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

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Outline

- Combining cloud properties for radiative transfer inputs for CCCM irradiance computations

- Necessity of constraining CCM-merged cloud profiles with MODIS information

- Constraining method 1 –Visible scaled cloud optical depth (VSCOD) method

- Constraining method 2 – IR cloud emission (IREMIS) method

- Hybrid method (VSCOD+IREMIS Method)

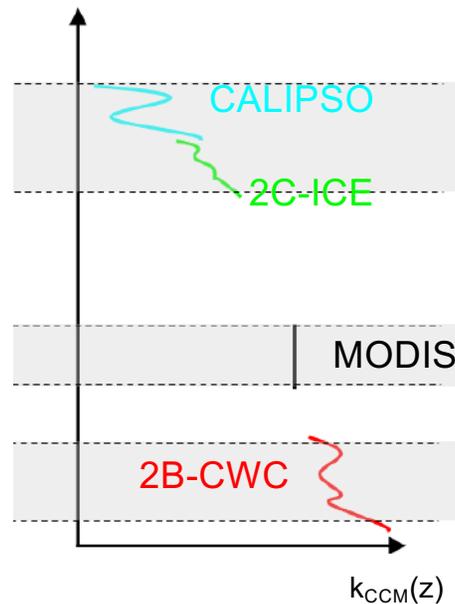- Uncertainty on LW surface irradiance computations

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

Step 1: Merging CC cloud top and base heights at a CALIPSO resolution and generating CC cloud groups in a CERES footprint
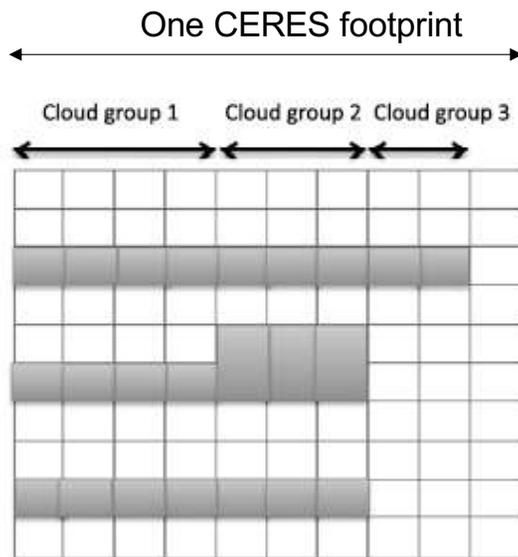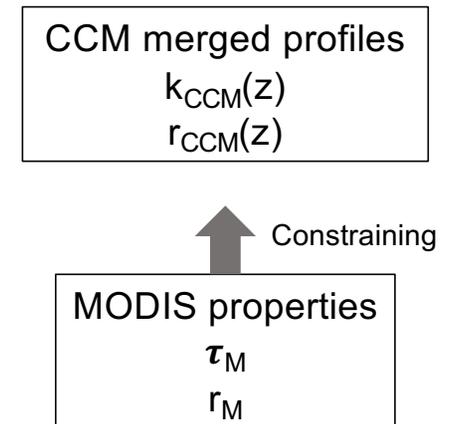
Step 2: Generating CALIPSO-CloudSat-MODIS (CCM)-merged $k_{ext}(z)$ and $r_e(z)$ profiles based on the predefined hierarchy

Step 3: Constraining CCM-merged $k_{ext}(z)$ by MODIS column properties

One CERES footprint

Cloud group 1   Cloud group 2   Cloud group 3

(Kato et al. 2010)

CALIPSO

2C-ICE

MODIS

2B-CWC

$k_{CCM}(z)$

CCM merged profiles
$k_{CCM}(z)$
$r_{CCM}(z)$

Constraining

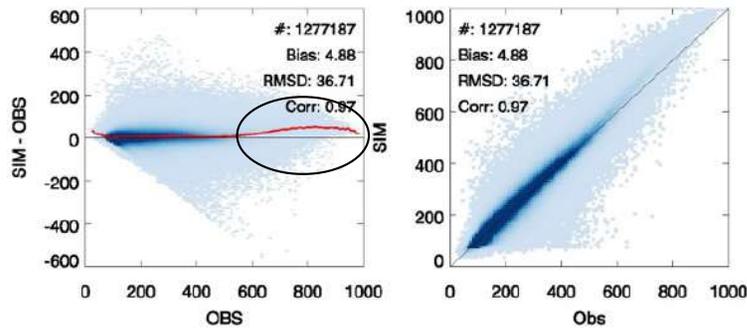MODIS properties
τ_M
r_M

(Kato et al. 2011; Ham et al. 2022)

Is It Beneficial To Combine CCM Cloud Properties Than MODIS Only Simulations? (1/2)

Yes, better agreement between computed and observed SW TOA irradiances is shown when CCM-merged cloud properties, particularly for optically thick clouds composed of large ice particles (Ham et al., CERES Fall STM 2021).
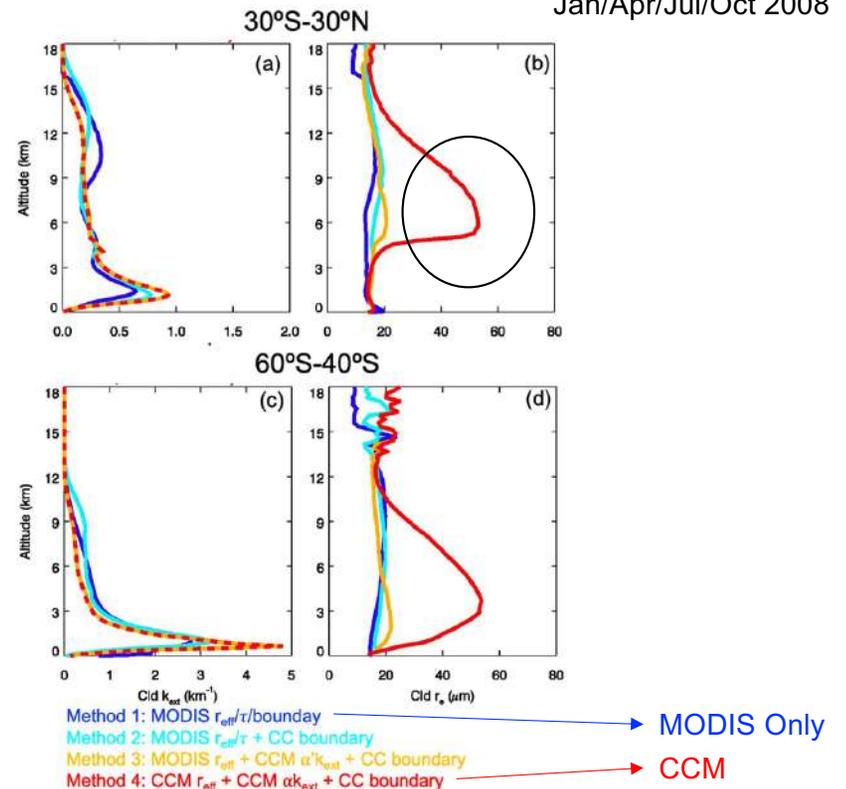

