Determination of the Earth’s Radiation Budget from CERES

(Clouds and the Earth’s Radiant Energy System)

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Bruce A. Wielicki, Tak Wong, Kory Priestley, Pat Minnis, David Kratz, Tom Charlock, Dave Doelling, Dave Young

NASA Langley Research Center, Hampton, VA
September 20, 2006
Global Radiation Budget

- Reflected solar radiation: 107 W m⁻²
- Incoming solar radiation: 342 W m⁻²
- Outgoing longwave radiation: 235 W m⁻²
- Reflected by clouds, aerosol, and atmosphere: 77 W m⁻²
- Reflected by the surface: 30 W m⁻²
- Absorbed by the surface: 168 W m⁻²
- Absorbed by the atmosphere: 67 W m⁻²
- Emitted by the atmosphere: 165 W m⁻²
- Atmospheric window: 40 W m⁻²
- Greenhouse gases: 30 W m⁻²
- Latent heat: 78 W m⁻²
- Thermals: 24 W m⁻²
- Evapotranspiration: 78 W m⁻²
- Surface radiation: 390 W m⁻²
- Back radiation: 324 W m⁻²
- Absorbed by the surface: 324 W m⁻²
Modelers and climatologists: USE THE SAME SUN!

We have only one!
Clouds, Radiation and Climate

- The largest uncertainty in global climate sensitivity over the next century is cloud feedback.

- A global cloud feedback can amplify or dampen global warming.

- Since global cloud feedback has been shown to be linear in changing cloud radiative forcing (CRF) (Soden and Held, 2006), this implies that changes in net CRF are directly related to climate sensitivity.

Climate Sensitivity: Globally-averaged equilibrium temperature change in response to a doubling of atmospheric CO₂

Cloud Feedback: Effects of changes in clouds and their associated radiative properties on a change of climate.

Cloud Radiative Forcing: Measures of how much clouds modify the net radiation of the Earth system at the top-of-atmosphere.
Observing the Earth’s Global Radiation Budget

All methods that attempt to observe the Earth’s radiation budget suffer from errors due to one or more of the following:

- Instrument calibration (absolute and relative)
- Spectral sampling
- Spatial sampling
- Angle sampling
- Temporal sampling
Clouds and the Earth’s Radiant Energy System

- Broadband satellite radiometer: 0.3-5 µm, 0.3-200 µm and 8-12 µm
- 20-km footprint (nadir)
- Capable of scanning in different azimuth planes
- Global coverage each day
CERES DATA PROCESSING FLOW

uses CERES data only

CERES DATA

CERES CALIBRATION/LOCATION

ERBE INVERSION

ERBE AVERAGING

ERBE-LIKE PRODUCTS

CLOUD IMAGER DATA

CLOUD IDENTIFICATION; TOA/SURFACE FLUXES

ANGULAR DISTRIBUTION MODELS

DIURNAL MODELS

ATMOSPHERIC STRUCTURE

SURFACE AND ATMOSPHERIC FLUXES

CERES SURFACE PRODUCTS

GEOSTATIONARY DATA

TIME/SPACE AVERAGING

CERES TIME AVERAGE CLOUD/RADIATION TOA, SFC, ATMOS

3-hourly 1-degree grid

CERES is a Sensor Web: up to 11 instruments on 7 spacecraft all integrated to obtain climate accuracy in top to bottom fluxes.
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

\[ \theta_o \]

\[ \phi \]
SSF & ERBE-Like Global Albedo & LW TOA Flux vs Viewing Zenith Angle

JANUARY 2003

Albedo

0.275
0.280
0.285
0.290
0.295
0.300
0.305

0 10 20 30 40 50 60 70

SSF
ES8

JULY 2003

LW TOA Flux (W m$^{-2}$)

232
233
234
235
236
237
238
239
240
241
242
243
244
245
246
247

0 10 20 30 40 50 60 70

Viewing Zenith Angle (°)

Loeb et al. 2006
JAOT, in press
CERES Temporal Interpolation & Spatial Averaging (TISA)

• Satellite instruments produce an enormous amount of data, but these data are NOT uniformly distributed in time or space.

