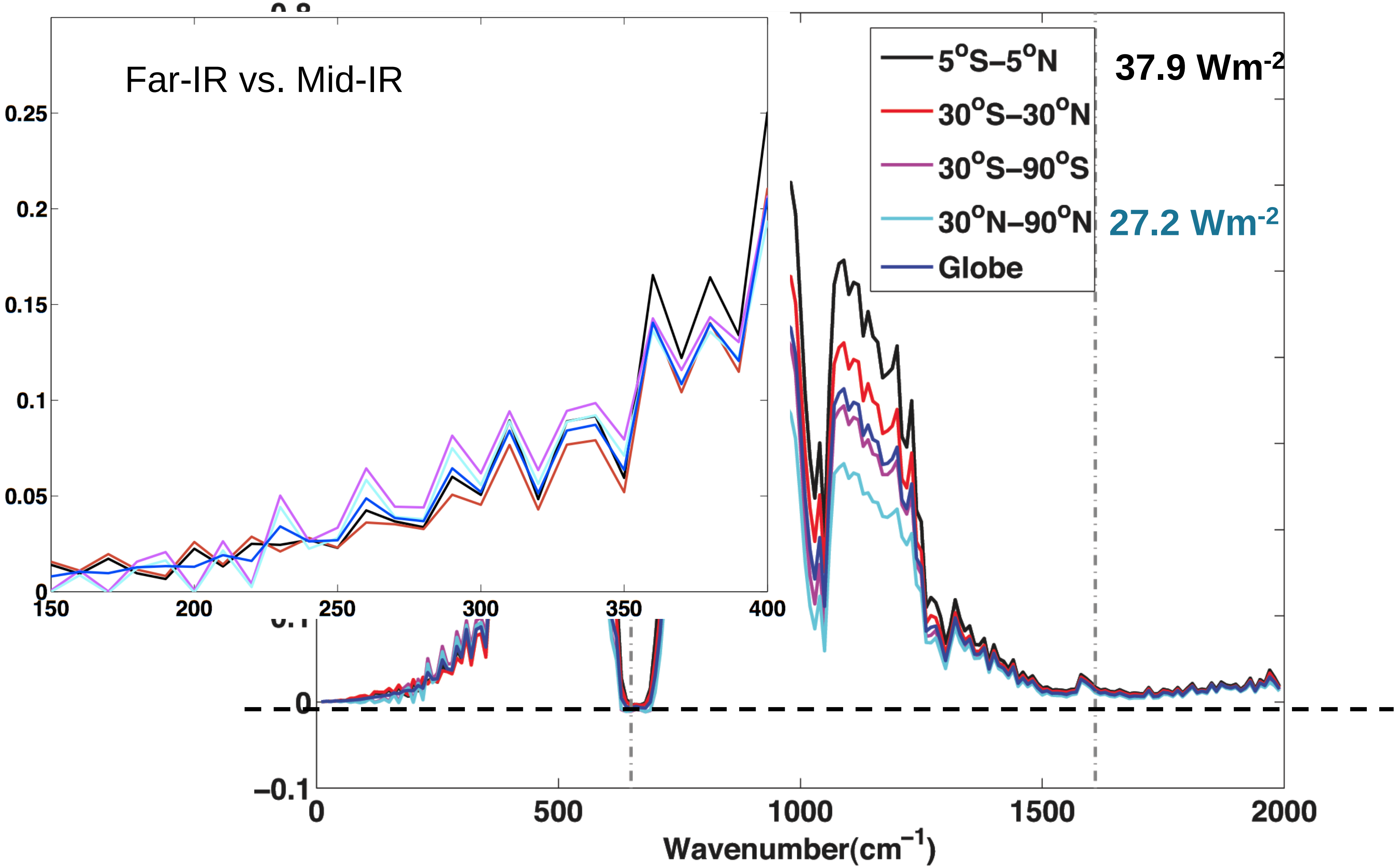
Spectrometer

CERES **AIRS**

Broadband radiometer

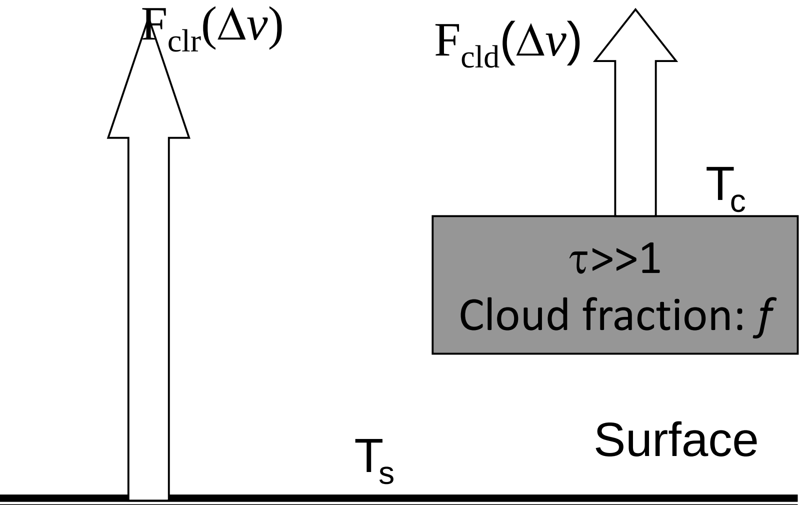
01:06:15 to 01:06:45 UTC on January 1, 2005

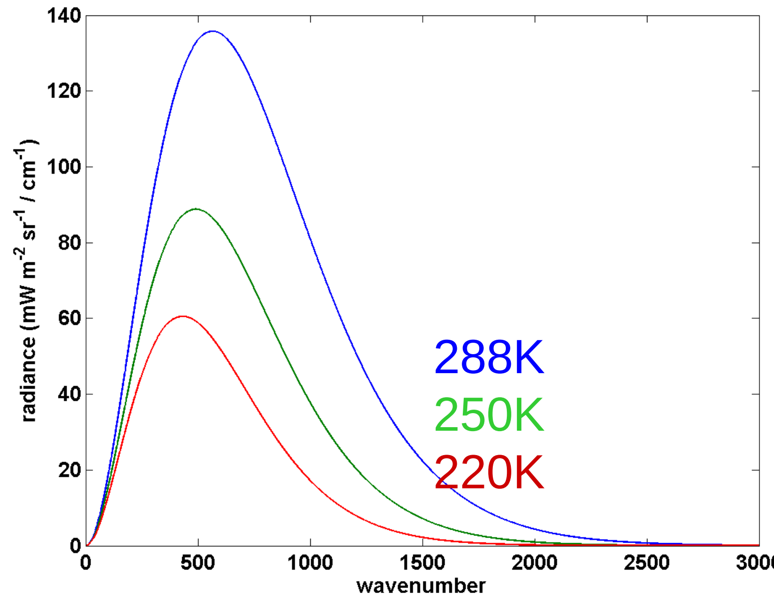
10-year mean spectral CRE over the different climate zones



