Multiple years of far-IR flux and cloud radiative forcing as inferred from the collocated AIRS-CERES observations and its application in GCM validation

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November 9, 2011
Outline

• Motivations
  – Broadband vs. band-by-band
    • Observations
    • Modeling
  – Band-by-band CRF: fraction also matters
• How to get it from observations?
  – Algorithm
  – Validation
• Case studies with GFDL AM2, NASA GEOS-5, and Canada CanAM4
  – Clear-sky band-by-band fluxes
  – Band-by-band cloud radiative forcings
• Further thoughts on the band-by-band CRFs
• Conclusions and discussions
CERES uses an ADM approach to invert radiance to flux. The legacy of last 30 years of work at Langley.

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

Spectral ADM $F = \frac{\pi}{R^2(u)}$
Motivations: every GCM center does this with OLR

- Tuning: to get TOA balance, to get numbers matched with ERBE’s
  - Different centers have different (empirical) tuning strategies
- Consequence:
  - Compensating biases from different bands
    - E.g. 1Wm\(^{-2}\) bias in AM2 originated from stratosphere but tuned away with tropospheric cloud parameters
  - Seemingly right outcome but due to wrong results

How much such compensation still holds for 2xCO2 run?

(GFDL GAMDT, 2004, J Clim)
Why go band-by-band?

- Practical reasons (for model evaluation):
  - Compensating biases for simulated broadband CRF and fluxes
  - Band-by-band quantities are directly computed by each GCM
  - Observationally it is possible to derive them

- Also
  - Band-by-band CRFs provides more insights
Why go band-by-band: Toy model A

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

\( CRF_{LW} \) sensitive to both \( f \) and \( T_c \)

1. Blackbody cloud
2. Ignore atmospheric absorption

\( \tau \gg 1 \)

Cloud fraction: \( f \)
Toy model B

- Typical tropical sounding profiles of T, q, O_3, etc (\textit{"McClatchey"} profiles)
- Realistic one-layer cloud ($\tau \gg 1$) with top varying from 2km to 15km
- 7 bands as used in the GFDL model

Band1: 0-560 and 1400-2500 cm$^{-1}$ (H$_2$O)
Band2: 560-800 cm$^{-1}$ (CO$_2$, N$_2$O)
Band3: 800-900 cm$^{-1}$ (WN)
Band4: 900-990 cm$^{-1}$ (WN)
Band5: 990-1070 cm$^{-1}$ (O$_3$)
Band6: 1070-1200 cm$^{-1}$ (WN)
Band7: 1200-1400 cm$^{-1}$ (N$_2$O, CH$_4$)
• Recap
  – Can we borrow CERES scene-type classification and get spectral fluxes from AIRS (for all-sky)
  – Can we show its merit in climate model evaluation and cloud feedback studies
Datasets

- **CERES SSF data product (edition 2A)**
  - Cross-scanning mode only
- **AIRS**
  - 3.74-4.61μm (2169-2673 cm⁻¹) excluded
  - Quality control: filtering out bad channels
- **Collocation criteria strategy**
  - Time separation ≤ 8 seconds
  - Spatial separation ≤ 3km
- **Measurements over the tropical oceans: 2003-2007**
Flowchart for the entire algorithm

- ECMWF 6-hourly \(<T, q>\) profiles
- Cloud parameters (cloud fraction, cloud top temperature, and cloud emissivity)
- Collocated AIRS measurements \(I_{AIRS}(v, \theta)\)
- CERES scene type discrete interval and discretized pseudoradiance

1. Modtran\textsuperscript{TM-5}
2. Synthetic AIRS spectra
3. Orthogonal basis \(\Phi\) and the subset \(\Phi_{AIRS}\)
4. Spectral ADMs for AIRS channels \(R_v(\theta)\)
5. Vector of spectral fluxes \(F_{AIRS} = \{F_v\}, F_v = \pi I_{AIRS}(v, \theta)/R_v(\theta)\)
6. Least-square estimates
   \(e \approx (\Phi_{AIRS}^* \Phi_{AIRS})^{-1} \Phi_{AIRS}^* (F_{AIRS} - F_{AIRS})\)
7. A complete set of \(F_v\) from 10 to 2000 cm\(^{-1}\)
8. Spectral fluxes at other channel \(F_{\text{non-airs}} = F_{\text{non-airs}} + \Phi_{\text{non-airs}} e\)