• Interpolate radiative fluxes and cloud properties between times of measurements to produce accurate temporal averages. Use 3-hrly geostationary data.

• Spatially average data on a 1°x1° latitude-longitude equal-area nested grid for science applications.
<table>
<thead>
<tr>
<th>Dominant Error Sources</th>
<th>Global Interannual Cld Rad Fcng Trend/decade</th>
<th>Zonal Eqtr - Pole Gradient Monthly</th>
<th>1 deg region Monthly (1 σ)</th>
<th>20km fov Instantaneous (1 σ) (S₀ = 1000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOA SW Flux</td>
<td>0.3 Wm⁻² Terra Rev1</td>
<td>3.5 Wm⁻²</td>
<td>3.0 Wm⁻²</td>
<td>10 Wm⁻²</td>
</tr>
<tr>
<td>TOA LW Flux</td>
<td>0.5 Wm⁻² Terra Rev1</td>
<td>2.0 Wm⁻²</td>
<td>1.5 Wm⁻²</td>
<td>5 Wm⁻²</td>
</tr>
<tr>
<td>TOA Net Flux</td>
<td>0.6 Wm⁻² Terra Rev1</td>
<td>4.0 Wm⁻²</td>
<td>3.5 Wm⁻²</td>
<td>11 Wm⁻²</td>
</tr>
<tr>
<td>Science Rqmt</td>
<td>0.15 Wm⁻² 25% feedback</td>
<td>1 - 3 Wm⁻²</td>
<td>2 - 5 Wm⁻²</td>
<td>10 Wm⁻²</td>
</tr>
</tbody>
</table>
ARM/BSRN/CMDL/Surfrad
Surface Radiation Sites
<table>
<thead>
<tr>
<th>Dominant Error Sources</th>
<th>Global Interannual Cld Rad Fcng Variability</th>
<th>SYN/AVG (est) Month, 1-deg Bias, Clr/All (1 σ)</th>
<th>SRBAVG Month, 1-deg Bias All (1σ)</th>
<th>CRS 20km fov Instantaneous 1 σ, Clr/All Sky (S_0 = 900)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Down SW Flux</td>
<td>0.5 Wm^{-2} (40 sites)</td>
<td>0 / +5 Wm^{-2} (σ = 6)</td>
<td>3 Wm^{-2} (σ = 20)</td>
<td>Angle Samp, Water Vapor Aerosol, Tair</td>
</tr>
<tr>
<td>Surface Down LW Flux</td>
<td>1.0 Wm^{-2} (40 Sites)</td>
<td>-7 / -6 Wm^{-2} (σ = 8)</td>
<td>&lt; 1 Wm^{-2} (σ = 10)</td>
<td>12 / 17 Wm^{-2}</td>
</tr>
<tr>
<td>Surface Down Total Net Flux</td>
<td>1.1 Wm^{-2} (40 Sites)</td>
<td>-7 / -1 Wm^{-2} (σ = 9)</td>
<td>4 Wm^{-2} (σ = 22)</td>
<td>26 / 26 Wm^{-2}</td>
</tr>
<tr>
<td>Science Rqmt</td>
<td>TBD</td>
<td>&lt; 5-10 Wm^{-2}</td>
<td>&lt; 5-10 Wm^{-2}</td>
<td>&lt; 25 Wm^{-2}</td>
</tr>
<tr>
<td>BSRN Acc.</td>
<td>TBD</td>
<td>5 SW?, 10 LW?</td>
<td>5 SW, 10 LW</td>
<td>15 SW, 10 LW</td>
</tr>
</tbody>
</table>
SW TOA Flux Interannual Variability: Tropical Ocean

SeaWiFS PAR and CERES FM1 Ed2B_rev1 SW TOA Flux Anomaly (Ocean; 30°S-30°N)

