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Shortwave Broadband Irradiance Computations Using Cloud Properties Combined from CALIPSO, CloudSat, and MODIS

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Objectives

- Obtain cloud vertical structure information by combining CALIPSO CALIOP (lidar), CloudSat CPR (radar), and Aqua MODIS (imager).
- Use the combined cloud profiles for TOA shortwave (SW) broadband (BB) flux simulations and compare the results with Clouds and the Earth's Radiant Energy System (CERES) SW measurements.

CCCM RelD1 product available at https://ceres.larc.nasa.gov/data/
B1 version reference: Kato et al. (2010, 2011)
D1 version reference: Ham et al. (2022, accepted)

Datasets

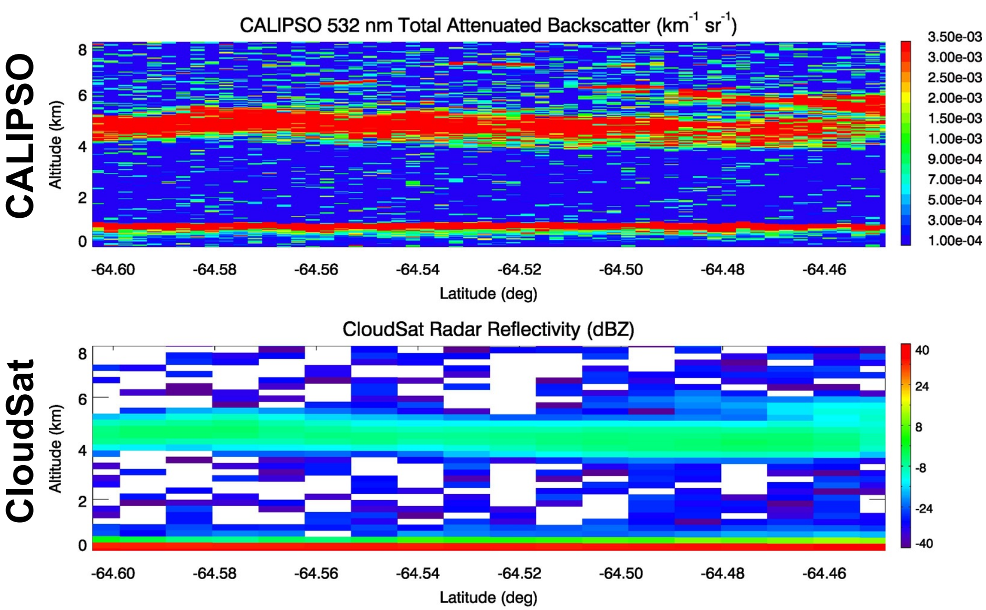
- CERES Ed4 SW broadband flux ; Used for validation of computed SW fluxes
- CERES-MODIS Ed4 cloud product
- CALIPSO V4 Vertical Feature Mask (VFM) (Lidar Only) cloud mask
- CALIPSO V4 CPRO 5 km (Lidar Only) cloud extinction coefficient profiles
- CloudSat R05 2B-CLDCLASS (Radar Only) cloud mask
- CloudSat R05 2B-CWC-RO (Radar Only) cloud extinction and effective radius profiles
- CloudSat R05 2C-ICE (**Radar+Lidar Combined**) ice cloud extinction and effective radius profiles