Output: spectral flux at 10 cm\(^{-1}\) intervals through the entire longwave spectral range
An PCA-based scheme to estimate flux: basic idea

\[
\begin{align*}
\begin{bmatrix}
F_{v1} \\
F_{v2} \\
F_{v3} \\
F_{v4} \\
F_{v5} \\
F_{v6} \\
F_{v7} \\
\vdots
\end{bmatrix}
&= 
\begin{bmatrix}
\bar{F}_{v1} \\
\bar{F}_{v2} \\
\bar{F}_{v3} \\
\bar{F}_{v4} \\
\bar{F}_{v5} \\
\bar{F}_{v6} \\
\bar{F}_{v7} \\
\vdots
\end{bmatrix}
+ e_1
+ e_2
+ e_3
+ O(F_v)
\end{align*}
\]

\[
< \phi^i, \phi^j > = \begin{cases} 
0 & i \neq j \\
1 & i = j 
\end{cases}
\]
Validations

• Theoretical validation
  – 10cm\(^{-1}\) Fluxes estimated from synthetic AIRS spectra
  – Directly computed 10cm\(^{-1}\) fluxes
    • Largest difference < ±5\% (clear-sky) < ±3.6\% (cloudy)

• Comparing with collocated CERES OLR
"predicted" – "directly computed" 10cm\(^{-1}\) clear-sky spectral flux.

Very limited samples
OLR\textsubscript{AIRS}: OLR estimated from AIRS spectra with Huang’s algorithm

OLR\textsubscript{CERES}: OLR from collocated CERES observation

Cloudy-sky over the tropical ocean

CERES 2\sigma radiometric calibration uncertainty: 1% (i.e. \sim 2.5 W m\textsuperscript{-2})
Stratifying $\text{OLR}_{\text{AIRS\_huang\_algorithm}} - \text{OLR}_{\text{CERES}}$ (2.15±5.51 Wm$^{-2}$)

<table>
<thead>
<tr>
<th>$f$</th>
<th>$\Delta T_{sc}$</th>
<th>$&lt;15K$</th>
<th>15K-40K</th>
<th>$&gt;40K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001-0.5</td>
<td>1.98±2.04Wm$^{-2}$</td>
<td>3.93±3.53Wm$^{-2}$</td>
<td>2.91±4.75Wm$^{-2}$</td>
<td></td>
</tr>
<tr>
<td>0.5-0.75</td>
<td>2.32±3.36Wm$^{-2}$</td>
<td>4.51±6.18Wm$^{-2}$</td>
<td>2.18±8.80Wm$^{-2}$</td>
<td></td>
</tr>
<tr>
<td>0.75-0.999</td>
<td>2.02±3.15Wm$^{-2}$</td>
<td>4.10±6.89Wm$^{-2}$</td>
<td>-0.12±10.40Wm$^{-2}$</td>
<td></td>
</tr>
<tr>
<td>0.999-1.0</td>
<td>2.00±2.49Wm$^{-2}$</td>
<td>5.08±5.70Wm$^{-2}$</td>
<td>1.58±7.99Wm$^{-2}$</td>
<td></td>
</tr>
</tbody>
</table>
**OLR\textsubscript{AIRS} - OLR\textsubscript{CERES}: annual means and year to year changes**

### Clear sky over the ocean

<table>
<thead>
<tr>
<th>Year</th>
<th>Nighttime (W m(^{-2}))</th>
<th>Daytime (W m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>0.80</td>
<td>0.86</td>
</tr>
<tr>
<td>2004</td>
<td>0.52</td>
<td>0.79</td>
</tr>
<tr>
<td>2005</td>
<td>0.93</td>
<td>1.81</td>
</tr>
<tr>
<td>2006</td>
<td>0.86</td>
<td>2.10</td>
</tr>
<tr>
<td>2007</td>
<td>0.83</td>
<td>2.45</td>
</tr>
</tbody>
</table>