SW TOA Simulations with MODIS Only Cloud Properties

SW TOA Simulation with CCM-Merged Cloud Properties
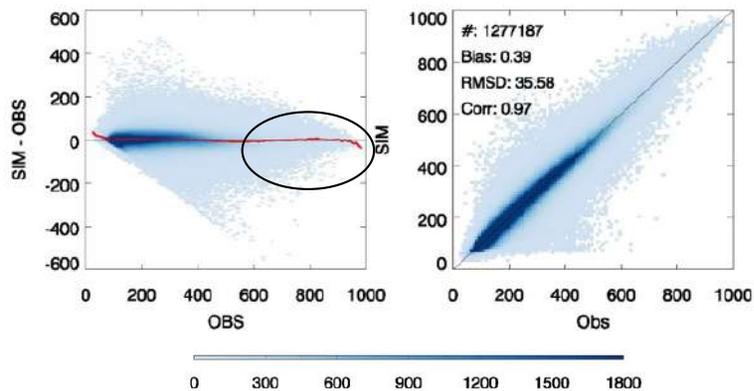
Jan/Apr/Jul/Oct 2008

30°S-30°N

60°S-40°S

Method 1: MODIS r$_{eff}$/τ/bounday
Method 2: MODIS r$_{eff}$/τ + CC boundary
Method 3: MODIS r$_{eff}$ + CCM α*k$_{ext}$ + CC boundary
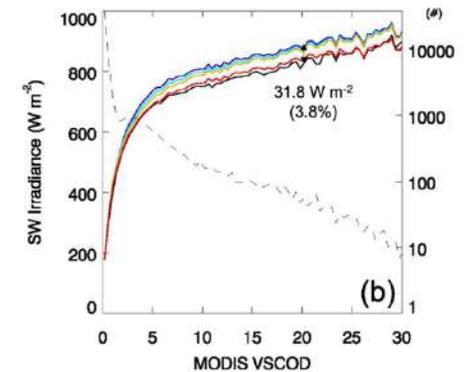Method 4: CCM r$_{eff}$ + CCM αk$_{ext}$ + CC boundary

MODIS Only

CCM

Is It Beneficial To Combine CCM Cloud Properties Than MODIS Only Simulations? (2/2)

The impact of ice particle sizes is significant for SWIR (0.89-2.5 μm) channel simulations, which eventually affect SW broadband irradiances. The smaller SW broadband irradiances from CCM ice particles are more consistent with CERES observations.
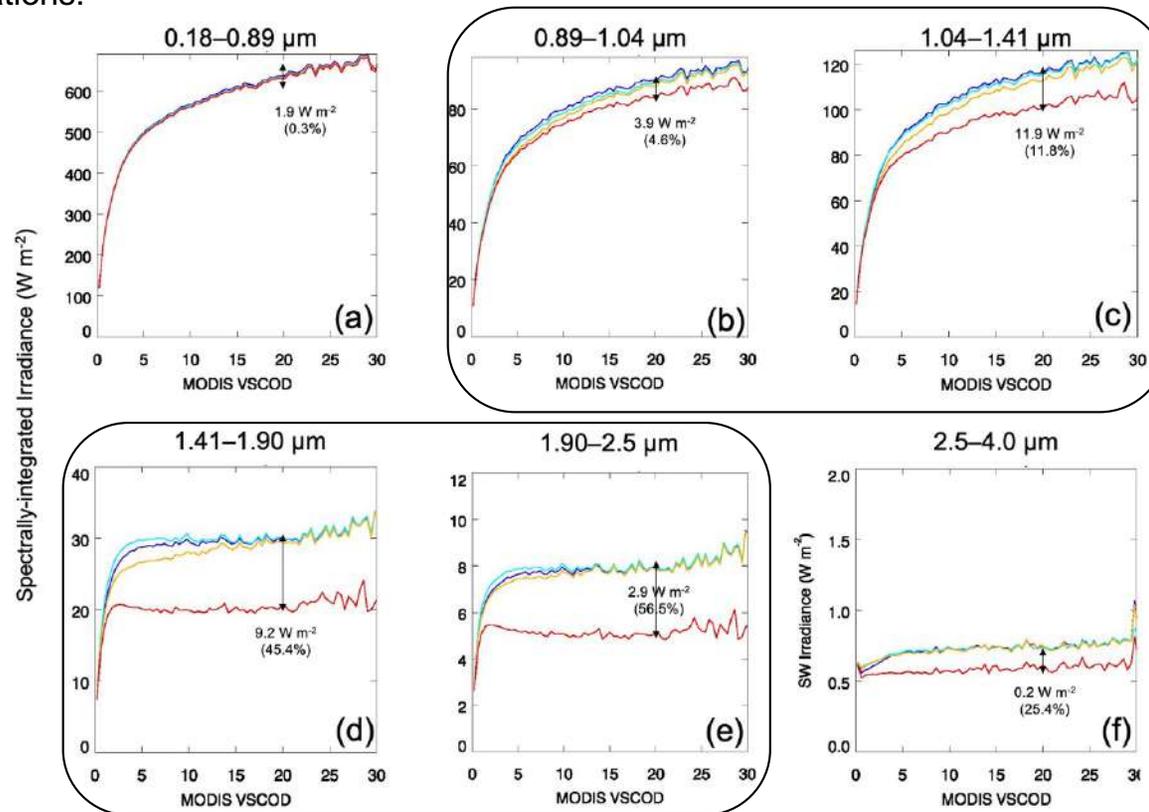
Jan/Apr/Jul/Oct 2008

