Surface Atmosphere Radiation Budget (SARB) working group update

Seiji Kato¹, Fred G. Rose², David A. Rutan², Alexander Radkevich², Seung Hee Ham², Tyler J. Thorsen¹
Thomas E. Caldwell², Antonio Viudez-Mora³, David Fillmore³, and Xianglei Huang⁴

¹NASA Langley Research Center
²Science System & Applications Inc.
³NCAR
⁴University of Michigan

CERES Science Team Meeting
October 29-31, 2019
Work done after the Spring 2019 CERES science team meeting

• Extended Edition 4.1 SYN1deg through May 2019
• Extended EBAF-surface through January 2019 (will be released through May 2019 after this meeting).
• Estimated the error in diurnally averaged TOA and surface irradiances computed by 2- and 4-stream models.
• Evaluated clear-sky surface irradiances
• Evaluated surface irradiances at two surface sites
  • McMurredo (complex surface types) and Macquarie Island
• Continue collaborating with GMAO in developing a new version of GEOS reanalysis for Ed5 CERES products.
• Continue updating Fu-Liou radiative transfer code
  • Revising shortwave and longwave k-distribution coefficient with HITRAN 2016 (work in progress)
Outline of this talk

• Edition 4.1 related
  • SYN surface downward shortwave and longwave irradiance evaluation over southern ocean with ship data (revised)
    • EBAF adjustment over southern ocean
    • Nighttime cloud issue
  • Entropy production estimates included in Edition 4.1 SYN1deg
  • Errors in diurnally averaged shortwave irradiances by 2- and 4-stream models.

• Edition 5 related (work in progress)
  • Revision of shortwave correlated-k
    • Longwave correlated-k will be revised using a similar approach.
  • Longwave fingerprinting to correct bias errors in temperature and humidity

• Publications
Edition 4.1 SYN1deg

• SYN1deg provides hourly computed surface irradiances at a $1^\circ \times 1^\circ$ grid resolution

• Edition 4.1 SYN1deg has been processed from March 2000 through Nay 2019 with
  • MATCH with Collection 6.1 Terra and Aqua (from July 2002)
  • Collection 5 MODIS from March 2000 through February 2016 and Collection 6.1 MODIS after March 2016 for cloud retrieval
  • GEOS-5.4.1 temperature and humidity
  • New surface albedo history map with Collection 6 (not 6.1) MODIS BRDF product
Edition 4.1 EBAF-surface

- EBAF-surface provides monthly computed surface irradiances that are consistent with CERES-derived TOA irradiance (i.e. computed TOA irradiances agree with EBAF-TOA irradiances) at a 1°×1° grid resolution.
- Temperature, humidity, surface, cloud and aerosol properties are adjusted to match CERES-derived TOA irradiances (input adjustments)
- SYN1deg Surface irradiances are adjusted based on input adjustments.
- Available through January 2019
- 4 more months (through May 2019) will be available after this meeting.
- Two types of clear-sky irradiances are included
  - Monthly mean weighted by observed hourly 1°×1° clear-sky fraction
  - Monthly mean (clear-sky occurs every hour over all grids)
Surface irradiance over Southern ocean
Surface downward **shortwave** irradiance
CMIP5 mean - EBAF

**Figure 5.** Biases between multimodel mean of surface incident shortwave radiation under all sky ($R_s$) from 48 CMIP5 ESMs and CERES EBAF $R_s$ for 2000–2005 (CMIP5-CERES EBAF, units: $\text{W m}^{-2}$). All of the CMIP5 models were resampled to a $1^\circ \times 1^\circ$ grid scale, which is the same size as that of CERES EBAF.
Evaluation of surface irradiances with ship data (revised)
Positive bias in downward shortwave

Negative bias in downward longwave especially during night
EBAF adjustments (Southern hemisphere Spring)

Downward shortwave is further increased and downward longwave is reduced in the EBAF adjustment process.
Cloud fraction

Geo derived cloud fraction is generally larger than MODIS or CALIPSO-CloudSat derived cloud fraction.
Daytime and nighttime cloud heights
Cloud optical thickness

This issue will be addressed in Edition 5
Entropy production by radiative processes

• Entropy production estimated from net irradiance and temperature is included in Edition 4.1 SYN1deg
Entropy production by irreversible processes

Diabatic heating due to frictional dissipation is often ignored
Entropy production

\[ F_{\text{net}}^{\text{TOA}} = (1 - \alpha)F_0 - F_{\text{atm}} - (1 - \varepsilon)F_{\text{sfc}} \quad (1) \]
\[ F_{\text{sfc}}^{\text{net}} = (1 - \alpha - \beta)F_0 + F_{\text{atm}} - F_{\text{sfc}} - F_{\text{tur}} \quad (2) \]

and

\[ F_{\text{atm}}^{\text{net}} = \beta F_0 + \varepsilon F_{\text{sfc}} + F_{\text{tur}} - 2F_{\text{atm}} \quad (3) \]