### Cloudy sky over the ocean

<table>
<thead>
<tr>
<th>Year</th>
<th>Nighttime (W m(^{-2}))</th>
<th>Daytime (W m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>1.63</td>
<td>3.73</td>
</tr>
<tr>
<td>2004</td>
<td>1.33</td>
<td>3.00</td>
</tr>
<tr>
<td>2005</td>
<td>1.75</td>
<td>4.06</td>
</tr>
<tr>
<td>2006</td>
<td>1.58</td>
<td>4.35</td>
</tr>
<tr>
<td>2007</td>
<td>1.50</td>
<td>4.57</td>
</tr>
</tbody>
</table>

- Standard deviation changes little from year to year
- Spectral darkening in CERES FM3/FM4 SW channels
- This issue is being addressed now in CERES SSF V3 data
Over the land surface (ongoing)

### 2004 July

<table>
<thead>
<tr>
<th>Surface Type</th>
<th>Daytime Difference (Wm^{-2})</th>
<th>Nighttime Difference (Wm^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>0.53±1.26</td>
<td>-0.28±1.41</td>
</tr>
<tr>
<td>Savannas</td>
<td>-0.98±2.44</td>
<td>0.86±1.81</td>
</tr>
</tbody>
</table>

### 2004 January

<table>
<thead>
<tr>
<th>Surface Type</th>
<th>Daytime Difference (Wm^{-2})</th>
<th>Nighttime Difference (Wm^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>0.45±1.63</td>
<td>-0.84±1.40</td>
</tr>
<tr>
<td>Savannas</td>
<td>0.24±2.3</td>
<td>0.08±1.17</td>
</tr>
<tr>
<td>Grassland</td>
<td>0.40±2.35</td>
<td>0.57±1.58</td>
</tr>
<tr>
<td>Dark Desert</td>
<td>-0.41±2.92</td>
<td>0.62±1.59</td>
</tr>
<tr>
<td>Bright Desert</td>
<td>2.87±2.89</td>
<td>2.93±1.70</td>
</tr>
</tbody>
</table>
Annual-mean Spectral CRF over tropical ocean in 2004 estimated from AIRS data
(Note: 1:30am/pm mean, no temporal interpolation)
Time series of CRF anomaly (tropical ocean average)

As for the absolute value of CRF (W m$^{-2}$), all band closely tracks LW broadband.
Seasonal Cycle of fractional contribution of each band CRF

In terms of fractional contribution, albeit its small variation with time

- CO$_2$ band tracks H$_2$O band ($r = 0.41$)
- Window bands negatively correlation ($r = -0.986 \sim -0.996$)
- O$_3$ band positively correlates with window band ($r \sim 0.72$)

For tropical mean: small variation at both seasonal and interannual timescale
(H$_2$O band, std $\sim 3\%$; other bands, std $< 1\%$)
Case studies with NOAA GFDL AM2, NASA GEOS-5, and Canada CanAM4 GCMs
Rearrange of LW Bands for comparison

<table>
<thead>
<tr>
<th>New band</th>
<th>GFDL AM2 Band ID</th>
<th>GEOS-5 Band ID</th>
<th>CanAM4 Band ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-560 and &gt; 1400</td>
<td>Band 1 (0-560 and &gt; 1400)</td>
<td>Band1-2 (0-540) Band8-9 (&gt;1380)</td>
<td>Band 1-3 (&gt;1400) Band 8-9 (0-540)</td>
</tr>
<tr>
<td>560-800</td>
<td>Band 2 (560-800)</td>
<td>Band3&amp;10 (540-800)</td>
<td>Band 7 (540-800)</td>
</tr>
<tr>
<td>800-980</td>
<td>Band 3-4 (800-990)</td>
<td>Band4 (800-980)</td>
<td>Band 6 (800-980)</td>
</tr>
<tr>
<td>980-1100</td>
<td>Band 5 (990-1070)</td>
<td>Band5 (980-1100)</td>
<td>Band 5 (980-1100)</td>
</tr>
<tr>
<td>1100-1400</td>
<td>Band 6 (1070-1200)</td>
<td>Band6 (1100-1215)</td>
<td>Band 4 (1100-1400)</td>
</tr>
<tr>
<td></td>
<td>Band 7 (1200-1400)</td>
<td>Band7 (1215-1380)</td>
<td></td>
</tr>
</tbody>
</table>

