CERES Angular Distribution Model Working Group Report

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Outline

• ADMs over cloudy ocean: consider more categories in effective cloud phase;

• Clear-sky sea ice ADMs for low sea ice fractions;

• Consider azimuthal dependence of daytime clear-sky LW ADMs;

• Developing ADMs for CERES NPP, will one year of rotating azimuth plane scan (RAPS) data provide sufficient angular coverage?
From radiance to flux: angular distribution models

- Sort observed radiances into angular bins over different scene types;
- Integrate radiance over all $\theta$ and $\phi$ to estimate the anisotropic factor for each scene type;
- Apply anisotropic factor to observed radiance to derive TOA flux;

\[
R(\theta_0, \theta, \phi) = \frac{\pi \hat{I}(\theta_0, \theta, \phi)}{\int_0^{2\pi} \int_0^{\pi/2} \hat{I}(\theta_0, \theta, \phi) \cos \theta \sin \theta \, d\theta \, d\phi} = \frac{\pi \hat{I}(\theta_0, \theta, \phi)}{\hat{F}(\theta_0)}
\]

\[
F(\theta_0) = \frac{\pi I_o(\theta_0, \theta, \phi)}{R(\theta_0, \theta, \phi)}
\]
**Normalize predicted and observed radiance**

Observed radiance:

\[ I^o_j, \quad j = 1, \cdots, n \]

Predicted radiance:

\[ \hat{I}_j, \quad j = 1, \cdots, n \]

\[ \overline{I^o} = \frac{1}{n} \sum_{j=1}^{n} I^o_j \quad \overline{\hat{I}} = \frac{1}{n} \sum_{j=1}^{n} \hat{I}_j \]

\[ RMS = \sqrt{ \frac{1}{n} \sum_{j=1}^{n} \left( \frac{\hat{I}_j}{\overline{\hat{I}}} - \frac{I^o_j}{\overline{I^o}} \right)^2 } \]

- RMS error between normalized predicted radiance and normalized observed radiance is closely related to the ADM error
Angular distribution model over cloudy ocean

- For glint angle $> 20^\circ$, or glint angle $< 20^\circ$ and $\ln(f\tau) > 6$:
  - Average instantaneous radiances in each angular bin into 775 intervals of $\ln(f\tau)$, separately for liquid, mixed, and ice clouds:

$$\bar{\rho} = \frac{f_1 \rho_1 + f_2 \rho_2}{f_1 + f_2}$$

- Liquid: $\bar{\rho} < 1.01$
- Mixed: $1.01 \leq \bar{\rho} \leq 1.75$
- Ice: $\bar{\rho} > 1.75$

- Apply a five-parameter sigmoidal fit to mean radiance and $\ln(f\tau)$:

$$I = I_0 + \frac{a}{1 + e^{-(x-x_0)/b}}c$$

![Liquid cloud: SZA[35], VZA[9], RAZ[3]]

- f=0-8%
- f=8-28%
- f=28-73%
- f=73-100%
- f=100-100%
Normalized RMS error calculated using ADMs constructed for three cloud phases

- RMS error between normalized ADM predicted radiance and normalized observed radiance is closely related to the ADM error;
- Mixed phase clouds have the largest RMS error, and ice clouds have the smallest RMS error.
Types of clouds over ocean: daytime retrievals from four seasonal months of 2008

Single layer clouds: Liquid (39.6%) \( \bar{\rho} < 1.01 \)  
Mixed (5.9%) \( 1.01 \leq \bar{\rho} \leq 1.99 \)  
Ice (6.2%) \( \bar{\rho} > 1.99 \)

Two layer clouds:

- Liquid over liquid: 2.7%  
- Mixed over liquid: 0.9%  
- Ice over liquid: 43.2%
- Liquid over mixed: 0.1%  
- Mixed over mixed: 0.2%  
- Ice over mixed: 0.3%
- Liquid over ice: 0.001%  
- Mixed over ice: 0.3%  
- Ice over ice: 0.9%

- Single layer clouds contribute about 51.7%
- Mixed phase clouds contribute about 7.6%
- Most of the ice clouds are over liquid clouds (43.2% compares to 6.2% single layer ice clouds)
Redefine the mixed and ice clouds

- Cloud phases are defined as:
  - Liquid: $\bar{\rho} < 1.01$
  - Mixed: $1.01 \leq \bar{\rho} \leq 1.95$
  - Ice: $\bar{\rho} > 1.95$