- SeaWiFS PAR (times -6.58)
- CERES SW TOA Flux

SeaWiFS Variability (1σ) = 1.07 W m⁻²
CERES Variability (1σ) = 1.03 W m⁻²
σ(CERES - SeaWiFS) = 0.21 Wm⁻²

Shows consistent calibration stability at < 0.3 Wm⁻² per decade (95% conf)
Unfortunately only works for tropical mean ocean (nband vs bband issues)
Regional trends differ by +2 to -5 Wm⁻²/decade SeaWiFS vs CERES

Loeb et al. 2006
JGR, in press
CERES SW TOA Flux and MODIS Cloud Fraction Anomalies

Loeb et al. 2006
GRL, submitted
Given climate variability, 15 to 20 years is required to first detect climate trends at cloud feedback level with 90% confidence.

Loeb et al. 2006
J. Climate, in press
Annual Mean Global SW TOA Flux Anomaly

Year

2000 2001 2002 2003 2004

SW TOA Flux Anomaly (W m$^{-2}$)

-5 -4 -3 -2 -1 0 1 2 3 4 5

Earthshine BBSO
CERES Global
ISCCP-FD Global
CERES Earthshine Simulation
Tropical (20S - 20N) TOA Radiation Anomalies: Requires Overlap Similar to Solar Constant

- Nimbus 7 nonscanner (has overlap to constrain)
- ERBS nonscanner (WFOV)
- ERBE scanner (has overlap to constrain)
- ScaRaB scanner (no overlap with ERBE scanner)
- CERES scanner (no overlap with ERBE scanner)

Conclusion:
Differences are within absolute accuracy:
1% ERBE LW = 2.5 Wm⁻²
0.5% CERES LW = 1.2 Wm⁻²
Difference = 3.7 Wm⁻² for absolute calibration.

Wong et al., J. Climate (in press)
Tropical (20S - 20N) TOA Radiation Anomalies: Comparison of Satellite Data Sets

Comparison for:
- ERBS WFOV cavity (Edition 3 with day/night correction)
- ISCCP FD
- AVHRR Pathfinder (Jacobowitz corrections never saved in archive)
- HIRS Pathfinder (Susskind)

ERBS Decadal Changes (1980s to 1990s)
- LW: 1.6 Wm\(^{-2}\)
- SW: -3.1 Wm\(^{-2}\)
- NET: 1.5 Wm\(^{-2}\)

Wong et al., J. Climate (in press)
We will need to carefully unscramble cloud feedback and natural variability in ocean heat storage: a fusion of ocean/atmosphere data

Wong et al. 2006
J.Climate, in press
Does CERES Net Radiation Indicate Recent Ocean Cooling?

- **Global Net CERES Terra FM1 Instrument ES-8 All-Sky TOA Flux Edition 2, Rev1**
- **12 mo running means (June = year center) current data (Wong)**
- **Same as above, but showing the level of changes expected in Edition 3 calibration improvements, primarily in daytime LW fluxes (Wong, Charlock, Mathews, Priestley, Loeb)**

**Graph Details:**
- **Globe, FM1, All-sky, Ed2_Rev1 (Black), Ed2_Rev1 + LWcor (Red)**
- **Lyman et al. Jan00 - Dec 03**
  - Ocean Warming: +0.7 W/m²
- **Lyman et al. Jan04 - Dec 05**
  - Ocean Cooling: -1.0 W/m²
- **04/05 Ocean Data => Cooling of 1.7 W/m² relative to 00-03**
- **Mar00 - Dec 03**
  - CERES Avg Net Anomaly: + 0.03 W/m²
- **Jan 04 - Dec 05**
  - Avg Net Anomaly: - 0.10 W/m²
- **04/05 CERES Net Radiation => Cooling of 0.13 W/m² relative to 00-03**

