The Spectral Decomposition of LW Cloud Radiative Feedbacks: Implications for Emergent Constrains

Xiuhong Chen, Xianglei Huang[1], Qing Yue[2]

[1] The University of Michigan

[2] JPL/Caltech

2017 CERES Fall Science Team Meeting
Greenbelt, MD
Sep 28, 2017

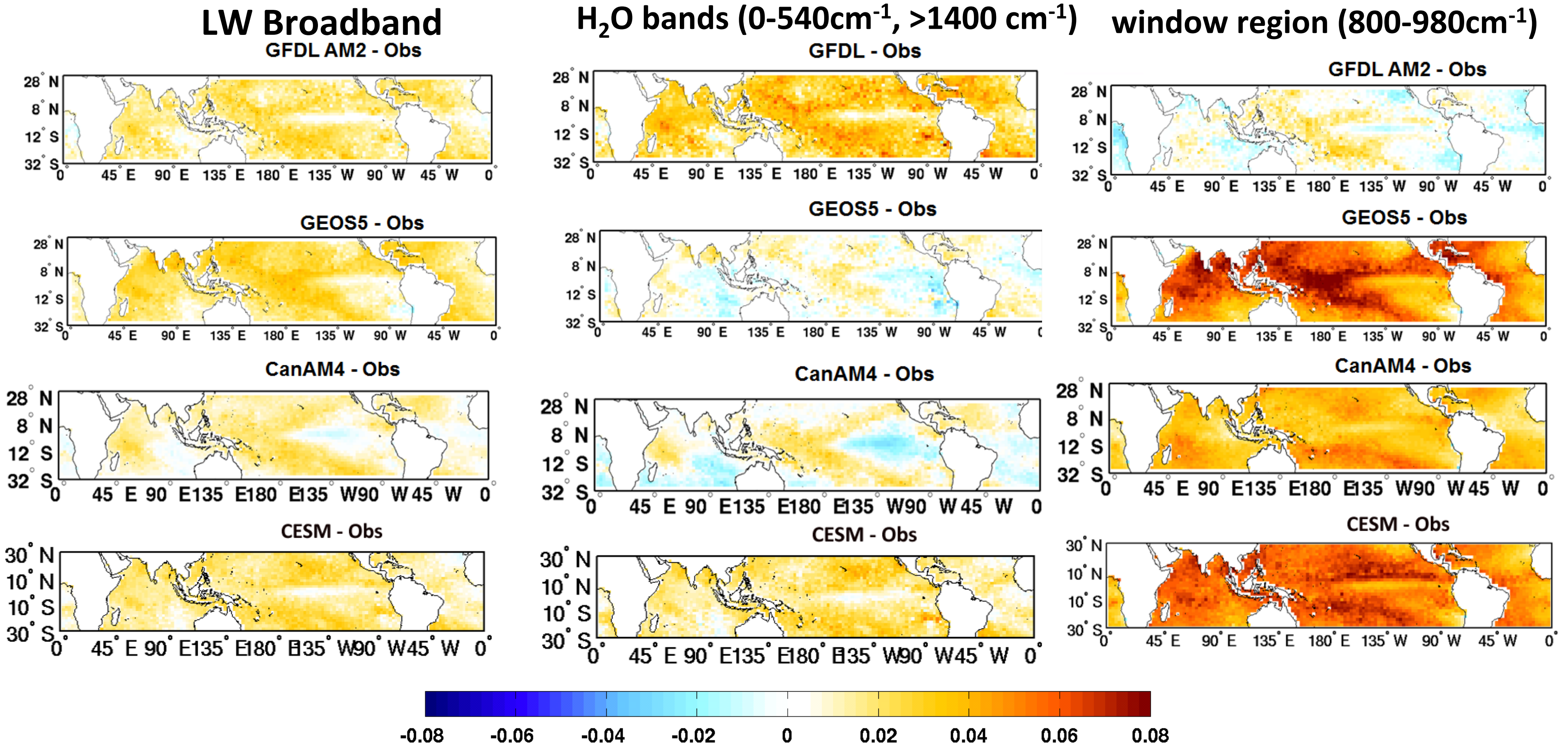
Acknowledgements: NASA CERES project, Terra/Aqua and CloudSat programs

Outline

- Motivations
  - Why go beyond the broadband comparison
- Methodology
- Band-by-band LW CRE: CESM vs. obs
- Band-by-band LW long-term cloud feedbacks
- Band-by-band LW short-term cloud radiative feedbacks (fluctuations): model vs. obs in 2003-2013
- Discussion and Conclusions

What spectral dimension can offer?

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



clear-sky green-house efficiency

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

AMIP runs forced by observed SST

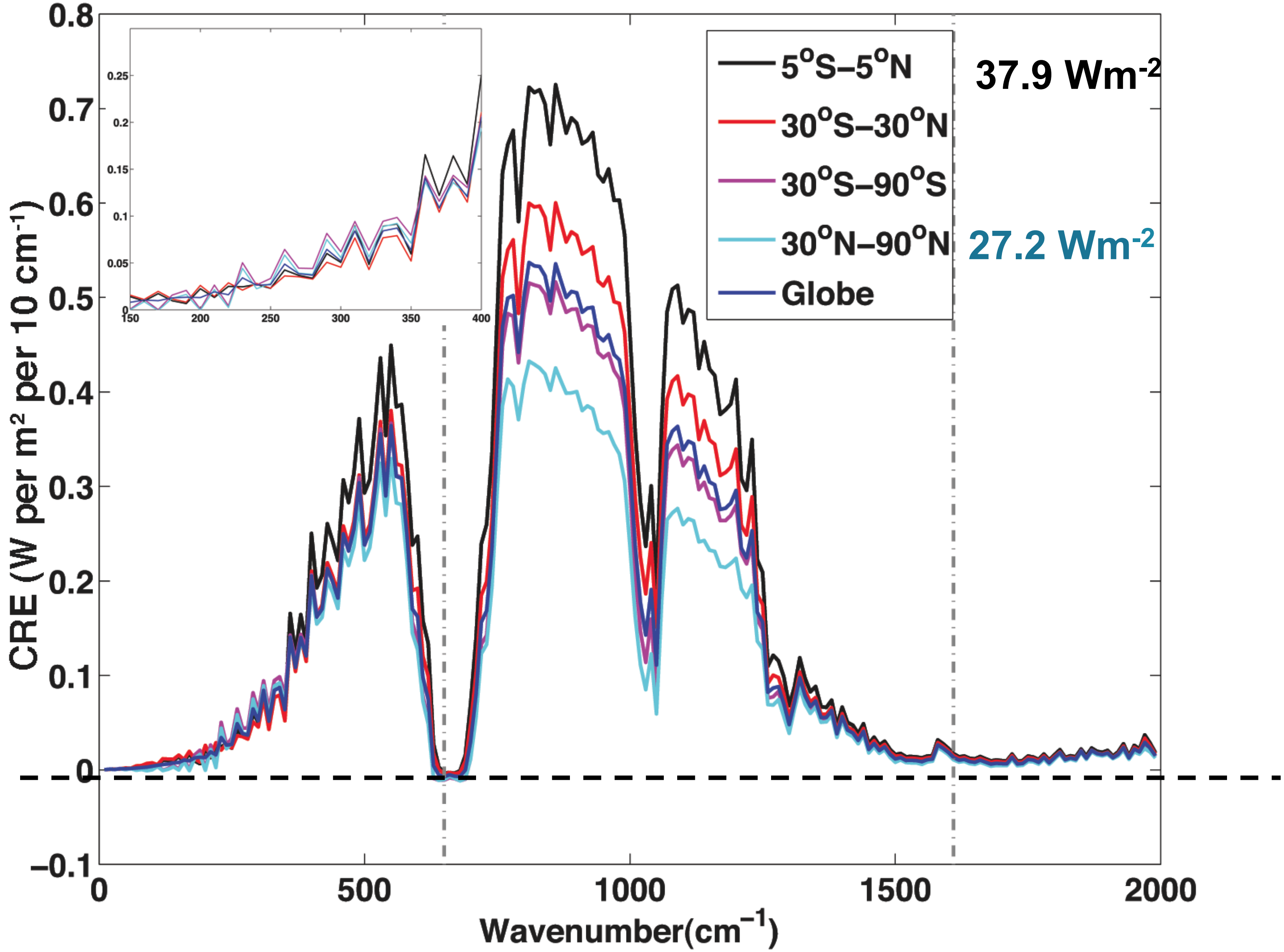
Obs from collocated AIRS and CERES (Huang et al., 2008; Chen et al., 2013)

(GEOS5 simulation provided by L. Oreopoulos et al; CanAM4 provided by J. Cole)

Derivation of spectrally resolved fluxes, CRE, and feedbacks

- Observations
  - Directly invert from AIRS radiances following the scene type classification of CERES (Huang et al., 2008; Chen et al, 2013; Huang et al., 2014)
  - Outcome: spectral flux at $10cm^{-1}$ interval over the entire LW spectrum (09/2002 to present)
  - Observation-based cloud radiative kernel (Yue et al., 2016)
    - Make use of CERES/MODIS/AIRS product
    - A composite approach (k-NN method in ML jargon)

10-year mean spectral CRE over the different climate zones



(Huang et al., 2014, J Climate)

Model: CESM

- NCAR CESM v1.1.1 (RRTMG_LW as LW rad scheme)
- Simple code modification to output band-by-band fluxes and CRE over each RRTMG_LW band.
- Spectral radiative kernels (Huang et al., 2014, GRL) to derive spectral details of Planck/Lapse-rate/WV feedbacks
- Cloud feedbacks (both broadband and band-by-band)
  - Adjustment method (Soden et al., 2008)

$$\delta_c R = dC_{RF} + ({K^0}_T - K_T)dT + ({K^0}_W - K_W)dW + ({K^0}_a - K_a)da + (G^0 - G). \quad (25)$$

  - Cloud radiative kernel method based on Yue et al. (2016), built for every RRTMG_LW band.