A trait of spectral (band-by-band) CRE

1. Blackbody cloud
2. Ignore atmospheric absorption





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

CRE_{LW} sensitive to both f and T_c

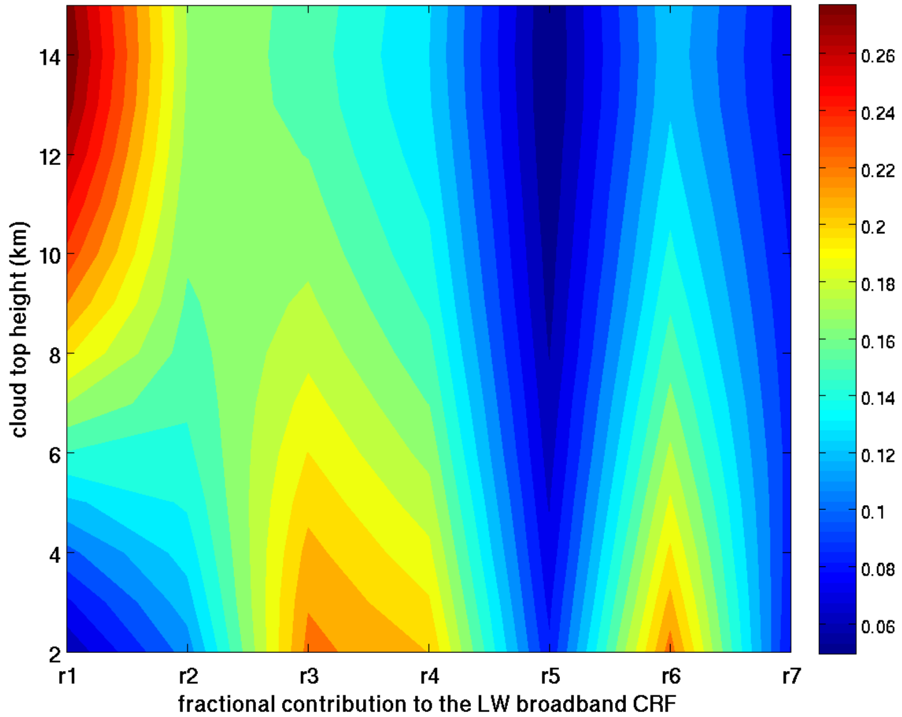
$$CRE(\Delta v) = f[F_{clr}(\Delta v) - F_{cld}(\Delta v)]$$

Fractional contribution

$$r(\Delta v) = \frac{CRE(\Delta v)}{CRE_{LW}} = \frac{F_{clr}(\Delta v) - F_{cld}(\Delta v)}{\left[\sigma T_s^4 - \sigma T_c^4\right]}$$

r(Δv) sensitive to T_c but not f

More realistic model of r(Δ*v*)



- 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)

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

Band4: 900-990 cm^{-1} (WN)

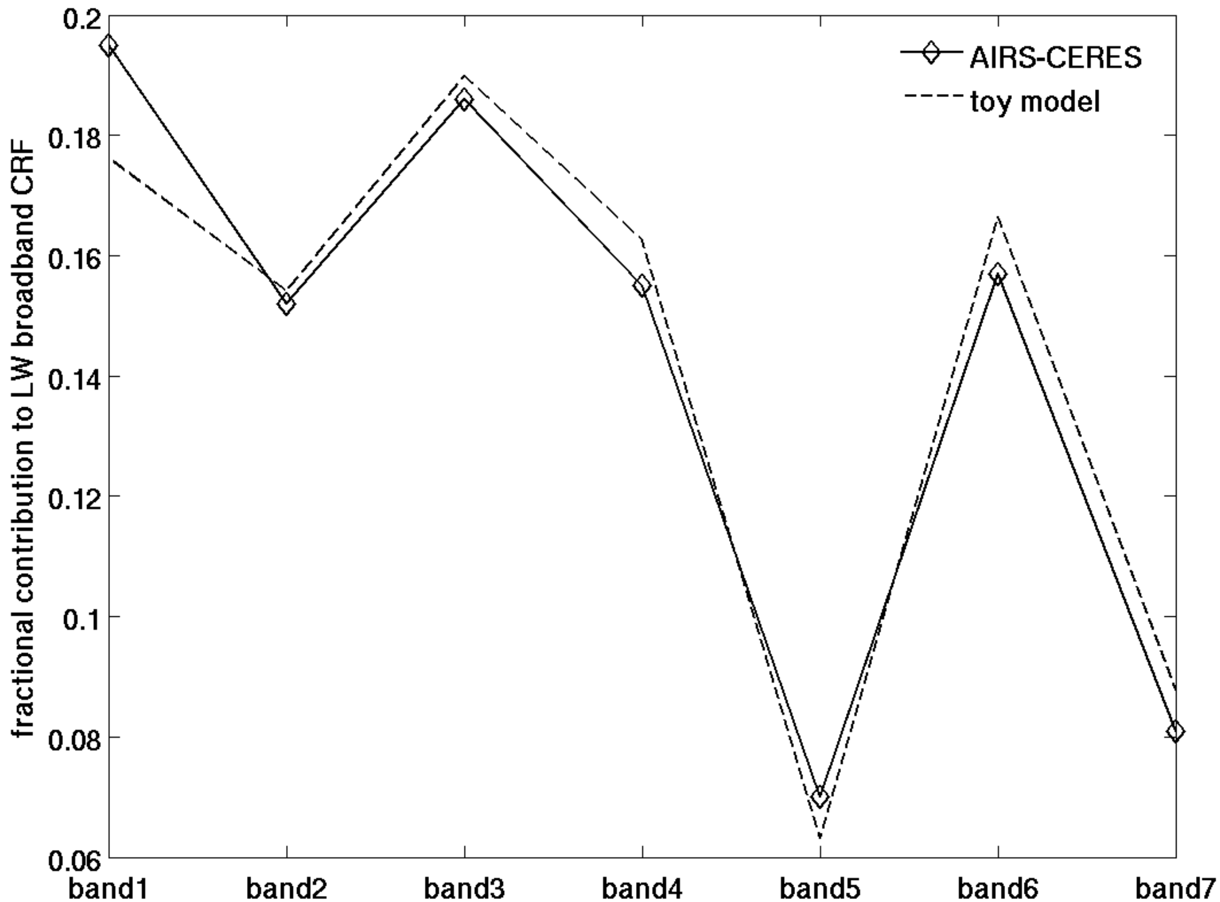
Band5: 990-1070cm^{-1} (O_3)

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

Band7: 1200-1400cm^{-1} (N2O, CH_4)

IR-effective CTH and Cloud Amount

- A step-wise inversion
  - **IR-effective CTH**: an opaque cloud that will minimize the
    Σ|f_CRE_model
  - **IR-effective**
    cloud amou
    one
- Both are qua
  budgets.



Validations

- "Theoretical validation": compare estimated spectral flux with directly computed spectral flux over each 10cm^{-1} interval
  - Largest difference < $\pm$5% (clear-sky) < $\pm$3.6% (cloudy)
- Comparing with collocated CERES OLR

All collocated clear-sky observations in 2004 (80° S-80° N)

Surface Type	Daytime	Nighttime
	OLR_{AIRS_Huang}-OLR_{CERES} (Wm^{-2})	OLR_{AIRS_Huang}-OLR_{CERES} (Wm^{-2})
Forest	0.58±1.43	-0.42±1.41
Savannas	-0.03±2.52	0.68±1.50
Grasslands	0.19±2.61	0.63±1.65
Dark Desert	-0.71±2.85	0.36±1.74
Bright Desert	1.67±2.62	1.42±2.28
Ocean	1.09±1.55	0.90±1.26

(Chen et al., J Climate, 2013)

