Outline

• Ed4 Angular Distribution Models (ADMs)
• Cloud property differences between Ed2 and Ed4
• Flux differences due to changes in cloud properties and ADMs
• Validation
  – Shortwave direct integration
  – Longwave direct integration
  – CERES-MISR flux consistency test
  – CERES-MODIS flux consistency test
  – Ed4 cloud fraction vs. Calipso-CloudSat
• Summary and future plan
<table>
<thead>
<tr>
<th>Scene</th>
<th>Ed2</th>
<th>Ed4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Land</td>
<td>1° regional monthly ADM using Ahmad&amp;Deering 8-parameter fit for different NDVI (0.1), cosθ (0.2);</td>
<td>1° regional monthly ADM using modified Ross-Li 3-parameter fit for different NDVI (0.1), cosθ (0.2), and surface roughness;</td>
</tr>
<tr>
<td>Clear Ocean</td>
<td>Function of wind speed; correction for AOD;</td>
<td>Function of wind speed, AOD, and aerosol type;</td>
</tr>
<tr>
<td>Cloud Ocean</td>
<td>Continuous 5-parameter sigmoid function of ln(ft) for three phases;</td>
<td>Update using the Ed2 method;</td>
</tr>
<tr>
<td>Cloud Land</td>
<td>Continuous 5-parameter sigmoid function of ln(ft) for three phases;</td>
<td>Update using the Ed2 method;</td>
</tr>
</tbody>
</table>
## SW ADM for different scene types: Ed2 vs Ed4

<table>
<thead>
<tr>
<th>Scene</th>
<th>Ed2</th>
<th>Ed4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh Snow</td>
<td>Cloud fraction (6), snow fraction, bright/dark surface (clear 100% snow cover and ovcst), cloud optical depth (ovcst);</td>
<td>Clear: 1° regional monthly ADM using Ross-Li 3-para fit for different NDVI (0.1), cosθ (0.2), and surface roughness;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Partly cloudy: surface brightness (6), and cloud fraction (4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Overcast: surface brightness (6), cloud phase (2), and cloud optical depth percentile bins (3)</td>
</tr>
<tr>
<td>Perm. Snow</td>
<td>Cloud fraction (6), bright/dark surface (clr&amp;ovcst), cloud optical depth (ovcst);</td>
<td>Clear Antarctica: use MISR data to develop ADMs that account for the effect of sastrugi</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Clear Greenland: one ADM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Partly cloudy: cloud fraction (4, same as Ed2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Overcast: cloud phase (2), and log optical depth bin (4)</td>
</tr>
<tr>
<td>Sea-Ice</td>
<td>Cloud fraction (6), ice fraction, bright/dark surface (clear 100% ice cover and ovcst), cloud optical depth (ovcst);</td>
<td>Clear: sea ice fraction (6), for 100% sea ice coverage use sea ice brightness index (3) to classify surface brightness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Partly cloudy: cloud fraction (4), for 100% sea ice coverage use sea ice brightness index (3) to classify surface brightness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Overcast: sea ice brightness index (5), phase (2), linear function of ln(tau)</td>
</tr>
</tbody>
</table>
### LW ADM for different scene types: Ed2 vs Ed4

<table>
<thead>
<tr>
<th>Scene</th>
<th>Ed2</th>
<th>Ed4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Ocean/Land</td>
<td>Discrete bins of precip. water, lapse rate, skin temp. for six surface types;</td>
<td>Increase skin temp. bins from 5 to 10 and add interpolation;</td>
</tr>
<tr>
<td>Cloudy Ocean/Land</td>
<td>Third-order polynomial fits between radiance and ‘pseudoradiance ( \Psi )’ for intervals of precip. water, cloud fraction, surface skin temp. and sfc-cld temp. difference;</td>
<td>Instead of a polynomial fit between pseudoradiance ( \Psi ) and radiance, the mean radiance for each 1 W m(^{-2}) sr(^{-1}) interval of ( \Psi ) is used. In addition, there are now 5 cloud fraction bins (0.1-25%, 25-50%, 50-75%, 75-99.9%, overcast).</td>
</tr>
</tbody>
</table>
### LW ADM for different scene types: Ed2 vs Ed4

