A PCRTM-based radiance simulator with full treatment of cloud overlapping and sub-grid variability

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Roadmap

- Motivation
- Implementation
- Comparisons with the model results
  - ECMWF ERA-interim (maximum random overlap)
  - GFDL AM2 (random overlap)
- Sensitivity and speed
- Implications for OSSE and spectral fingerprinting
- Conclusion and discussion
Motivations

• Simulator or OSSE should be designed with maximum consistency with the GCM formulation.
  – Gaseous absorption and emission
    • Both should have been tested against the benchmark LBLRTM
  – Optical properties of Cloud and aerosol
    • In principal, they can be specified in simulator or OSSE
  – Cloud overlap
  – Subgrid variability of other variables
Motivations (II)

- Cloud overlap assumptions in the GCMs
  - Maximum random overlap
  - Random overlap
  - Pincus’ Monte-Carlo scheme

\[
1 - C^k = \frac{1 - \max(a^{k-1}, a^k)}{1 - \min(a^{k-1}, 1 - \delta)}
\]

\[
C^k \text{ : total cloud fraction at the } k\text{-th layer (top down)}
\]

\[
a^k \text{ : cloud fraction of the } k\text{-th layer}
\]

<table>
<thead>
<tr>
<th>Total cloud fraction: 0.5</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cloud fraction: 0.75</td>
<td>0.75</td>
</tr>
</tbody>
</table>

**Question:** To what extent such different realizations affect OLR, spectral radiances, and spectral fingerprints, respectively?
Motivations (III): A straightforward solution — sub-column

(Klein and Jakob, 1999, MWR)
Motivations (IV)

Why not compute $T$ of gas and cloud separately?

- Sub-grid variability not only for clouds
- Total water, $q_t$ (vapor+condensed), assumed to have a certain PDF
- Joint PDF of vertical velocity, $T$, and $q_t
Motivation (V): PCRTM

- Computationally expensive for sub-column realization
- PCRTM is very fast and can afford such calculations

<table>
<thead>
<tr>
<th>Model</th>
<th>$N_{ch}$</th>
<th>Number of RT run ($N_{RT}$)</th>
<th>$N_{RT}$ for each channel</th>
<th>Run-time for each channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCRTM</td>
<td>19901</td>
<td>964</td>
<td>0.048</td>
<td>0.2 s</td>
</tr>
<tr>
<td>MODTRAN5</td>
<td>19901</td>
<td>19901</td>
<td>1</td>
<td>6 s</td>
</tr>
<tr>
<td>LBLRTM</td>
<td>19901</td>
<td>8198549</td>
<td>412</td>
<td>224 s</td>
</tr>
</tbody>
</table>

$10^{-2000}$ cm$^{-1}$, $dv = 0.1$ cm$^{-1}$

Single processor of a 6-core Opteron 4174 HE
PCRTM VS. MODTRAN5

Clear
\[ \theta = 24.3^\circ \]
STD = 1.9%

Ice Cloud
\[ \theta = 53.8^\circ \]
STD = 2.3%

\[ \tau_{vis} = 0.5, \quad H_{top} = 10.24\text{km} \]
Implementation

One grid at one time step

Subcolumn Generator

T(z), q_{H2O}(z), q_{CO2}(z), q_{O3}(z), f_{cl}(z)

Cloud-Rad properties

q_{ice}(z), q_{liq}(z), D_{ice}(z), etc

PCRTM

N sets of profiles

N spectra

Averaged spectrum

Done in matlab, code not optimized

GCM dependent
Comparison with model results

- Use PCRTM to compute OLR
- Compare with the OLR from 6-hourly ERA-interim results (OLR is not an assimilated quantity)
- Do the same thing for the GFDL AM2 simulation

ERA-interim: maximum-random
GFDL: random
Case of ERA-Interim

90° S-90° N
(one snapshot: 12:00UTC, 01-01-2010, 100 sub-columns)

2010, Jan. 1
Slope: 0.9922 ± 0.0036
Intercept: 1.7806 ± 0.8433
$R^2$: 0.9074
Case of ERA-Interim

90° S-90° N
(one snapshot: 12:00 UTC, 07-01-2010, 100 sub-columns)

2010, Jul.1
Slope: 1.0032 ± 0.0033
Intercept: -0.4665 ± 0.7792
$R^2$: 0.9252
Case of ERA-Interim

(3) $\text{OLR}_P - \text{OLR}_E$ (100 sub-columns)

Averaged onto $9^\circ \times 30^\circ$ grids
Case of GFDL AM2

90°S-90°N, 00:00 UTC, 02-01-2003

Slope: 0.9916 ± 0.0014
b: 3.245 ± 0.46
R²: 0.9929

Slope: 0.9459 ± 0.0021
b: 13.20 ± 0.46
R²: 0.9841

All sky

Clear sky
Case of GFDL AM2

90°S-90°N, 00:00 UTC, 02-01-2003

GFDL AM2 used a different H₂O continuum from the PCRTM (CKD 2.1 vs. MT_CKD 2.4)