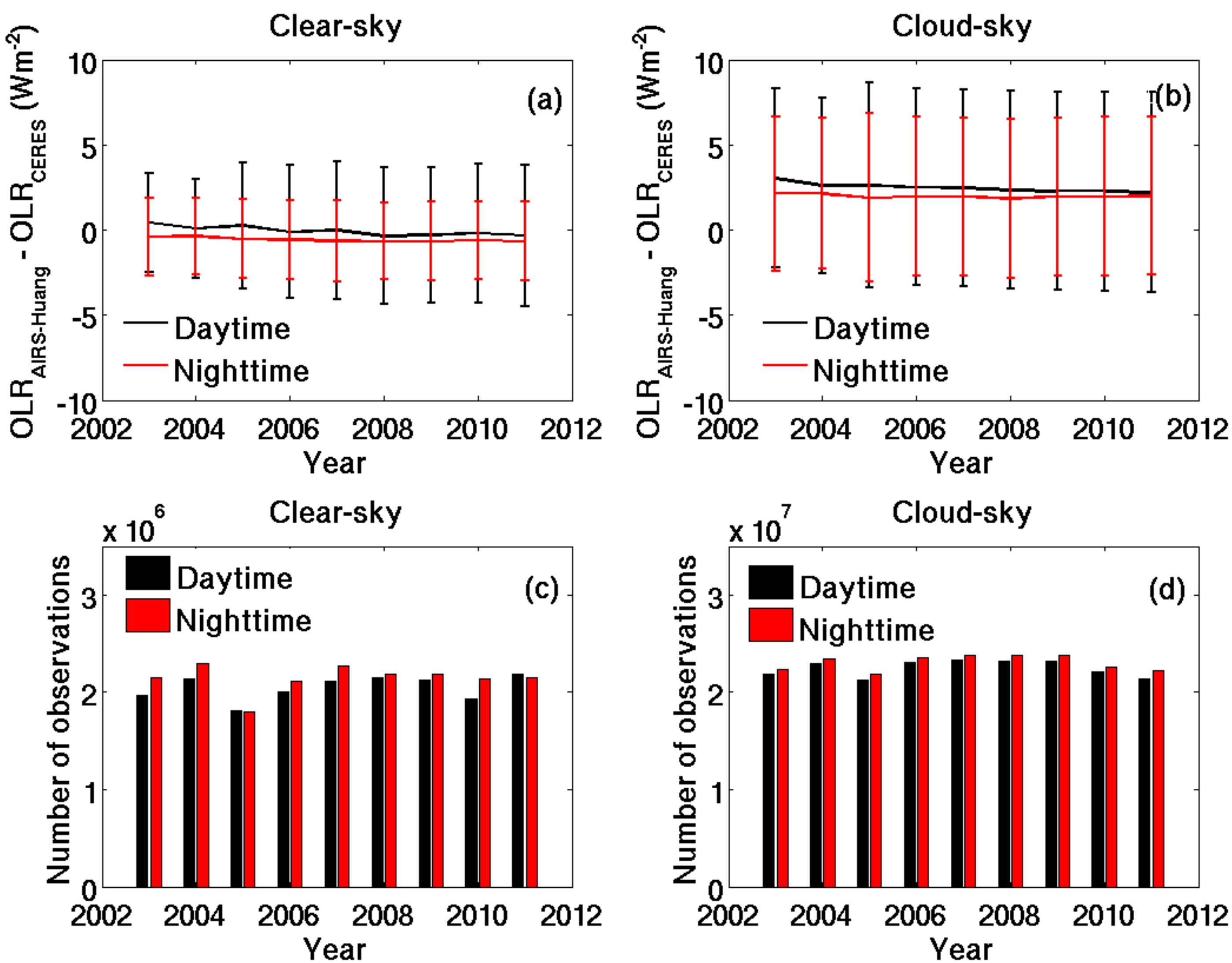
CERES 2σ radiometric calibration uncertainty: 1% (i.e. ~ 2.5W m^{-2})

Stratifying OLR_{AIRS_Huang}-OLR_{CERES} (Wm^{-2}): cloudy observations over the lands

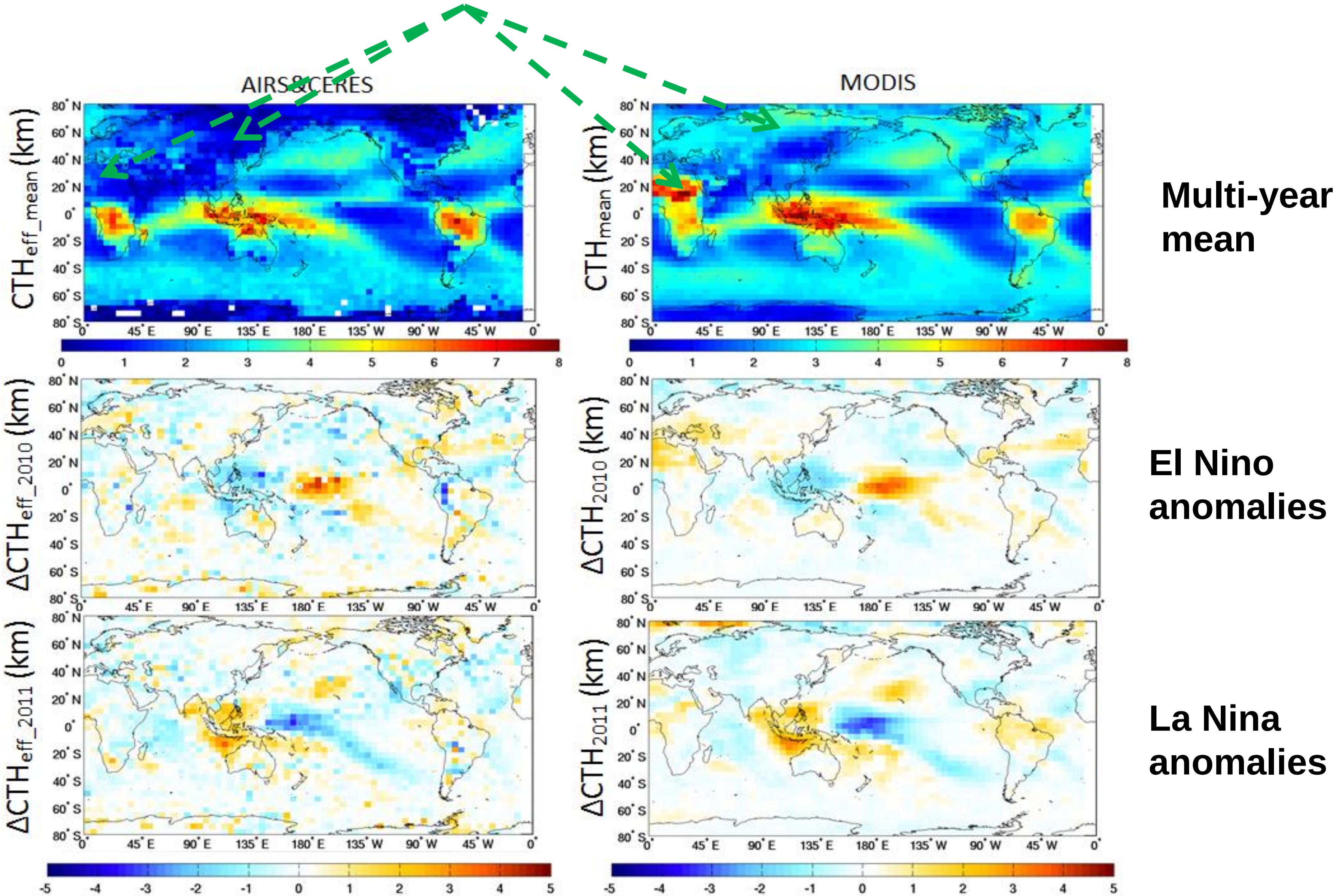
ΔT_{sc} / *f*	Over deserts			Over non-desert lands		
	<15k	15K-40K	>40K	<15k	15K-40K	>40K
0.001-0.5	**2.44±3.79 (0.9%)**	**3.25±5.12 (1.2%)**	**1.49±7.61 (0.5%)**	**2.34±2.86 (0.8%)**	**3.62±4.48 (1.3%)**	**2.84±5.94 (1.0%)**
0.5-0.75	**2.79±4.16 (1.1%)**	**3.34±7.80 (1.3%)**	**1.39±12.75 (0.5%)**	**2.90±3.86 (1.1%)**	**4.24±7.25 (1.7%)**	**2.61±11.38 (1.0%)**
0.75-0.999	**2.67±3.67 (1.1%)**	**1.45±6.47 (0.6%)**	**-1.17±10.97 (-0.5%)**	**2.81±3.56 (1.2%)**	**3.14±6.68 (1.4%)**	**0.47±11.45 (0.2%)**
0.999-1.0	**2.61±2.80 (1.2%)**	**3.15±4.00 (1.6%)**	**1.28±6.64 (0.7%)**	**2.86±2.83 (1.3%)**	**4.04±4.33 (2.0%)**	**2.48±7.16 (1.5%)**

