Constraining CALIPSO-CloudSat-MODIS (CCM) Merged Cloud Profiles by MODIS Column Properties for CCCM Irradiance Computations

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Overview of CERES-CALIPSO-CloudSat-MODIS (CCCM)
CCCM Irradiance Computation Algorithm

**Step 1:** Merging CALIPSO-CloudSat (CC) cloud mask at a CALIPSO resolution (1/3 km) and generating CC cloud groups in a CERES footprint.

**Step 2:** Generating CALIPSO-CloudSat-MODIS (CCM)-merged $k_{CCM}(z)$ and $r_{CCM}(z)$ profiles by bringing available product based on the predefined hierarchy.

**Step 3:** Constraining CCM-merged $k_{CCM}(z)$ and $r_{CCM}(z)$ by MODIS column properties ($\tau_M, r_M$).

**Step 4:** Running Fu-Liou radiative transfer model and comparing computed irradiances with CERES observations.

(Kato et al. 2010)

(Kato et al. 2011; Ham et al. 2022)
Our main objective is to generate more realistic and accurate cloud profiles from multi-sensors for irradiance computations from TOA through surface.
Necessity of The Constraining Method: Biases When TOA SW Fluxes Is Computed Without Step 3

- Large SW negative biases occur in the high-latitude regions where 1) CALIPSO signal is fully attenuated, and 2) low clouds < 1km are present. This indicates bottom parts of low clouds are missed by CloudSat and CALIPSO, causing negative SW biases.
- CALIPSO profiles have larger noise near the attenuation level.
- Noises due to differences across the satellite product.

⇒ These uncertainties can be reduced if we use additional information of MODIS column cloud properties.
Visible Scaled Cloud Optical Depth (VSCOD) Constraining Method

• While CALIPSO and CloudSat active sensors provide detailed cloud vertical profiles, these do not often see the entire cloud column. In contrast, MODIS passive sensor provides more reliable cloud column-integrated values.

• Therefore, we take the shape of merged cloud vertical profiles ($k_{CCM}$, $r_{CCM}$), while the merged cloud profiles are normalized/constrained by MODIS cloud column-cloud ($\tau_M$ and $r_M$) properties.

• The scaling factor to $k_{CCM}(z)$ is derived to have a consistent VSCOD with MODIS (Kato et al., 2011)

$$\tau_M (1 - g(r_M)) = \alpha \sum_{i=1}^{n} k_{CCM}(i) \Delta z_i \{1 - g(r_{CCM}(i))\}$$

- MODIS Scaled Cloud Optical Depth
- $\alpha$ is a scaling factor to reproduce MODIS-equivalent scaled optical depth from the merged extinction profile ($\alpha k_{CCM}(i)$).

• Note that visible channel (non-absorbing) radiance is a function of VSCOD (Van de Hulst 1974), and thus the use of MODIS VSCOD reproduces MODIS visible channel radiances. By constraining $k_{CCM}(z)$ with MODIS VSCOD, the scaled $\alpha k_{CCM}(z)$ would reproduce MODIS-equivalent visible channel radiances too.

• Since SW broadband and visible channel radiances are correlated well, this method also guarantees close agreement with SW TOA broadband observations.
No Constraining (without Step 3) vs VSCOD Constraining Method

$k_{CCM}(z)$

$\alpha k_{CCM}(z)$ where $\alpha$ is derived from VSCOD method

$\alpha k_{CCM}(z) - k_{CCM}(z)$

- $k_{CCM}(z)$ in low clouds in high-latitude regions is increased by VSCOD constraining method.
- $k_{CCM}(z)$ over the tropical regions is generally reduced by VSCOD method. This may imply the overestimation of cloud extinction coefficient used for the ice phase (CALIPSO or 2C-ICE).
SW and LW Biases (W m$^{-2}$) to CERES Obs When VSCOD Constraining Method is used for $\alpha k_{CCM}(z)$

Daytime SW

Daytime LW

Nighttime LW

VSCOD method produces SW TOA irradiances close to CERES observations.

Negative LW biases indicate too high radiative center of $k_{CCM}(z)$ profiles: 1) overestimated $k_{ext}(z)$ used for upper clouds in merging process. 2) Missed cloud bottom parts are compensated by the increased $\alpha$ scaling factor.

VSCOD method generally works well but nighttime LW biases are sometimes large negative in instantaneous footprint scales.

Jan/Apr/Jul/Oct 2008
Coupled MODIS $T_c$ and $\tau_c$ Biases in MODIS IR (Nighttime) Retrievals

Nighttime MODIS $\tau_c$ is derived from MODIS IR channel, which is affected by the cloud height (or $T_c$). If MODIS cloud height is low-biased (or warm-biased $T_c$), MODIS $\tau_c$ would be positively biased.

$$R_{IR,MODIS} \sim \varepsilon_s B(T_s) \exp(-\tau_c) + B(T_c)(1 - \exp(-\tau_c))$$

When the biased MODIS $\tau_c$ is used for VSCOD method, the bias also affects $\alpha_{K_{CCM}(z)}$. The negative LW biases indicate that $\alpha_{K_{CCM}(z)}$ might be overestimated due to the overestimated MODIS $\tau_c$ (\& warm-biased $T_c$)

Both clouds reproduce TOA IR radiances close to MODIS IR observations.
Which Month Shows Large Negative Nighttime LW Biases (likely from warm-biased MODIS $T_c$ and positively biased MODIS $\tau_c$) When VSCOD Method Is Used?