SW Broadband (0.18-4 μm)

MODIS Only ← Method 1: MODIS r_{eff}/τ/bounday   Method 2: MODIS r_{eff}/τ + CC boundary
Method 3: MODIS r_{eff} + CCM αk_{ext} + CC boundary   Method 4: CCM r_{eff} + CCM αk_{ext} + CC boundary → CCM

# Why do we need to constrain the CCM merged profile with MODIS? (Step 3)

Reason 1: Missed clouds by both active sensors
Low clouds (< 1km) can be missed by both CALIPSO and CloudSat and in this case, cloud extinction for these clouds are assigned as 0 (clear). By comparing with MODIS column τ, the missed cloud parts are compensated by increased $k_{CCM}(z)$ profile at other altitudes.
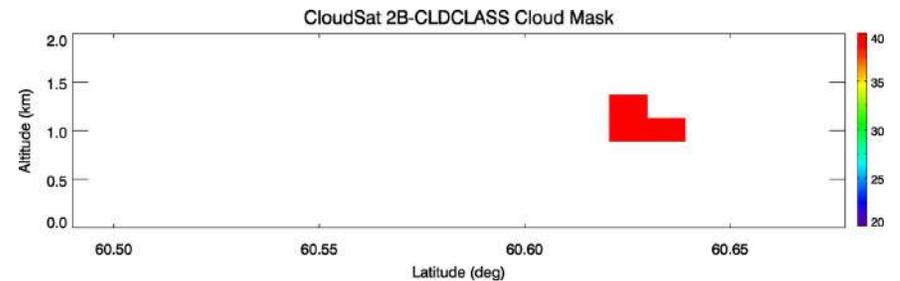
Reason 2: Large noises in active sensor profiles (especially for CALIPSO):
CALIPSO k_{ext} profile has large fluctuations due to the small spatial coverages, and the noise can be corrected/smoothed by constraining $k_{CCM}(z)$ profile with MODIS τ information.
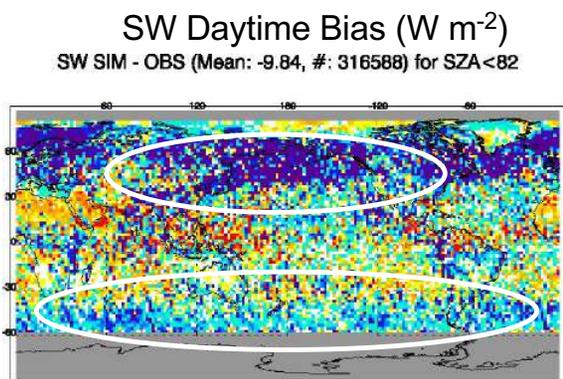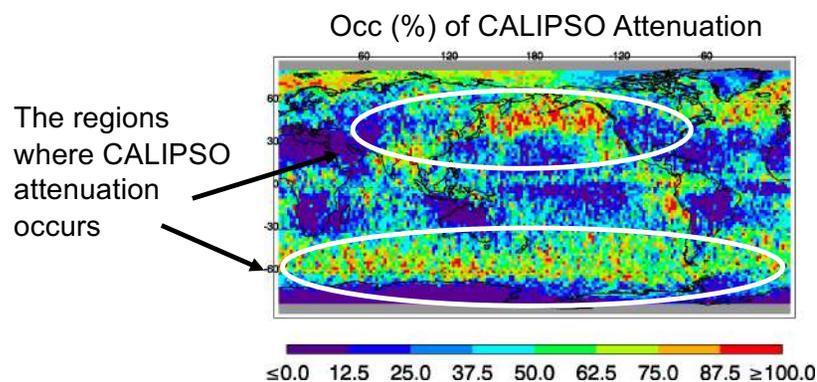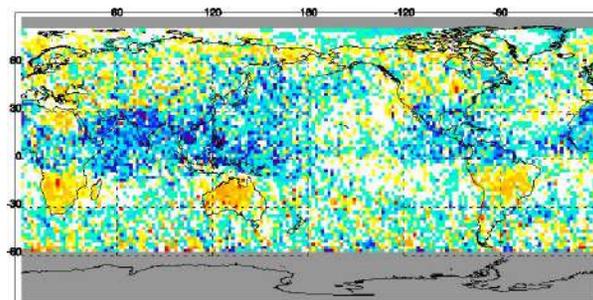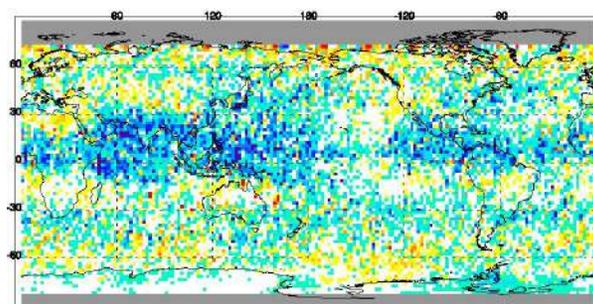
CALIPSO Clouds