<table>
<thead>
<tr>
<th>Scene</th>
<th>Ed2</th>
<th>Ed4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh Snow</td>
<td>Discrete bins of cloud fraction, surface skin temp., and sfc-cld temp. difference;</td>
<td>Clr: Add Ts bins and interpolation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Clld: Use mean radiance for each 1 W m(^{-2}) sr(^{-1}) interval of (\Psi) for intervals of cloud fraction, surface skin temp. and sfc-cld temp. difference;</td>
</tr>
<tr>
<td>Permanent Snow</td>
<td>Discrete bins of cloud fraction, surface skin temp., and sfc-cld temp. difference;</td>
<td>Clr: Add Ts bins and interpolation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Clld: Use mean radiance for each 1 W m(^{-2}) sr(^{-1}) interval of (\Psi) for intervals of cloud fraction, surface skin temp. and sfc-cld temp. difference;</td>
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<tr>
<td>Sea-Ice</td>
<td>Discrete bins of cloud fraction, surface skin temp., and sfc-cld temp. difference;</td>
<td>Clr: Add Ts bins and interpolation</td>
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<td>Clld: Use mean radiance for each 1 W m(^{-2}) sr(^{-1}) interval of (\Psi) for intervals of cloud fraction, surface skin temp. and sfc-cld temp. difference;</td>
</tr>
</tbody>
</table>
Daytime cloud property difference between Ed3 and Ed4: Aqua FM4 200410

200410:FM4 Cloud fraction Ed4: mean $f=65.3\%$

200410:FM4 Cloud fraction diff (Ed4−Ed3): $\Delta f=3.6\%$

200410:FM4 Cloud $\tau$ for Ed4: mean $\tau=3.7$

200410:FM4 Cloud $\tau$ diff (Ed4−Ed3): $\Delta \tau=0.2$
SW flux change between Ed3 and Ed4: Aqua FM4 200410

Ed4 SW flux

200410:FM4 SW flux Ed4: mean SW=237.5Wm$^{-2}$

SW flux diff: Ed4-Ed3

Flux change due to cloud change

200410:FM4 SW Diff (Ed4S/Ed2A-Ed3S/Ed2A): $\Delta$SW=0.2Wm$^{-2}$

Flux change due to ADM change

200410:FM4 SW Diff (Ed4S/Ed4A-Ed4S/Ed2A): $\Delta$SW=0.9Wm$^{-2}$
Daytime LW flux change between Ed3 and Ed4: Aqua FM4 200410

Ed4 LW flux

200410:FM4 LW flux Ed4: LW=245.3 Wm\(^{-2}\)

LW flux diff: Ed4-Ed3

200410:FM4 LW flux Diff (Ed4−Ed3): ΔLW=0.4 Wm\(^{-2}\)

Flux change due to cloud change

200410:FM4 ΔLW (Ed4S/Ed2A−Ed3S/Ed2A): ΔLW=−0.1 Wm\(^{-2}\)

Flux change due to ADM change

200410:FM4 ΔLW (Ed4S/Ed4A−Ed4S/Ed2A): ΔLW=0.5 Wm\(^{-2}\)
Nighttime cloud property difference between Ed3 and Ed4: Aqua FM4 200410

200410:FM4 Cloud fraction Ed4: mean $f=70.0\%$

200410:FM4 Cloud fraction diff (Ed4−Ed3): $\Delta f=9.3\%$

200410:FM4 Cloud $\tau$ for Ed4: mean $\tau=2.6$

200410:FM4 Cloud $\tau$ diff (Ed4−Ed3): $\Delta \tau=-0.7$

10/29/2013
Nighttime LW flux change between Ed3 and Ed4: Aqua FM4 200410

Ed4 LW flux

200410:FM4 LW flux Ed4: mean LW=236.6Wm$^{-2}$

LW flux diff: Ed4-Ed3

200410:FM4 $\Delta$LW (Ed4-Ed3): $\Delta$LW=−0.0Wm$^{-2}$

Flux change due to cloud change

200410:FM4 $\Delta$LW (Ed4S/Ed2A-Ed3S/Ed2A): $\Delta$LW=−0.3Wm$^{-2}$

Flux change due to ADM change

200410:FM4 $\Delta$LW (Ed4S/Ed4A-Ed4S/Ed2A): $\Delta$LW=0.3Wm$^{-2}$
Global monthly mean flux difference between Ed4 and Ed3