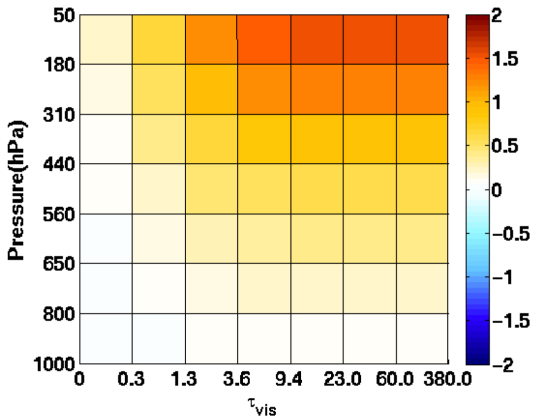
Derived cloud radiative kernels

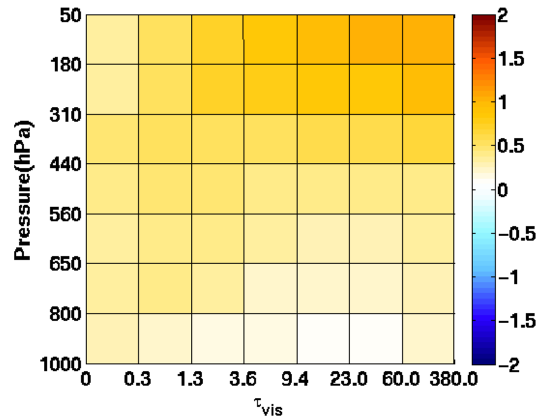
Model-based kernel (Zelinka et al., 2012)

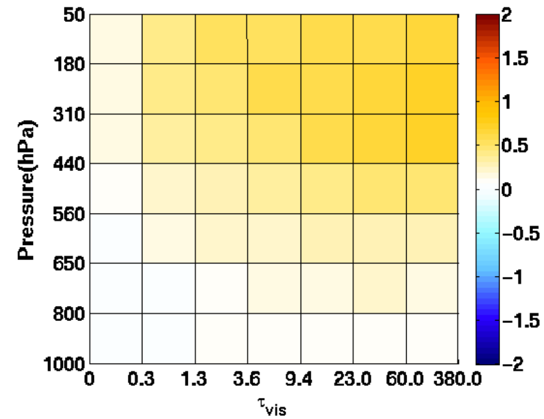
MODIS-based kernel (Yue et al. 2016)

CESM-based kernel following Yue et al. (2016)

January

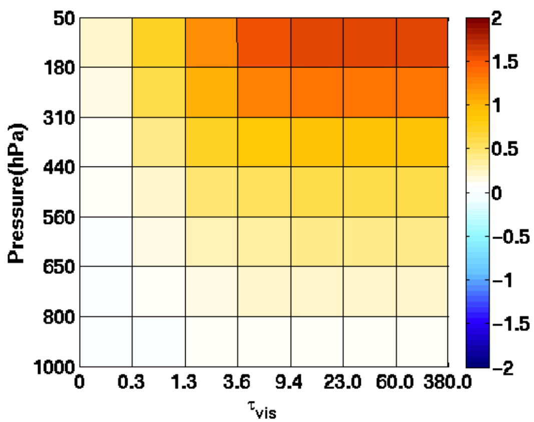


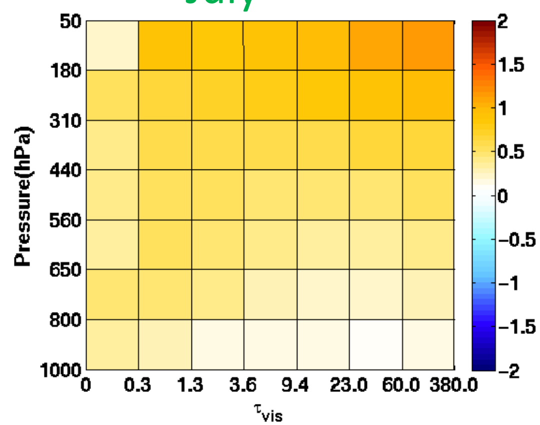


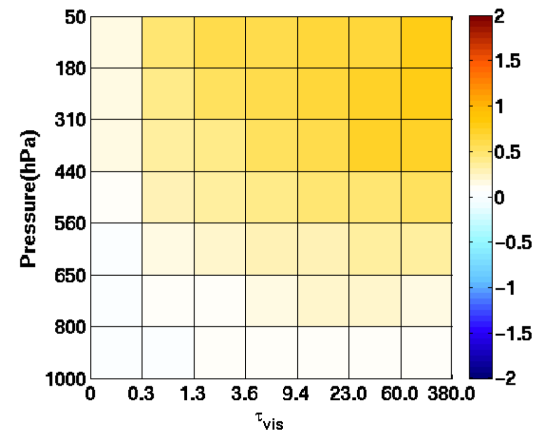


$Wm^{-2}/\%$

July





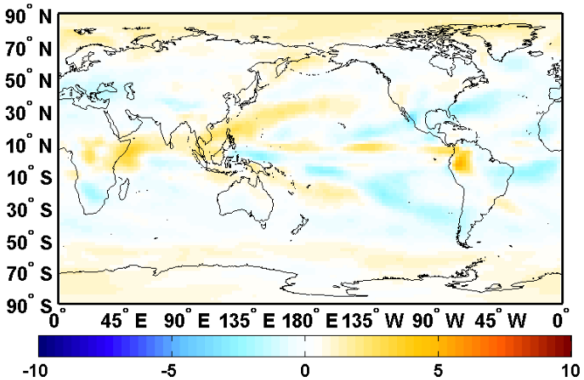


$Wm^{-2}/\%$

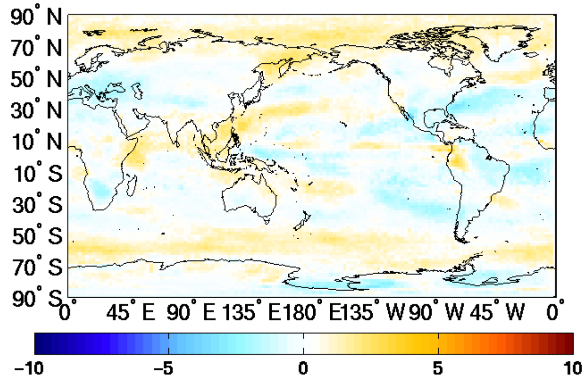
Cloud feedbacks from two methods: adjust vs. kernel

LW Cloud feedbacks for 2×CO_2 fully-coupled run

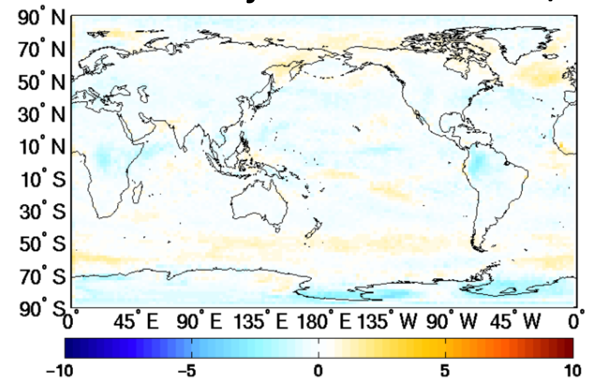
Adjust: 0.16 Wm^{-2}/K



Kernel:0.16 Wm^{-2}/K

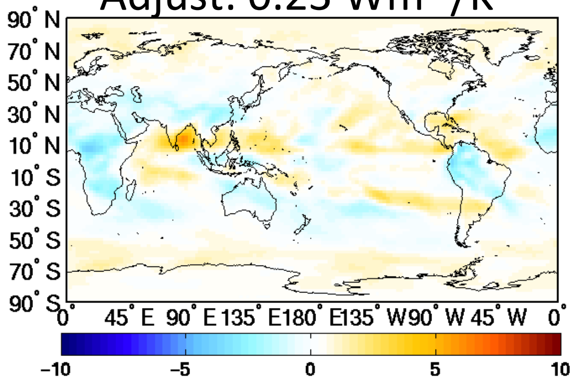


Kernel – Adjust:0.008Wm^{-2}/K

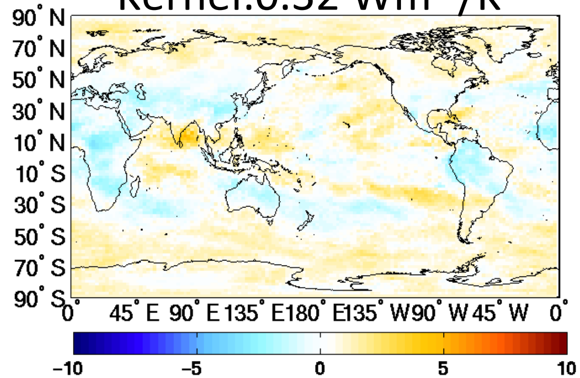


LW Cloud feedbacks for +2K SST run

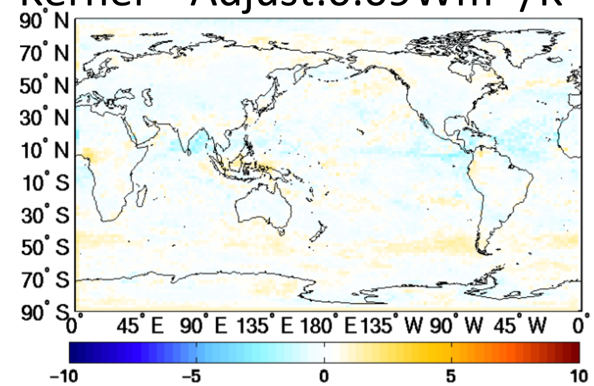
Adjust: 0.23 Wm^{-2}/K



Kernel:0.32 Wm^{-2}/K

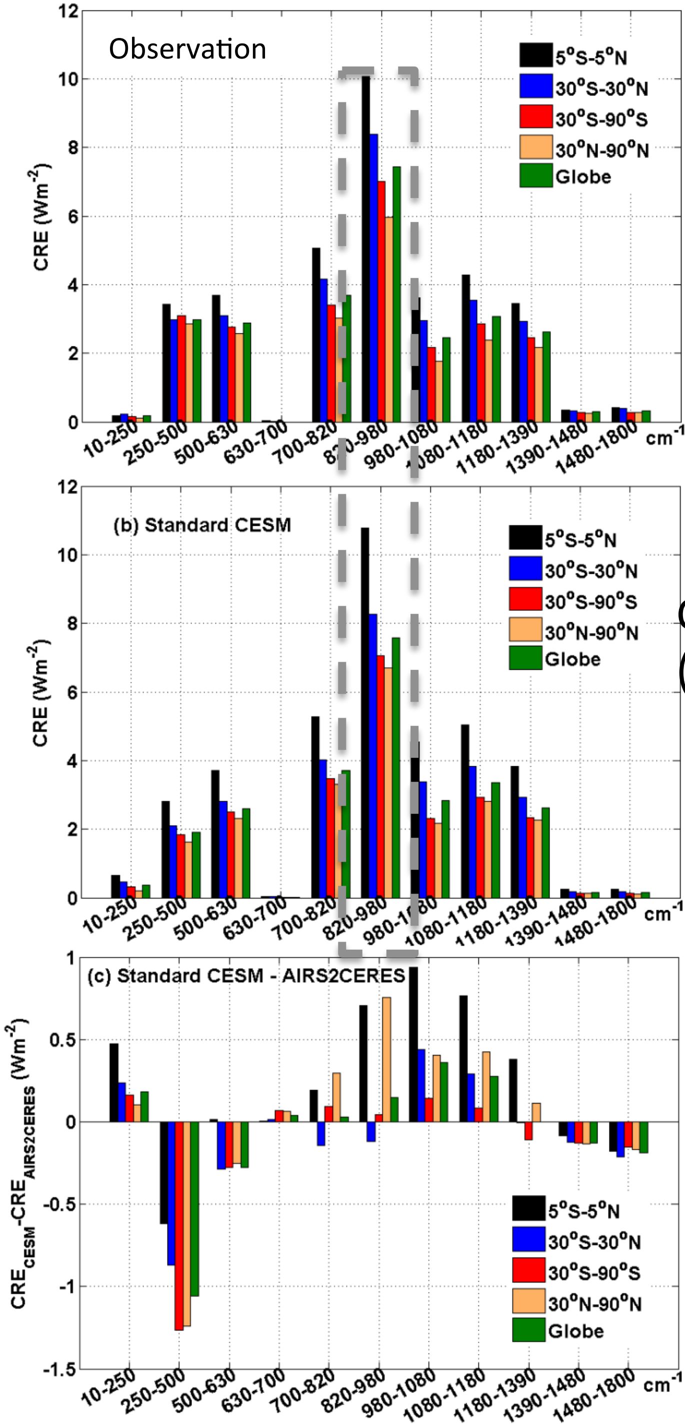


Kernel – Adjust:0.09Wm^{-2}/K



Results

Band-by-band CRE (RRTMG_LW bandwidths)

