Spectral Decomposition of Cloud Radiative Effect and Cloud Radiative Feedbacks

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Outline

• Why go from broadband to spectral?
  – Two examples
• Traits in the spectral decomposition of CRE
• Band-by-band LW CRE: CESM vs. obs
• Band-by-band LW cloud feedbacks: 2xCO₂ CESM simulations
• 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.

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

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

1. Blackbody cloud
2. Ignore atmospheric absorption

$r(\Delta \nu)$ 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)
Derivation of spectral fluxes/CRE/feedbacks

• Observations
  – 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)

• Models
  – Simple code modification to output band-by-band fluxes
  – Spectral radiative kernels (Huang et al., 2014, GRL) to derive spectral details of Planck/Lapse-rate/WV feedbacks
  – Adjustment methods to get spectral cloud radiative feedbacks
10-year mean spectral CRE over the different climate zones

(Huang et al., 2014, J Climate)
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

CESM fully-coupled run 30-year mean

500-630 cm\(^{-1}\)

820-980 cm\(^{-1}\)
Band-by-band LW cloud feedback in the NCAR CESM (2xCO$_2$ run)

- **Broadband LW cloud feedback**
  - Slab ocean run: 0.25 Wm$^{-2}$/K
  - Fully coupled run: 0.31 Wm$^{-2}$/K

- Not scaled with the band-by-band decomposition of CRE
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$^{-1}$, 2e-4  

1180-1390 cm$^{-1}$, 0.020  

1390-1480 cm$^{-1}$, 0.004  

Fully coupled run  

Cloud feedback in each band Wm$^{-2}$/K
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

CESM, 0.61 Wm$^{-2}$/K

Obs, -0.21 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
Conclusion and Discussion

• Spectral decomposition helps revealing compensating biases.
  – For cloud, it helps untangle the biases in CTH and cloud amount

• For RRTMG bandwidths, 820-980cm\(^{-1}\) contributes most to the CRE. But 700-820 cm\(^{-1}\) contributes most to the cloud feedback (2xCO\(_2\) run)

• The long-term vs. short-term cloud feedback has different spectral decomposition
  – Implications
Geophysical variables

- $T(z)$
- $q_{H_{2}O}(z)$
- $q_{O_{3}}(z)$
- $q_{C_{4}H_{4}}(z)$
- Aerosols
- $T_{\text{skin}}$, $\varepsilon_{s}(\nu)$
- Cloud,

Spectral Radiances

$I_{TOA}(\nu; \theta, \phi)$

Spectral Flux

$F_{\nu} = \int_{0}^{2\pi} d\phi \int_{0}^{\pi} I_{TOA}(\nu; \theta, \phi) \cos \theta \sin \theta d\theta$

Broadband Radiation Budget

$F = \int_{\Delta \nu} F_{\nu} d\nu$

Broadband Radiative Feedbacks

$\lambda_{x,\nu} = -\frac{\delta_{x} F_{\nu}}{\delta X} \frac{\delta X}{\delta T_{s}}$

Spectral Radiative Feedbacks

Energy budget and feedbacks community

ISCCP effort

Sounding community
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.
Backup slides
Cloud feedback Wm\(^{-2}\)/K

Slab ocean run, 6-35 yr

<table>
<thead>
<tr>
<th>Wavenumber Range</th>
<th>Cloud Feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-250 cm(^{-1})</td>
<td>0.003</td>
</tr>
<tr>
<td>250-500 cm(^{-1})</td>
<td>0.046</td>
</tr>
<tr>
<td>500-630 cm(^{-1})</td>
<td>0.072</td>
</tr>
<tr>
<td>700-820 cm(^{-1})</td>
<td>0.070</td>
</tr>
<tr>
<td>820-980 cm(^{-1})</td>
<td>0.023</td>
</tr>
<tr>
<td>980-1080 cm(^{-1})</td>
<td>0.012</td>
</tr>
<tr>
<td>1080-1180 cm(^{-1})</td>
<td>0.002</td>
</tr>
<tr>
<td>1180-1390 cm(^{-1})</td>
<td>0.020</td>
</tr>
<tr>
<td>1390-1480 cm(^{-1})</td>
<td>0.004</td>
</tr>
</tbody>
</table>
Fig 3. Short-term longwave cloud feedback (LC), lapse-rate feedback (LR), and water vapor feedback (Q) derived from different segments of 35-year CM3 simulations.
All collocated clear-sky observations in 2004 (80° S-80° N)