- Annual mean SW flux increases 0.8 Wm\(^{-2}\)
- Annual mean daytime LW flux increases 0.2 Wm\(^{-2}\)
- Annual mean nighttime LW flux decreases 0.1 Wm\(^{-2}\)

Global monthly mean flux diff (Ed4–Ed3) for Terra FM1 2002

- Annual mean SW flux increases 1 Wm\(^{-2}\)
- Annual mean daytime LW flux increases 0.4 Wm\(^{-2}\)
- Annual mean nighttime LW flux is the same

Global monthly mean flux diff (Ed4–Ed3) for Aqua FM4 2004
Validation
Direct integration

\[ F(\theta_0) = \int_0^{2\pi} \int_0^{\pi/2} I(\theta_0, \theta, \phi) \cos \theta \sin \theta \, d\theta \, d\phi \]
Direct integration for SW flux

- Use observed ($I_o$) and ADM-predicted ($\hat{I}$) radiances to construct two sets of regional (10° X 10°) all-sky ADMs for each season

$$F(\theta_0) = \frac{\pi I_o(\theta_0, \theta, \phi)}{R(\theta_0, \theta, \phi)}$$

$$R(\theta_0, \theta, \phi) = \frac{\pi \hat{I}(\theta_0, \theta, \phi)}{\hat{F}(\theta_0)}$$

- Both sets of regional all-sky ADMs have the same sampling

- Compare fluxes derived from these two sets of ADMs
Direct integration SW flux error for 2002 Terra FM1
(flux from predicted radiance ADM - flux from observed radiance ADM)

Direction integration using Ed4ADM

Direction integration using Ed2ADM

Jan
DI flux difference for Jan. 2002 FM1 Ed4ADM

July
DI flux difference for July 2002 FM1 Ed4ADM
Zonal mean SW flux error for 2002 Terra FM1

DI flux difference for Jan. 2002:FM1

- **bias** = 0.07
- **rms** = 0.79

DI flux difference for Apr. 2002:FM1

- **bias** = 0.08
- **rms** = 0.65

DI flux difference for July 2002:FM1

- **bias** = -0.33
- **rms** = 0.96

DI flux difference for Oct. 2002:FM1

- **bias** = -0.08
- **rms** = 0.84

DI flux difference for July 2002:FM1

- **bias** = -0.20
- **rms** = 0.89

DI flux difference for Oct. 2002:FM1

- **bias** = -0.15
- **rms** = 0.75
Direct integration SW flux error for 2004 Aqua FM4 (flux from predicted radiance ADM - flux from observed radiance ADM)

Direction integration using Ed4ADM

Direction integration using Ed2ADM

Apr. DI flux difference for Apr. 2004:FM4 Ed4ADM

Wm$^{-2}$


Wm$^{-2}$
Zonal mean SW flux error for 2004 Aqua FM4

Jan.

DI flux difference for Jan. 2004:FM4

Ed4ADM

Ed2ADM

bias=0.12
rms=0.87
bias=-0.12
rms=0.98

Apr.

DI flux difference for Apr. 2004:FM4

Ed4ADM

Ed2ADM

bias=-0.10
rms=0.65
bias=-0.20
rms=0.74

July

DI flux difference for July 2004:FM4

Ed4ADM

Ed2ADM

bias=0.10
rms=0.75
bias=-0.17
rms=0.92

Oct.

DI flux difference for Oct. 2004:FM4

Ed4ADM

Ed2ADM

bias=0.13
rms=0.64
bias=-0.04
rms=0.86
Direct integration for LW

- LW flux is a weak function of solar zenith angle
- Use standard direct integration for LW flux
- Done separately for daytime and nighttime observations
- Weight the daytime and nighttime flux error by fraction of daylight at each latitude for each month to derive the 24h-averaged flux error
Direct integration LW flux error for 2002 Terra FM1
(ADM flux – DI flux)

Direction integration using Ed4ADM

Jan
DI flux difference for 24h Jan. 2002 FM1 Ed4ADM

July
DI flux difference for 24h July 2002 FM1 Ed4ADM

Direction integration using Ed2ADM

DI flux difference for 24h Jan. 2002 FM1 Ed2ADM

DI flux difference for 24h July 2002 FM1 Ed2ADM
Zonal mean LW flux error for 2002 Terra FM1