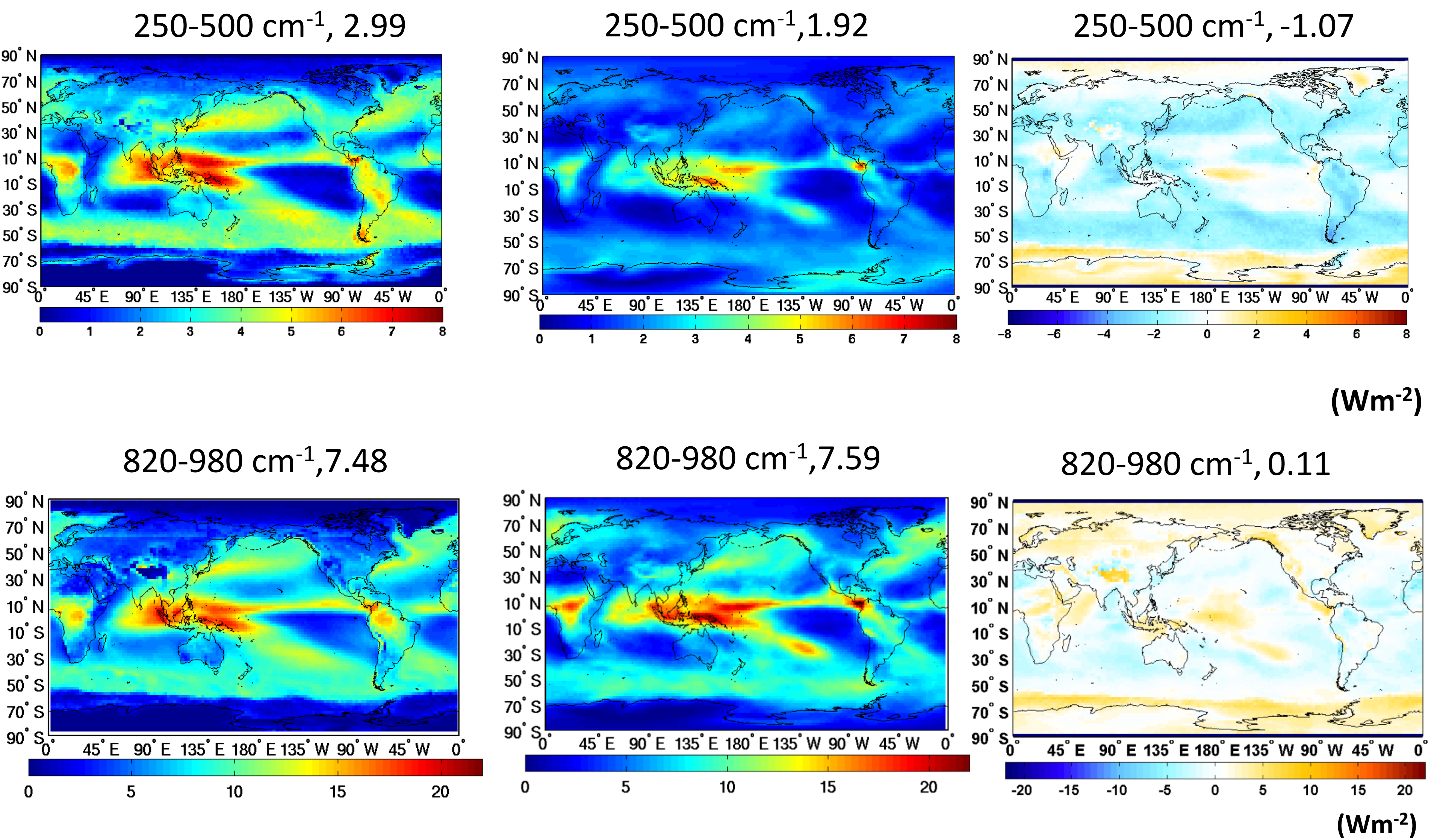


Observed averages of 2003-2015

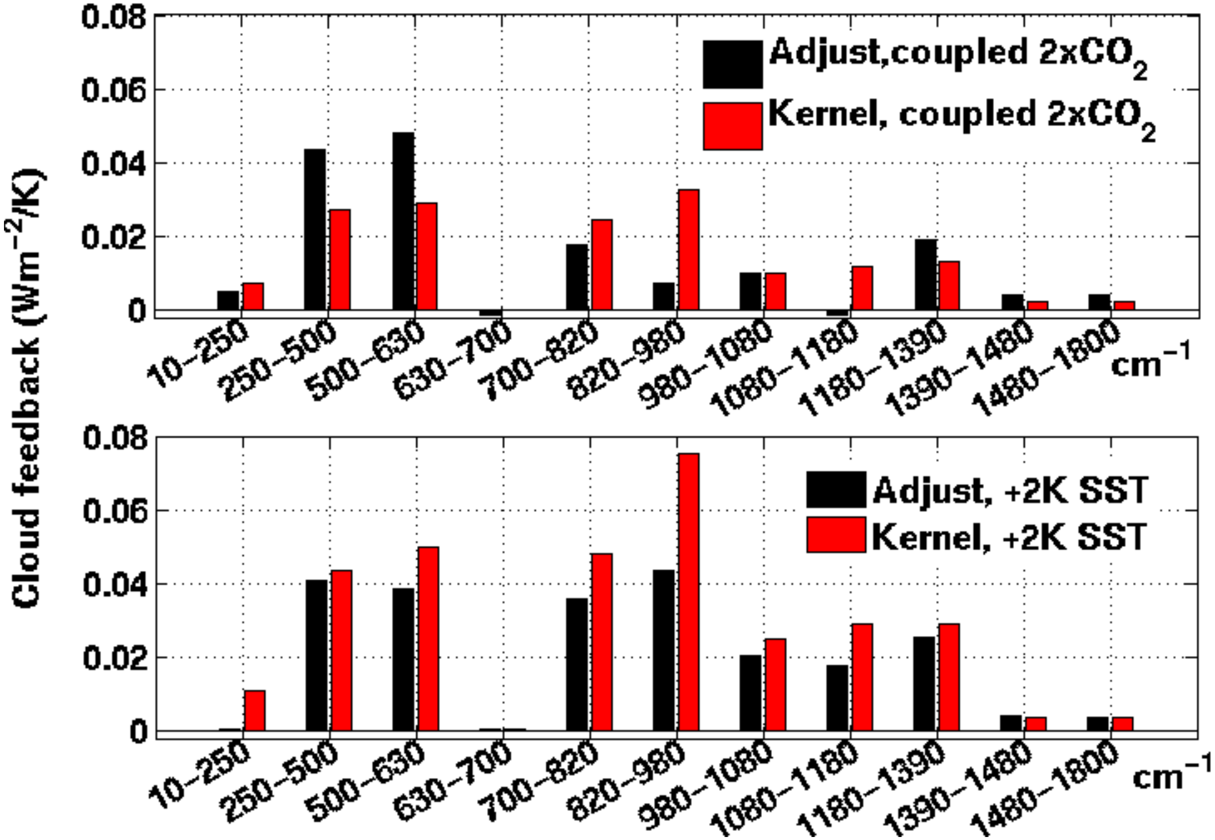
CAM5 forced with observed SST from 2003 to 2015 (total run 2000-2015)

Differences of Model - Obs

Observation: 2003-2015 | **CAM5 forced by observed SST 2003-2015** | **CAM5-Obs**