The sum among these net energy fluxes is

\[ F_{\text{net}}^{\text{TOA}} = F_{\text{sfc}}^{\text{net}} + F_{\text{atm}}^{\text{net}} \quad (4) \]

\[ \frac{dS}{dt} = \frac{\dot{Q}_a}{T_a} - \frac{\dot{Q}_e}{T_e} + \Sigma_{\text{irr}} \quad (14) \]

Where

\[ \dot{Q}_a = (1 - \alpha)F_0 \quad (15) \]
\[ \dot{Q}_e = (1 - \varepsilon)F_{\text{sfc}} + F_{\text{atm}} \quad (16) \]

\[ \dot{\Sigma}_{\text{tur}} = -\left[ \frac{F_{\text{net}}^{\text{sfc}, \text{SW}}}{T_{\text{sfc}}} + \frac{F_{\text{net}}^{\text{atm}, \text{SW}}}{T_{\text{atm}}} + \frac{F_{\text{net}}^{\text{sfc}, \text{LW}}}{T_{\text{sfc}}} + \frac{F_{\text{net}}^{\text{atm}, \text{LW}}}{T_{\text{atm}}} \right] \]

Figure 1: One-dimensional isothermal atmosphere model. \( F_0 \) is solar irradiance at top-of-atmosphere, \( \beta \) is the absorptivity of the atmosphere, \( \alpha \) is the reflectivity of the surface, \( T_{\text{sfc}} \) is the surface temperature, \( T_{\text{atm}} \) is the temperature of the atmosphere, \( \varepsilon \) is the emissivity of the atmosphere, and \( F_{\text{tur}} \) is the energy flux by turbulence.

Kato and Rose 2019
Production of entropy by Irreversible processes

<table>
<thead>
<tr>
<th>Entropy production (Wm⁻²K⁻¹)</th>
<th>Estimated from radiation (Wm⁻²K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frictional dissipation of turbulence (Goody 2000)</td>
<td>0.0100</td>
</tr>
<tr>
<td>Frictional dissipation of falling rain drops (Pauluis and Dias 2012)</td>
<td>0.0100</td>
</tr>
<tr>
<td>Water phase change (Goody 2000)</td>
<td>0.0188</td>
</tr>
<tr>
<td>Turbulent enthalpy transport (Goody 2000)</td>
<td>0.0024</td>
</tr>
<tr>
<td>Ocean (Bannon and Najjar 2019)</td>
<td>0.0016</td>
</tr>
<tr>
<td>Total</td>
<td>0.0428</td>
</tr>
</tbody>
</table>
Entropy production by irreversible process estimated in CMIP5 models

Table 2. Annual mean values of a 20-year subset of control runs from 12 models participating in CMIP5 for TOA and surface energy budgets ($B_t$ and $B_s$, respectively), maximal and minimal peaks of atmospheric and oceanic meridional enthalpy transports (with peak locations in latitude degrees specified in brackets) ($T_{a_{max}}$, $T_{a_{min}}$, $T_{o_{max}}$, $T_{o_{min}}$), water mass budget ($\overline{E} - \overline{P}$), latent energy budget ($\overline{R_L}$), mechanical work by the Lorenz energy cycle, and material entropy production computed with the direct and indirect methods ($\overline{\Sigma_{mat_{dir}}} \quad \text{and} \quad \overline{\Sigma_{mat_{ind}}}$, respectively).

