Diurnally Integrated Two- and Four-Stream Biases in SW Irradiances in Comparison to Monte Carlo Method

Seung-Hee Ham¹, Seiji Kato², and Fred Rose¹

¹Science Systems and Applications, Inc. (SSAI), Hampton, Virginia, USA
²NASA Langley Research Center, Hampton, Virginia, USA
Motivation

- Two- and four-stream approximations are used for irradiance calculations of CERES processing.
- The two- and four-stream biases are well understood for simplified cloud scenarios, but it is not clear how these biases will affect diurnally-integrated monthly or annual means of SW irradiances.
Objectives

1. Understand two- and four-stream biases for simplified cases
2. Integrate the two- and four-stream biases using CERES SYN surface, atmosphere, and cloud properties monthly and annually
3. Suggest long-term effects of the two- and four-stream biases in SW irradiance computations
Used Models and Methods

- Fu-Liou radiative transfer model modified by CERES team (FLCKKR) (Kratz and Rose 1999; Kato et al. 1999, 2005; Rose et al. 2006).

1) **Delta-two-stream-Eddington (2strEdd)**  
(Irvine 1968; Kawata and Irvine 1970; Shettle and Weinman 1970)  
\[ l(\mu, t) = l_0(t) + \mu l_1(t) \]  
The radiance is expressed by a polynomial of \( \mu \) along with the zeroth \( (l_0) \) and first \( (l_1) \) Legendre polynomial moments of the radiance.

2) **Delta-two-stream-quadrature (2strQuad)** (Liou 1992)  
The angular integral of the radiance is expressed using the two-point gaussian quadrature.

3) **Delta-four-stream-quadrature (4strQuad)** (Liou et al. 1988; Fu 1991)  
The angular integral of the radiance is expressed using the four-point gaussian quadrature.

Simplified Case: Water clouds (2-3 km) over ocean

- The two-stream methods give negative biases at TOA and positive biases at surface.
- The four-stream method gives better results than the two-stream methods.
- Biases in absorbed flux are smaller than those at TOA or surface.

2strEdd – MC

2strQuad – MC

4strQuad – MC
Large Two-stream Biases over Snow (Water Clouds 2-3 km)

- The two-stream methods give large biases at surface downward irradiances over snow surface type.

### 2strEdd – MC

### 2strQuad – MC

### 4strQuad – MC
Impact of Diurnal Integration:
For the same cloud optical depth, diurnal variation of SZAs leads cancellation of two- and four-stream biases.

Given that the cloud optical depth remains over the course of day, diurnal variation of SZAs leads cancellation of two- and four-stream biases.
Impact of Diurnal Integration:
Diurnally integrated two- and four-stream biases are smaller than hourly biases.

Usually biases are decreased by > 50% from diurnal integration.
Two- and Four-stream biases for SW heating rates (Water Clouds at 2-3km, Tau=10)

- Both two-stream methods (2strEdd and 2strQuad) produce negative biases at the altitude of cloud layers, and positive biases below the cloud layers.
- The four-stream method (4strQuad) produces close agreement with MC results.
- The sign of biases remain the same for different SZAs for two stream methods (less cancellation in diurnal integration), but not four-stream method (more cancellation).

Monte Carlo (MC): Reference
- 2strEdd – MC
- 2strQuad – MC
- 4strQuad – MC
Model Inputs – CERES Ed4 SYN hourly Product

- **Surface:** CERES SYN ocean and snow/ice coverages
  - Snow albedo model (Jin et al., 2004) when snow/ice coverage > 10%
  - Ocean albedo model (Jin et al., 2004) when the ocean coverage ≥ 50% and snow/ice coverage ≤ 10%
  - Land surface albedo 0.1 for clear sky, and 0.12 for cloudy sky when ocean coverage is < 50% and snow/ice coverage ≤ 10%

- **Clouds:** CERES SYN cloud properties for up four cloud types – low (> 700 hPa), mid-low (500-700 hPa), mid-high (300-500 hPa), and high (< 300 hPa)
  - Cloud phase: liquid or ice
  - Cloud top & base heights: truncated at a 1-km resolution
  - Cloud optical depth: truncated at 51 cloud optical depth bins