Band-by-band LW cloud feedback in the NCAR CESM



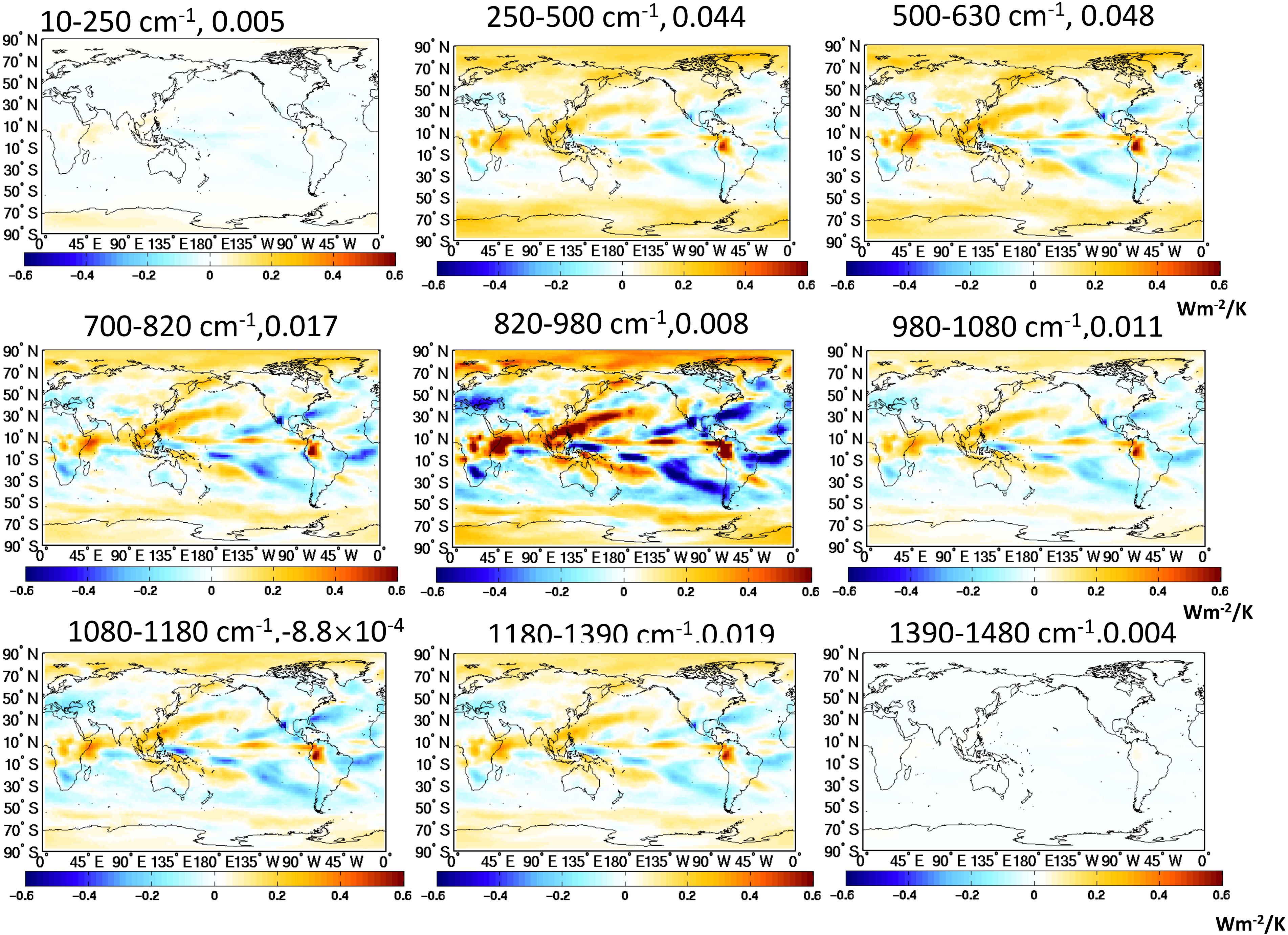
Broadband LW cloud feedback

0.16 Wm^{-2}/K
0.16 Wm^{-2}/K

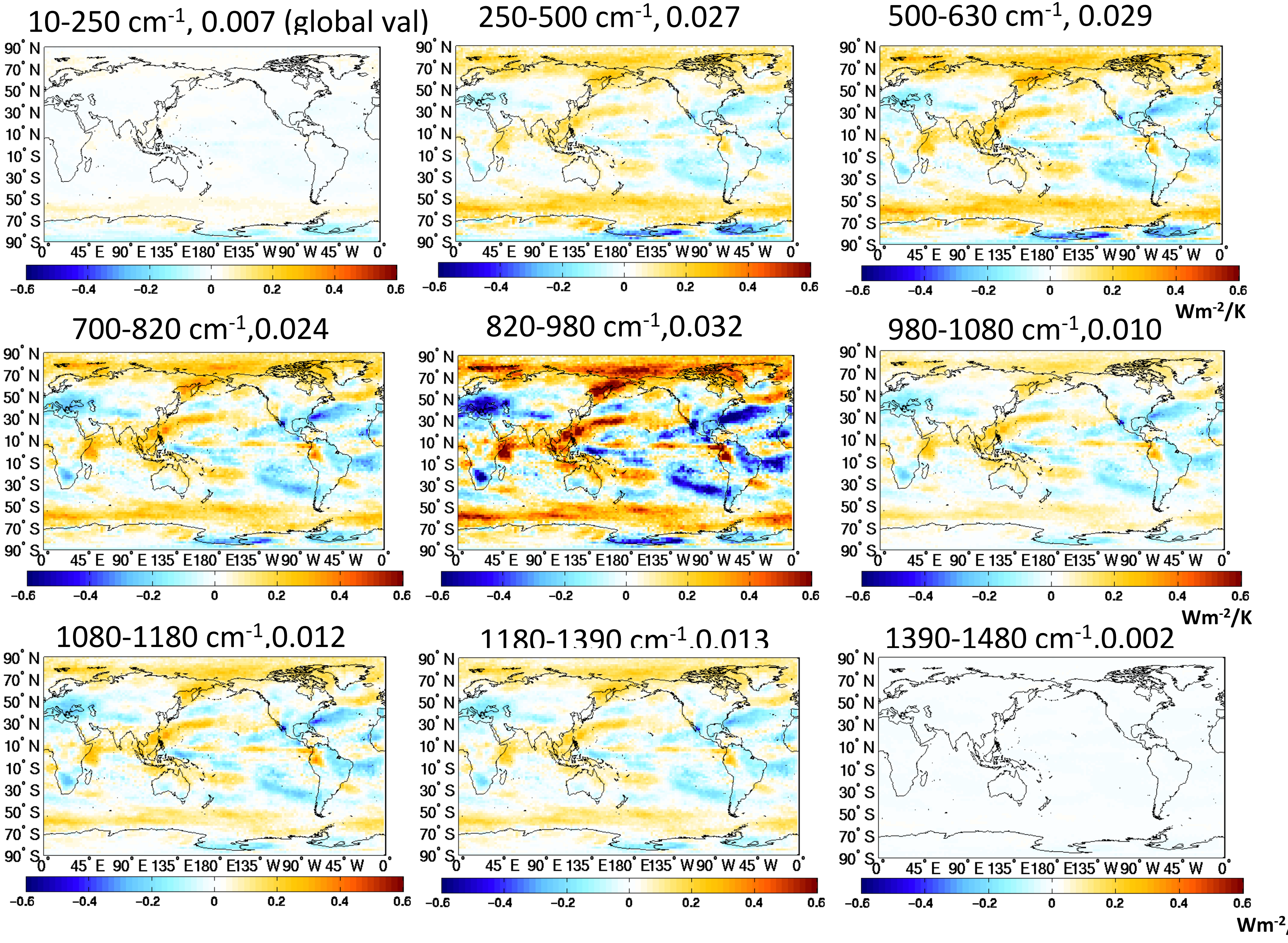
0.23 Wm^{-2}/K
0.32 Wm^{-2}/K

The band-by-band decomposition of LW cloud feedback is different for double CO_2 and +2K SST run. The decomposition from different methods can be different too, even the broadband numbers are identical.

Band-by-band Cloud radiative feedback from 2×CO_2 run (Adjust method)



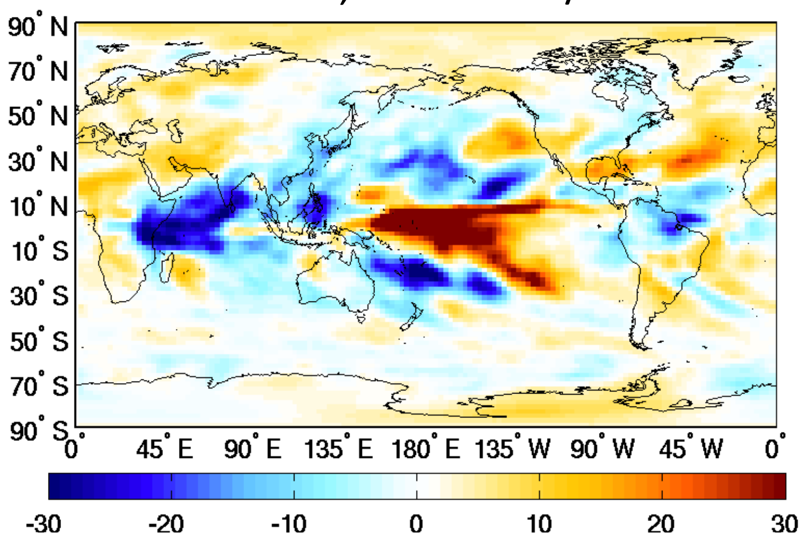
Band-by-band Cloud radiative feedback from 2×CO_2 run (kernel method)



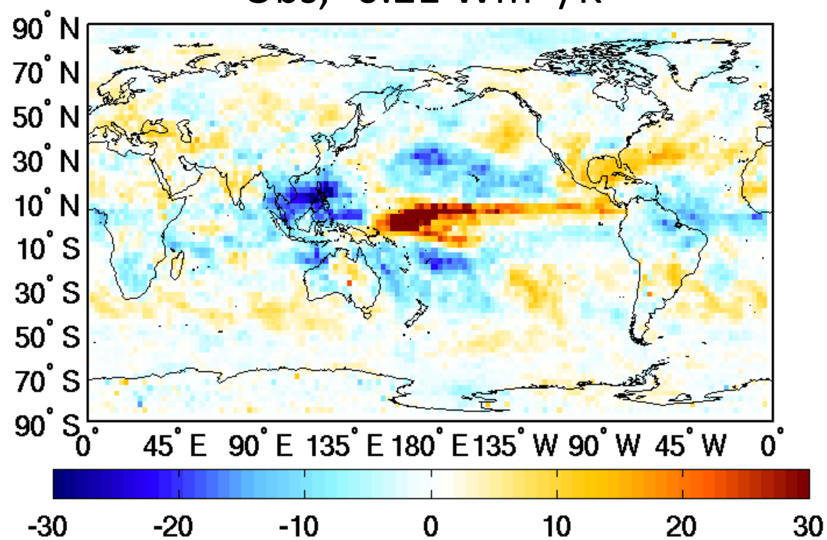
Short-term fluctuation of 2003-2015 (Preliminary)

- CESM simulation: using Dessler's method to obtain an estimation of short-term cloud feedback
- Observation: applying Yue et al. (2016) to MODIS, AIRS and CERES data to obtain the same quantity (preliminary)