Slight differences in bandwidths of each GCM scheme lead to no more than 10% flux difference except for the ozone band (band4).
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

Obs: 289.5 W m⁻²
GFDL AM2: 283.3 W m⁻²
GEOS5: 281.0 W m⁻²
CGCM3.1: 286.6 W m⁻²
Collocated AIRS & CERES obs. H₂O bands (0-540 cm⁻¹, >1400 cm⁻¹)

GFDL - Obs

GEOS5 - Obs

CanAM4 - Obs

0.02 in fraction ~ 2.7 Wm⁻²
Collocated AIRS & CERES obs., window region (800-980 cm⁻¹)

GFDL AM2 - Obs

GEOS5 - Obs

CanAM4 - Obs
### Annual-mean CRF in 2004 (Tropical oceans)

<table>
<thead>
<tr>
<th></th>
<th>AIRS&amp;CERES observed CRF (Wm$^{-2}$)</th>
<th>AM2 simulated CRF (Wm$^{-2}$)</th>
<th>GEOS-5 simulated CRF (Wm$^{-2}$)</th>
<th>CanAM4 simulated CRF (Wm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>H$_2$O</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LW broadband</td>
<td>27.45 (100%)</td>
<td>28.13 (100%)</td>
<td>28.30 (100%)</td>
<td>27.27 (100%)</td>
</tr>
<tr>
<td>0-560 cm$^{-1}$; &gt;1400 cm$^{-1}$</td>
<td>5.36 (19.5%)</td>
<td>5.33 (19.0%)</td>
<td>5.08 (17.9%)</td>
<td>4.45 (16.3%)</td>
</tr>
<tr>
<td>560-800 cm$^{-1}$</td>
<td>4.18 (15.2%)</td>
<td>3.74 (13.3%)</td>
<td>5.15 (18.2%)</td>
<td>4.82 (17.7%)</td>
</tr>
<tr>
<td>800-990 cm$^{-1}$</td>
<td>9.35 (34.1%)</td>
<td>10.03 (35.6%)</td>
<td>9.06 (32.0%)</td>
<td>8.78 (32.2%)</td>
</tr>
<tr>
<td><strong>CO$_2$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>990-1070 cm$^{-1}$</td>
<td>2.02 (7.0%)</td>
<td>1.68 (6.0%)</td>
<td>3.62 (12.8%)</td>
<td>3.73 (13.7%)</td>
</tr>
<tr>
<td><strong>WN</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1070-1400 cm$^{-1}$</td>
<td>6.53 (23.8%)</td>
<td>7.34 (26.1%)</td>
<td>5.43 (19.1%)</td>
<td>5.48 (20.1%)</td>
</tr>
<tr>
<td><strong>H$_2$O NO$_2$ CH$_4$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- LW CRF differs ~ 1 Wm$^{-2}$
- CRF of Individual band can have difference as large as that, or even larger
Annual-mean CRF map

AIRS & CERES obs

CanAM4
Band 1: 0-560 cm$^{-1}$ and > 1400 cm$^{-1}$

AIRS & CERES obs

GFDL AM2

GEOS-5

CanAM4
Annual-mean CRF map: 1070-1400 cm$^{-1}$

**AIRS & CERES obs**

**CanAM 4**

**GEOS-5**

**GFDL AM2**

GEOS-5: lower than obs. and a narrow range: 0.18-0.22

GFDL AM2: higher than obs.
Conclusions

- Using CERES scene-type classification, spectral fluxes can be derived from AIRS spectra with good agreements with CERES OLR
- Band-by-band CRF fractional contribution is more sensitive to cloud height, less sensitive to cloud fraction
- Band-by-band flux and CRF consist more rigorous test for climate model
  - Compensating biases: bias in each band could be as large as the broadband bias
  - What’s the implication for climate changes?
- Perspectives
  - The overkill of CERES scene-type for spectra
    - Scene type should be able to inferred from spectrum alone
  - How band-by-band CRF changes in future climate