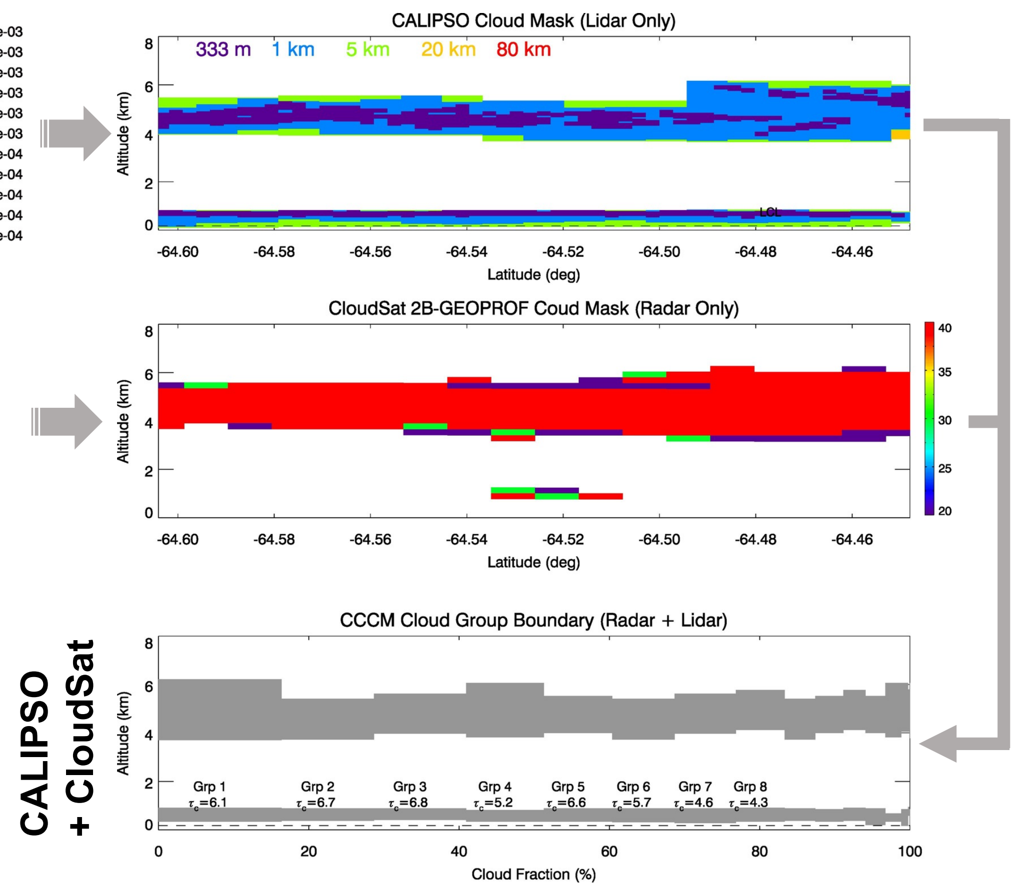
Combining CALIPSO + CloudSat Cloud Mask

To enhance cloud detections, CALIPSO and CloudSat masks are combined.

L1B Image

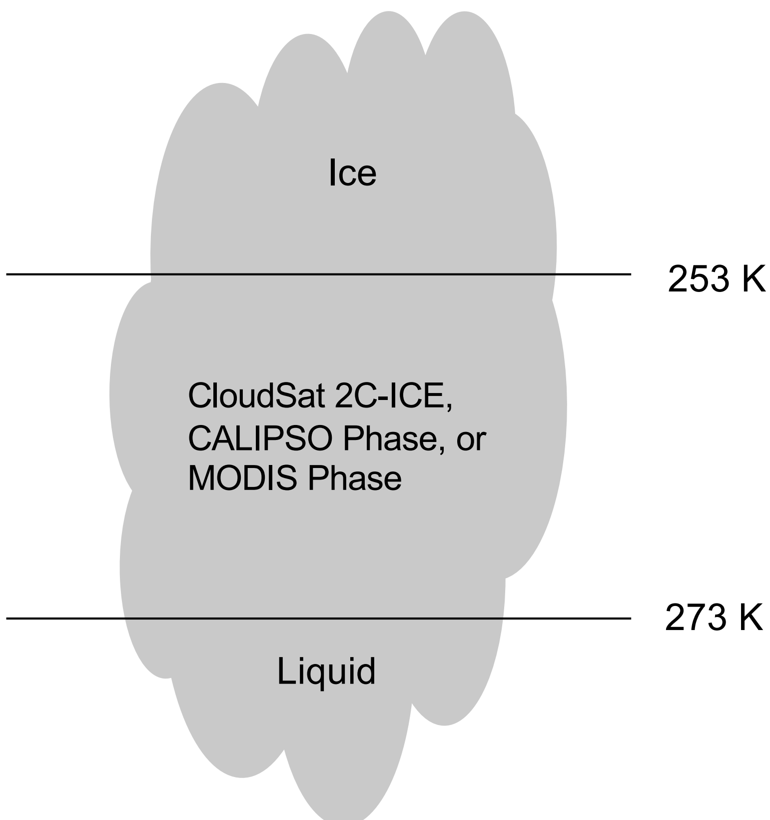
Cloud Mask





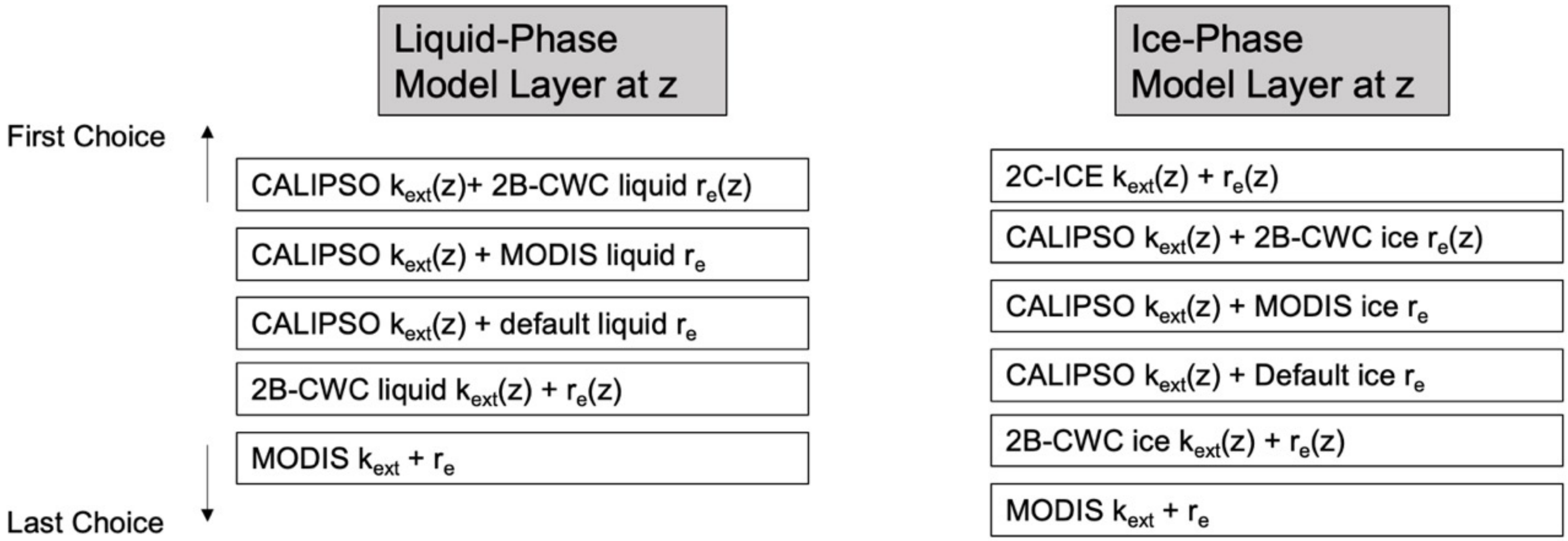
- A higher vertical resolution (30 m or 60 m) of CALIPSO cloud mask is preferred to CloudSat (480 m) when both sensors detect clouds.
- If CloudSat detects additional layers to CALIPSO clouds, these are added.