DI flux difference for 24h Jan. 2002 FM1

- Bias = 0.37
- RMS = 0.55

DI flux difference for 24h July 2002 FM1

- Bias = 0.44
- RMS = 0.57

DI flux difference for 24h Apr. 2002 FM1

- Bias = 0.47
- RMS = 0.54

DI flux difference for 24h Oct. 2002 FM1

- Bias = 0.40
- RMS = 0.48
Direct integration LW flux error for 2004 Aqua FM4 (ADM flux - DI flux)

Direction integration using Ed4ADM

Direction integration using Ed2ADM

Apr. DI flux difference for 24h Apr. 2004 FM4 Ed4ADM

Zonal mean LW flux error for 2004 Aqua FM4

**DI flux difference for 24h Jan. 2004 FM4**
- bias = 0.29
- rms = 0.51
- bias = 0.03
- rms = 0.56

**DI flux difference for 24h Apr. 2004 FM4**
- bias = 0.37
- rms = 0.41
- bias = 0.15
- rms = 0.43

**DI flux difference for 24h July 2004 FM4**
- bias = 0.31
- rms = 0.53
- bias = 0.05
- rms = 0.55

**DI flux difference for 24h Oct. 2004 FM4**
- bias = 0.36
- rms = 0.46
- bias = 0.10
- rms = 0.48
Flux consistency from nine MISR cameras

- MISR instrument has 4 spectral bands;
- MISR instrument has 9 cameras;
- Average MISR pixel-level radiances into along-track CERES footprint using CERES convolution algorithm.
CERES-MISR consistency test

- Convert narrow band MISR radiance to broadband radiance for each MISR camera
  \[ I_{sw}^m = c_0 + c_1 I_{0.45} + c_2 I_{0.67} + c_3 I_{0.87} \]

- Apply CERES ADM to MISR broadband radiances to derive fluxes from different MISR cameras (j)

- Calculate flux consistency in the MISR fluxes using sample standard deviation:
  \[ s_i = \sqrt{\frac{\sum_{j=1}^{n} (F_{ij} - \overline{F_{sw}})^2}{n - 1}} \]
CERES-MISR consistency test

- Calculate the overall relative consistency of the TOA fluxes for a population of CERES footprint:

\[
CV_T = \left( \sqrt{\frac{1}{M} \sum_{i=1}^{M} s_i^2} \right) \times 100\%
\]

- Determine narrow-to-broadband regression error

- Calculate the flux consistency error from ADM

\[
CV_{ADM} = \sqrt{CV_T^2 - CV_{NB}^2}
\]

- 137 alongtrack days used
# Cloud layer classification

<table>
<thead>
<tr>
<th></th>
<th>Partly cloudy</th>
<th>Mostly cloudy</th>
<th>Overcast</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High</strong></td>
<td>19 20 21</td>
<td>22 23 24</td>
<td>25 26 27</td>
</tr>
<tr>
<td><strong>Mid</strong></td>
<td>10 11 12</td>
<td>13 14 15</td>
<td>16 17 18</td>
</tr>
<tr>
<td><strong>Low</strong></td>
<td>1 2 3</td>
<td>4 5 6</td>
<td>7 8 9</td>
</tr>
<tr>
<td>Thin</td>
<td></td>
<td>Thin</td>
<td>Thick</td>
</tr>
<tr>
<td>Mod</td>
<td></td>
<td>Mod</td>
<td>Thick</td>
</tr>
<tr>
<td>Thick</td>
<td></td>
<td>Thin</td>
<td>Mod</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Partly cloudy: CF =0.1-40%</th>
<th>High: EP&lt;440 hPa</th>
<th>Thin: $\tau &lt; 3.35$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mostly cloudy: CF=40-99%</td>
<td>Mid: EP = 440-680 hPa</td>
<td>Mod: $\tau = 3.35 -22.63$</td>
<td></td>
</tr>
<tr>
<td>Overcast: CF=99-100%</td>
<td>Low: EP &gt; 680 hPa</td>
<td>Thick: $\tau &gt; 22.63$</td>
<td></td>
</tr>
</tbody>
</table>
Flux consistency for single layer clouds over ocean