CloudSat Clouds

CALIPSO Attenuation
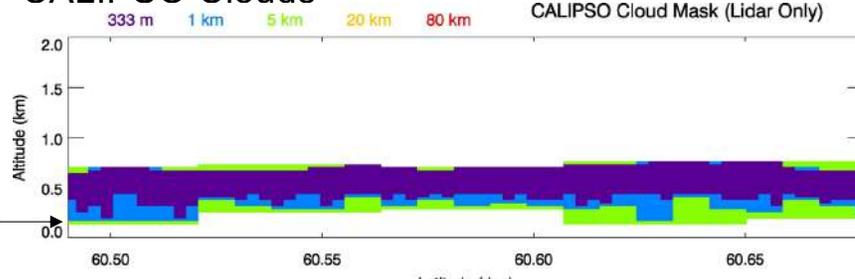
TOA SW and LW Biases Without Step 3 (Without Constraining with MODIS)

Occ (%) of CALIPSO Attenuation

LW Daytime Bias (W m^{-2})
LW SIM - OBS (Mean: -2.15, #: 316804) for SZA<82

July 2008

The regions where CALIPSO attenuation occurs

SW Daytime Bias (W m^{-2})
SW SIM - OBS (Mean: -9.84, #: 316588) for SZA<82

LW Nighttime Bias (W m^{-2})
LW SIM - OBS (Mean: -2.40, #: 383004) for 82≤SZA≤180

Large SW negative biases occur in the high-latitude regions where low clouds are located. This indicates some low clouds are missed by CloudSat and CALIPSO. The impact of missing low clouds on LW biases are small due to the close cloud temperature to surface temperatures.

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 (τ_M and r_M) properties.

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

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

MODIS Scaled Cloud Optical Depth

α is a scaling factor to reproduce MODIS-equivalent scaled optical depth from the merged extinction profile (α $k_{CCM}(i)$).

- Note that visible channel (non-absorbing) radiance is a function of VSCOD, and thus the use of MODIS VSCOD reproduces MODIS visible channel radiances. By constraining $k_{CCM}(z)$ with MODIS VSCOD, the scaled α $k_{CCM}(z)$ 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

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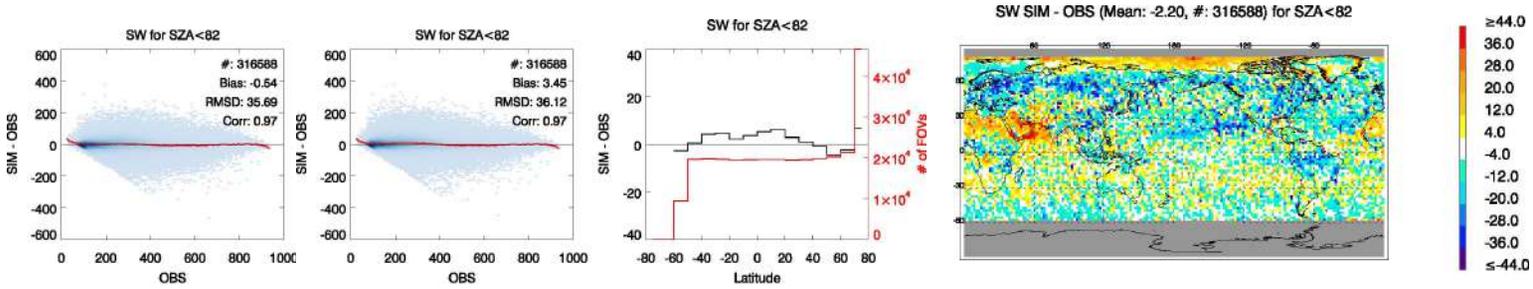SZA < 82°   SZA ≥ 82°
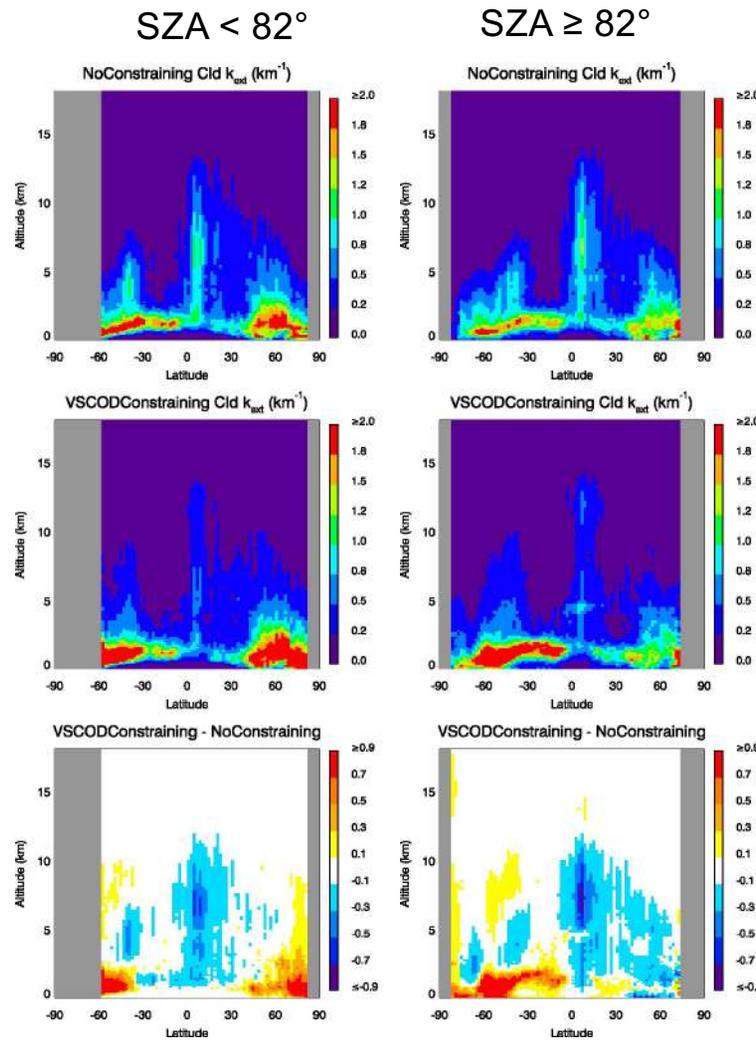
$k_{CCM}(z)$