Combining CALIPSO, CloudSat, and MODIS Cloud Phase ($\phi_{CCM}(z)$)



- Vertical model layers for radiative transfer computations are defined every 120 m below 3 km and 240 m above 3 km.
- If the temperature of the model layer > 273 K, liquid phase is assumed.
- If the temperature < 253 K, ice phase is assumed.
- For the temperature between 253 – 273 K, ice is assumed if valid 2C-ICE parameters are available. For the rest case, CALIPSO phase information is used. If none of 2C-ICE or CALIPSO does not provide the phase information, MODIS cloud phase is applied for the temperature zone between 253 and 273 K.
- In theory, supercooled water particles can be still present for the temperature < 253 K. This occurs about 3.65% of ice cloud layers, according to CALIPSO measurements (Ham et al. 2013).

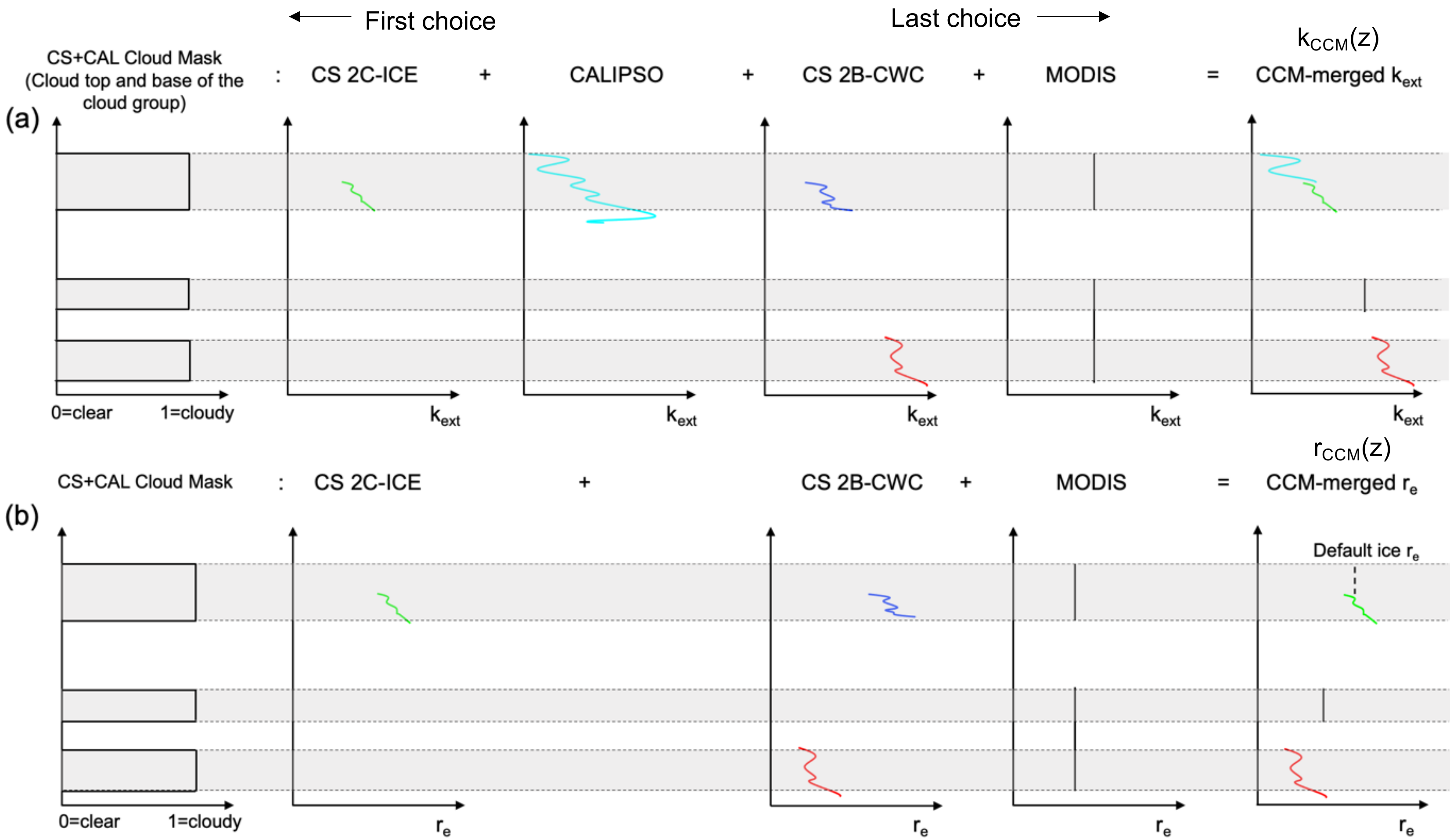
Combining Cloud Extinction ($k_{CCM}(z)$) and Effective Radius ($r_{CCM}(z)$) Profiles from CALIPSO-CloudSat-MODIS (CCM)