<table>
<thead>
<tr>
<th></th>
<th>$R_t$ (W m$^{-2}$)</th>
<th>$F_s$ (W m$^{-2}$)</th>
<th>$T_{a_{max}}$ (PW)</th>
<th>$T_{a_{min}}$ (PW)</th>
<th>$T_{o_{max}}$ (PW)</th>
<th>$T_{o_{min}}$ (PW)</th>
<th>$\overline{E} - \overline{P}$ (kg m$^{-2}$ s$^{-1}$ $\times 10^{-8}$)</th>
<th>$\overline{R_L}$ (W m$^{-2}$)</th>
<th>$W$ (W m$^{-2}$)</th>
<th>$\overline{\Sigma_{mat_{dir}}}$ (mW m$^{-2}$ K$^{-1}$)</th>
<th>$\overline{\Sigma_{mat_{ind}}}$ (mW m$^{-2}$ K$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNU</td>
<td>2.37</td>
<td>0.79</td>
<td>4.9 (42)</td>
<td>-5.1 (-39)</td>
<td>1.9 (19)</td>
<td>-0.9 (-17)</td>
<td>-207.1</td>
<td>-5.89</td>
<td>2.0</td>
<td>64.9</td>
<td>58.7</td>
</tr>
<tr>
<td>Can2</td>
<td>0.08</td>
<td>0.19</td>
<td>4.7 (41)</td>
<td>-5.1 (-39)</td>
<td>1.5 (20)</td>
<td>-1.1 (-13)</td>
<td>5.32</td>
<td>-0.55</td>
<td>2.2</td>
<td>42.7</td>
<td>56.6</td>
</tr>
<tr>
<td>IPSL-M</td>
<td>0.33</td>
<td>0.32</td>
<td>4.6 (40)</td>
<td>-5.2 (-39)</td>
<td>1.5 (19)</td>
<td>-1.4 (-14)</td>
<td>11.1</td>
<td>-0.48</td>
<td>1.6</td>
<td>38.7</td>
<td>57.9</td>
</tr>
<tr>
<td>MIR-C</td>
<td>-3.16</td>
<td>1.50</td>
<td>4.8 (42)</td>
<td>-5.7 (-37)</td>
<td>1.4 (19)</td>
<td>-0.4 (-9)</td>
<td>-1.24</td>
<td>-0.70</td>
<td>1.3</td>
<td>39.8</td>
<td>56.5</td>
</tr>
<tr>
<td>MIR5</td>
<td>1.06</td>
<td>1.13</td>
<td>4.2 (42)</td>
<td>-4.6 (-40)</td>
<td>1.3 (18)</td>
<td>-0.6 (-10)</td>
<td>-2.94</td>
<td>-0.71</td>
<td>1.4</td>
<td>43.4</td>
<td>60.3</td>
</tr>
<tr>
<td>MPI-LR</td>
<td>0.36</td>
<td>0.58</td>
<td>5.0 (42)</td>
<td>-5.5 (-38)</td>
<td>1.9 (19)</td>
<td>-1.3 (-12)</td>
<td>-4.58</td>
<td>-0.88</td>
<td>1.8</td>
<td>43.4</td>
<td>58.7</td>
</tr>
<tr>
<td>MPI-MR</td>
<td>0.45</td>
<td>0.60</td>
<td>5.1 (42)</td>
<td>-5.6 (-39)</td>
<td>1.8 (19)</td>
<td>-1.3 (-11)</td>
<td>-4.03</td>
<td>-0.86</td>
<td>1.7</td>
<td>43.4</td>
<td>58.9</td>
</tr>
</tbody>
</table>

Lembo et al. 2019

CERES estimate = 49 mWm$^{-2}$
Errors in diurnally averaged shortwave irradiances by 2- and 4-stream models
Modeling error due to 2- and 4-stream approximations

Edition 4 uses:
- a 2-stream model for horizontally inhomogeneous clouds (gamma-weighted-two-stream) and
- a 4-stream model for homogeneous clouds and clear-sky

Although the error in instantaneous irradiances are known, the error in diurnally averaged irradiances is unknown

Liou et al. 1988
Diurnally averaged Irradiance error computed with 2-stream and 4-stream models

Ham et al. 2019 JAS
Fu-Liou correlated-\(k\) update

• Shortwave and Longwave
  • LBLRTM 2018 package with HITRAN 2012 and MT_CKD_3.2 continuum
  • Correlated \(k_s\) are generated by the method described in Kato et al. (1999)
Optical thickness by $k$

**Edition 5 approach**

**Edition 4 approach**

- K1@ 22.0%: Solid
- K2@ 51.0%: Dotted
- K3@ 22.0%: Dashed
- K4@ 5.0%: DotDash

- Edition 4 treats water vapor continuum as an independent gas.
- Effect of the optical depth differences on flux computations need to be tested.
Use spectral radiance to correct monthly mean temperature and humidity

Theoretical estimate of the error in correcting mean temperature and humidity
Next step is to use observed spectral radiances by AIRS
Publications


Summary

• Evaluation of Edition 4.1 SYN and EBAF downward surface irradiances over southern ocean is revised
  • Downward shortwave irradiances are overestimated by up to 10 Wm\(^{-2}\) depending on season
  • Downward longwave irradiances are underestimated especially during night
• Entropy production derived from radiation is included in Edition 4.1 SYN.
• Fu-Liou shortwave and longwave radiative transfer code will be revised for Edition 5.
Cloud fraction bias

Geo derived cloud fraction is generally larger than MODIS or CALIPSO-CloudSat derived cloud fraction.
EBAF adjustments (Southern hemisphere Fall)
Carnot efficiency of the Earth system

\[ Ta = \frac{\text{Shortwave irradiance absorbed by Earth}}{\text{Entropy production by shortwave}} = 282 \text{ K (9 °C)} \]
\[ Te = \frac{\text{Longwave irradiance emitted by Earth}}{\text{Entropy production by longwave}} = 259 \text{ K (-14 °C)} \]

\[ \eta = \frac{T_a - T_e}{T_a} = 0.085 \]

Carnot efficiency of a gasoline engine \( \sim \frac{(1089 \text{ K} - 300 \text{ K})}{1089 \text{ K}} = 0.725 \)

Theoretical upper limit of thermal efficiency