“...understanding cloud feedback will be gleaned neither from observations nor proved from simple theoretical argument alone. The blueprint for progress must follow a more arduous path that requires a carefully orchestrated and systematic combination of model and observations.” Stephens (2005 J Clim)
Thank You

References:


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

\[ F = \int_{\Delta v} 4\pi dv \int_{0}^{\pi} F(v, \mu, \theta) \mu d\mu d\theta \sin \theta \]

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

A typical tropical clear sky
Measuring broadband flux: ERBE/CERES approach

\[ I_{\text{filter}}(\Delta v; \theta) = I(v; \theta) \otimes SRF(v) \]

unfiltering

\[ I_{\text{unfilter}}(\Delta v; \theta) = \int_{\Delta v} I(v; \theta) dv \]

\( R_{\Delta v}(\theta) \) 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)

\[ F = \pi d_{\text{unfilter}}(\Delta v; \theta) R_{\Delta v}(\theta) \]
TABLE 3. Precipitable water \((w)\), lapse rate \((\Delta T)\), and surface skin temperature \((T_s)\) intervals used to determine LW and WN ADMs under clear-sky conditions over the ocean, land, and desert.

<table>
<thead>
<tr>
<th>(w) (cm)</th>
<th>(\Delta T) (K)</th>
<th>(T_s) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–1</td>
<td>&lt;15</td>
<td>&lt;270</td>
</tr>
<tr>
<td>1–3</td>
<td>15–30</td>
<td>270–290</td>
</tr>
<tr>
<td>3–5</td>
<td>30–45</td>
<td>290–310</td>
</tr>
<tr>
<td>&gt;5</td>
<td>&gt;45</td>
<td>&gt;330</td>
</tr>
</tbody>
</table>

TABLE 4. Surface type, precipitable water \((w)\), cloud fraction \((f)\), surface–cloud temperature difference \((\Delta T_{sc})\), and surface skin temperature \((T_s)\) intervals used to determine LW and WN ADMs under cloudy conditions over the ocean, land, and desert.

<table>
<thead>
<tr>
<th>Surface type</th>
<th>(w) (cm)</th>
<th>(f)</th>
<th>(\Delta T_{sc}) (K)</th>
<th>(T_s) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean</td>
<td>0–1</td>
<td>0.001–0.5</td>
<td>&lt;-15; -15 to</td>
<td>&lt;275; 275 to</td>
</tr>
<tr>
<td>Land</td>
<td>1–3</td>
<td>0.5–0.75</td>
<td>85 every 5 K</td>
<td>320 every 5 K</td>
</tr>
<tr>
<td>Desert</td>
<td>3–5</td>
<td>0.75–0.999</td>
<td>-10-&gt;85</td>
<td>&gt;320</td>
</tr>
<tr>
<td></td>
<td>&gt;5</td>
<td>0.999–1.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Loeb et al., 2005)
\[ F_v = \frac{\pi I_v}{R_v(\theta)} \text{ or } R_v(\theta) = \frac{\pi I_v}{F_v} \]

US 1976 standard atmosphere

\( \theta = 0 \)

\( \theta = 52.96 \) (1/\( \mu \)=1.66)

\( \theta = 60 \)

(Huang et al., JGR, 2008)
AIRS channels

“filled-in” channels
“predicted” – “directly computed” 10cm⁻¹ clear-sky spectral flux

Very limited samples
“predicted” – “directly computed” 10cm\(^{-1}\) cloudy spectral flux

- High cld
- Mid. cld
- Low cld
- Inversion cld

(fractional difference)
A fit using Toy Model B (Typical Tropical profiles + a fractional thick cloud layer)
Best fit: cloud top height at 9.3km, cloud fraction 23%

\[ f = \frac{CRF}{CRF(\text{overcast})} \]

The deviation from usual climatology of \( CTH \) and \( f \)
Low cloud amount and low cloud height

“Feedbacks involving low-level clouds remain a primary cause of uncertainty in global climate model projections.” (Clement et al., Science)

“CCSM4 still has significant biases, such as the mean precipitation distribution in the tropical Pacific Ocean, too much low cloud in the Arctic, and the latitudinal distributions of short-wave and long-wave cloud forcings.” (Gent et al., J Climate)