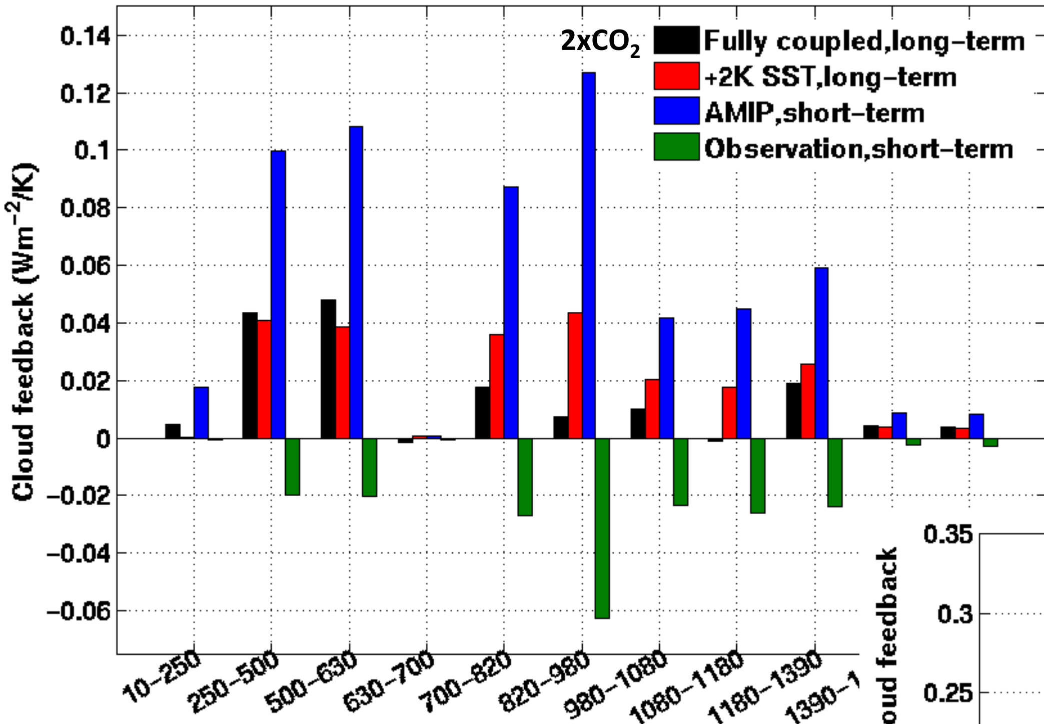
CESM, 0.61 Wm^{-2}/K



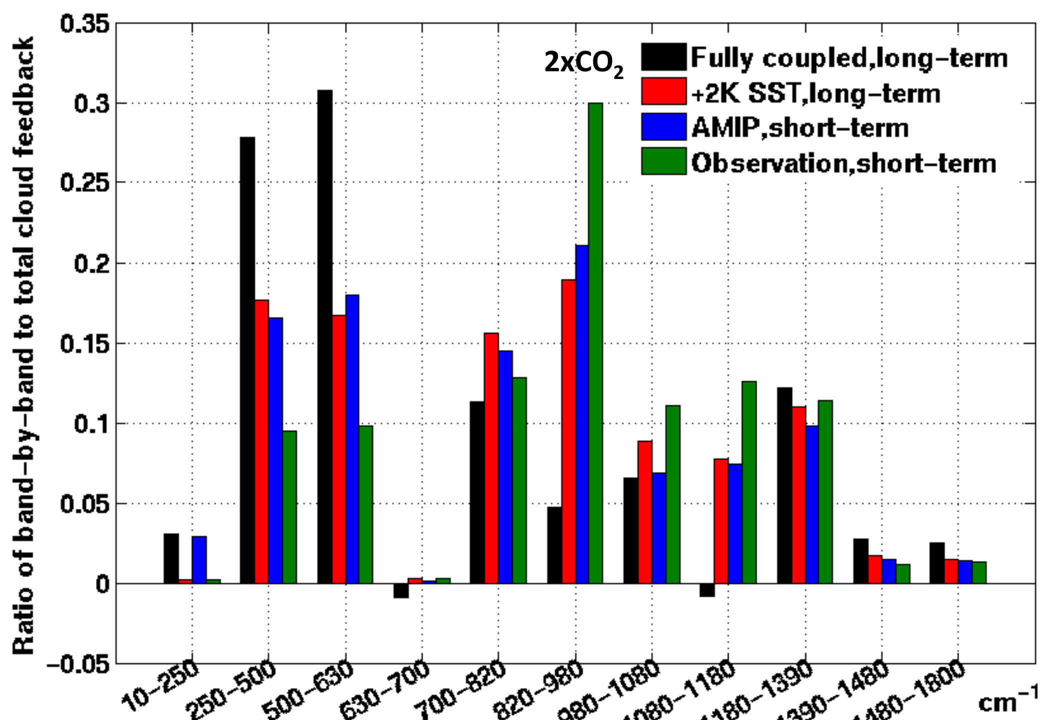
Obs, -0.21 Wm^{-2}/K



Long-term vs. short-term contrast



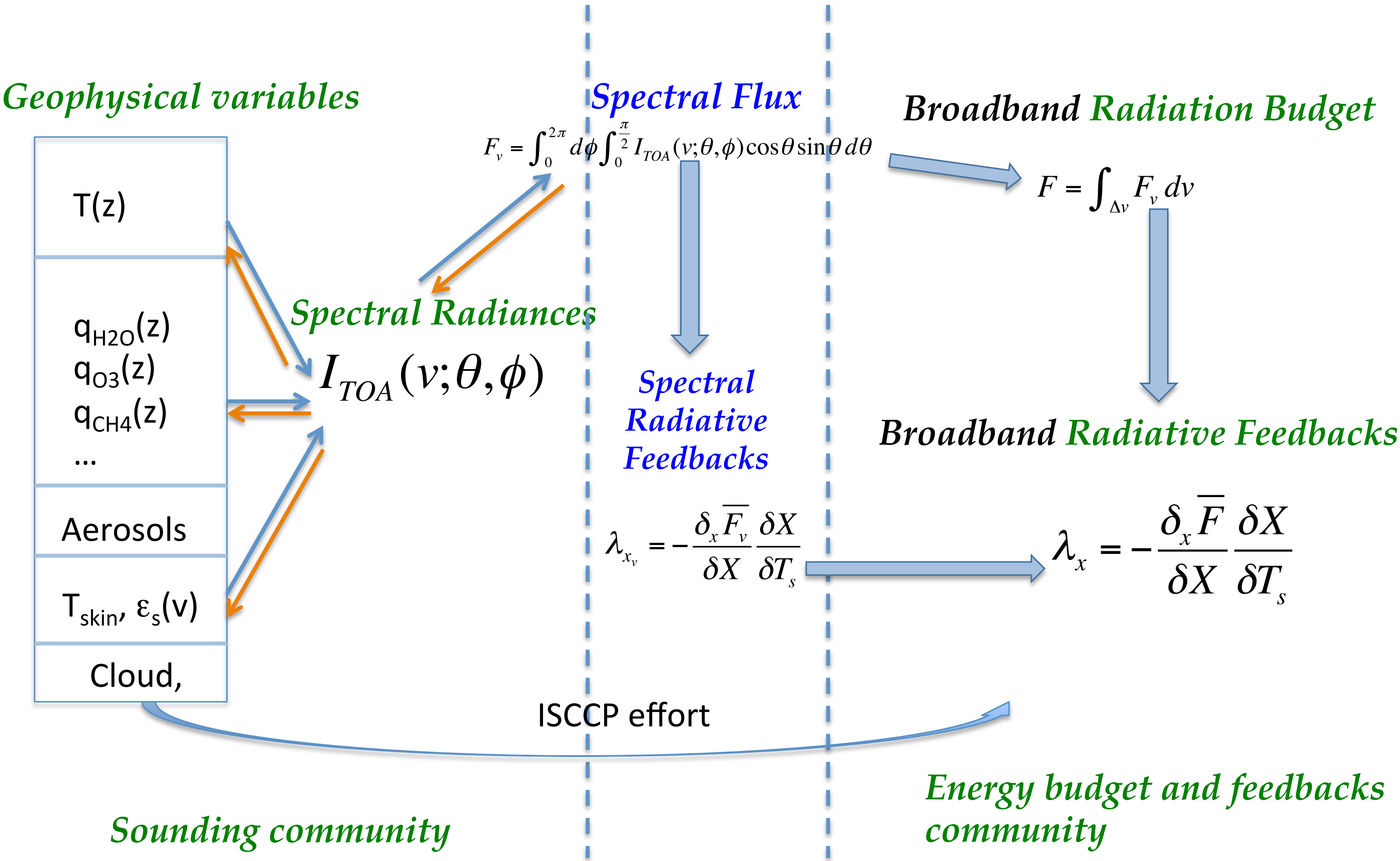
Band-by-band partitioning of LW CRE
Long-term vs. short-term
$2xCO_2$ vs. +2K SST



Broadband LW cloud feedback
Fully coupled run (long-term): 0.16 Wm^{-2}/K
+2K SST run (long-term): 0.23 Wm^{-2}/K
AMIP run (short-term): 0.61 Wm^{-2}/K
Observation (short-term): -0.21 Wm^{-2}/K

Conclusion and Discussion

- Spectral decomposition helps revealing compensating biases.
  - Compensating biases (t; x, y, **p**) vs. (t; x, y, ***v***)
- Different ways of estimating cloud feedbacks can lead to different spectral decomposition.
- The long-term vs. short-term cloud feedbacks have different spectral decomposition
  - Implications for emergent constrains


Geophysical variables
T(z)
q_H2O(z)
q_O3(z)
q_CH4(z)
...
Aerosols
T_skin, ε_s(v)
Cloud,
Spectral Radiances
$I_{TOA}(v;\theta,\phi)$
Spectral Flux
$F_v = \int_0^{2\pi} d\phi \int_0^{\frac{\pi}{2}} I_{TOA}(v;\theta,\phi)\cos\theta\sin\theta\, d\theta$
Spectral Radiative Feedbacks
$\lambda_{x_v} = -\frac{\delta_x \overline{F_v}}{\delta X}\frac{\delta X}{\delta T_s}$
Broadband Radiation Budget
$F = \int_{\Delta v} F_v\, dv$
Broadband Radiative Feedbacks
$\lambda_x = -\frac{\delta_x \overline{F}}{\delta X}\frac{\delta X}{\delta T_s}$
ISCCP effort
Sounding community
Energy budget and feedbacks community

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. 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.
3. 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.
4. Huang, X. L., X. H. Chen, B. J. Soden, X. Liu, 2014: The spectral dimension of longwave feedbacks in the CMIP3 and CMIP5 experiments, *Geophysical Research Letters*, 41, doi:10.1002/2014GL061938.
5. Yue, Q., B. H. Kahn, E. J. Fetzer, M. Schreier, S. Wong, X. H. Chen, X. L. Huang, 2016: Observation-based Longwave Cloud Radiative Kernels Derived from the A-Train, Journal of Climate, 29, 2023-2040.

Monthly gridded spectral flux and CRE available via http://www-personal.umich.edu/~xianglei/datasets.html.
The spectral radiative kernels available upon request.

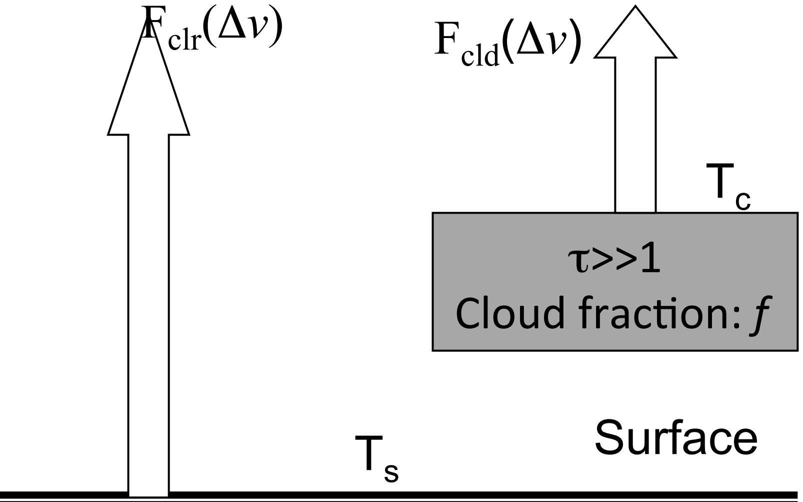
CESM cloud radiative kernel

- 3-hourly CESM output from coupled CESM runs (3 years of control run);
- Mean cloud top pressure is calculated as the average of pressure on different layer weighted by layer cloud fraction;
- In cloud optical depth is computed from liquid/ice water content using method in Chen et al. (2013); then mean cloud optical depth is weighted average by layer cloud fraction.
- ISCCP-like histogram is generated;
- Cloud radiative kernel is computed by dividing mean CRF by mean cloud fraction for each bin of the histogram.