(Kato et al. 2011; Ham et al. 2022, under review)

- For liquid-phase cloud layer, CALIPSO > 2B-CWC liquid > MODIS products are considered to assign cloud extinction coefficient (k_{ext}) and effective radius (r_e).
- For ice-phase cloud layer, 2C-ICE > CALIPSO > 2B-CWC Ice > MODIS products are considered.
- CloudSat 2C-ICE product is considered as a first choice since the parameters were retrieved by combining CALIPSO and CloudSat observations.

Examples of Merging Cloud Properties from CALIPSO, CloudSat, and MODIS (CCM)



By combining three sensor information, we can consider more realistic vertical variations within the cloud layers.

Scaling CCM-merged profiles ($k_{CCM}(z)$, $r_{CCM}(z)$, and $\phi_{CCM}(z)$) Using MODIS-derived VSCOD

- CCM-merged cloud profiles capture realistic features of vertical inhomogeneity, but these also have noises and biases because of 1) uncertainty in each satellite cloud product, 2) uncertainty in the phase assignment, 3) spatial mismatch among satellite products, and 4) both CALIPSO and CloudSat can miss the cloud bottom parts.
- Note that MODIS visible scaled cloud optical depth (VSCOD) ($\tau_M \times (1 - g(r_M,\phi_M))$ is well constrained by MODIS visible channel radiances. This is because non-cloud absorbing channel is mainly a function of VSCOD (Van de Hulst, 1974), and MODIS visible channel radiance is used to obtain τ_M and r_M.
- Therefore, we take the shape of $k_{CCM}(z)$ but we also scale the profile to have a consistent VSCOD to the MODIS VSCOD.

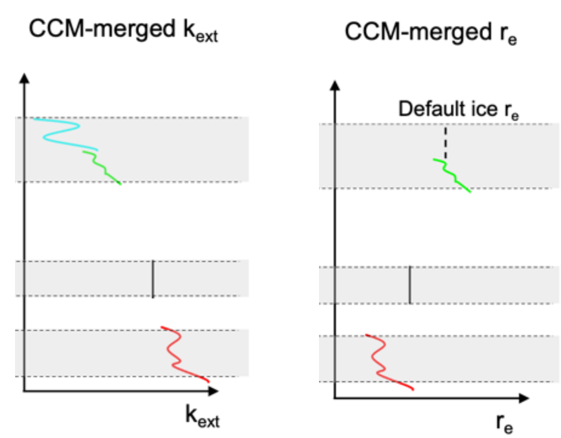
$$I_{VIS,OBS} \approx I_{VIS}\left(\tau_M\left(1 - g(r_M, \Phi_M)\right)\right)$$ (Van de Hulst, 1974)

MODIS VSCOD
~ MODIS visible radiance

CCM-Merged VSCOD

$$\tau_M\left(1 - g(r_M, \Phi_M)\right) = \int_{z_B}^{z_T} \alpha k_{CCM}(z)\{1 - g[r_{CCM}(z), \Phi_{CCM}(z)]\}dz$$

α is a scaling factor to $k_{CCM}(z)$ to have a consistent VSCOD to MODIS value.



Would the Multi-Sensor-Combined Cloud Information Improve SW Computations?

To examine whether the CCM profiles brings improvements of SW computations, we consider four methods.

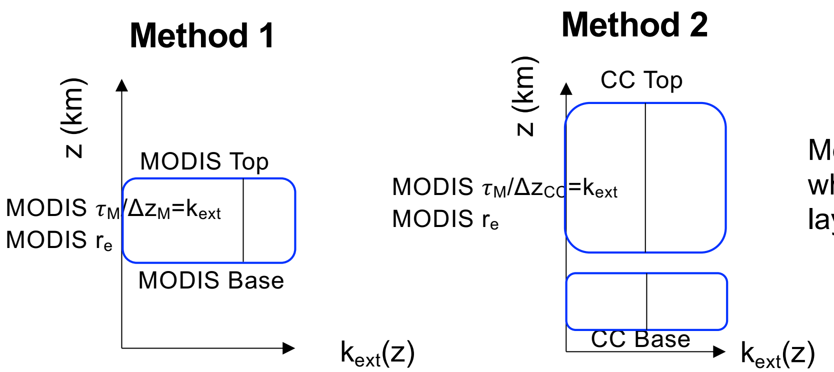
- **Method 1 (MODIS Only):**

  MODIS τ, r_e, phase, cloud heights are used with a single layer assumption.

- **Method 2 (MODIS cloud properties + CC boundary)**

  MODIS τ, r_e, and phase are expanded between CC-detected cloud top and base with homogeneous assumption.

Would
CC boundary improve the
SW simulations?



Method 1 considers a thin single layer clouds, while Method 2 considers multi-layered cloud layers detected from CALIPSO+CloudSat.