- **Temperature and WV profiles:** CERES precipitable water (PW)
  - Midlatitude summer (MLS) standard profile when PW > 1 cm
  - Midlatitude winter (MLW) standard profile when PW ≤ 1 cm

→ Radiative computations are performed up to five scenarios (clear, low, mid-low, mid-high, and high) for each hourly grid box, and these are averaged based on cloud areas. Then fluxes at hourly grid boxes are monthly and annually averaged.
Integrated Two- and Four-stream biases in TOA SW Upward Irradiances

- The large negative two-stream biases appear in cloudy regions.
- Annual and monthly global means of biases are very similar, suggesting that the biases are not cancelled for long-term means.
Integrated Two- and Four-stream biases in SW SFC Dn Irradiances

- The large positive two-stream biases appear in cloudy region.
- Annual and monthly global means are very similar, suggesting that the biases are not cancelled for long-term means.
Global Mean and RMS Biases depending on Averaging Time Window

TOA Upward
- Global Mean Bias
  - +0.1 W m\(^{-2}\) (0.1%)
  - +0.2 W m\(^{-2}\) (0.2%)
  - +0.3 W m\(^{-2}\) (0.2%)
  - +0.6 W m\(^{-2}\) (0.5%)
  - +0.9 W m\(^{-2}\) (0.8%)
  - +1.1 W m\(^{-2}\) (0.8%)

ATM Abs
- Global Mean Bias
  - +1.4 W m\(^{-2}\) (0.8%)
  - +2.6 W m\(^{-2}\) (1.4%)

SFC Down
- Global Mean Bias
  - +2.6 W m\(^{-2}\) (1.4%)
  - +1.4 W m\(^{-2}\) (0.8%)
  - +0.2 W m\(^{-2}\) (0.2%)
  - +0.3 W m\(^{-2}\) (0.2%)
  - +0.6 W m\(^{-2}\) (0.5%)
  - +0.9 W m\(^{-2}\) (0.8%)
  - +1.1 W m\(^{-2}\) (0.8%)

Global RMS Bias
- Stabilize after 10 days
  - 2strEdd
  - 2strQuad
  - 4strQuad
Integrated Two- and Four-stream biases in SW Heating Rates

- 2strEdd produces negative biases at cloud layers, and positive biases below cloud layers.
- 2strQuad produces larger negative biases than 2strEdd method.
- 4strQuad method produces negligible biases in computed heating rates.
Conclusions

- When integrating biases diurnally, positive and negative signs are compensating and the magnitude gets smaller by more than 50%. The biases are further smoothed when considering various cloud optical depths using CERES SYN product. However, monthly and annual global means are very close, and RMS biases stabilize once the averaging time window > 10 days. The global mean two-stream biases can be order of 0.5–1 W m\(^{-2}\) at TOA and 1.5–2.5 W m\(^{-2}\) at surface in the long-term means (corresponding < 1.5%).

- Delta-four-stream-quadrature (4strQuad) method shows much smaller biases (< 0.2%) than two-stream methods.

- Compared to 2strQuad, 2strEdd method generally shows a better performance (e.g. snow surface, and HR profiles).
Thank you for your attention!
Simplified Case: 
Ice clouds (10–12 km) over ocean

- Overall signs and magnitudes are very similar to the water cloud case.
- Slight differences from water cloud cases are due to different scattering phase functions (or simply asymmetry parameter).

\[
\text{TOA UP} - \text{TOA bias} \\ + \text{SFC bias} \\
\text{Atms Abs} \\ + \text{SFC bias} \\
\text{SFC DN} - \text{TOA bias} - \text{SFC bias} \\
\text{2strEdd} - \text{MC} \\
\text{2strQuad} - \text{MC} \\
\text{4strQuad} - \text{MC}
\]
## Summary of Annual SW Biases Due to Two- and Four-Stream Approximations (Annual Mean)