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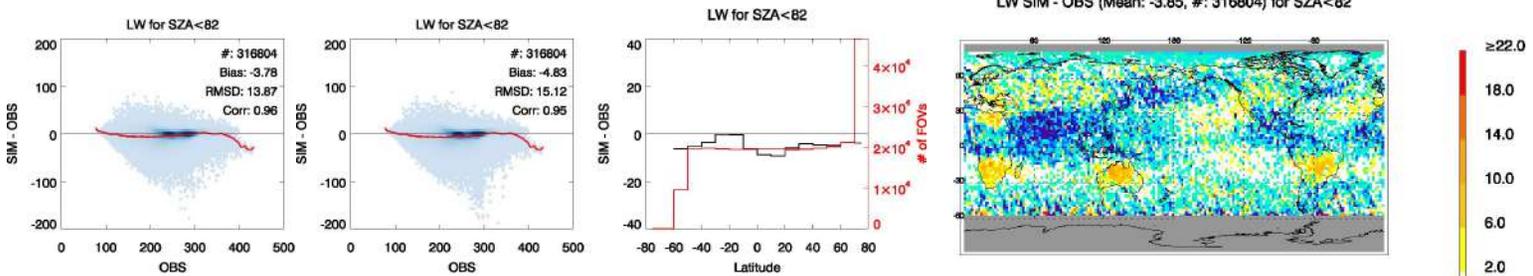from VSCOD method

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

- $k_{CCM}(z)$ 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.

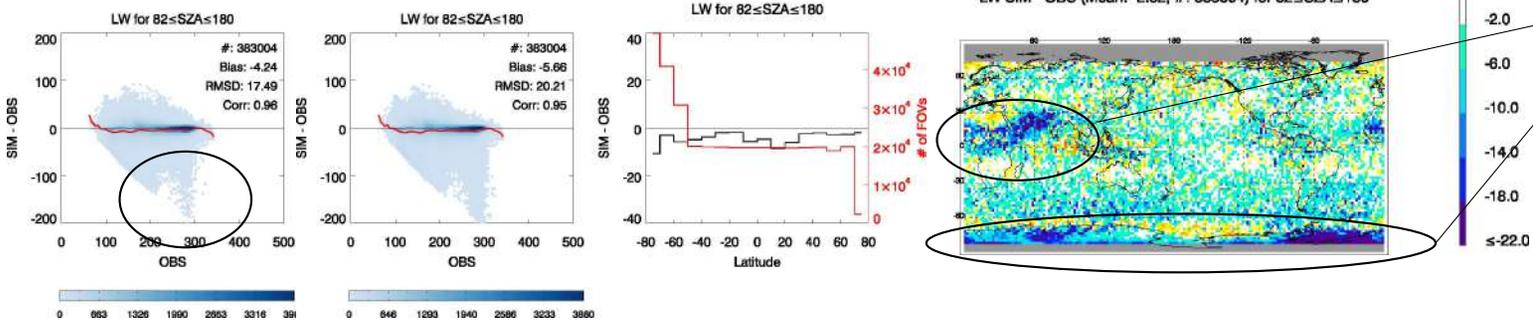# SW and LW Biases (W m^{-2}) when VSCOD Constraining Method is used for $\alpha k_{CCM}(z)$

VSCOD Method generally works well but nighttime LW biases are sometimes large negative over the Antarctica and Arabian peninsula.

Daytime SW

Daytime LW

Nighttime LW

200807_CC_num_filter

RelD1–beta3/v7_vgrp_tarea_calip_top_PSCrvd_CAL_aer3_ir11_pts1_THM_ee2_wo_2BCWC_Liq_if_liqprcp_rmv_80km_Tw_Top_P850_ssf4_omee_ocn_alb1_vis_adj_2re_enh_re_ncrs_ENH/

Polar Stratospheric Cloud Type II (Consisting of Ice Particles) Missed in MODIS

- 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 clouds below the tropopause (~ 11 km).

January 2008

PSC areal coverage over the Antarctic
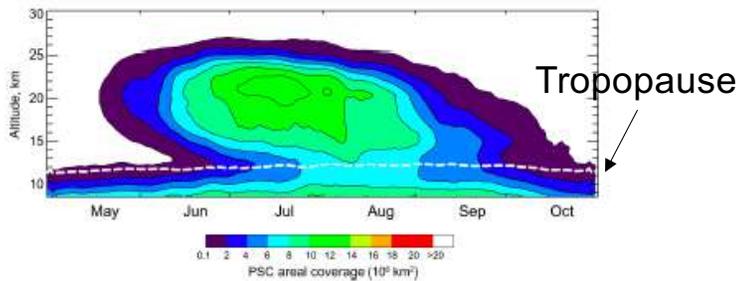
Tropopause