**Slope:** 0.8427 ± 0.0022
**b:** 13.78 ± 0.22
**R²:** 0.9780

**Slope:** 0.8935 ± 0.0019
**b:** 4.89 ± 0.09
**R²:** 0.9854

0-560 cm⁻¹

560-800 cm⁻¹

**Slope:** 0.9081 ± 0.0022
**b:** 2.02 ± 0.05
**R²:** 0.9800

800-900 cm⁻¹

**Slope:** 1.0614 ± 0.004
**b:** 0.2813 ± 0.04
**R²:** 0.9540

990-1070 cm⁻¹
Case of GFDL AM2
90°S-90°N, 00:00 UTC, 02-01-2003

\[
\text{Slope: } 0.9459 \pm 0.0021 \\
b: 13.20 \pm 0.46 \\
R^2: 0.9841
\]

\[
\text{Slope: } 0.9926 \pm 0.0018 \\
b: 4.70 \pm 0.39 \\
R^2: 0.9892
\]

All sky

\[\text{OLR}_{\text{GFDL}}\]

\[\text{OLR}_{\text{PCRTM}} \text{ VS. } \text{OLR}_{\text{GFDL}}\]

\[\text{OLR}_{\text{GFDL}} - \text{F}_{\text{GFDL}}(0-560 \text{ cm}^{-1}, >1400 \text{ cm}^{-1}) + \text{F}_{\text{PCRTM}}(0-560 \text{ cm}^{-1}, >1400 \text{ cm}^{-1})\]
# Sensitivity to number of sub-columns

ECMWF: 90°S-90°N, 180°W-180°E  
12:00 UTC 07-01-2010

<table>
<thead>
<tr>
<th>Number of sub-columns</th>
<th>80</th>
<th>40</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Slope</strong></td>
<td>1.0033 ± 0.0033</td>
<td>1.0028 ± 0.0033</td>
<td>1.0034 ± 0.0034</td>
</tr>
<tr>
<td><strong>Intercept</strong></td>
<td>-0.479 ± 0.780</td>
<td>-0.390 ± 0.789</td>
<td>-0.502 ± 0.798</td>
</tr>
<tr>
<td><strong>R-Square</strong></td>
<td>0.9251</td>
<td>0.9235</td>
<td>0.9219</td>
</tr>
<tr>
<td><strong>Time</strong></td>
<td>6427 s</td>
<td>4810 s</td>
<td>3564 s</td>
</tr>
</tbody>
</table>

Run on an Oracle/Sun *Fire X2100* workstation  
1.5 × 1.5 resolution, coded in Matlab script (not optimized)
# Sensitivity to number of sub-columns

**GFDL: 90°S-90°N, 180°W-180°E**

00:00 UTC 02-01-2003

<table>
<thead>
<tr>
<th>Number of sub-columns</th>
<th>80</th>
<th>40</th>
<th>20</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>0.9459±0.0021</td>
<td>0.9459±0.0022</td>
<td>0.9455±0.0024</td>
<td>0.9450±0.003</td>
</tr>
<tr>
<td>Intercept</td>
<td>13.204</td>
<td>13.212</td>
<td>13.301</td>
<td>13.37</td>
</tr>
<tr>
<td>R-Square</td>
<td>0.984</td>
<td>0.982</td>
<td>0.979</td>
<td>0.971</td>
</tr>
<tr>
<td>Time</td>
<td>5429 s</td>
<td>3337 s</td>
<td>2102 s</td>
<td>1376 s</td>
</tr>
</tbody>
</table>

Run on an Oracle/Sun *Fire X2100* workstation

2×2.5 resolution, coded in Matlab script (not optimized)
Implication: Maximum-Random vs. Random overlap

One month of 6-hourly results averaged onto 10° by 30° grids

2003Feb., 100 sub-columns
Conclusions and discussion

- **PCRTM-based simulator**
  - Fully accommodate the sub-grid variability for now and for the future
  - Easy to take scattering into account

- **Comparison with the modeled OLR show consistency**
  - Water vapor continuum can make noticeable differences

- **Implications for constructing spectral fingerprints**
  - Global mean difference is not prominent, but SHAPES change!
    - Channels are not “equal” though a fit treat each channel equally
  - Regionally it could be significant (more for flux than for difference of flux)

- **Future work**
  - Radiiances from ERA-interim 1989-present
  - GPU-version of the simulator
An update from the talk last Fall
AIRS 900.7 cm⁻¹ Original 16-day averaged time series (0-10S, 150-180E)

Brightness temperature (K)

MODIS 11 μm BT
Thank You!