Influence of 3D Cloud Effects on Satellite-Derived Earth Radiation Budget Estimation

Norman G. Loeb
Hampton University/NASA Langley Research Center
Hampton, VA

October 14, 2005, Kiel, Germany
CERES Instrument

• 5 instruments on 3 satellites (TRMM, Terra, Aqua) for diurnal and angular sampling.

• Narrow field-of-view scanning radiometer with nadir footprint size of 10 km (TRMM); 20 km (Terra & Aqua).

• Measures radiances in 0.3-5 µm, 0.3-200 µm and 8-12 µm.

• Capable of scanning in several azimuth plane scan modes: fixed (FAP) or crosstrack, rotating azimuth plane (RAP), programmable (PAP).

• Coincident Cloud and Aerosol Properties from MODIS/VIRS
Instantaneous Fluxes at TOA and Angular Distribution Models

CERES Radiance Measurement

\[ L(\theta_o, \theta, \phi) \]

TOA Flux Estimate

\[ F(\theta_o) = \int_{0}^{2\pi} \int_{0}^{\pi} L(\theta_o, \theta, \phi) \cos\theta \sin\theta \, d\theta \, d\phi \]

Satellite

Sun

\[ \theta_o \]

\[ \theta \]

\[ \phi \]
TOA flux estimate from CERES radiance:

\[
\hat{F}(\theta_o, \theta, \phi) = \frac{\pi L(\theta_o, \theta, \phi)}{R_j(\theta_o, \theta, \phi)}
\]

where,

\[
R_j(\theta_o, \theta, \phi) = \frac{\pi L_j(\theta_o, \theta, \phi)}{\int_0^{2\pi} \int_0^\pi L_j(\theta_o, \theta, \phi) \cos \theta \sin \theta \, d\theta \, d\phi}
\]

\(R_j(\theta_o, \theta, \phi)\) is the Angular Distribution Model (ADM) for the \(^{jth}\) scene type.
CERES Single Scanner Footprint (SSF) Product

- Coincident CERES radiances and imager-based cloud and aerosol properties (including MOD04 and NOAA-NESDIS aerosol products).

- Use VIRS (TRMM) or MODIS (Terra, Aqua) to determine the following parameters in up to 2 cloud layers over every CERES FOV:

  Macrophysical: Fractional coverage, Height, Radiating Temperature, Pressure
  Microphysical : Phase, Optical Depth, Particle Size, Water Path
  Clear Area      : Skin Temperature, Aerosol optical depth, Emissivity
NEW MERGED CERES-MISR-MODIS DATASET

CERES and MISR teams are working together to produce the first merged CERES-MISR-MODIS dataset.

MISR radiances
MODIS clouds and aerosols
CERES radiances and fluxes

Contains all CERES-MODIS parameters on the CERES SSF product and all available MISR radiances (9 angles and 4 channels) averaged over every CERES footprint.

⇒ Can be extended to include other MISR and MODIS derived parameters
<table>
<thead>
<tr>
<th>Scene Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Ocean</td>
<td>Function of wind speed; Correction for aerosol optical depth included.</td>
</tr>
<tr>
<td>Cloud Ocean</td>
<td>Function of cloud phase; Continuous function of cloud fraction and cloud optical depth (5-parameter sigmoid).</td>
</tr>
<tr>
<td>Land &amp; Desert Clear</td>
<td>1° regional monthly ADMs using Analytical Function of TOA BRDF (Ahmad and Deering, 1992).</td>
</tr>
<tr>
<td>Land &amp; Desert Cloud</td>
<td>Function of cloud phase; continuous function of cloud cover and cloud optical depth; uses 1°-regional clear-sky BRDFs to account for background albedo.</td>
</tr>
<tr>
<td>Permanent Snow</td>
<td>Cloud Fraction, Surface Brightness, cloud optical depth</td>
</tr>
<tr>
<td>Sea-Ice</td>
<td>Cloud Fraction, Surface Brightness, Ice Fraction, cloud optical depth</td>
</tr>
</tbody>
</table>
SW Anisotropy of Liquid Water Clouds from CERES Terra

![Graph showing SW Anisotropic Factor vs. θ (°) for different θ₀ conditions.](image)

- θ₀ = 30°-32°
- θ₀ = 40°-42°
- θ₀ = 50°-52°

Φ = 178°-180° and Φ = 0°-2°
Uncertainty in Regional Mean SW TOA Flux: CERES ADMs vs 1D Theory
Approach

i) Construct 10°x10° latitude-longitude regional ADMs by season (e.g., DJF, JJA) from:
   
i) Measured CERES radiances
   ii) Radiance predicted by CERES ADMs
   iii) Radiance predicted by 1D theory

ii) Apply all 3 regional ADMs to determine fluxes from the same data.

iii) Determine regional mean error in SW TOA flux.

