On the use of Simulated Photon Paths to Co-register TOA Radiances in EarthCARE Radiative Closure Experiments

Florian Tornow, Carlos Domenech, Howard Barker

Institute for Space Sciences, FU Berlin

10.10.2014
Overview of EarthCARE

- retrieval of vertical profiles of cloud, aerosol, and precipitation parameters with CPR, ATLID, and MSI
- verisimilitude of retrieval through Radiative Closure: 3 along-track measurements of BBR versus simulations of 1D RTM or 3D Monte Carlo RTM
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Introduction

Idea of the Radiative Closure

- **BBR measurements**
  - broadband radiances (SW and LW) at 3 along-track viewing angles
- **3D Monte Carlo RTM**
  - acting on retrieved properties
  - simulating BBR TOA SW radiances (or radiative fluxes)
- measurement versus simulation
  - difference indicating inaccuracies of retrieved properties

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co-registration aims at observing the same scene from all 3 angles

▷ EarthCARE: co-registration helps to identify domains with incorrect retrieval

▷ up-to-date: at heighest reflecting layer
  - cloud top height
  - surface

▷ problematic for transparent or broken cloud layers
  - need for more information vertical distribution of refl. layers
  - develope method to utilize this new information
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- control run
  - using original CCCM data
  - apply 3D MC RTS
  - obtain BBR-like radiances

- perturbed run
  - adding noise to cloud parameters (i.e. liquid, ice water contents, droplet effective radius and crystal effective diameter)
  - apply 3D MC RTS with inaccurate retrieval
  - and output 3D photon path information
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Results 1

Co-registered TOA radiance differences

Performance: 50.78%

Surface

Domain

TOA radiance difference [W/m²/sr]

Cirrus, Cirrostratus

Max. Sim. deals better with broken cloud fields
Results 1

Co-registered TOA radiances in EarthCARE Radiative Closure Experiments

Results 1

Performance: 50.78 %

Frontal 

TOA radiance difference [W/m²/sr]

Co-registered TOA radiance differences

Surface

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## Results

### Domain Height [km]

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- **Cirrus** accurately retrieved
- **Cirrostratus** inaccuracy retrieved

### Co-registered TOA radiance differences

#### Surface

- Performance: 50.78%

#### Highest Reflecting Layer

- Performance: 68.38%

### ▶ Max. Sim. deals better with broken cloud fields
Results 1

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Results 1

Max. Sim. deals better with broken cloud fields
Results 2

Co-registered TOA radiance differences

Performance: 61.4%

Max. Sim. allocates off-nadir radiances more reliably
Results 2

- Maximum Similarity allocates off-nadir radiances more reliably
Results 2

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- **Performance**: 61.4%
- **Performance**: 80.47%
- **Performance**: 89.35%

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### Results 2

**Co-registered TOA radiance differences**

- **Performance:** 61.4%
- **Surface**
- **Performance:** 80.47%
- **Highest Reflecting Layer**
- **Performance:** 89.35%

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Wrap Up

EarthCARE's Radiative Closure compares, among others:

- BBR SW radiances at 3 along-track viewing angles
- against simulated counterparts by 3D Monte Carlo RTM

co-registration of off-nadir radiances

- helps to identify domains with inaccurately retrieved parameters
- problematic for semi-transparent or broken cloud fields
- need for information on 3D structure of clouds/aerosols

aim of this work:

- use 3D MC photon paths
to estimate a profile of reflecting layers to each radiance
- find off-nadir radiances with most similar profile to nadir profile
  (Maximum Similarity Co-Registration)

results:

- improved radiance co-registration for semi-transparent and broken cloud fields
- no improvement for optically thick clouds (not shown here)

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Alternative: Closure with SW and LW fluxes

▷ BBR flux retrieval algorithm is based on the multi-view capability of the BBR and the synergy between BBR and MSI

▷ BBR viewing design characterizes the radiance field of the observed target from 3 AT directions → improving observation of the surface-atmosphere anisotropy

▷ Non-linear combination of MSI radiances provides information on the scene anisotropy of the target

▷ The radiance-to-flux models convert the 3 BBR measurements, collocated at the HRL of the atmosphere-surface system, into flux estimates. Then the radiative fluxes are merged, thereby enabling comparison of measurement-derived fluxes against model-derived fluxes from 1D and 3D RT models.
Methodology