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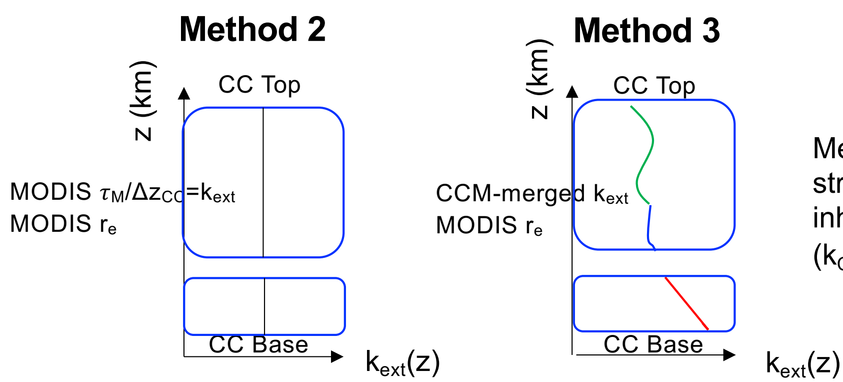
- **Method 2 (MODIS cloud properties + CC boundary)**

  MODIS τ, r_e, and phase are expanded between CC-detected cloud top and base with homogeneous assumption.

- **Method 3 ($\alpha' k_{CCM}(z)$ + CCM phase + MODIS r_e + CC boundary)**

  CCM-merged k_{ext} and phase profiles are used between CC-detected cloud top and base heights. However, a constant value of MODIS r_e is applied to the entire column.

Would
the inhomogeneous vertical profile
of cloud extinction coefficient
($k_{CCM}(z)$) improve SW simulations?



Method 2 considers a homogeneous cloud structure, while Method 3 considers inhomogeneous cloud extinction profile ($k_{CCM}(z)$).

Would the Multi-Sensor-Combined Cloud Information Improve SW Computations?

To examine whether the CCM profiles brings improvements of SW computations, we consider four methods.

- **Method 1 (MODIS Only):**

  MODIS τ, r_e, phase, cloud heights are used with a single layer assumption.

- **Method 2 (MODIS cloud properties + CC boundary)**

  MODIS τ, r_e, and phase are expanded between CC-detected cloud top and base with homogeneous assumption.

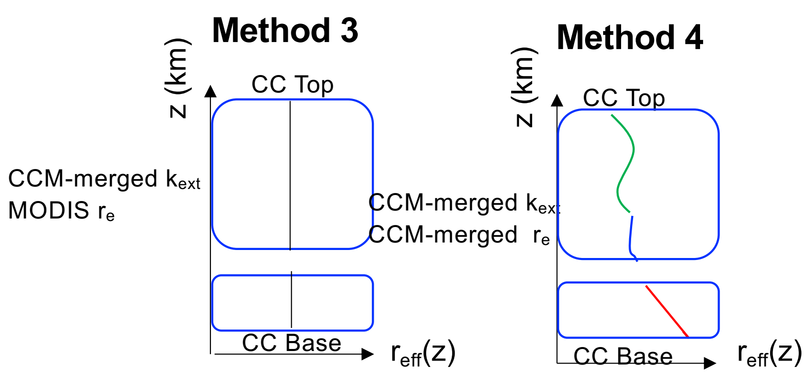
- **Method 3 (α'k_{CCM}(z) + CCM phase + MODIS r_e + CC boundary)**

  CCM-merged k_{ext} and phase profiles are used between CC-detected cloud top and base heights. However, a constant value of MODIS r_e is applied to the entire column.

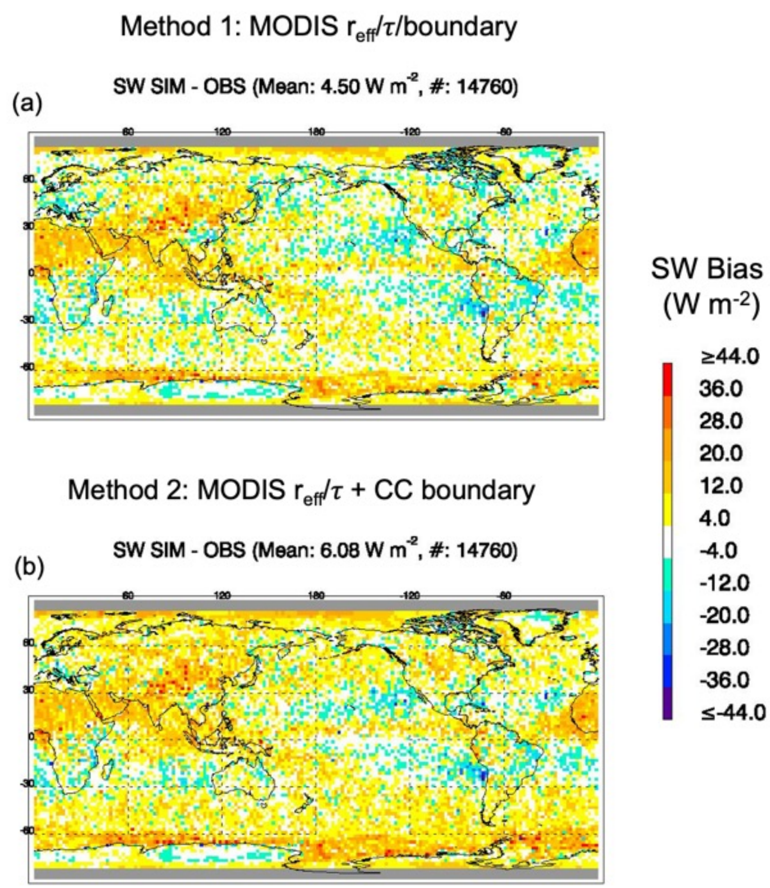
- **Method 4 (αk_{CCM}(z) + CCM phase + r_{CCM}(z) + CC boundary)**