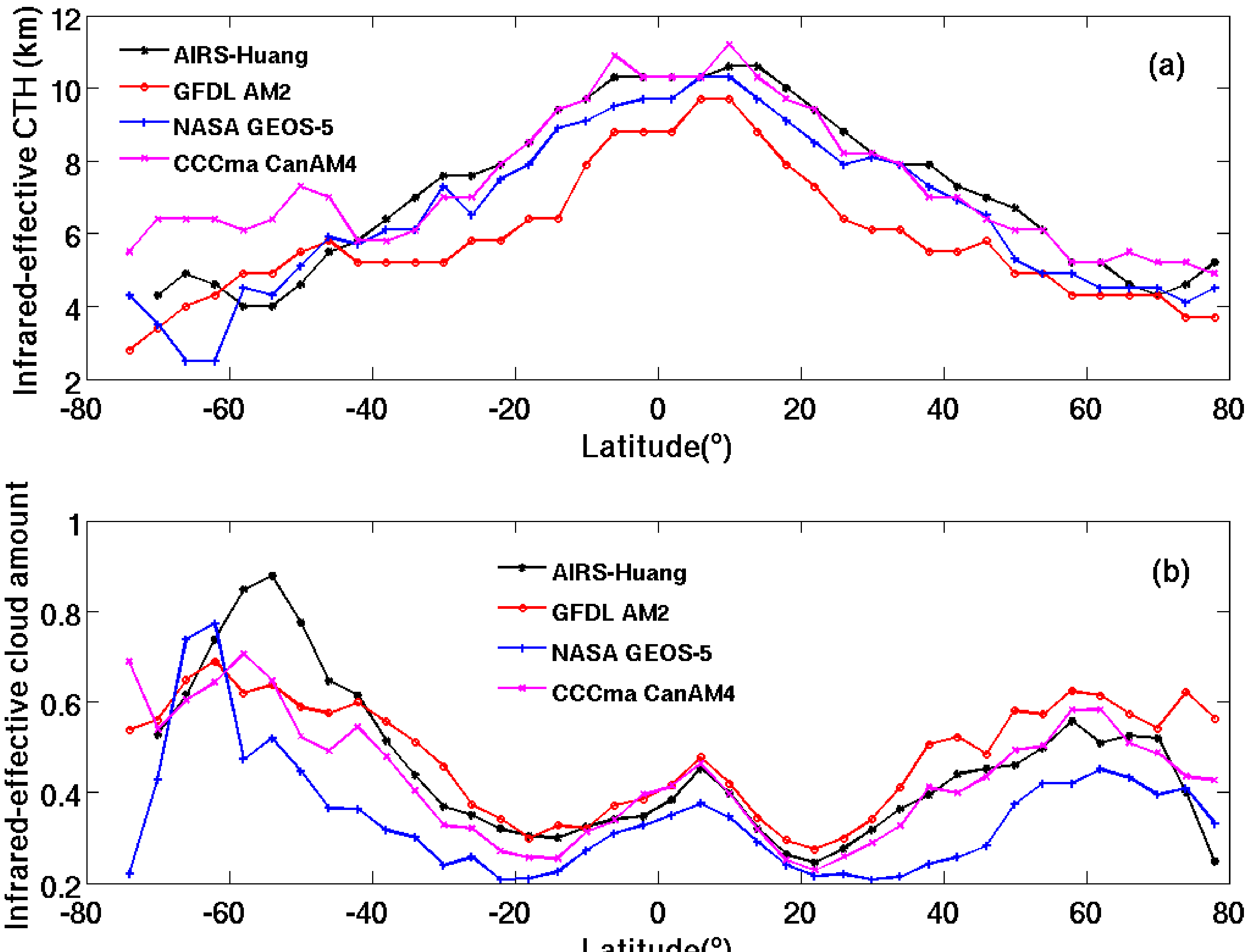
CERES 2σ radiometric calibration uncertainty: 1% (i.e. ~ 2.5W m^{-2})