- SW ADMs for every BBR viewing angle are constructed using a feed-forward back-propagation artificial neural network (ANN) technique.
- CERES radiance, solar geometry, MODIS radiances over clear/cloudy FOV area, cloud cover and surface ancillary parameters are inputs of the ANN training.
- CERES SW anisotropic factors are used as outputs.
- Election of ANN input parameters depend on the scene class observed.
- LW TOA Fluxes are obtained through theoretical polynomial second order regressions on the MSI 'split-window' channels BT differences.
- Anisotropy models are classified in bins of 20 $Wm^{-2}sr^{-1}$.
- A large RT-based geophysical database is used to train the data.
- Anisotropic Factors are estimated from theoretical simulated thermal radiances and fluxes.
## Overall Results

Within the 5000km-long frame, different co-registration methods led to following results:

<table>
<thead>
<tr>
<th>Domains</th>
<th>Characteristics</th>
<th>P(SRF)</th>
<th>P(HRL)</th>
<th>P(MXS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1400-1600</td>
<td>Cirrus and Cirrostratus Clouds</td>
<td>50.78%</td>
<td>68.38%</td>
<td>81.81%</td>
</tr>
<tr>
<td>1600-1800</td>
<td>Cirrus Clouds</td>
<td>61.4%</td>
<td>80.47%</td>
<td>89.35%</td>
</tr>
<tr>
<td>2800-3000</td>
<td>Deep Convective Clouds (horizontally heterogeneous)</td>
<td>49.62%</td>
<td>90.23%</td>
<td>92.04%</td>
</tr>
<tr>
<td>3000-3200</td>
<td>Deep Convective Clouds (horizontally homogeneous)</td>
<td>36.14%</td>
<td><strong>82.10%</strong></td>
<td>78.17%</td>
</tr>
<tr>
<td>3600-3800</td>
<td>Cirrus Clouds and cloud-free zones</td>
<td>47.49%</td>
<td>87.27%</td>
<td>89.32%</td>
</tr>
<tr>
<td>1052/5000</td>
<td>Only domains with Cumulus Clouds</td>
<td>84.37%</td>
<td><strong>85.75%</strong></td>
<td>85.27%</td>
</tr>
<tr>
<td>1933/5000</td>
<td>Only domains with Cirrus Clouds</td>
<td>71.94%</td>
<td>87.38%</td>
<td><strong>91.98%</strong></td>
</tr>
<tr>
<td>181/5000</td>
<td>Only domains with Deep Convective Clouds</td>
<td>75.52%</td>
<td><strong>93.12%</strong></td>
<td>89.98%</td>
</tr>
<tr>
<td>1286/5000</td>
<td>Only cloud-free domains</td>
<td>0.45%</td>
<td>0.45%</td>
<td><strong>15.01%</strong></td>
</tr>
</tbody>
</table>
How does Maximum Similarity Co-registration work?

In order to select an off-nadir radiance:

- take the nadir line-of-sight through reflecting layers of domain D
- and a subset of relevant off-nadir lines-of-sight (all intersecting with D)

- determine pairwise similarity:
  \[ s = \cos \Theta = \langle \frac{C_{\text{nadir}}}{\|C_{\text{nadir}}\|}, \frac{C_{\text{oblique}}}{\|C_{\text{oblique}}\|} \rangle \]

- pick the off-nadir radiance, belonging to the most similar off-nadir line-of-sight
How to measure the goodness of co-registration?

- in EarthCARE, co-registration serves to identify inaccurate retrieval
- for simplicity, we assume:
  - inaccurate retrieval of cloud parameters reduces/enhances radiances by a fraction
  - equal relative difference between measured and simulated radiances in all 3 VZAs

relative difference:
\[ d_i^\% = \frac{l_M(i) - l_S(i)}{l_M(i)} \]

form a point \( m \) in \( \mathbb{R}^3 \):
\[ m_i = (d_i^B, d_i^N, d_i^F) \]

which ideally lies on \( \bar{u} \) with \( n \in \mathbb{R} \):
\[ \bar{u} = (1, 1, 1) \cdot n \]

hence, \( X \) should scatter around \( \bar{u} \):
\[ X = [m_1, \ldots, m_{n_D}] \]