<table>
<thead>
<tr>
<th>Method</th>
<th>Global 90°S–90°N</th>
<th>Ocean 60°S–60°N</th>
<th>Land 60°S–60°N</th>
<th>Antarctic 90°S–60°S</th>
<th>Arctic 60°N–90°N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TOA upward Irradiances (W m⁻²)</td>
<td>Surface Downward Irradiances (W m⁻²)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>MC</strong></td>
<td>101.19</td>
<td>97.08</td>
<td>103.83</td>
<td>109.68</td>
<td>122.57</td>
</tr>
<tr>
<td>2strEdd</td>
<td>100.33</td>
<td>96.00</td>
<td>103.29</td>
<td>109.18</td>
<td>122.32</td>
</tr>
<tr>
<td></td>
<td>(−0.87)</td>
<td>(−1.09)</td>
<td>(−0.54)</td>
<td>(−0.50)</td>
<td>(−0.25)</td>
</tr>
<tr>
<td>2strQuad</td>
<td>100.64</td>
<td>96.20</td>
<td>103.62</td>
<td>109.92</td>
<td>123.17</td>
</tr>
<tr>
<td></td>
<td>(−0.55)</td>
<td>(−0.88)</td>
<td>(−0.21)</td>
<td>(−0.24)</td>
<td>(−0.60)</td>
</tr>
<tr>
<td>4strQuad</td>
<td>101.32</td>
<td>97.21</td>
<td>103.90</td>
<td>109.95</td>
<td>122.77</td>
</tr>
<tr>
<td></td>
<td>(+0.13)</td>
<td>(+0.13)</td>
<td>(+0.07)</td>
<td>(+0.28)</td>
<td>(+0.19)</td>
</tr>
</tbody>
</table>
CERES SYN Ed4 Cloud Properties

(a) Cloud Amount (%) (2010/01)
(b) Cloud Amount (%) (2010/07)

(c) Cloud Optical Depth (2010/01)
(d) Cloud Optical Depth (2010/07)
CERES SYN Ed4 Surface and Atmospheric Properties

- Snow Coverage (%) (2010/01) & (2010/07)
- Total Precipitable Water (cm) (2010/01) & (2010/07)
Radiative Transfer Method (Meador and Weaver, 1980)

### Table 1. Coefficients $\gamma_i$ in the two-stream equations (12) and (13).

<table>
<thead>
<tr>
<th>Method</th>
<th>$\gamma_1$</th>
<th>$\gamma_2$</th>
<th>$\gamma_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eddington</td>
<td>$\frac{1}{4}(7 - \omega_0(4 + 3g))$</td>
<td>$-\frac{1}{4}[1 - \omega_0(4 - 3g)]$</td>
<td>$\frac{1}{4}(2 - 3g \mu_0)$</td>
</tr>
<tr>
<td>Modified Eddington Quadrature</td>
<td>$\frac{1}{4}(7 - \omega_0(4 + 3g))$</td>
<td>$-\frac{1}{4}[1 - \omega_0(4 - 3g)]$</td>
<td>$\beta_0$</td>
</tr>
<tr>
<td>Modified quadrature*</td>
<td>$(3^{1/2}/2)[2 - \omega_0(1 + g)]$</td>
<td>$(3^{1/2}\omega_0/2)(1 - g)$</td>
<td>$\beta_0$</td>
</tr>
<tr>
<td>Hemispheric constant</td>
<td>$2[1 - \omega_0(1 - \beta)]$</td>
<td>$3^{1/2}\omega_0\beta_1$</td>
<td>$\beta_0$</td>
</tr>
<tr>
<td>Delta function</td>
<td>$\mu_0^{-1}[1 - \omega_0(1 - \beta_0)]$</td>
<td>$2\omega_0 \beta$</td>
<td>$\beta_0$</td>
</tr>
<tr>
<td>Hybrid modified Eddington-delta function</td>
<td>$7 - 3g^2 - \omega_0(4 + 3g) + \omega_0g^2(4\beta_0 + 3g)$</td>
<td>$- \frac{1}{4} - g^2 - \omega_0(4 - 3g) - \omega_0g^2(4\beta_0 + 3g - 4)$</td>
<td>$\beta_0$</td>
</tr>
</tbody>
</table>

* $\beta_1$ corresponds to $\mu_1 = 3^{-1/2}$. 


A standard deviation of computed irradiances is computed among 100 batches, which can be considered as a Monte Carlo noise.

The noise decreases with the number of photons, largely decreases at $10^4 \rightarrow 10^6$ photons.

Once the number of photons exceeds $10^6$ photons, the results get reliable, showing $< 0.6$ W m$^{-2}$. 

![Graph showing Monte Carlo Noise](image-url)