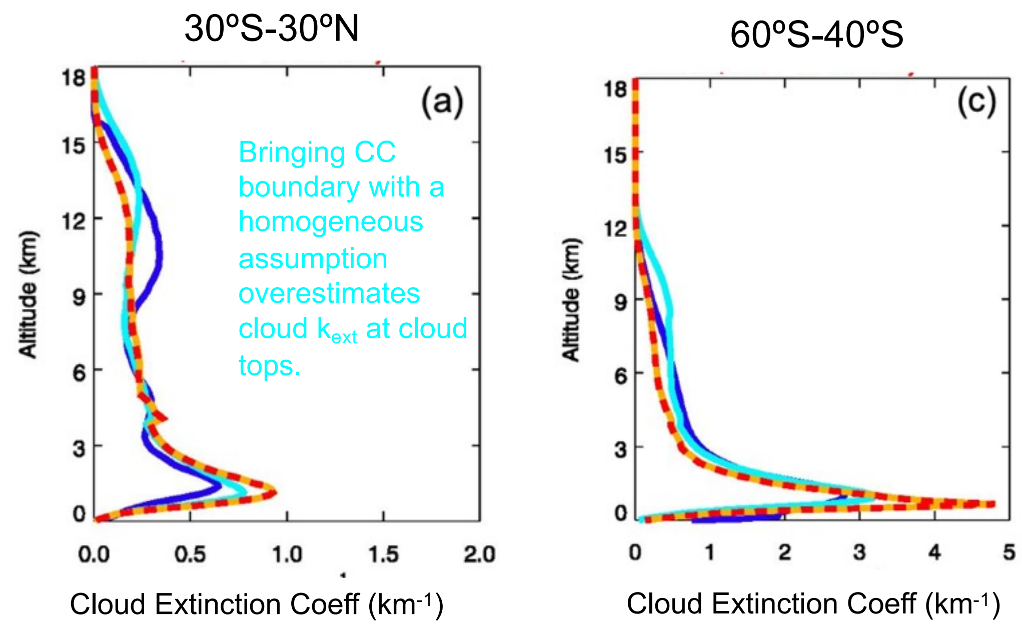
  CCM-merged k_{ext}, r_e, and phase profiles are used between CC-detected cloud boundary.

Would CCM-merged effective radius profile (r_{CCM}(z)) improve SW simulation?



When the homogeneous assumption is used, CC cloud boundary does not improve SW simulations over the MODIS cloud height.





Method 1: MODIS reff/tau/pha/hgt

Method 2: MODIS reff/tau/pha + CC boundary

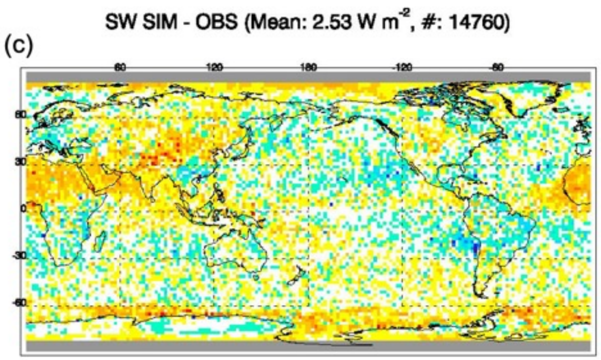
Method 3: MODIS reff+ CCM kext/pha+ CC boundary

Method 4: CCM reff/kext/pha+ CC boundary

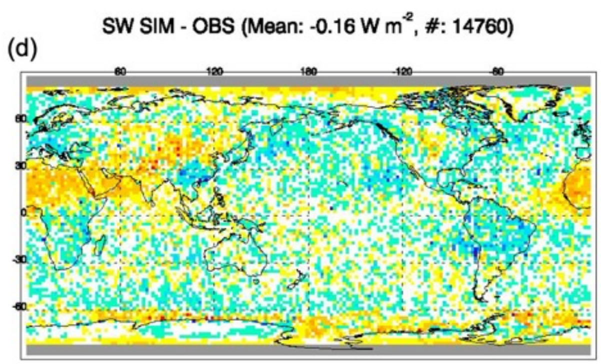
Inhomogeneous cloud extinction profile ($k_{CCM}(z)$) or cloud particle size ($r_{CCM}(z)$) profile improves SW simulations.

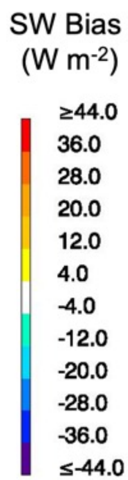
- Taking into account of the vertical variations of k_{ext} (Method 3) reduces the SW positive biases.
- Taking into account of vertical variations of k_{ext} and r_e (Method 4) further improves SW simulations.