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)
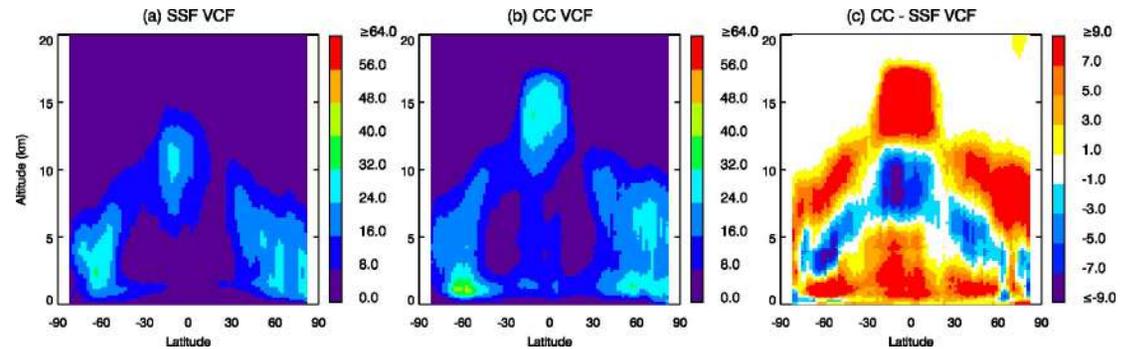
July 2008
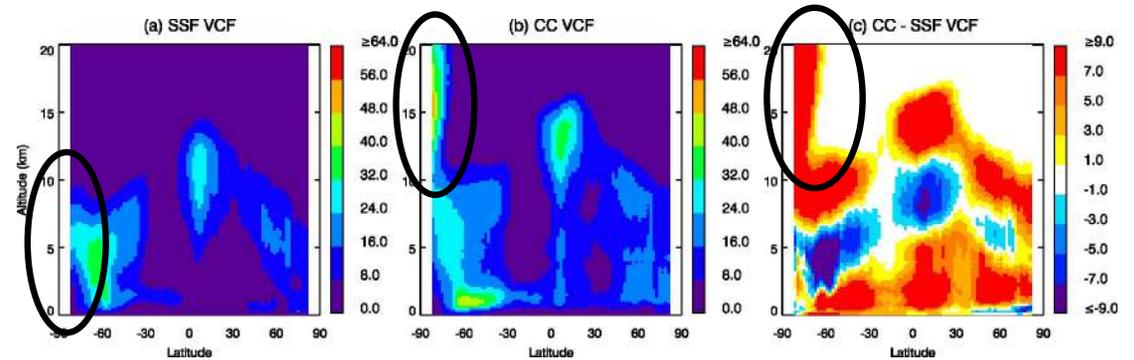
Amplification of Nighttime LW Biases If MODIS Tc (MODIS cloud height) is biased

SZA<82

LW Bias

CC T$_c$ - MOD T$_c$

Daytime MODIS COD is derived from MODIS visible channel, which is less affected by the cloud height assumption than in IR COD retrievals.
When MODIS cloud height is low-biased (and thus MODIS Tc > CC Tc) and we use more accurate CC cloud height information (higher cloud height), negative LW biases occur. This implies that the radiative center of k$_{CCM}$(z) is biased high, particularly for deep convective clouds.

82≤SZA≤90

LW Bias

CC T$_c$ - MOD T$_c$

Larger negative means that MODIS Tc is warmer than CC Tc.
MODIS COD is more positively biased.

Nighttime MODIS COD is derived from MODIS IR channel, which is significantly affected by the cloud height assumption. If MODIS cloud height is low-biased (or warm-biased), MODIS COD would be positively biased.
In addition to the biased radiative center issue, the positively biased MODIS COD will amplify LW negative biases.

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

Warm biased   Positively biased

0   73   146   220   293   366   440

warmer Tc
Larger τ_c

True (CC cloud)   MODIS cloud
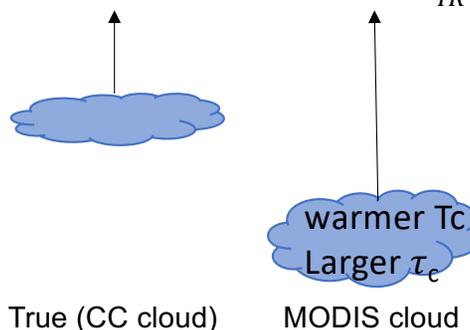
Optical Properties of PSC

- CERES footprints over Antarctica are analyzed.
- Small cloud optical depth (or cloud extinction coefficient) according to CALIPSO or 2C-ICE
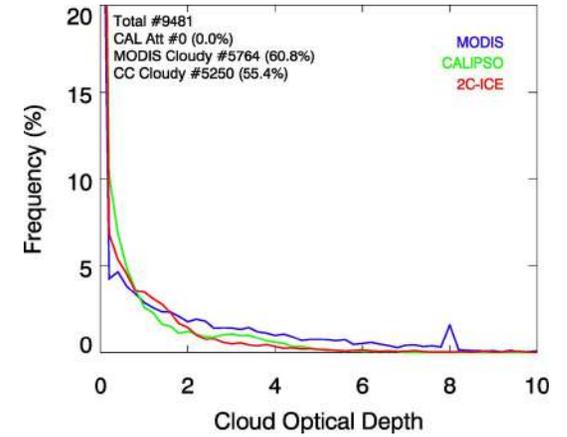- High altitude above tropopause (~ 11 km) located between 10-20 km
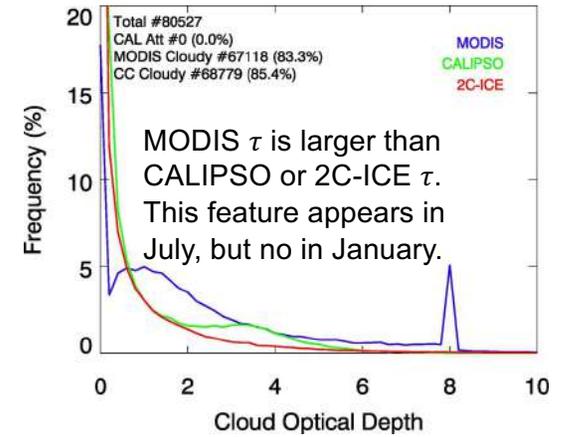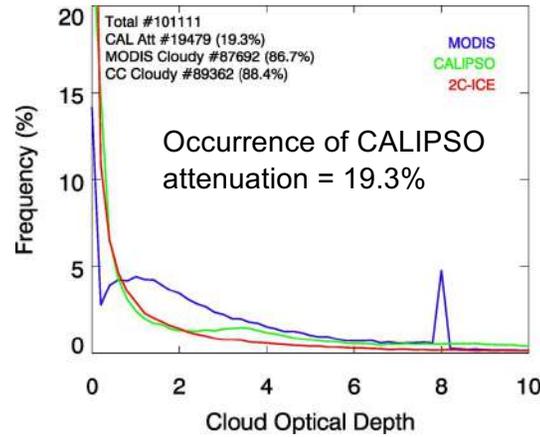
All CERES footprints over Antarctica
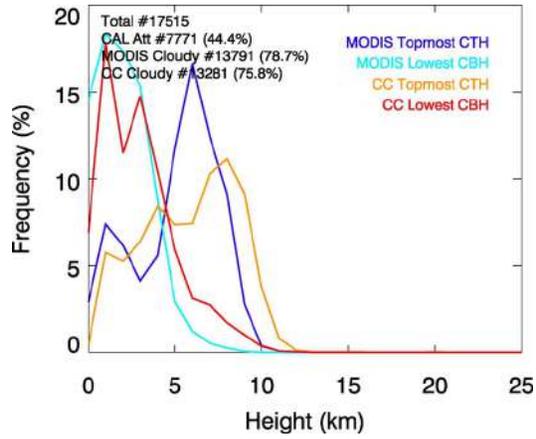
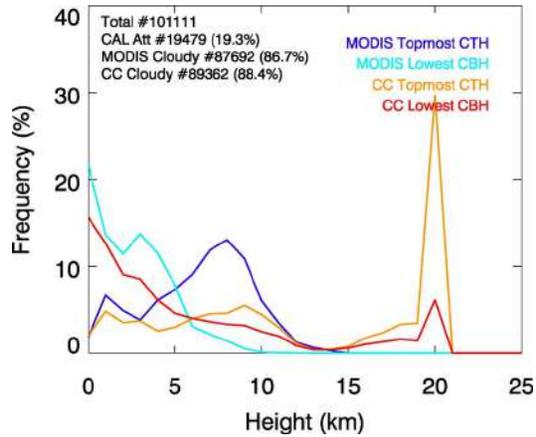All CERES footprints over Antarctica
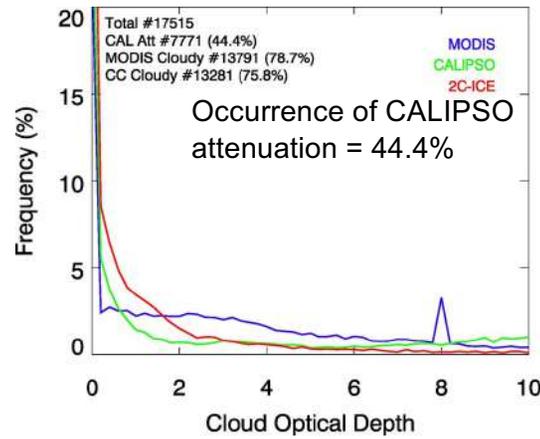
CERES footprints with no CALIPSO attenuation