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

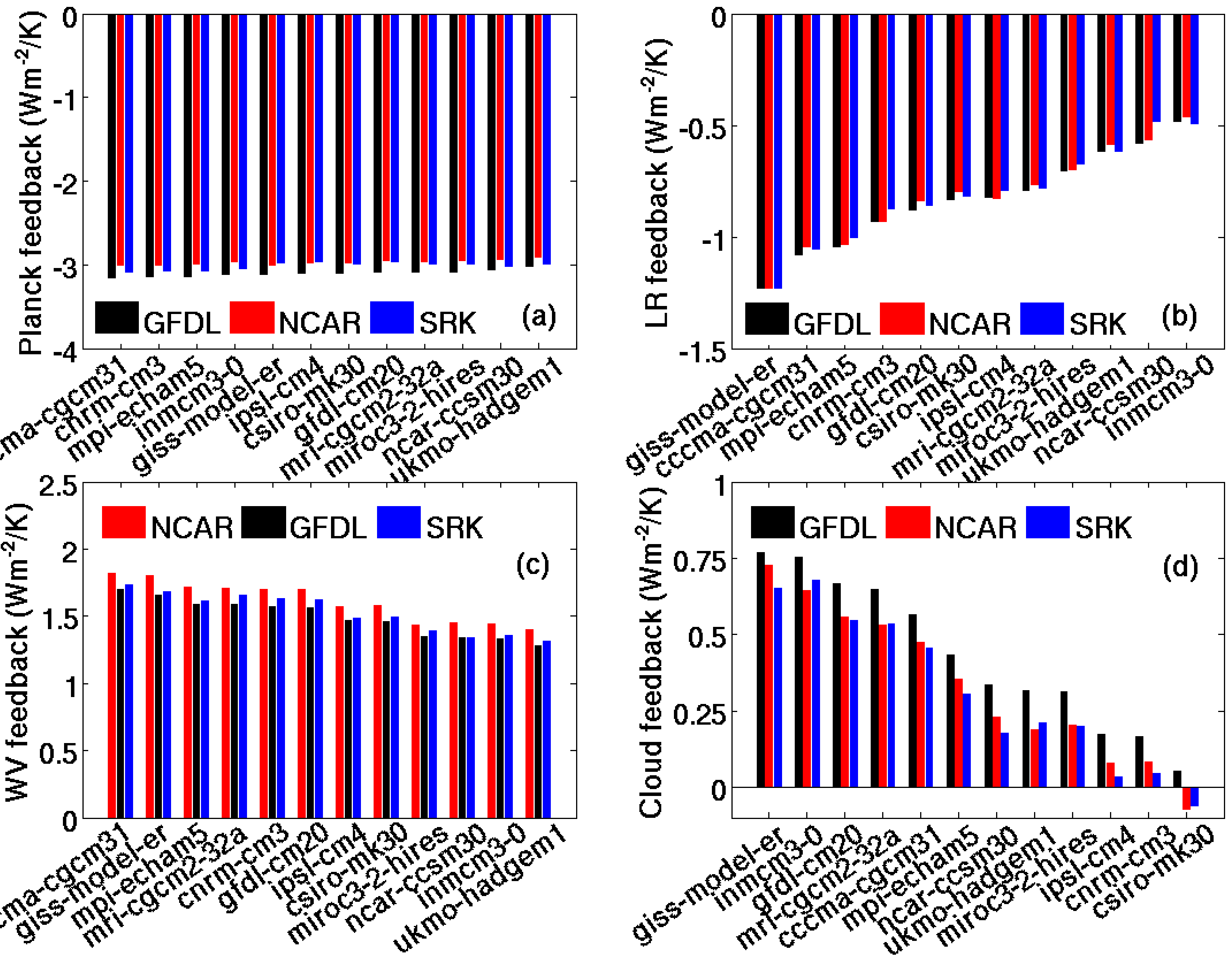


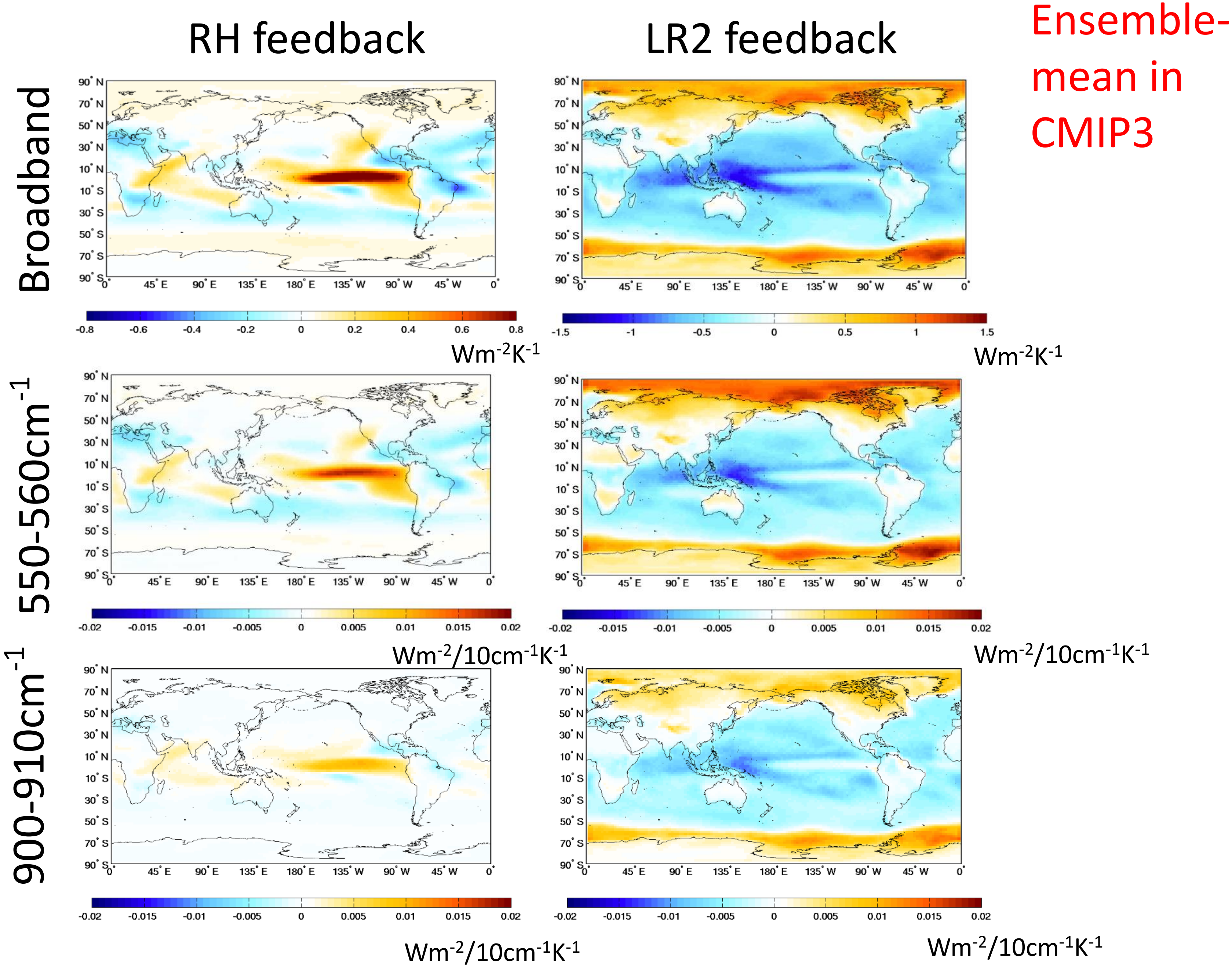
IR-effective CTH vs. MODIS CTH




Infrared-effective CTH (km)
AIRS-Huang
GFDL AM2
NASA GEOS-5
CCCma CanAM4
(a)
Latitude(°)
Infrared-effective cloud amount
AIRS-Huang
GFDL AM2
NASA GEOS-5
CCCma CanAM4
(b)
Latitude(°)

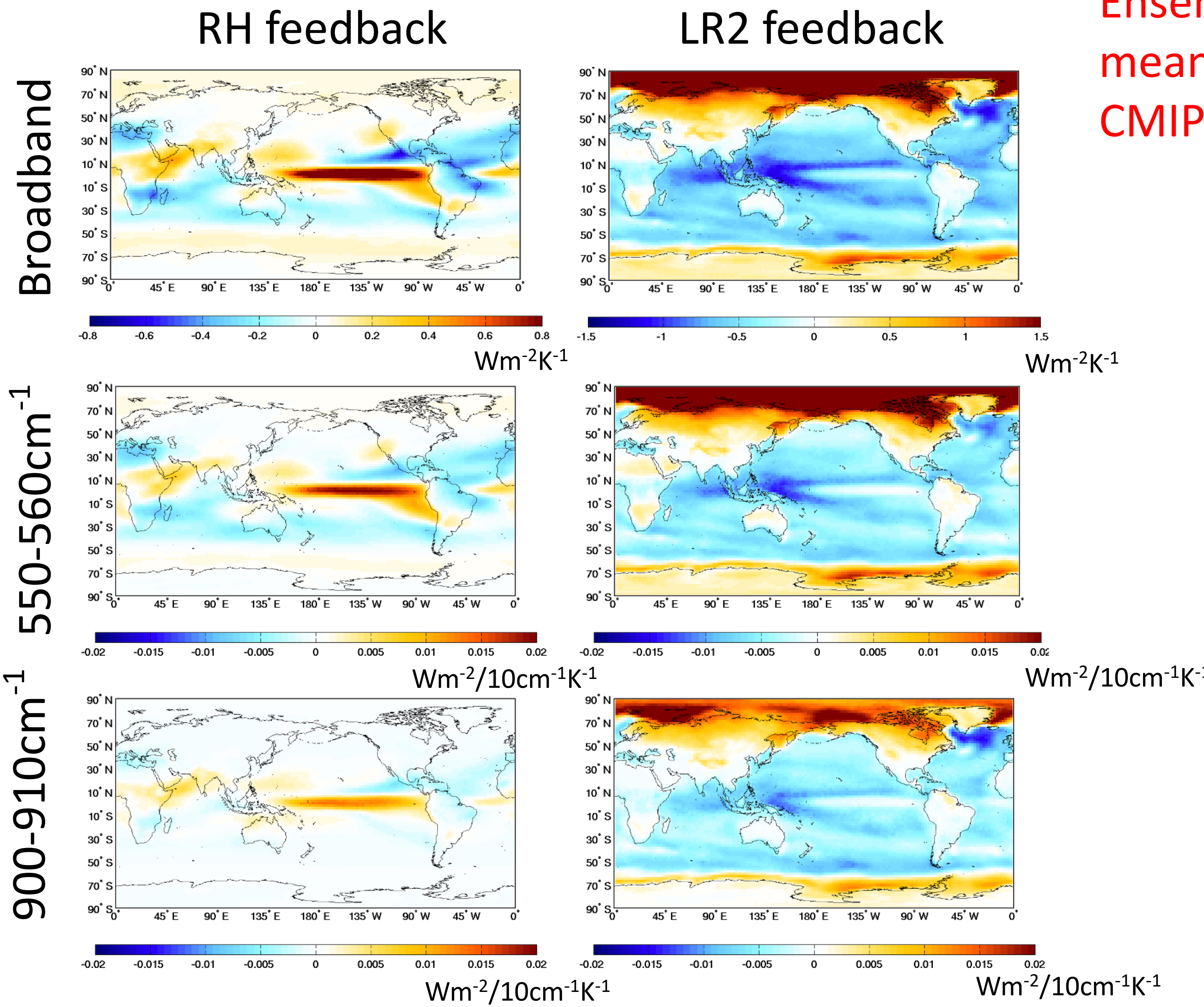
Validation: comparisons with the PRP results





