Spectrum: An Underutilized Dimension in the Climate Diagnostics and Climate Change Studies

Xianglei Huang
University of Michigan
with contributions from collaborators in Univ. of Michigan, NASA GMAO, Environment Canada, NASA Langley, NOAA/GFDL, and Univ. of Miami

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Outline

• Motivations
  – The spectral dimension
  – What additional info it can offer?
  – Two examples:
    • Clear-sky flux diagnostics
    • Radiative feedbacks
• LW spectral flux from collocated AIRS&CERES observations (Sep 2002 to Nov 2014)
• Spectral radiative feedbacks: a kernel approach
  – Developments
  – Applications in the CMIP3 and CMIP5 diagnostics
• Conclusions and discussions
OLR: important player in radiation budget, CRE, radiative forcings, and thus in climate change

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

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

Flux of each band is easy to output from GCMs
What can the spectral dimension offer?

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

<table>
<thead>
<tr>
<th>Model</th>
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<tbody>
<tr>
<td>Obs</td>
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</tr>
<tr>
<td>CanAM4</td>
<td>286.6 W m⁻²</td>
</tr>
<tr>
<td>CESM</td>
<td>279.3 W m⁻²</td>
</tr>
</tbody>
</table>

Legend:
- Colored scale from 0.2 to 0.35
Collocated AIRS & CERES obs. H$_2$O bands (0-540 cm$^{-1}$, >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

Contribution to $\Delta T_s @2xCO_2$

<table>
<thead>
<tr>
<th></th>
<th>0-400 LR</th>
</tr>
</thead>
<tbody>
<tr>
<td>CanESM2</td>
<td>-0.08K</td>
</tr>
<tr>
<td>INMCM4</td>
<td>-0.04K</td>
</tr>
</tbody>
</table>
Can we get spectral flux from satellite observations? the Spectral ADM approach

*Soundings (AIRS, CrIS, IASI, HIRS, etc.): radiance (W m^{-2} per freq per sr.)*

*Flux (ERBE, CERES, GERB): flux (W m^{-2})*

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

Output: spectral flux at 10cm^{-1} intervals through the entire longwave spectral range (Huang et al., 2008; Huang et al., 2010; Chen et al., 2013; Huang et al., 2014)

http://www-personal.umich.edu/~xianglei/airs2ceres.html
Obtain spectral flux from observations

- ECMWF 6-hourly \(<T, q>\) profiles
- Cloud parameters (cloud fraction, cloud top temperature, and cloud emissivity)
- Synthetic AIRS spectra
- Synthetic spectral fluxes
- Orthogonal basis \(\Phi\) and the subset \(\Phi_{\text{AIRS}}\)
- CERES scene type discrete interval and discretized pseudoradiance
- Collocated AIRS measurements \(I_{\text{AIRS}}(v, \theta)\)
- Spectral ADMs for AIRS channels \(R_v(\theta)\)
- Vector of spectral fluxes \(F_{\text{AIRS}} = \{F_v\}, F_v = \pi I_{\text{AIRS}}(v, \theta)/R_v(\theta)\)
- Least-square estimates
  \[ e \approx (\Phi_{\text{AIRS}}^* \Phi_{\text{AIRS}})^{-1} \Phi_{\text{AIRS}}^* (F_{\text{AIRS}} - \bar{F}_{\text{AIRS}}) \]
- Spectral fluxes at other channel \(F_{\text{non-air}} = \bar{F}_{\text{non-air}} + \Phi_{\text{non-air}} e\)
- A complete set of \(F_v\) from 10 to 2000 cm\(^{-1}\)

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

Output: spectral flux at 10 cm\(^{-1}\) intervals through the entire longwave spectral range
Stratifying $\text{OLR}_{\text{AIRS_Huang}} - \text{OLR}_{\text{CERES}}$ (Wm$^{-2}$): 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>
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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

Usages: (1) Model evaluation; (2) Tuning for SARB product; (3) Obs-based cloud radiative kernel (Yue et al., 2016, J Climate)
Spectral radiative feedbacks

• Following the broadband radiative kernel approach, we have developed and validated a set of LW Spectral Radiative Kernel (SRK; Huang et al., 2014b)

• With this set of LW SRK, you can derive LW spectral feedbacks from **monthly-mean** CMIP3/CMIP5 archives.

\[
\lambda_X = - \frac{\delta_x \overline{R} \, \delta X}{\delta X \, \delta T_s} \quad \text{Wm}^{-2} \text{K}^{-1}
\]

\[
\lambda_{x_v} = - \frac{\delta_x \overline{R_v} \, \delta X}{\delta X \, \delta T_s} \quad \text{Wm}^{-2} \text{cm}^{-1} \text{K}^{-1}
\]

The LW SRK can be provided upon request
The “constant-RH” feedbacks

<table>
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<th>Broadband RH feedback (W/m²/K)</th>
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<tbody>
<tr>
<td>BCC-CSM1.1</td>
</tr>
<tr>
<td>BNU-ESM</td>
</tr>
<tr>
<td>CanESM2</td>
</tr>
<tr>
<td>CCSM4</td>
</tr>
<tr>
<td>CESM1-CAM5</td>
</tr>
<tr>
<td>CNRM-CM5</td>
</tr>
<tr>
<td>GFDL-CM3</td>
</tr>
<tr>
<td>GISS-E2-H</td>
</tr>
<tr>
<td>GISS-E2-R</td>
</tr>
<tr>
<td>HadGEM2-ES</td>
</tr>
<tr>
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</tr>
<tr>
<td>IPSL-CM5A-LR</td>
</tr>
<tr>
<td>MIROC5</td>
</tr>
<tr>
<td>MPI-ESM-LR</td>
</tr>
<tr>
<td>MRI-CGCM3</td>
</tr>
<tr>
<td>NorESM1-M</td>
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Spectral RH feedback (W/m²/K/cm⁻¹)

Wavenumber(cm⁻¹)

16 CMIP5 models
Scrambling information from the spectral dimension

Profiles of cumulative RH feedback (W/m²/K)
Scrambling information from the spectral dimension: a truncated SVD approach (in progress)

True: actual $\Delta \log(\text{RH})$
From CM3 1% CO$_2$ simulation.

Reconstructed: a truncated-SVD estimate from the CM3 spectral RH feedback (9 leading singular values).
Conclusions and Discussions

• Spectral dimension has its potential in model development and climate diagnostics
  – It can help expose offset biases
  – Available from observations
  – Computable from model archives (or online simulator)
• How to include spectral band info in the tuning of GCM/NWP model?
• Biases in radiation budget and biases in geophysical variables
  – Can the spectral diagnostics be the bridge to make the closure for error diagnostics in energy budgets and in thermodynamic fields?

Monthly gridded spectral flux and CRE (Sep 2002 to Nov 2014) are available via http://www-personal.umich.edu/~xianglei/datasets.html. The spectral radiative kernels available upon upon request.
Thank You!

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

$$\lambda_X = - \frac{\delta_x \bar{R} \delta X}{\delta T_s}$$

Change of global-mean surface temperature

$X : \text{[Temp, WV, cloud, albedo]}$

(Soden et al., 2008)

$\bar{R}$ has another dimension, the frequency $\nu$

Spectral radiative feedbacks

$$\lambda_{x_v} = - \frac{\delta_x \bar{R}_\nu \delta X}{\delta T_s}$$

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