Jan 2008

April 2008

July 2008

October 2008

In July, large negative LW biases occur, implying large MODIS cloud height biases.
Large Cloud Height Differences between MODIS and CC over Antarctica During Wintertime

Cloud Volume Frac (CVF) (%)

MODIS

CC

MODIS – CC

CC – MODIS Uppermost Cloud Top Height (km)

(Mean: 2.2, #: 571413)

Jan 2008

July 2008
Polar Stratospheric Cloud Type II (Consisting of Ice Particles) Missed in MODIS IR Cloud Retrievals

- Type II PSC is prevalent over the Antarctica during wintertime (June – Sep) (Noel et al. 2008; Pitt 2018). MODIS often detects this type of clouds as low/mid clouds below the tropopause (~ 11 km).

Figure 14. Twelve-year mean daily PSC areal coverage over the Antarctic. The climatological daily maximum MERRA-2 tropopause height is indicated by the dashed white line.

(Pitt et al. 2018)
IR Emission (IREMIS) Constraining Method

- Even though each term of MODIS $\tau_c$ and $T_c$ is biased in IR retrievals, these two parameters would be able to reproduce MODIS IR channel radiances by the algorithm design.
- Therefore, instead of using MODIS $\tau_c$ (or VSCOD=$(1-g)\tau_c$) for constraining $k_{CCM}$, we can use both terms (MODIS $\tau_c$ and $T_c$) to obtain IR emission, which can be further used for constraining merged $k_{CCM}$.
- We use 11 $\mu$m for computing IR emission term.

\[
\text{MODIS-estimated IR emission} \quad \alpha \text{ is a scaling factor to reproduce MODIS-equivalent IR emission from the merged extinction profile ($\alpha k_{CCM(i)}$).}
\]

\[IREMIS(T_{c,M}, \tau_M) = IREMIS(\alpha k_{CCM}(z), r_{CCM}(z))\]

Approximately, IREMIS for a single cloud layer is

\[\varepsilon_s B(T_s) \exp(-\tau_M) + B(T_{c,M})(1 - \exp(-\tau_M))\]
Limitations of the IREMIS Method

- If cloud temperature is too close to surface temperature, the IR emission value becomes nearly constant regardless of the scaling factor, and the uncertainty of the scaling factor gets larger. In this case, the uncertainty of surface temperature and temperature profile also significantly change the scaling factor.
- In addition, the sensitivity of IR emission gets quickly reduced as COD increases, meaning that retrieval of accurate $\alpha$ factor is not possible for optically thick clouds.

\[
I_{REMIS}(T_{c,M}, \tau_M) = I_{REMIS}(\alpha k_{CCM}(z), r_{CCM}(z))
\]

For high clouds ($T_{c,CCM} << T_s$)

\[
\varepsilon \beta(T_s) \exp(-\tau_M) + \beta(T_{c,M})(1 - \exp(-\tau_M))
\]

For low clouds ($T_{c,CCM} \sim T_s$)

\[
\varepsilon \beta(T_s) \exp(-\tau_M)
\]

Temperature uncertainty ($\Delta T$)

Approximately

Solution of $\alpha$

Scaling Factor $\alpha$

Scaling Factor $\alpha$

MODIS-estimated IR emission

CCM-estimated IR emission with changing $\alpha$

For high clouds ($T_{c,CCM} << T_s$)

For low clouds ($T_{c,CCM} \sim T_s$)
SW and LW Biases (W m$^{-2}$) to CERES Obs when IREMIS Constraining Method is used for $\alpha k_{CCM}(z)$

Daytime SW

Daytime LW

Nighttime LW

Large negative SW biases for Low cloud regions due to the limitation of IREMIS method.

Large nighttime LW negative biases over the Antarctica are removed by IREMIS method.
Hybrid Approach

In this approach, VSCOD method is mostly used. However, if MODIS $T_c$ is different from CC $T_c$ (that indicates MODIS $T_c$ bias), and CC $T_c$ is distinctive from skin temperature, IREMIS method is applied.
When combining VSCOD and IREMIS, SW and LW biases are reduced.
Day+Night LW Surface Downward (W m\(^{-2}\)) over Antarctica

\[ \Delta F_{\text{LW,SFCDN}} = 3.0 \]

- MODIS Only
- CCM with VSCOD
- CCM with Hybrid

<table>
<thead>
<tr>
<th>Date</th>
<th>SIM LW SFCDN (W m(^{-2}))</th>
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<tbody>
<tr>
<td>200801</td>
<td>214.6±54.1 214.8±51.4 211.8±50.4</td>
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<tr>
<td>200804</td>
<td>191.5±51.7 192.7±51.7 189.5±49.8</td>
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<tr>
<td>200807</td>
<td>176.3±49.1 177.0±48.6 172.9±50.7</td>
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<tr>
<td>200810</td>
<td>188.1±60.7 189.4±61.1 187.6±61.5</td>
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</tbody>
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1.79 W m\(^{-2}\)
Summary

- VSCOD method is shown to improve SW simulations by increasing $\alpha k_{\text{CCM}}(z)$ in case that both CALIPSO and CloudSat miss low clouds. However, the VSCOD method sometimes induces nighttime negative LW biases when MODIS cloud height is low-biased.
- IREMIS method is shown to improve nighttime LW simulation especially for PSC over the Antarctica. However, IREMIS method does not work well for low clouds when the cloud temperature is too close to surface temperature, or for optically thick clouds.
- A hybrid method is considered by combining VSCOD and IREMIS methods.
- By implementing the hybrid method, wintertime surface LW downward is reduced by 4 W m$^{-2}$ over the Antarctic, compared to VSCOD scaling method.
Thank you for your attention!