RH feedback
LR2 feedback
Ensemble-mean in CMIP3
Broadband
550-560cm-1
900-910cm-1
Wm-2K-1
Wm-2K-1
Wm-2/10cm-1K-1
Wm-2/10cm-1K-1
Wm-2/10cm-1K-1
Wm-2/10cm-1K-1

Ensemble-mean in CMIP5



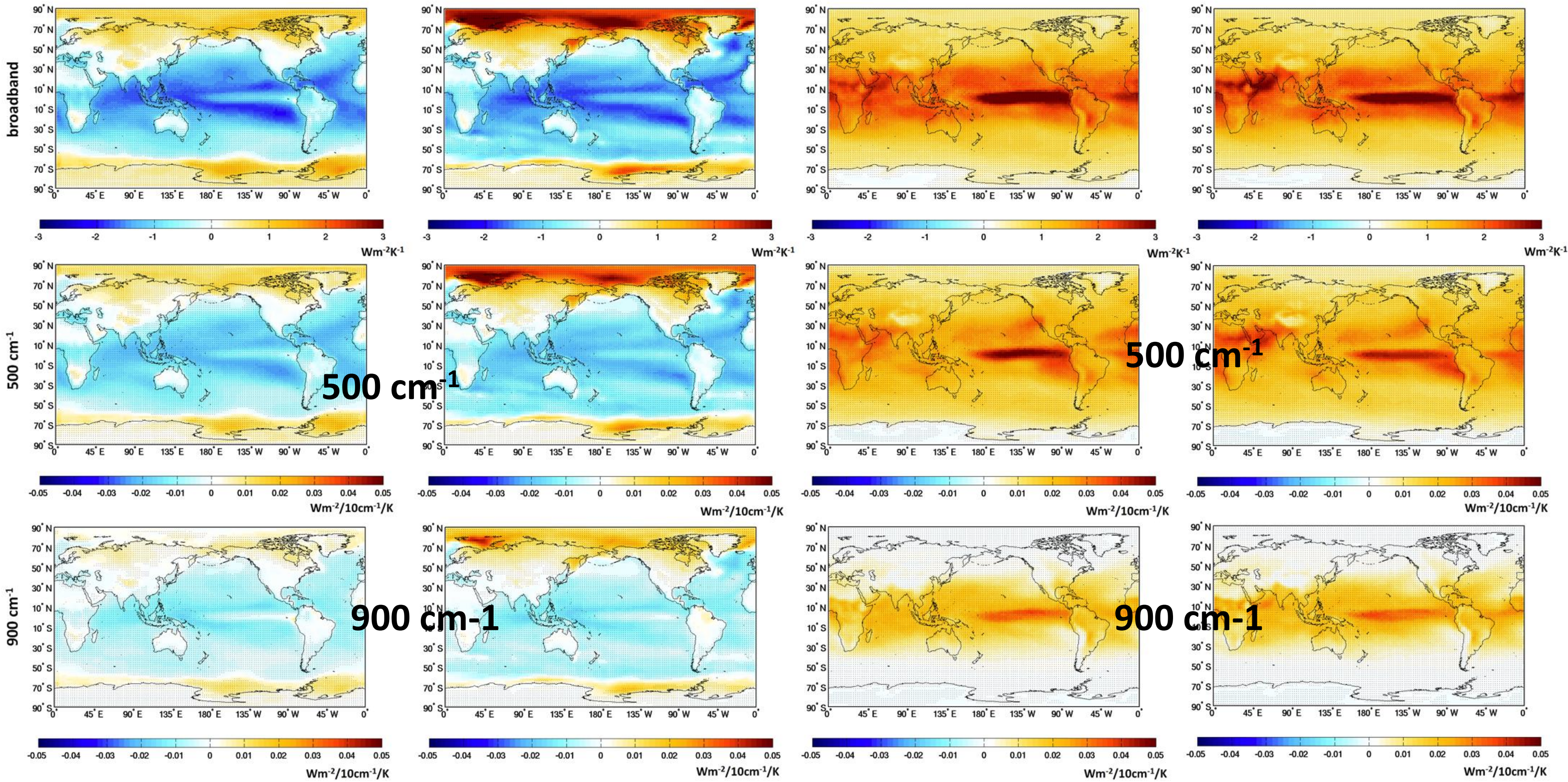
Spatial distribution of the all-sky spectral feedback: deciphering the broadband feedback