Different from the MAST-MODIS cloud retrieval algorithm, the CERES-MODIS cloud properties are reported up to two cloud layers for each pixel at the nadir resolution of 20 km (Minnis et al. 2011a). The column-mean cloud fraction is calculated as the summation over two cloud layers, and the mean CTP and τ are calculated as the average of values on different layers weighted by layer CF.

Yue et al. (2016)

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



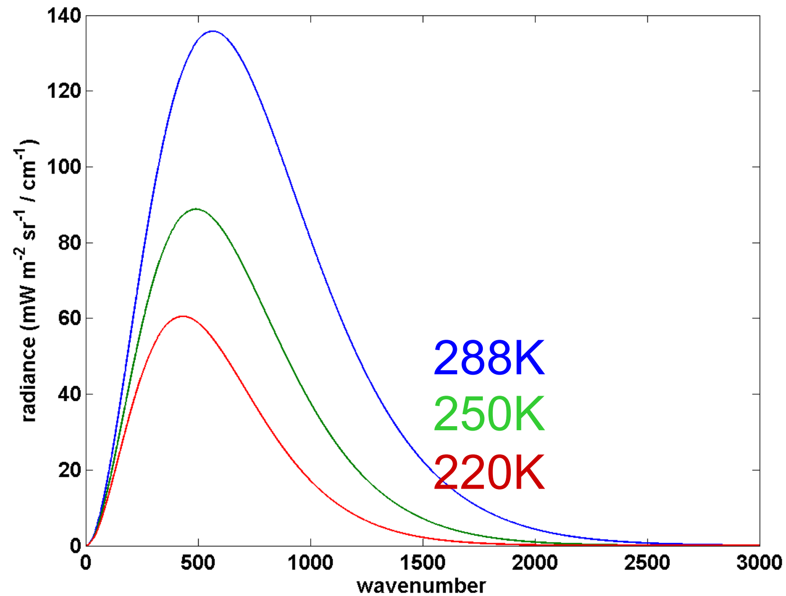
$$CRE_{LW} = \sigma T_s^4 - [f\sigma T_c^4 + (1-f)\sigma T_s^4] = f\left[\sigma T_s^4 - \sigma T_c^4\right]$$

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

Fractional contribution

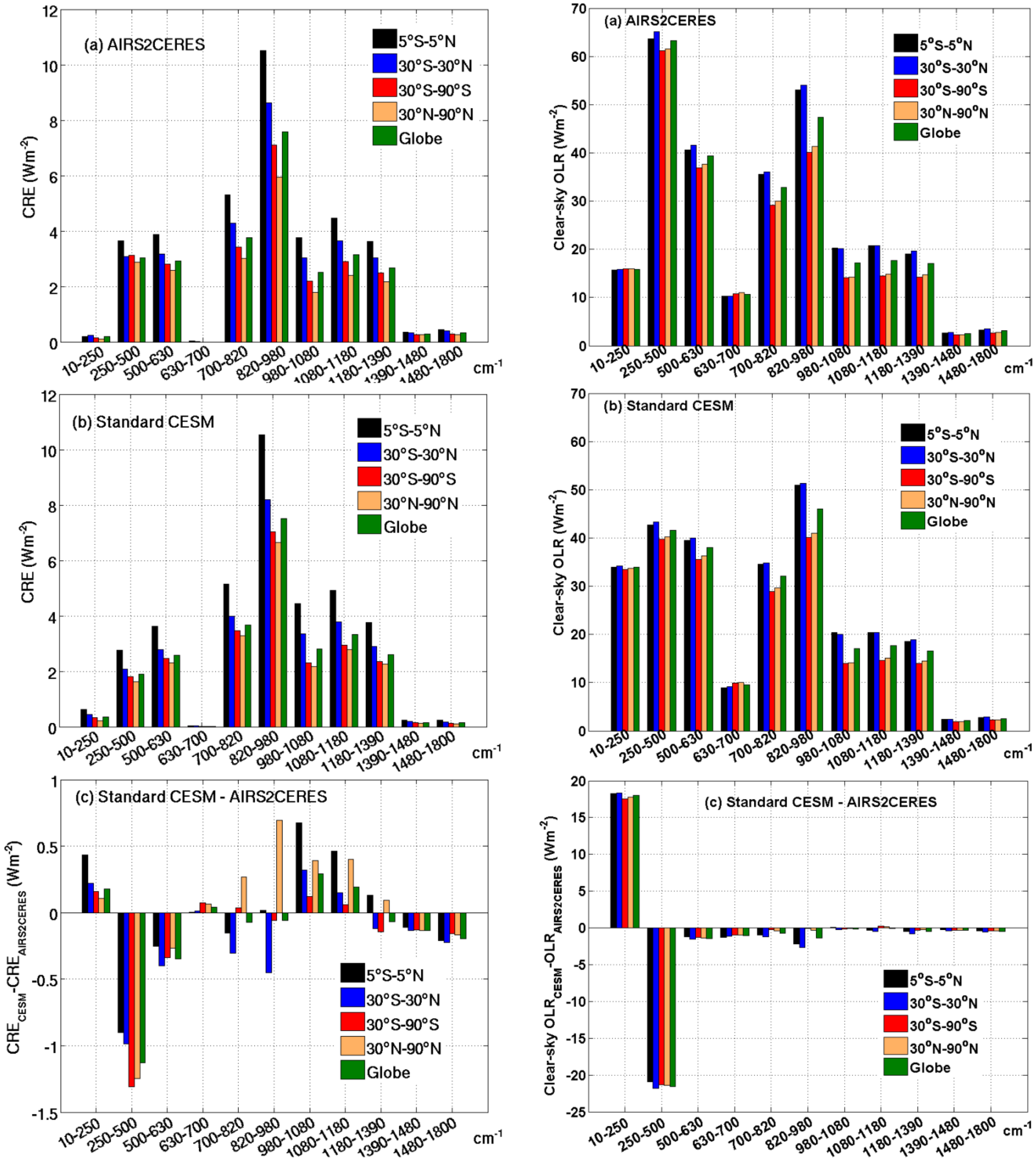
$$\mathrm{r}(\Delta v) = \frac{CRE(\Delta v)}{CRE_{LW}} = \frac{F_{clr}(\Delta v) - F_{cld}(\Delta v)}{\left[\sigma T_s^4 - \sigma T_c^4\right]}$$

1. Blackbody cloud
2. Ignore atmospheric absorption



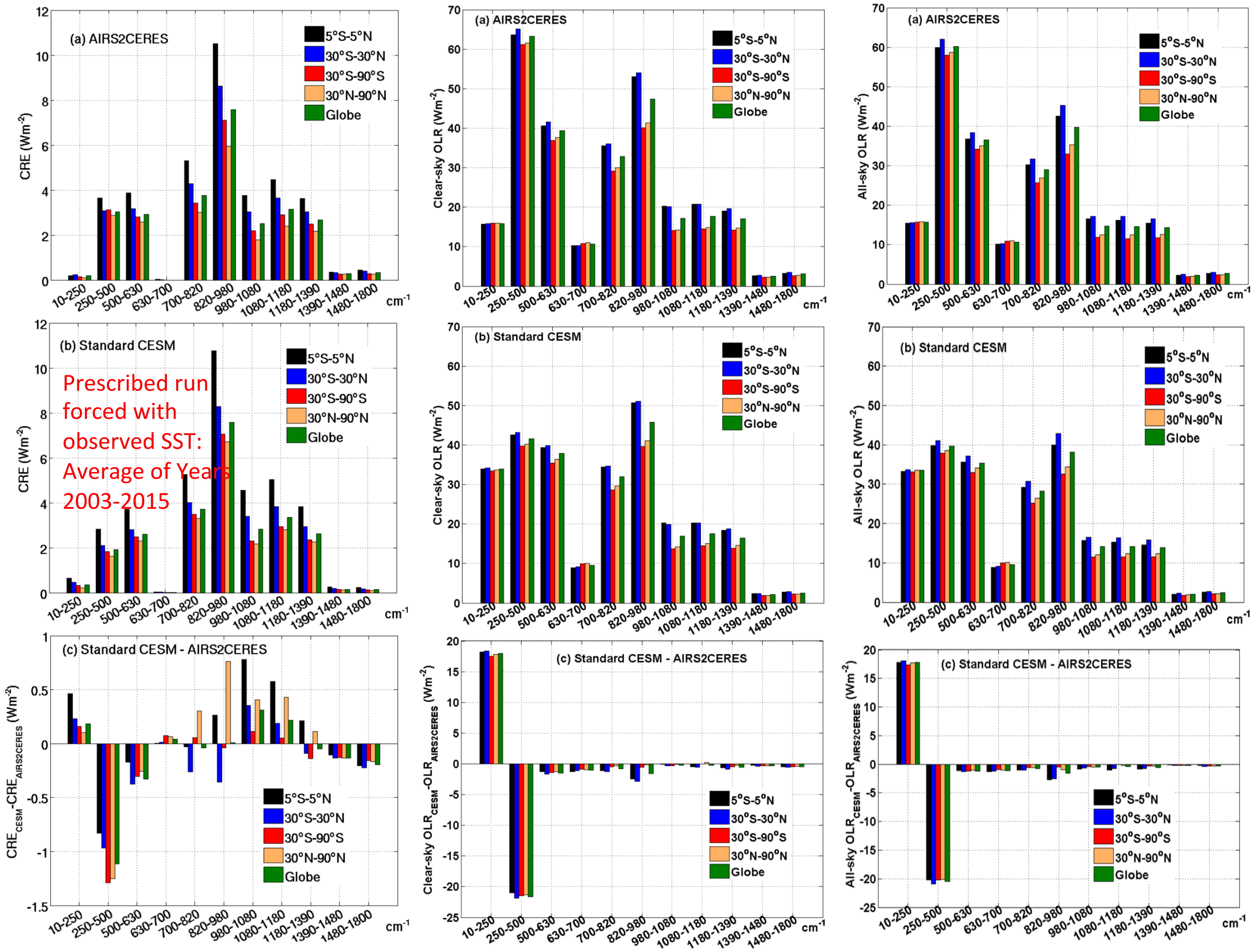
r(Δv) changes with T_c

Band-to-Band ratio: sensitive to CTH but not cloud amount
LW CRE: sensitive to both CTH and cloud amount
Outcome: ratio-then-broadband approach (Huang et al., 2014, J Climate)