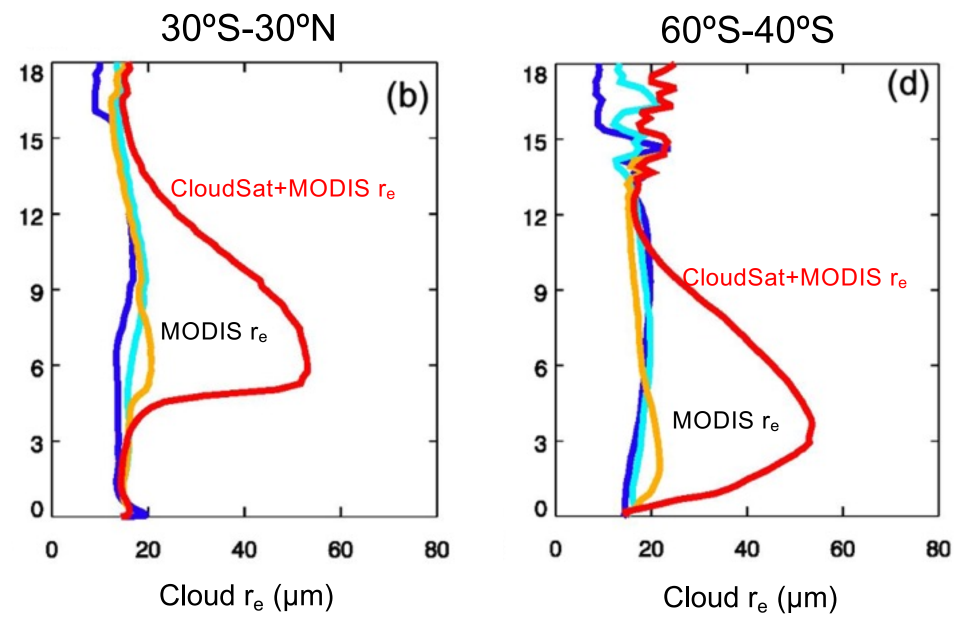
Method 3: MODIS r_{eff} + CCM $\alpha' k_{ext}$ + CC boundary