<table>
<thead>
<tr>
<th>Surface Type</th>
<th>Daytime</th>
<th>Nighttime</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \text{OLR}<em>{\text{AIRS_Huang}} - \text{OLR}</em>{\text{CERES}} ) (Wm(^{-2}))</td>
<td>( \text{OLR}<em>{\text{AIRS_Huang}} - \text{OLR}</em>{\text{CERES}} ) (Wm(^{-2}))</td>
</tr>
<tr>
<td>Forest</td>
<td>0.58 ± 1.43</td>
<td>-0.42 ± 1.41</td>
</tr>
<tr>
<td>Savannas</td>
<td>-0.03 ± 2.52</td>
<td>0.68 ± 1.50</td>
</tr>
<tr>
<td>Grasslands</td>
<td>0.19 ± 2.61</td>
<td>0.63 ± 1.65</td>
</tr>
<tr>
<td>Dark Desert</td>
<td>-0.71 ± 2.85</td>
<td>0.36 ± 1.74</td>
</tr>
<tr>
<td>Bright Desert</td>
<td>1.67 ± 2.62</td>
<td>1.42 ± 2.28</td>
</tr>
<tr>
<td>Ocean</td>
<td>1.09 ± 1.55</td>
<td>0.90 ± 1.26</td>
</tr>
</tbody>
</table>

*(Chen et al., J Climate, 2013)*

CERES 2σ radiometric calibration uncertainty: 1% (i.e. ~ 2.5W m\(^{-2}\))
Stratifying $\Delta T_{sc}$:

$$\text{OLR}_{\text{AIRS-Huang}} - \text{OLR}_{\text{CERES}} \text{ (Wm}^{-2}\text{)}: \text{cloudy observations over the lands}$$

<table>
<thead>
<tr>
<th>$\Delta T_{sc}$</th>
<th>Over deserts</th>
<th>Over non-desert lands</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;15k</td>
<td>15K-40K</td>
</tr>
<tr>
<td>$f$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.001-0.5</td>
<td>2.44 ± 3.79</td>
<td>3.25 ± 5.12</td>
</tr>
<tr>
<td></td>
<td>(0.9%)</td>
<td>(1.2%)</td>
</tr>
<tr>
<td>0.5-0.75</td>
<td>2.79 ± 4.16</td>
<td>3.34 ± 7.80</td>
</tr>
<tr>
<td></td>
<td>(1.1%)</td>
<td>(1.3%)</td>
</tr>
<tr>
<td>0.75-0.999</td>
<td>2.67 ± 3.67</td>
<td>1.45 ± 6.47</td>
</tr>
<tr>
<td></td>
<td>(1.1%)</td>
<td>(0.6%)</td>
</tr>
<tr>
<td>0.999-1.0</td>
<td>2.61 ± 2.80</td>
<td>3.15 ± 4.00</td>
</tr>
<tr>
<td></td>
<td>(1.2%)</td>
<td>(1.6%)</td>
</tr>
</tbody>
</table>

CERES 2σ radiometric calibration uncertainty: 1% (i.e. ~ 2.5W m$^{-2}$)
Global $\text{OLR}_{\text{AIRS_Huang}} - \text{OLR}_{\text{CERES}}$ : annual means and year to year changes
Construction of the SRK
Validation: comparisons with the PRP results

(a) Clear-sky T & T_s
(b) All-sky T & T_s
(c) Clear-sky WV
(d) All-sky WV
(e) Clear-sky residual
(f) All-sky residual

- PRP
- SRK

Broadband:
- Clear-sky: 4.11 Wm^-2 K^-1
- All-sky: 3.96 Wm^-2 K^-1
- Clear-sky: 4.07 Wm^-2 K^-1
- All-sky: 3.85 Wm^-2 K^-1
- Clear-sky: 1.63 Wm^-2 K^-1
- All-sky: 1.62 Wm^-2 K^-1

Normalized flux difference (W/m^2/10cm^-1/K)
Wavenumber (cm^-1)
Validation: comparisons with the PRP results

(a) Planck feedback (Wm⁻²/K)

(b) LR feedback (Wm⁻²/K)

(c) WV feedback (Wm⁻²/K)

(d) Cloud feedback (Wm⁻²/K)