January 2008

Total #17515
CAL Att #7771 (44.4%)
MODIS Cloudy #13791 (78.7%)
CC Cloudy #13281 (75.8%)

MODIS Topmost CTH
MODIS Lowest CBH
CC Topmost CTH
CC Lowest CBH

Total #17515
CAL Att #7771 (44.4%)
MODIS Cloudy #13791 (78.7%)
CC Cloudy #13281 (75.8%)

MODIS
CALIPSO
2C-ICE

Occurrence of CALIPSO attenuation = 44.4%

Total #9481
CAL Att #0 (0.0%)
MODIS Cloudy #5764 (60.8%)
CC Cloudy #5250 (55.4%)

MODIS
CALIPSO
2C-ICE

July 2008

Total #101111
CAL Att #19479 (19.3%)
MODIS Cloudy #87692 (86.7%)
CC Cloudy #89362 (88.4%)

MODIS Topmost CTH
MODIS Lowest CBH
CC Topmost CTH
CC Lowest CBH

Total #101111
CAL Att #19479 (19.3%)
MODIS Cloudy #87692 (86.7%)
CC Cloudy #89362 (88.4%)

MODIS
CALIPSO
2C-ICE

Occurrence of CALIPSO attenuation = 19.3%

Total #80527
CAL Att #0 (0.0%)
MODIS Cloudy #67118 (83.3%)
CC Cloudy #68779 (85.4%)

MODIS
CALIPSO
2C-ICE

MODIS τ is larger than CALIPSO or 2C-ICE τ. This feature appears in July, but no in January.

IR Cloud Emission (IREMIS) Constraining Method

- When MODIS COD is retrieved using infrared channels, cloud effective temperature (T_c) is also derived together. In other words, the errors in MODIS COD are coupled with T_c errors, which is different from daytime MODIS COD retrievals.
- If MODIS IR cloud emission is estimated by combining MODIS COD and MODIS T_c, the errors of these two parameters are cancelled out, and the estimated IR cloud emission is strongly correlated with MODIS IR channel radiances. As a result, it is also well correlated with LW broadband irradiances. Therefore, we constrain the merged k_{CCM} using MODIS IR cloud emission.
- We use 11 µm for computing IR emission term.

MODIS-estimated IR cloud emission from cloud layers

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

$$IREMIS\big(T_{eff,MODIS}, \tau_{MODIS}\big) = IREMIS(\alpha k_{CCM}(z), r_{CCM}(z))$$

Limitations of the IREMIS Method

If cloud temperature is too close to surface temperature, the IR emission value become 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.

Approximately
$$\varepsilon_s B(T_s) \exp(-\tau_{MODIS})$$
$$+ B(T_{eff,MODIS}) \times$$
$$(1 - \exp(-\tau_{MODIS}))$$

$$IREMIS(T_{eff,MODIS}, \tau_{MODIS}) = IREMIS(\alpha \, k_{CCM}(z), r_{CCM}(z))$$

MODIS-estimated IR emission   CCM-estimated IR emission with changing α

For high clouds (Tc << Ts)

$IREMIS(\alpha \, k_{CCM}(z))$

z

$k_{CCM}(z)$

$k_{MODIS}(z)$ or τ_{MODIS}

$k_{ext}(z)$

$B(T_s)$

MODIS-estimated IR emission

$B(T_{eff,CCM})$

Solution of α   Scaling Factor α

For low clouds (Tc ~ Ts)

