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

Xiuhong Chen, Xianglei Huang\textsuperscript{1}, Qing Yue\textsuperscript{2}
\begin{itemize}
\item \textsuperscript{1} The University of Michigan
\item \textsuperscript{2} JPL/Caltech
\end{itemize}

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

Acknowledgements: NASA CERES project, Terra/Aqua and CloudSat programs
• 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.
LW Broadband

H$_2$O bands (0-540 cm$^{-1}$, >1400 cm$^{-1}$) window region (800-980 cm$^{-1}$)

\[
\int \Delta v B_v(T_s) dv - F_{\Delta v}(TOA) \\
\int \Delta v B_v(T_s) dv
\]

clear-sky greenhouse efficiency

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

Pressure(hPa)

\( \tau_{\text{vis}} \)

\( Wm^{-2}/\% \)

July

Pressure(hPa)

\( \tau_{\text{vis}} \)

\( Wm^{-2}/\% \)
Cloud feedbacks from two methods: adjust vs. kernel

LW Cloud feedbacks for 2xCO$_2$ fully-coupled run

Adjust: 0.16 Wm$^{-2}$/K  
Kernel: 0.16 Wm$^{-2}$/K  
Kernel – Adjust: 0.008 Wm$^{-2}$/K

LW Cloud feedbacks for +2K SST run

Adjust: 0.23 Wm$^{-2}$/K  
Kernel: 0.32 Wm$^{-2}$/K  
Kernel – Adjust: 0.09 Wm$^{-2}$/K
Results
Observed averages of 2003-2015

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

Differences of Model - Obs
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×CO₂ run (Adjust method)

10-250 cm⁻¹, 0.005
250-500 cm⁻¹, 0.044
500-630 cm⁻¹, 0.048
700-820 cm⁻¹, 0.017
820-980 cm⁻¹, 0.008
980-1080 cm⁻¹, 0.011
1080-1180 cm⁻¹, -8.8x10⁻⁴
1180-1390 cm⁻¹, 0.019
1390-1480 cm⁻¹, 0.004
Band-by-band Cloud radiative feedback from 2×CO₂ run (kernel method)

10-250 cm⁻¹, 0.007 (global val)

250-500 cm⁻¹, 0.027

500-630 cm⁻¹, 0.029

700-820 cm⁻¹, 0.024

820-980 cm⁻¹, 0.032

980-1080 cm⁻¹, 0.010

1080-1180 cm⁻¹, 0.012

1180-1390 cm⁻¹, 0.013

1390-1480 cm⁻¹, 0.002
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
2xCO₂ 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
- \( T_{skin}, \varepsilon_s(v) \)
- Cloud,

Spectral Radiances

\[ I_{TOA}(v; \theta, \phi) \]

Spectral Flux

\[ F_v = \int_0^{2\pi} d\phi \int_0^{\frac{\pi}{2}} I_{TOA}(v; \theta, \phi) \cos \theta \sin \theta d\theta \]

Broadband Radiation Budget

\[ F = \int_{\Delta v} F_v dv \]

Spectral Radiative Feedbacks

\[ \lambda_v = -\frac{\delta_x \overline{F_v} \delta X}{\delta X \delta T_s} \]

Broadband Radiative Feedbacks

\[ \lambda_x = -\frac{\delta_x \overline{F} \delta X}{\delta X \delta T_s} \]

Energy budget and feedbacks community

Sounding community

ISCCP effort
Thank You!

References:


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.


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 $\tau$ 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

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

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

Fractional contribution

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

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
Prescribed run forced with observed SST: Average of Years 2003-2015
Band-by-band Cloud radiative feedback from $2\times$CO$_2$ run

- **10-250 cm$^{-1}$**, 0.005 (global val)
- **250-500 cm$^{-1}$**, 0.044
- **500-630 cm$^{-1}$**, 0.095
- **700-820 cm$^{-1}$**, 0.102
- **820-980 cm$^{-1}$**, 0.017
- **980-1080 cm$^{-1}$**, 0.017
- **1080-1180 cm$^{-1}$**, $-2\times10^{-4}$
- **1180-1390 cm$^{-1}$**, 0.020
- **1390-1480 cm$^{-1}$**, 0.004

Wm$^{-2}$/K
Long-term vs. short-term contrast

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\(^{-2}/K\)

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

500-630 cm\(^{-1}\) (2.89 Wm\(^{-2}\))

CAM5 forced by observed SST 2003-2015

500-630 cm\(^{-1}\) (2.61 Wm\(^{-2}\))

CAM5-Obs

500-630 cm\(^{-1}\) (-0.28 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\(^{-2}\))
*** Please make another page with two plots for CAM5-Obs (i.e., middle column – left column)