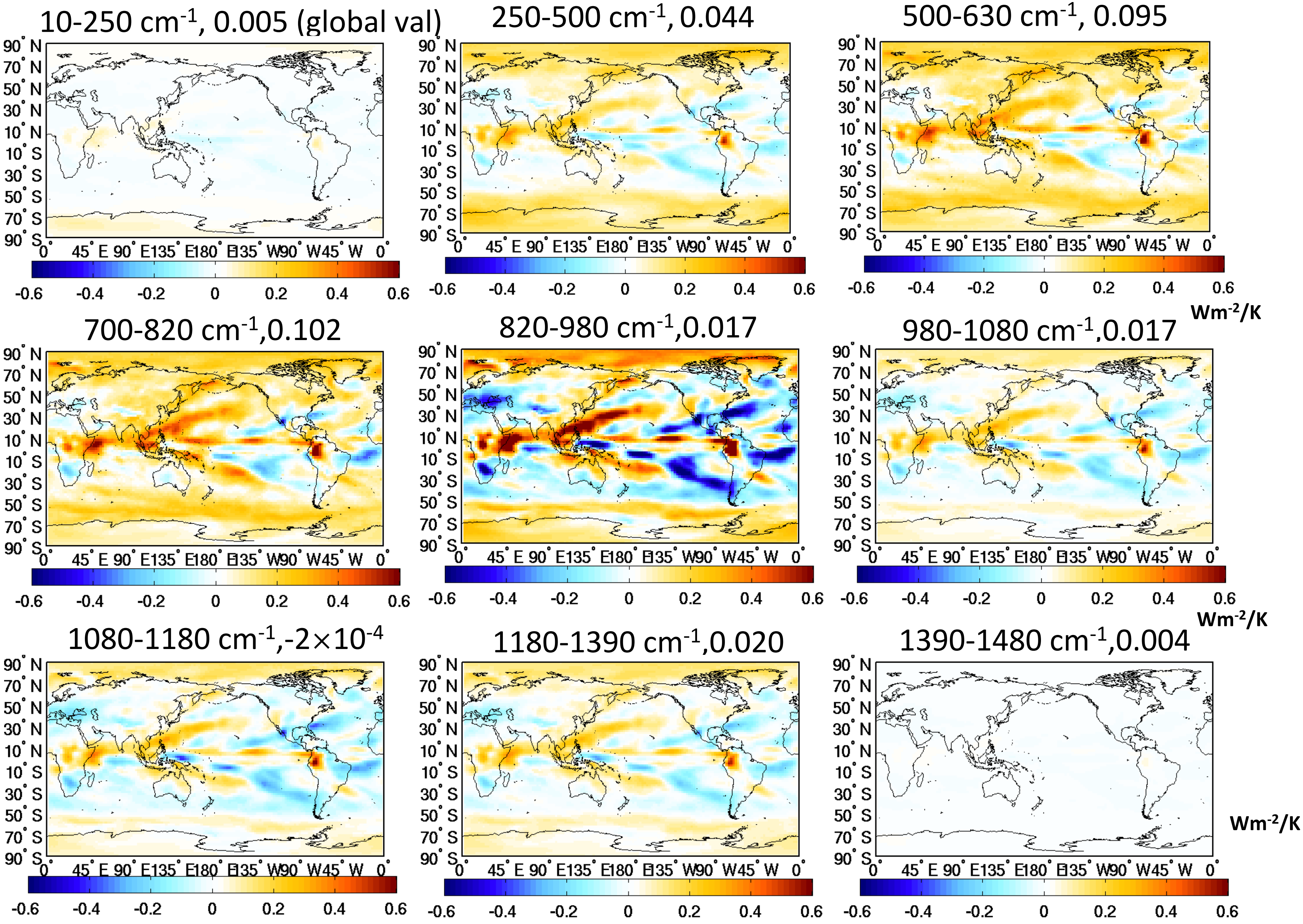


AIRS2CERES:
Average of 2003-2015

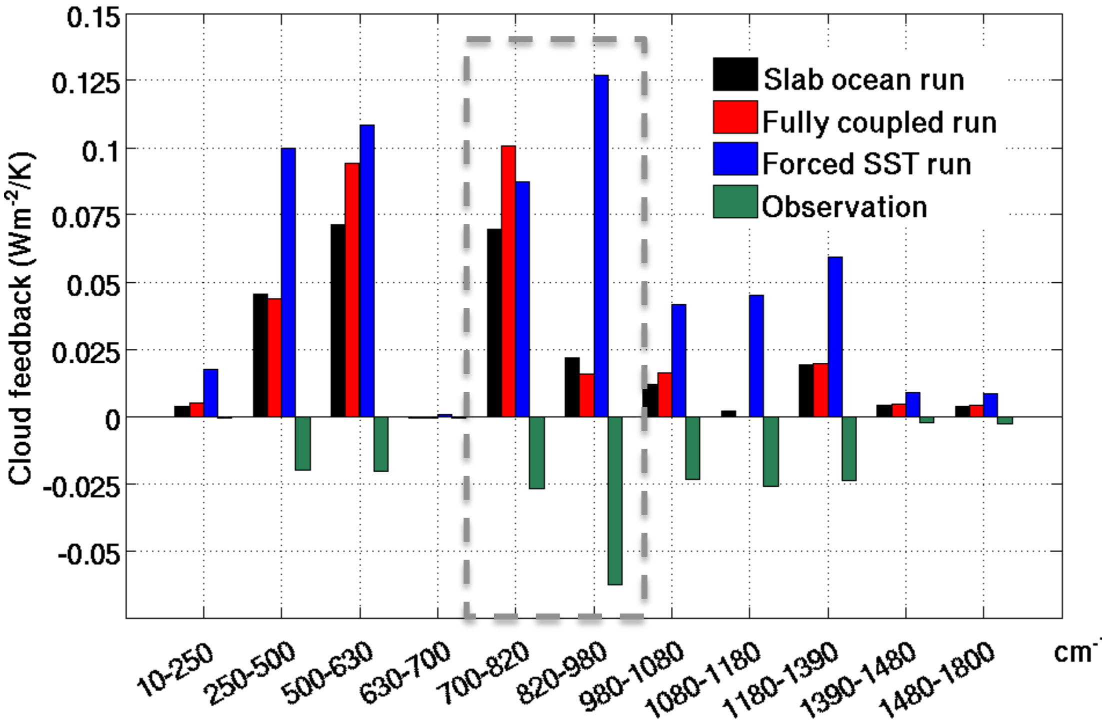
Fully coupled run:
Average of Years 6-35


(a) AIRS2CERES
(b) Standard CESM
(c) Standard CESM - AIRS2CERES
CRE (Wm^{-2})
Clear-sky OLR (Wm^{-2})
All-sky OLR (Wm^{-2})
CRE$_{CESM}$-CRE$_{AIRS2CERES}$ (Wm^{-2})
Clear-sky OLR$_{CESM}$-OLR$_{AIRS2CERES}$ (Wm^{-2})
All-sky OLR$_{CESM}$-OLR$_{AIRS2CERES}$ (Wm^{-2})
5°S-5°N
30°S-30°N
30°S-90°S
30°N-90°N
Globe
10-250
250-500
500-630
630-700
700-820
820-980
980-1080
1080-1180
1180-1390
1390-1480
1480-1800
cm^{-1}
Prescribed run forced with observed SST: Average of Years 2003-2015