- Changing the ice phase definition towards higher phase value (less mixed clouds) reduced the RMS error from 4.5% to 3.2%;

- However, the RMS error for the mixed phase increased from 9.1% to 10.0%.
Split mixed clouds into two categories

- As most of the mixed clouds are from ice over water case, mixed clouds are further stratified into two categories:
  - Liquid: $\bar{\rho} < 1.01$
  - Mixed 1: $1.01 \leq \bar{\rho} < 1.30$
  - Mixed 2: $1.30 \leq \bar{\rho} \leq 1.95$
  - Ice: $\bar{\rho} > 1.95$
- The RMS error for the mixed phase clouds is the lowest among the different stratifications that we tested.
Liquid clouds

• To test whether the liquid cloud ADMs can be further improved, constructing three liquid cloud ADMs based upon the effective cloud top temperature:
  
  Cold: \( T_e \leq 273K \)
  Cool: \( 273K < T_e \leq 290K \)
  Warm: \( T_e > 290K \)

• The RMS error for liquid clouds improved slightly, decreasing from 7.0% (without \( T_e \) stratification) to 6.8%. 
RMS error for the three types of liquid clouds

- Warm liquid clouds have the largest RMS error, and the RMS error is elevated near the aerosol source regions;
- Cold liquid clouds have the smallest RMS error, even in regions near the aerosol source regions.
A lot of the warm liquid clouds are very thin

Cumulative PDF of $\ln(f\tau)$ for warm ($T_e > 290$ K) liquid cloud

<table>
<thead>
<tr>
<th>$\ln(f\tau)$</th>
<th>percentage</th>
<th>$f=100%$</th>
<th>$f=10%$</th>
</tr>
</thead>
</table>
| $< 0$         | 7%         | $\ln(f\tau)=0$ \ 
$\tau=0.01$ | $\ln(f\tau)=0$ \ 
$\tau=0.1$ |
| $< 1$         | 13%        | $\ln(f\tau)=1$ \ 
$\tau=0.03$ | $\ln(f\tau)=1$ \ 
$\tau=0.3$ |
| $< 2$         | 24%        | $\ln(f\tau)=2$ \ 
$\tau=0.07$ | $\ln(f\tau)=2$ \ 
$\tau=0.7$ |
Warm liquid clouds with small $\ln(f\tau)$: RMS error calculated using cloudy-ocean ADMs

- $\ln(f\tau) < -1.0$: RMS = 3.34%
- $-1.0 < \ln(f\tau) < 0.0$: RMS = 4.35%
- $0.0 < \ln(f\tau) < 1.0$: RMS = 5.17%
- $1.0 < \ln(f\tau) < 2.0$: RMS = 5.75%
Warm liquid clouds with small $\ln(f\tau)$: RMS error calculated using clear-ocean ADMs.

- $\ln(f\tau) < -1.0$: RMS = 2.11%
- $-1.0 < \ln(f\tau) < 0.0$: RMS = 2.94%
- $0.0 < \ln(f\tau) < 1.0$: RMS = 3.70%
- $1.0 < \ln(f\tau) < 2.0$: RMS = 4.68%

9/10/2018
Clear-sky Sea Ice ADMs

• Clear-sky sea ice ADMs were developed for discrete sea ice fraction bins;
• When 10% sea ice fraction bins are used, both reflectance and anisotropic factors show sensitivity for low sea ice fractions;
• Fluxes can increase up to 10 Wm\(^{-2}\) for clear-sky low sea-ice fraction footprints, but the overall effect on clear-sky sea ice flux is small due to the sample size of these footprints.

<table>
<thead>
<tr>
<th>Clear-sky sea ice ADMs</th>
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<tbody>
<tr>
<td>Sea Ice fraction ≤1%</td>
</tr>
<tr>
<td>1% &lt; Sea Ice fraction ≤25%</td>
</tr>
<tr>
<td>25% &lt; Sea Ice fraction ≤50%</td>
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<tr>
<td>50% &lt; Sea Ice fraction ≤75%</td>
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<tr>
<td>75% &lt; Sea Ice fraction &lt;99%</td>
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<tr>
<td>99% ≤ Sea Ice fraction, SIBI ≤0.85</td>
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<tr>
<td>99% ≤ Sea Ice fraction, 0.85&lt; SIBI ≤0.935</td>
</tr>
<tr>
<td>99% ≤ Sea Ice fraction, SIBI &gt;0.935</td>
</tr>
</tbody>
</table>

9/10/2018
Clear-sky daytime LW ADM over land/desert

- Clear-sky LW ADMs were developed for discrete intervals of precipitable water, lapse rate, and surface skin temperature as a function of viewing zenith angle;
- Minnis et al (2004) noted that the shadowing by vegetation and landforms can cause azimuthal variations of the LW radiance;
- Examine the sensitivity of daytime LW ADMs to solar zenith angle, relative azimuth angle, and surface variability (SV) following the method used in Minnis et al. (2004).