Method 4: CCM r_{eff} + CCM αk_{ext} + CC boundary







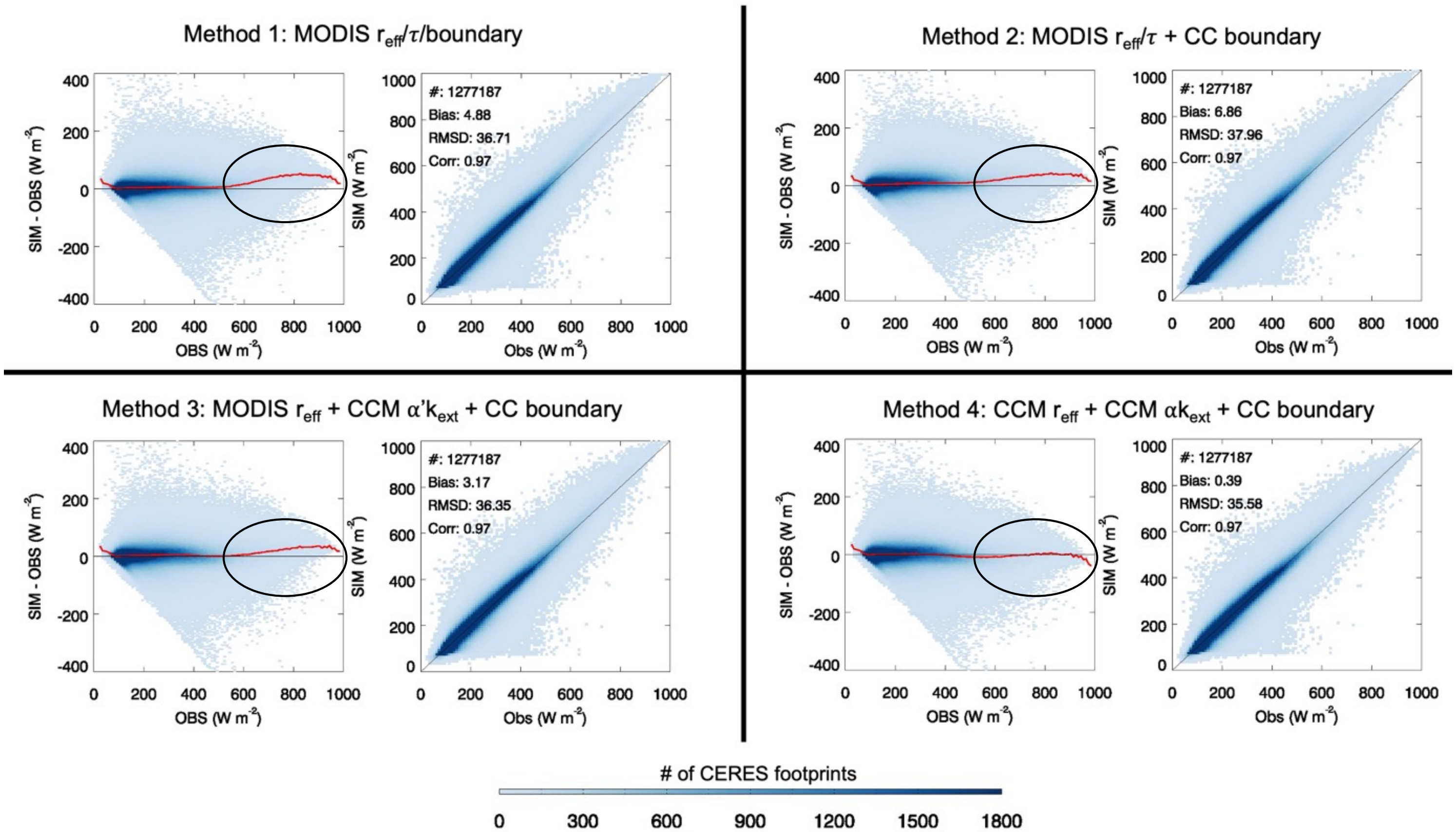
Method 1: MODIS reff/tau/pha/hgt

Method 2: MODIS reff/tau/pha + CC boundary

Method 3: MODIS reff+ CCM kext/pha+ CC boundary

Method 4: CCM reff/kext/pha+ CC boundary

Positive SW biases for Bright Targets when MODIS r_e Is Used



- Larger SW biases when the observed SW flux is large > 600 W m^{-2} ("bright targets").
- The bright targets are related to optically thick clouds with strong reflection over the Tropics
- Implementing cloud inhomogeneous extinction profile (k_{CCM}) in Method 3 slightly reduces the positive SW biases for the bright target.
- When $r_{CCM}(z)$ profile is used (Method 4), the positive SW biases for the bright targets are mostly disappeared.
- This suggests that the impact of $r_{CCM}(z)$ profile is important for optically thick clouds.

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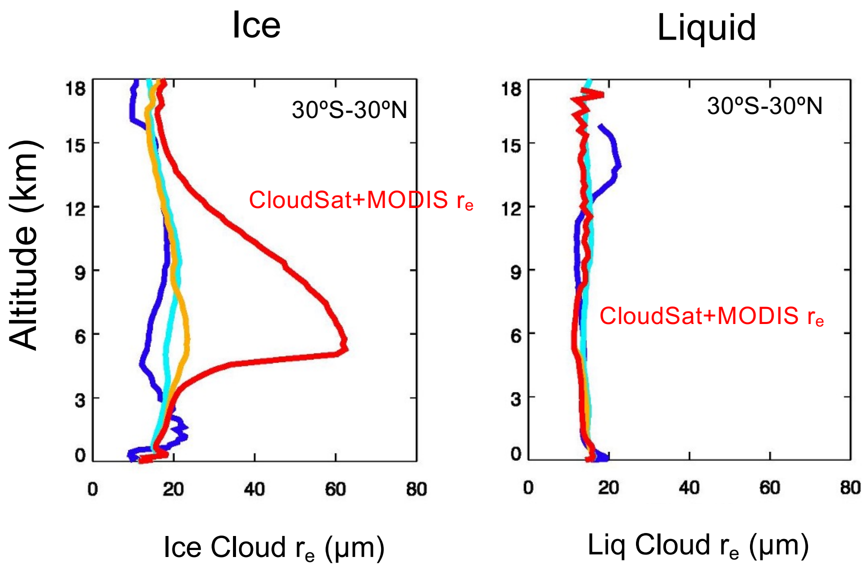
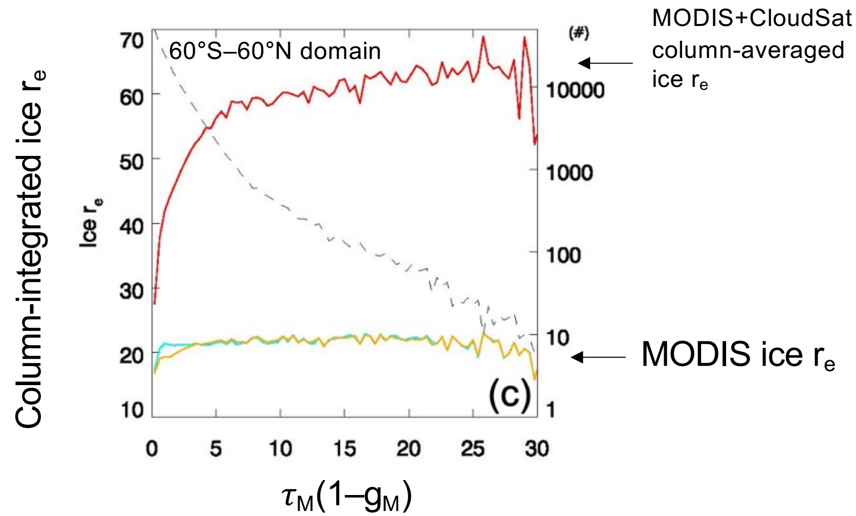
Differences between MODIS (r_M) and CCM (r_{CCM}) Cloud Particle Size

Method 1 Method 2 Method 3 Method 4



The differences between MODIS and CCM particle sizes are significant for ice clouds, but not liquid-phase clouds.



The differences between MODIS and CCM ice particle sizes are larger for optically thicker clouds.

Summary

- Expanding MODIS cloud optical depth between CC cloud top and base heights would not improve SW broadband computations.
- The use of CCM-merged cloud extinction and phase profiles reduces the SW broadband biases compared to the homogeneous assumption.
- When CCM-merged cloud particle size ($r_{CCM}(z)$; mostly from 2C-ICE or 2B-CWC ice r_e) is used, the positive SW biases are mostly removed for the bright targets. In contrast, the underestimated MODIS ice re introduced the positive SW biases at the bright targets.

Thank you for your attention!

Any questions or comments, please contact to
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