Band-by-band Cloud radiative feedback from $2\times CO_2$ run



Long-term vs. short-term contrast



***Do we have an update on this slide, especially the obs plot?

Broadband LW cloud feedback

Slab ocean run: 0.25 Wm^{-2}/K

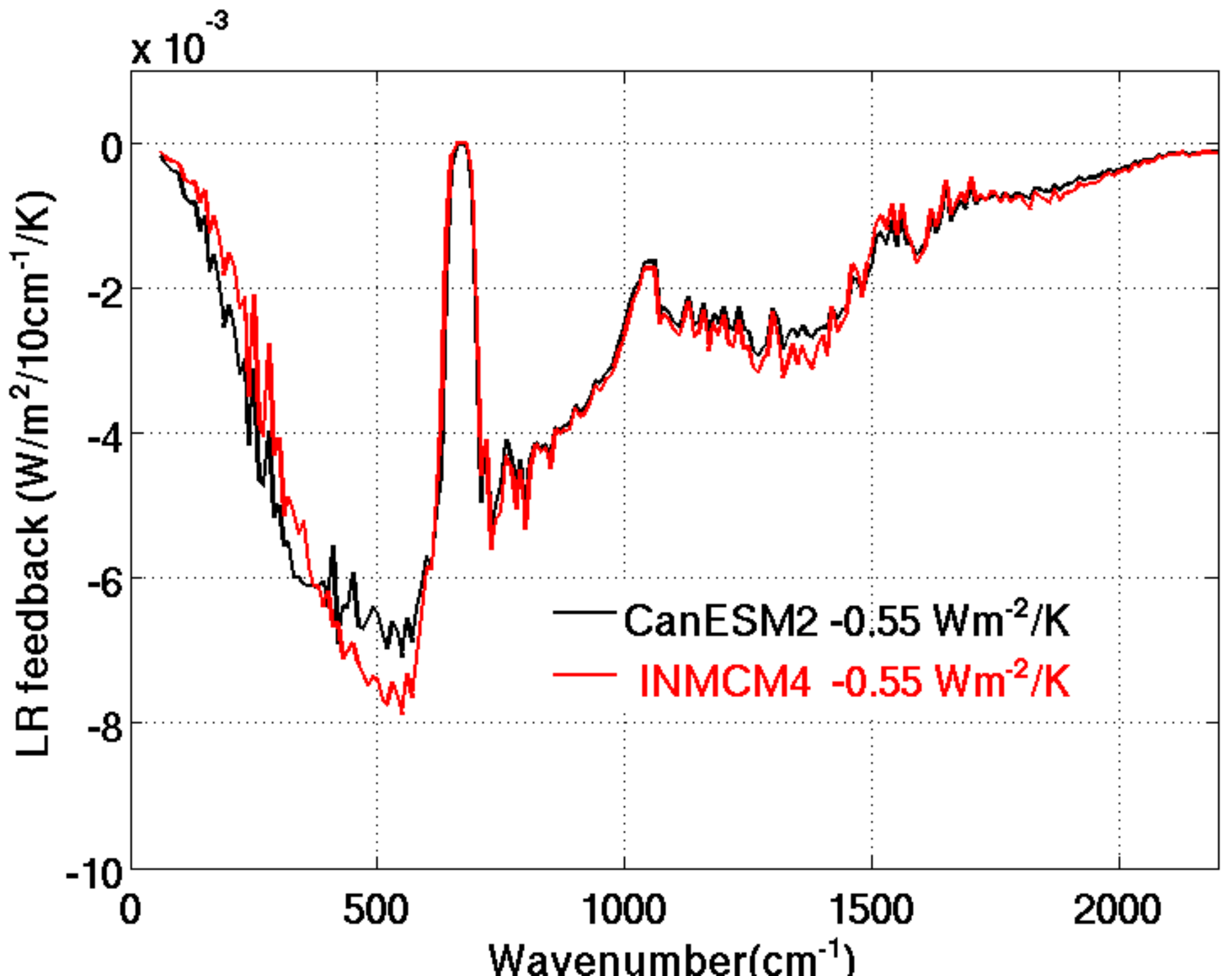
Fully coupled run: 0.31 Wm^{-2}/K

Forced SST run: 0.61 Wm^{-2}/K

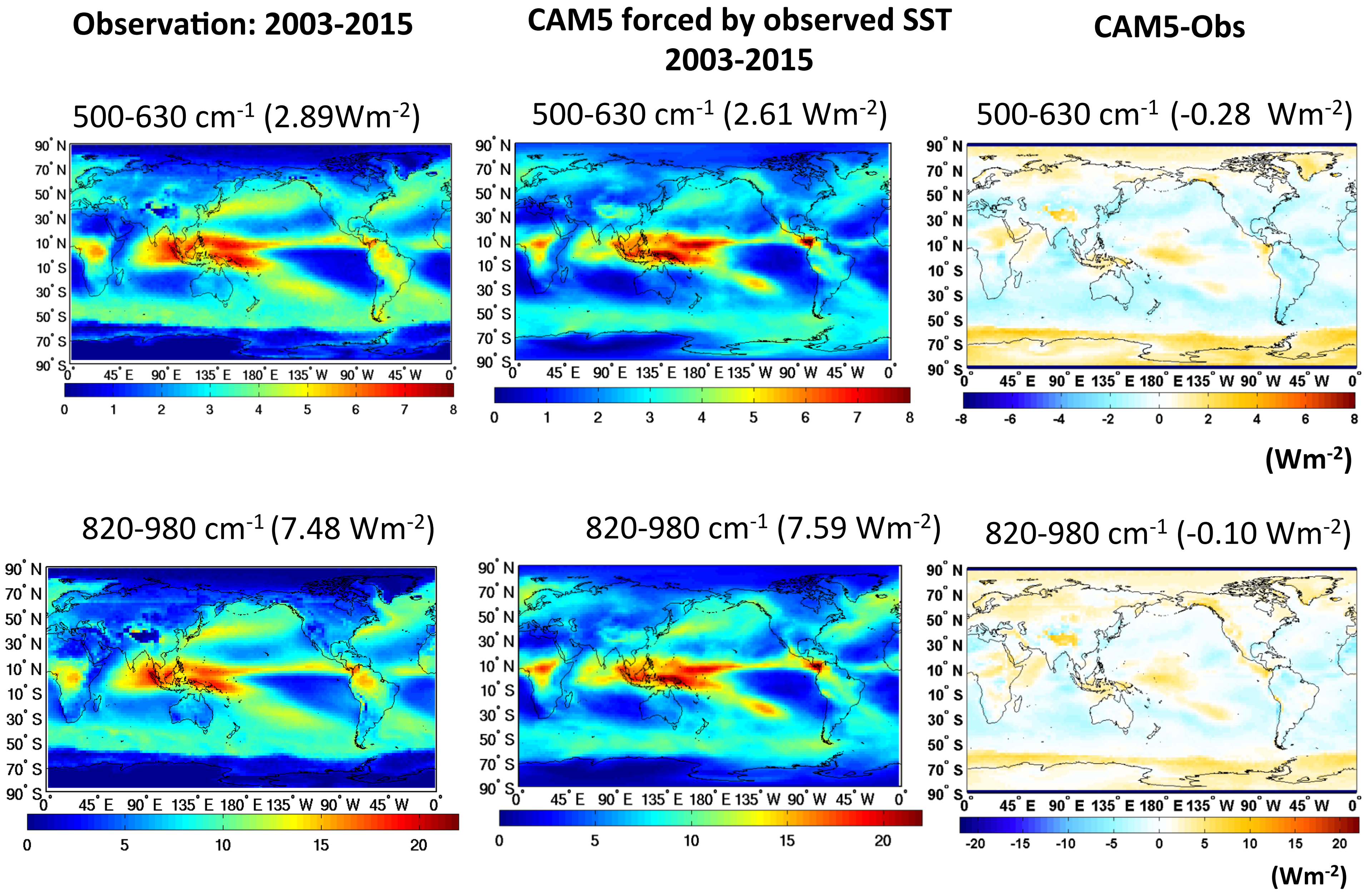
Observation: -0.21 Wm^{-2}/K

What spectral dimension can offer?

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



Spectral decomposition of broadband lapse-rate feedback
(Huang et al., 2014, GRL)



Observation: 2003-2015
CAM5 forced by observed SST 2003-2015
CAM5-Obs
500-630 cm-1 (2.89Wm-2)
500-630 cm-1 (2.61 Wm-2)
500-630 cm-1 (-0.28 Wm-2)
(Wm-2)
820-980 cm-1 (7.48 Wm-2)
820-980 cm-1 (7.59 Wm-2)
820-980 cm-1 (-0.10 Wm-2)
(Wm-2)

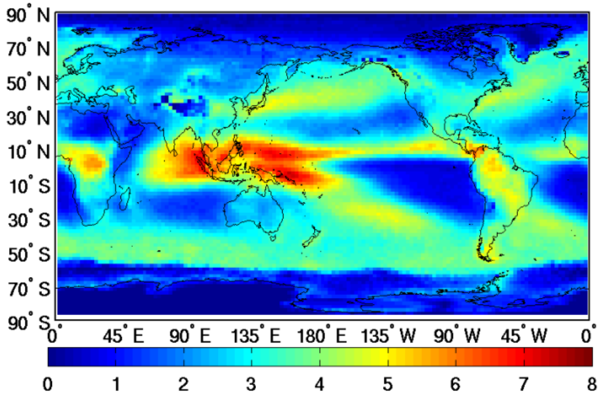
*** Please make another page with two plots for CAM5-Obs (i.e., middle column − left column)

Observation: 2003-2015

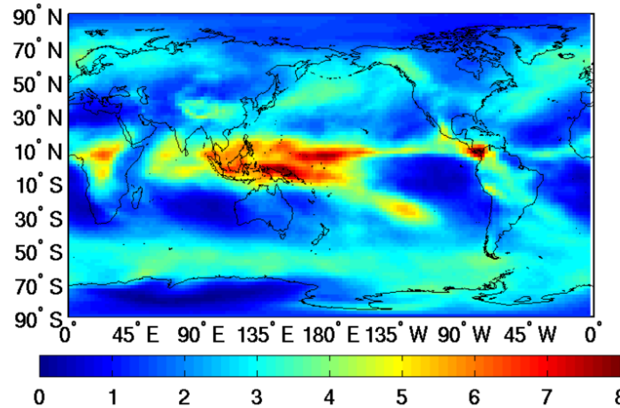
CAM5 forced by observed SST 2003-2015

CESM fully-coupled run 30-year mean

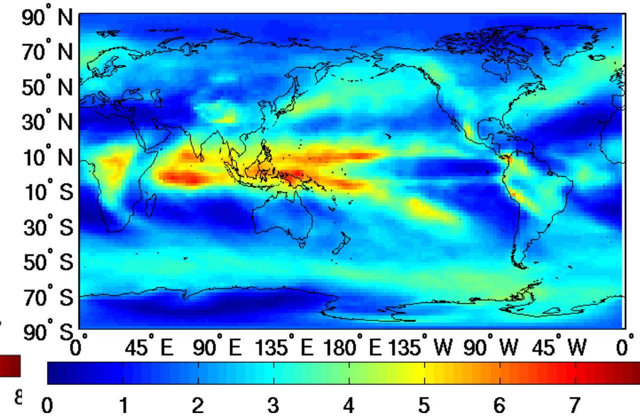
500-630 cm^{-1}



500-630 cm^{-1}

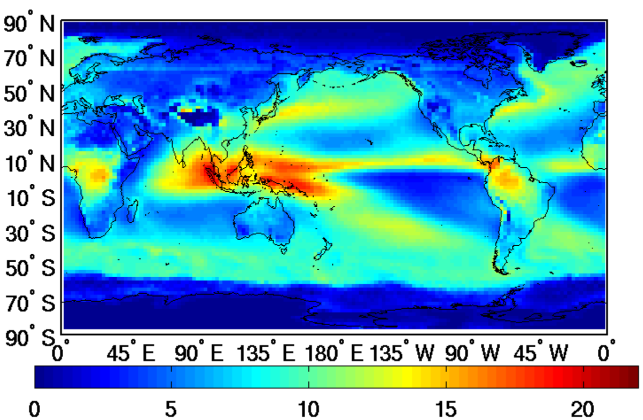


500-630 cm^{-1}

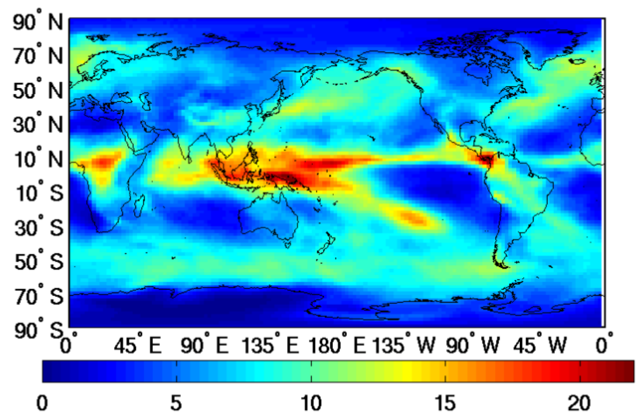


(Wm^{-2})

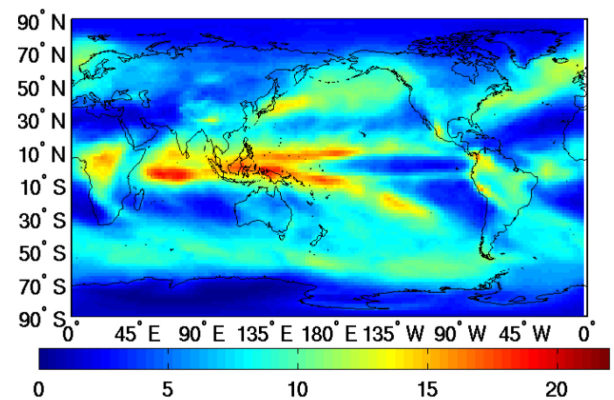
820-980 cm^{-1}



820-980 cm^{-1}



820-980 cm^{-1}



(Wm^{-2})