or \( \bar{w}_1 \), the first Eigenvector of \( X \), lines up with \( \bar{u} \):
\[ XX^T W = \lambda W = \lambda [\bar{w}_1, \bar{w}_2, \bar{w}_3] \]

with Eigenvalues \( \lambda \):
\[ \lambda = [\lambda_1, \lambda_2, \lambda_3] \]

we measure the goodness of co-registration:
\[ P = \left( \frac{\bar{w}_1}{||\bar{w}_1||} \cdot \frac{\bar{u}}{||\bar{u}||} \right) \cdot \lambda_1 \cdot 100\% \]
Caveats of using 3D photon paths

unrealistic 3D photon paths may happen because of:

▷ inaccurate retrieval  
▷ inconsistent methodologies (3D scene constr., 3D MC RTM, ...)

potentially:

▷ we expect to see something, which is not there  
▷ we miss something, which is actually there

in case:

▷ the real structure is inaccurately retrieved  
  ▷ we identify it (by assigning just another erroneous radiance difference)  
  ▷ we fail identifying it (by selecting a low radiance difference)  

▷ the real structure is fine  
  ▷ we falsely identify it  
  ▷ we consider it fine
On the use of Simulated Photon Paths to Co-register TOA Radiances in EarthCARE Radiative Closure Experiments

BBR - details on set-up
Overview of instruments

atmospheric lidar - ATLID

- measurements at 355\textit{nm}
- molecule/cloud/aerosol separation
- every 100m with diameter of 5/12m

cloud profiling radar - CPR

- dopplerized 94\textit{GHz}
- liquid/ice clouds, light rain
- resolution: vertical 500m, horizontal 750m

multispectral imager - MSI

- 500m pixel size, 150km swath width
- 4 solar channels, 3 thermal channels

broadband radiometer - BBR

- 3 spatial direction - alongtrack 55° backward, nadir, 55° forward
- solar/thermal radiance
- 1km $\times$ 1km footprint in nadir
- for comparability/noise reduction transformed into 10km $\times$ 10km
Scene construction algorithm

Data
- 2D cross section (RXS)
  - vertical and horizontal information
  - clouds (liquid/ice), aerosols, gases
- 2D image of MSI (along and across track)

Algorithm
- combine RXS details and MSI info
  - donate RXS properties to off-track pixels
  - picking the most similar spectral footprint
  - in certain region around recipient pixel
→ obtain detailed information in 3D
On the use of Simulated Photon Paths to Co-register TOA Radiances in EarthCARE Radiative Closure Experiments

CCCM Data

- CERES-CALIPSO-CloudSat-MODIS (CCCM) consists of:
  - CloudSat’s Cloud-Profiling Radar
  - CALIPSO’s lidar
  - Terra’s MODIS
  - and CERES

- CERES provides only radiances close to nadir, and lacks BBR’s 2 off-nadir views
  - therefore, we generate both *BBR measurement* and *3D Monte Carlo RTS outputs*

- using a 5000km long section, measured on 5th July 2006 over equatorial Pacific
For devouring...

[Barker al., 2003]

[Barker al., 2011]

[Domenech et al., 2011]
FLURB - FLUx Retrievals from EarthCARE BBR Observations, *FU Berlin, Environment Canada, RMI of Belgium, Atmospheric and Climate Applications Inc.*, 2006.

[EarthCARE Mission Advisory Group, 2006]

[ESA, 2011]
3D Monte Carlo RTS

- 3D radiative transfer
- distribute photons over whole domain
- follow each bunch of photons
- at each event:
  - use phase function
  - calculate rad. contribution to BBR observations
3D Monte Carlo RTS

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initial horizontal position
3D Monte Carlo RTS

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3D Monte Carlo RTS

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On the use of Simulated Photon Paths to Co-register TOA Radiances in EarthCARE Radiative Closure Experiments

3D Monte Carlo RTS

- obtain TOA radiances
  - the sum over all radiative contributions
- and full atmospheric paths for each viewing direction
  - a vector of radiative contributions for each vertical level
3D Monte Carlo RTS

▷ obtain TOA radiances
  ▷ the sum over all radiative contributions
▷ and full atmospheric paths for each viewing direction
  ▷ a vector of radiative contributions for each vertical level