![Graph showing LW Anisotropic Factor vs. VZA for crops/grassland with PW=1-3 cm, Lapse rate=15-30K, Ts=300-310K.](image)

Figure 1. Schematic of satellite-Sun configuration with shadowing and relative infrared radiance emission.

From Minnis et al. (2004)
Mean radiance difference between $I(SZA, RAA, VZA, SV)$ and $I(VZA)$ over crops/grassland

Surface Variability: low

Surface Variability: high

SZA=0-48°

SZA=48-70°

PW=1-3 cm
Lapse rate=15-30 K
Ts=300-310 K
Mean radiance difference between $I(SZA, RAA, VZA, SV)$ and $I(VZA)$ over dark desert

Surface Variability: low

Surface Variability: high

SZA=0-48°

SZA=48-70°

PW=0-1 cm

Lapse rate=30-45 K

Ts=300-310 K

9/10/2018
Anisotropic factors over crops/grassland

Surface Variability: low

SZA=0-48°

Surface Variability: high

SZA=48-70°
Ratio of $R(SZA, VZA, RAA, SV)/R(VZA)$ over crops/grassland

Surface Variability: low

Surface Variability: high

SZA=0-48°

SZA=48-70°
Impact on daytime clear-sky LW flux

• Clear-sky daytime LW ADMs consider the solar zenith angle, relative azimuth angle, and surface variability can alter the instantaneous LW flux by up to 10 Wm\(^{-2}\).
• For a given scene type, the mean flux change is less than 1 Wm\(^{-2}\) with RMS errors about 2-3 Wm\(^{-2}\).

Crops/Grassland

\[ \Delta F = -0.9 \text{ Wm}^{-2} \]

\[ \text{RMS} = 2.1 \text{ Wm}^{-2} \]

Dark Deserts

\[ \Delta F = -0.3 \text{ Wm}^{-2} \]

\[ \text{RMS} = 3.1 \text{ Wm}^{-2} \]
Placing NPP in rotating azimuth plane scan (RAPS) mode to collect data for ADM development

- Use NOAA20 (JPSS1) to continue the CERES Aqua record once Aqua’s orbit starts to drift;
- Aqua will be used as the “bridge” for inter-calibrating NPP and NOAA20;
- Once NOAA20 CERES is stable and has a minimum of one year of measurements, we plan to put NPP into RAPS mode to collect data for constructing ADMs;
- Once the Aqua (also Terra) orbit starts to drift, we will consider to put them into RAPS mode to augment the SZAs coverage;
- Using one year of Aqua RAPS data (2004, total of 321 days) to investigate the angular coverage over different scene types.
Number of samples in each angular bin over clear-sky ocean from 1 year of RAPS data

*SZA=20                          SZA=30                          SZA=40

*SZA=50                          SZA=60                          SZA=70

*Wind speed 4-6 m/s
Number of samples in each angular bin over clear-sky sea ice (1%<sea ice fraction<25%) from 1 year of RAPS data
Number of samples in each angular bin over clear-sky sea ice (sea ice fraction > 99%, and mid SIBI bin) from 1 year of RAPS data.
Summary

• Adding more cloud phase bins reduces the ADM uncertainty

• Clear-sky daytime LW ADMs show azimuthal dependence, especially for large SZA and high surface variability
  – Clear-sky daytime LW ADMs consider the solar zenith angle, relative azimuth angle, and surface variability can alter the instantaneous LW flux by up to 10 Wm$^{-2}$
  – For a given scene type, the mean flux change is less than 1 Wm$^{-2}$ with RMS errors about 2-3 Wm$^{-2}$

• To build ADMs for NPP, a minimum of one year of RAPS data are needed to ensure that clear-sky scenes are sufficiently sampled