Lapser-rate feedback

LW Water-vapor feedback

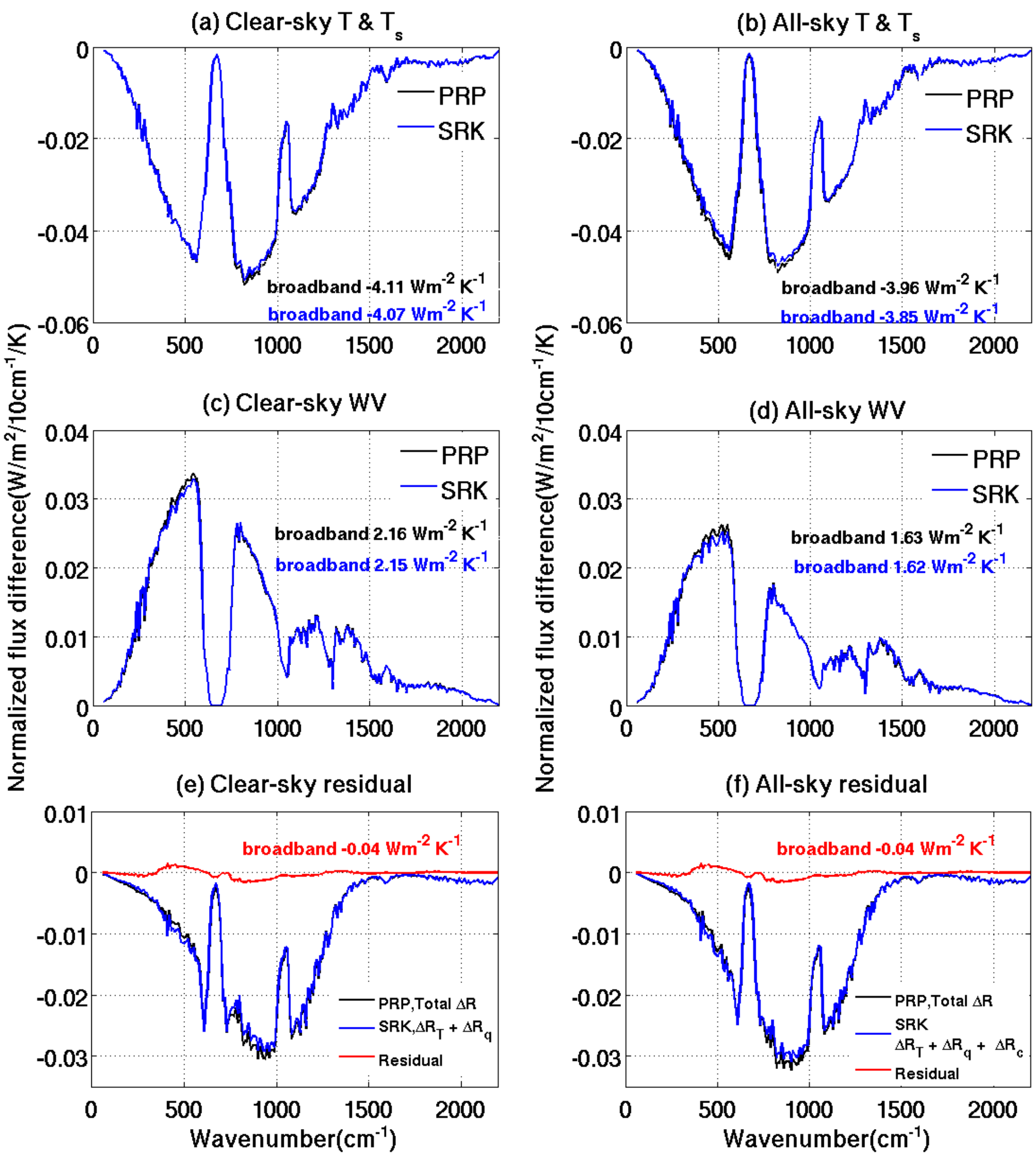
CMIP3 **Broadband** **CMIP5**

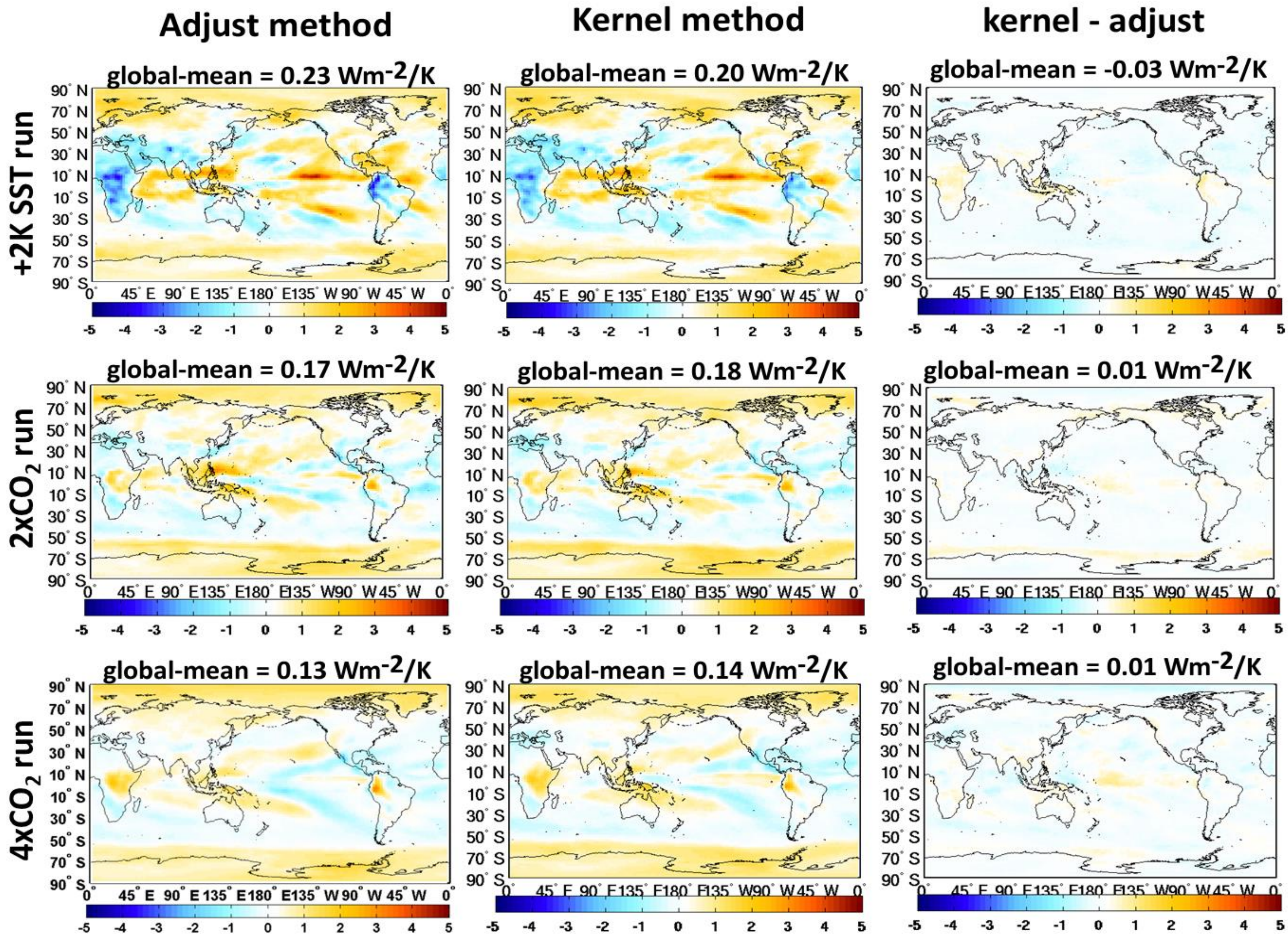
CMIP3 **Broadband** **CMIP5**



Maps of clear-sky feedbacks are similar

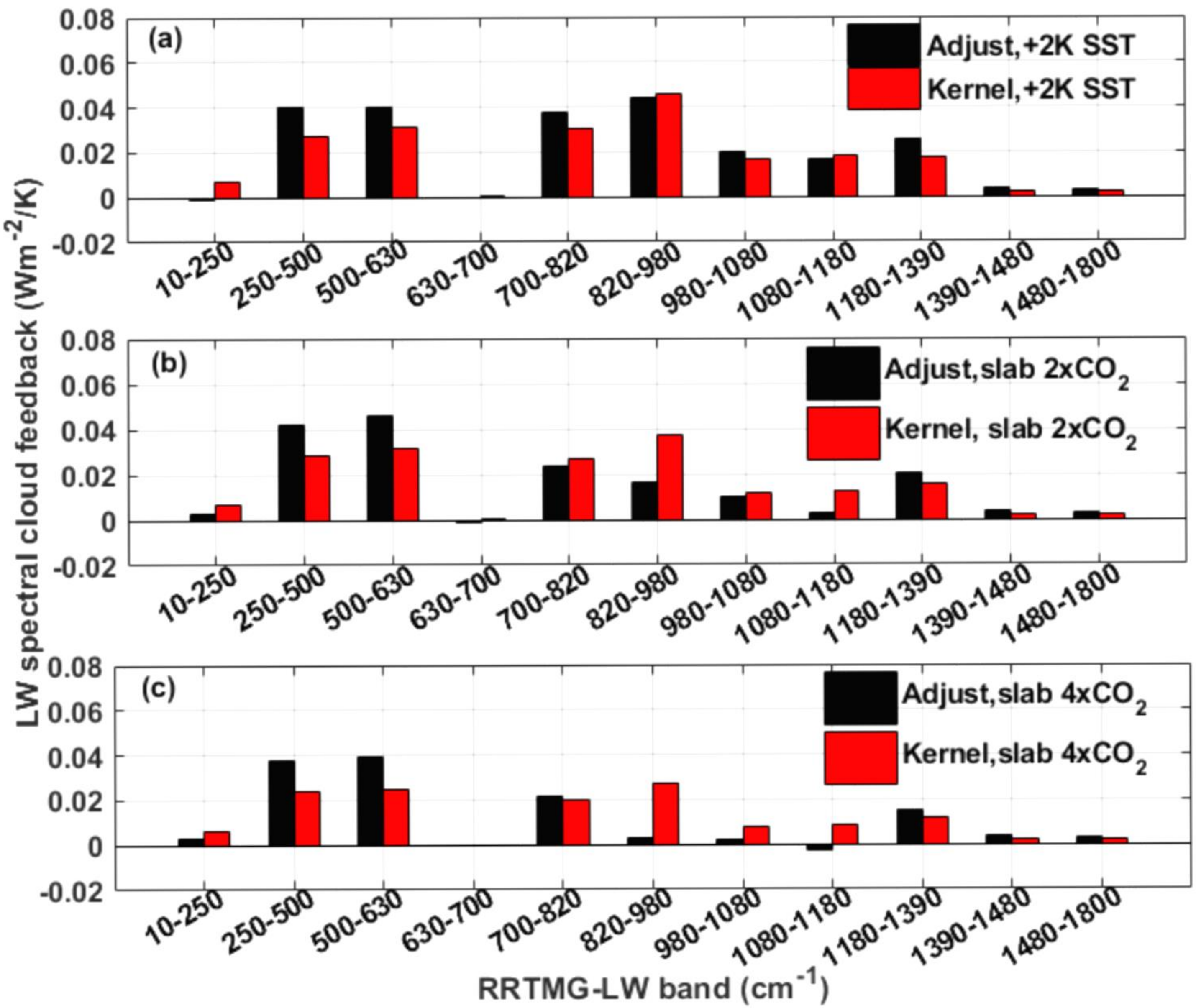
Validation: comparisons with the PRP results





Adjust method
Kernel method
kernel - adjust
+2K SST run
2xCO2 run
4xCO2 run
global-mean = 0.23 Wm-2/K
global-mean = 0.20 Wm-2/K
global-mean = -0.03 Wm-2/K
global-mean = 0.17 Wm-2/K
global-mean = 0.18 Wm-2/K
global-mean = 0.01 Wm-2/K
global-mean = 0.13 Wm-2/K
global-mean = 0.14 Wm-2/K
global-mean = 0.01 Wm-2/K

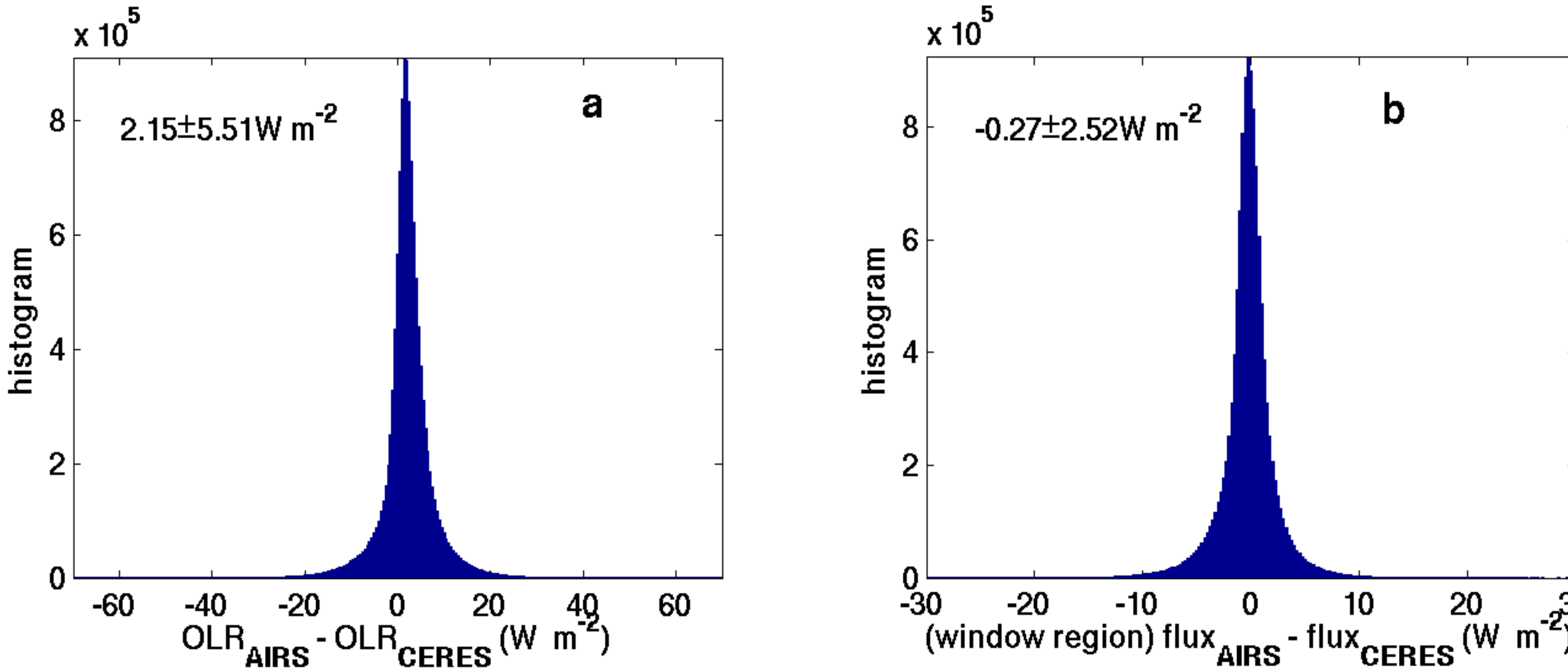
Band-by-band decomposition of the cloud radiative feedback