Perform above steps separately for: liquid water clouds, ice clouds and all-sky.
1D Model Assumptions

\[ I_{1D}(\theta, \phi) = (1 - f) I_{\text{CER}}^{\text{clr}}(\theta, \phi) + f I_{1D}^{\text{ovc}}(\theta, \phi; \tau, P) \]

- \( f \) = Cloud Fraction
- \( I_{\text{CER}}^{\text{clr}} \) = Clear-sky radiance from CERES ADMs
- \( I_{1D}^{\text{ovc}} \) = Overcast radiance from 1D theory
- \( P \) = Cloud Phase (liquid or ice)
- \( \tau \) = Cloud Optical Depth

RT Model: Nakajima rstar5b

Cloud Properties:
- Liquid water: \( r_e = 10 \mu m \); fixed cloud-top height 2 km
- Ice Clouds: nonspherical; mix of crystal types (Ping Yang).
Regional Mean SW TOA Flux Error – Liquid Water Clouds (JJA)

(a) 1D Theory

(b) CERES ADMs

TOA Flux Error (W m\(^{-2}\))

-20
-16
-12
-8
-4
0
4
8
12
16
20
Regional Mean SW TOA Flux Error – Liquid Water Clouds (DJF)

(a) 1D Theory

(b) CERES ADMs
Regional Mean SW TOA Flux Error – Ice Clouds (JJA)

(a) 1D Theory

(b) CERES ADMs

TOA Flux Error (W m\(^{-2}\))

-20
-16
-12
-8
-4
0
4
8
12
16
20
Regional Mean SW TOA Flux Error – Ice Clouds (DJF)

(a) 1D Theory

(b) CERES ADMs
Zonal Distribution of SW TOA Flux Errors (Liquid Water Clouds)

JJA

Latitudinal distribution of SW TOA flux errors for JJA season.

DJF

Latitudinal distribution of SW TOA flux errors for DJF season.

Legend:
- 1D Theory
- CERES ADM

SW TOA Flux Error (W m⁻²)
Zonal Distribution of SW TOA Flux Errors (Ice Clouds)

JJA

- Latitude (°)
- SW TOA Flux Error (W m^-2)

- 1D Theory
- CERES ADM

DJF

- Latitude (°)
- SW TOA Flux Error (W m^-2)
## Global SW TOA Flux Error Over Ocean

<table>
<thead>
<tr>
<th></th>
<th>JJA</th>
<th></th>
<th>DJF</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1D Theory (W m⁻²)</td>
<td>CERES ADM (W m⁻²)</td>
<td>1D Theory (W m⁻²)</td>
<td>CERES ADM (W m⁻²)</td>
</tr>
<tr>
<td>Liq H₂O Cld</td>
<td>3.3</td>
<td>-0.29</td>
<td>3.6</td>
<td>0.31</td>
</tr>
<tr>
<td>Ice Cld</td>
<td>1.9</td>
<td>-0.35</td>
<td>3.4</td>
<td>-0.53</td>
</tr>
<tr>
<td>All-Sky</td>
<td>2.6</td>
<td>-0.28</td>
<td>3.3</td>
<td>0.14</td>
</tr>
</tbody>
</table>
SW TOA Flux Error by Latitude and Viewing Zenith Angle (DJF 2000-2001)

1D Theory

CERES ADM

Lat. (deg) vs View. Zen. Angle (deg)

SW TOA Flux Error (W m\(^{-2}\))
Albedo by Latitude and Viewing Zenith Angle (Comparison with ERBE ADMs)

- July, 2003
- Crosstrack Only
Summary

- Bias in SW TOA flux (oceans) from 1D ADMs is 3 W m\(^{-2}\) compared to 0.3 W m\(^{-2}\) from CERES ADMs.

- 1D SW TOA flux bias depends systematically on latitude (solar zenith angle), especially for liquid water clouds.

  => small negative bias in tropics and large positive bias (10-15 W m\(^{-2}\)) in midlatitudes.

- No noticeable viewing zenith angle dependence in TOA albedo from the new CERES ADMs.