**Time:** (8/2000 to 6/2005)
## CERES Global TOA Fluxes (3-year mean)

<table>
<thead>
<tr>
<th>Wm$^{-2}$</th>
<th>CERES ERBE-Like</th>
<th>CERES SRBAVG (non-GEO)</th>
<th>CERES SRBAVG (GEO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW (all-sky)</td>
<td>98.5</td>
<td>96.7</td>
<td>97.8</td>
</tr>
<tr>
<td>LW (all-sky)</td>
<td>239.0</td>
<td>237.7</td>
<td>237.1</td>
</tr>
<tr>
<td>Net (all-sky)</td>
<td>3.8</td>
<td>6.9</td>
<td>6.4</td>
</tr>
<tr>
<td>SW (clr-sky)</td>
<td>49.4</td>
<td>51.2</td>
<td>51.1</td>
</tr>
<tr>
<td>LW (clr-sky)</td>
<td>266.7</td>
<td>266.3</td>
<td>264.0</td>
</tr>
<tr>
<td>Net (clr-sky)</td>
<td>25.4</td>
<td>23.8</td>
<td>26.3</td>
</tr>
</tbody>
</table>
Global Net Flux Balance Error Budget  
(out of 1365/4 = 341.25 Wm⁻² = SW + LW)

<table>
<thead>
<tr>
<th>Error Source</th>
<th>SW</th>
<th>LW</th>
<th>Net</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error Source (white = heating)</td>
<td></td>
<td></td>
<td>+1.0</td>
</tr>
<tr>
<td>Solar Constant (1361 vs 1365)</td>
<td>+1.0</td>
<td>0.0</td>
<td>+1.0</td>
</tr>
<tr>
<td>Absolute Calibration</td>
<td>1.0</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Spectral Correction</td>
<td>0.5</td>
<td>0.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Spatial Sampling</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Angle Sampling (ADMs)</td>
<td>+0.2</td>
<td>-0.1</td>
<td>+0.1</td>
</tr>
<tr>
<td>Time Sampling (diurnal)</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>Reference Altitude (20km)</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Twilight SW Flux (= 0.25 Wm⁻²) &lt; 0.1</td>
<td>0.0</td>
<td>&lt;0.1</td>
<td></td>
</tr>
<tr>
<td>Near Terminator SW Flux</td>
<td>+0.7</td>
<td>0.0</td>
<td>+0.7</td>
</tr>
<tr>
<td>3-D Cloud τ&lt;sub&gt;vis&lt;/sub&gt; bias on α(θ&lt;sub&gt;o&lt;/sub&gt;)</td>
<td>+0.7</td>
<td>0.0</td>
<td>+0.7</td>
</tr>
<tr>
<td>Ocean Heat Storage</td>
<td></td>
<td></td>
<td>+0.4-1.0</td>
</tr>
<tr>
<td>Expected Global Net Range:</td>
<td></td>
<td></td>
<td>0 to +6.5</td>
</tr>
<tr>
<td>CERES SRBAVG Ed2D Global Net</td>
<td></td>
<td></td>
<td>+6.4</td>
</tr>
</tbody>
</table>

*Will provide community with advice for optimal global “closure”*
Future Issues

• Current IPCC AR4 climate model predictions/papers show
  — uncertainty in climate sensitivity low clouds (Bony, GRL 2005)
  — climate sensitivity linear in cloud radiative forcing (Soden and Held, 2006).

• NPOESS has just eliminated the CERES follow-on sensor called ERBS.

• The last remaining CERES sensor (FM-5) is currently scheduled on NPOESS C2 in 2013/14: but gap risk is large.

• Better solution is to fly CERES FM-5 on NPP in 2010.
  — Would delay the most serious gap issue to 2015.
  — Still need a plan for broadband global data 2015-2025.
Summary

CERES goes well beyond ERBE:

• Coincident imager-based cloud and aerosol properties together with broadband CERES radiative fluxes.

• Improved accuracy of TOA fluxes by a factor of 2-5.

• Merges CERES and geostationary data for improved characterization of diurnal variations in clouds and radiation.

• Radiative flux profiles: surface, within atmosphere, TOA

Data Record Stability:

• From first 5 years of CERES Terra, CERES-SeaWiFS trend consistency: $0.02 \pm 0.3 \text{ Wm}^{-2}$ per decade.


• Future is uncertain due to revised NPOESS plan.