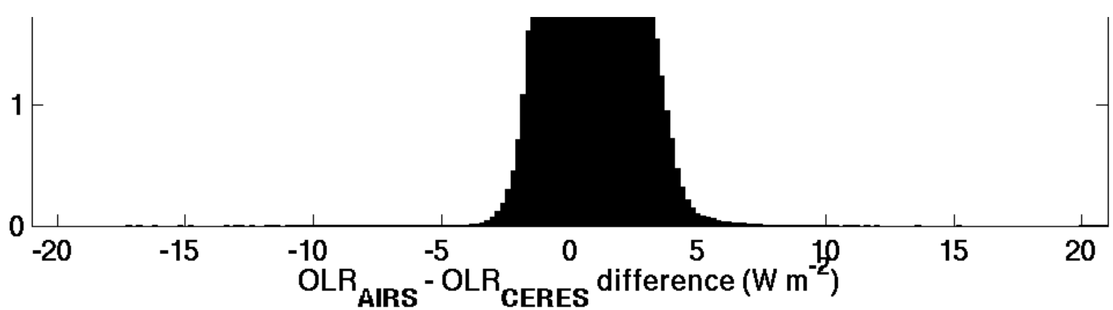


OLR_{AIRS}: OLR estimated from AIRS spectra

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})

Construction of Spectral Radiative Kernel (SRK): PCRTM

- PCRTM (Principal-component-based radiative transfer model)
  - Perform LBL calculation at selected monochromatic channels
  - Using pre-determined PCs to infer radiances in all the other channels
- Pseudo LBL calculation, can incorporate scattering clouds
- Advantages:
  - Fast and yet accurate enough
  - Can compute Jacobian all together. No numerical perturbation
  - Nearly all post processing can be done in PC space. Only need to covert back to radiance space at the very last time step
- Disadvantages:
  - Training is very time consuming and specific