Occurrence frequency: <0.1% 0.1-1% 1-5% 5-10% 10-20% >20%

CV_T  CV_{ADM}
Flux consistency for multi-layer clouds over ocean

Occurrence frequency:
- <0.1%
- 0.1-1%
- 1-5%
- 5-10%
- 10-20%
- >20%

CERES	STM
Ed4ADM improves the MISR flux consistency over ocean for clear, cloudy, and all-sky conditions

<table>
<thead>
<tr>
<th></th>
<th>Clear Ocean</th>
<th>Single Layer</th>
<th>Multilayer</th>
<th>All sky</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ed4ADM</td>
<td>Ed2ADM</td>
<td>Ed4ADM</td>
<td>Ed2ADM</td>
</tr>
<tr>
<td>$cv_{adm}(%)$</td>
<td>3.7</td>
<td>3.8</td>
<td>5.0</td>
<td>5.2</td>
</tr>
<tr>
<td>$Cv_{adm}(Wm^{-2})$</td>
<td>3.2</td>
<td>3.3</td>
<td>13.2</td>
<td>13.7</td>
</tr>
<tr>
<td>Population (%)</td>
<td>2.3</td>
<td>2.3</td>
<td>56.4</td>
<td>56.4</td>
</tr>
</tbody>
</table>
Ed4ADM improve the MISR flux consistency

Clear sky
Single-layer clouds
Multi-layer clouds
All sky

Clear sky
Single-layer clouds
Multi-layer clouds
All sky

SW TOA flux consistency (%)

Ocean
Land
PermSnow
FshSnow
Sealce
CERES-MODIS instantaneous TOA flux consistency test
CERES-MODIS instantaneous TOA flux consistency test

- Convert MODIS narrow band radiance to broad band radiance
  \[ I_{sw}^{md} = d_0 + d_1 I_{0.65} + d_2 I_{0.86} + d_3 I_{1.63} \]

- Apply CERES ADM to nadir-viewing MODIS “broadband” radiance and to oblique-viewing (θ=50°-60°) CERES broadband radiance

- Calculate the relative RMS difference between nadir-viewing and oblique-viewing fluxes
  \[ \psi = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left[ F(\theta_{ni}) - F(\theta_{oi}) \right]^2} \times 100\% \]
CERES-MODIS flux consistency over clear ocean: dependence on MODIS fine mode fraction is smaller than using Ed2ADM
Cloud fraction difference between Ed4 cloud mask and Calipso-Cloudsat: Ocean daytime
Cloud fraction difference between Ed4 cloud mask and Calipso-Cloudsat: Land nighttime
More talks on ADM

• Zach Eitzen: Edition 4 longwave angular distribution models

• Joe Corbett: Use MODIS spectral information for CERES fresh snow angular distribution models

• Yong Hu: CALIPSO/MODIS comparisons of multi-layer clouds, and potential impact on radiation budget estimates
Summary

- Ed4 cloud algorithm produces higher cloud fraction and thinner clouds than Ed2 cloud algorithm.

- Compare to Ed3, Ed4 global annual mean instantaneous SW flux increases by 0.8~1.0 Wm\(^{-2}\), daytime LW flux increases by 0.2~0.4 Wm\(^{-2}\), and nighttime LW flux is about the same.

- Direct integration of SW indicates that zonal mean flux error is generally less than 0.5 Wm\(^{-2}\), and global mean flux error is less than 0.2 Wm\(^{-2}\).

- Direct integration of LW indicates that zonal mean flux error is generally less than 0.5 Wm\(^{-2}\), and global mean flux error is less than 0.4 Wm\(^{-2}\).

- CERES-MISR consistency test shows that the overall relative consistency of all-sky TOA fluxes is between 5~6% (14~18 Wm\(^{-2}\)).

- CERES-MODIS consistency test over clear ocean indicates that the dependence of flux error on MODIS aerosol optical depth and fine mode fraction is reduced.
Future plan

• Ed4 ADMs is almost complete
• Validation effort is underway
• Deliver Ed4ADM first week of Dec. 2013
• Summarize Ed4ADM algorithm/validation for publication