$IREMIS(\alpha \, k_{CCM}(z))$

Scaling Factor α
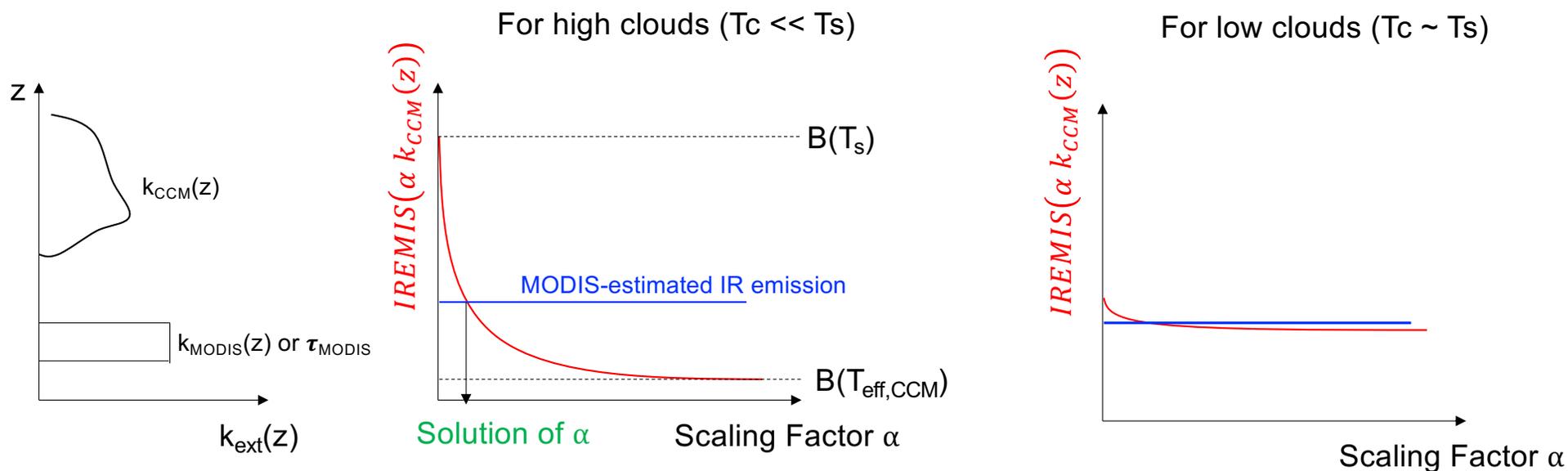
v7_vgrp_tarea_calip_top_PSCrvd_CAL_aer3_ir39_pts1_THM_ee2_wo_2BCWC_Liq_if_liqprcp_rmv_80km_Tw_Top_P850_ssf4_omee_ocn_alb1_ir_adj_2
re_enh_re_ncrs_ENH
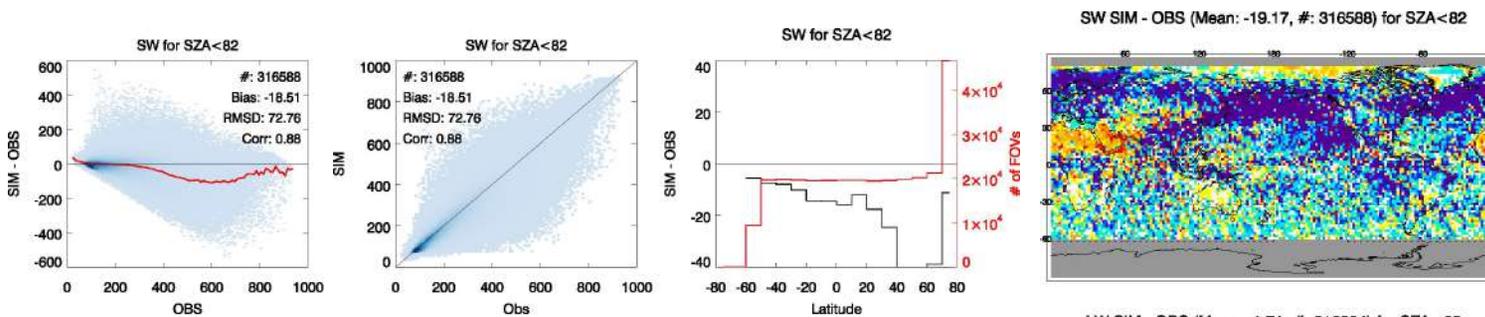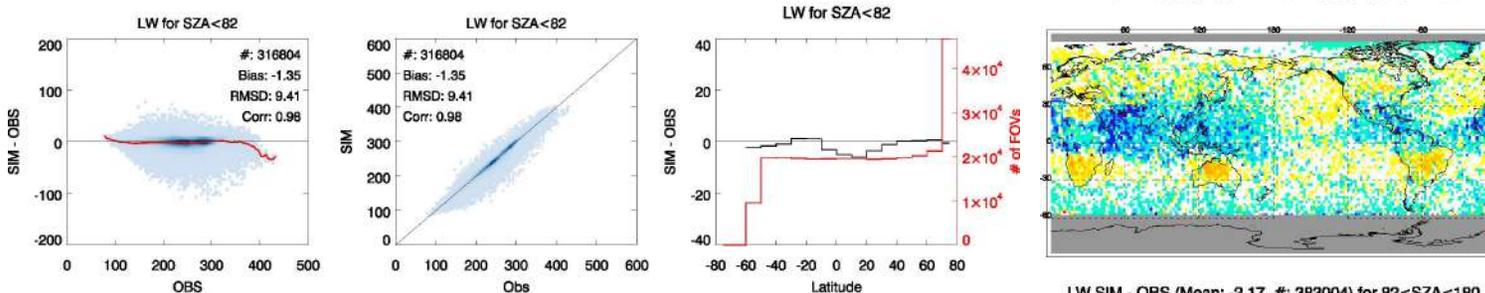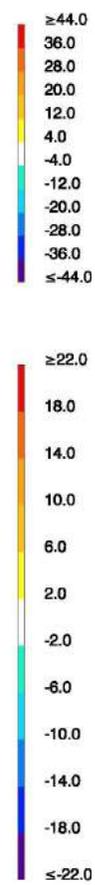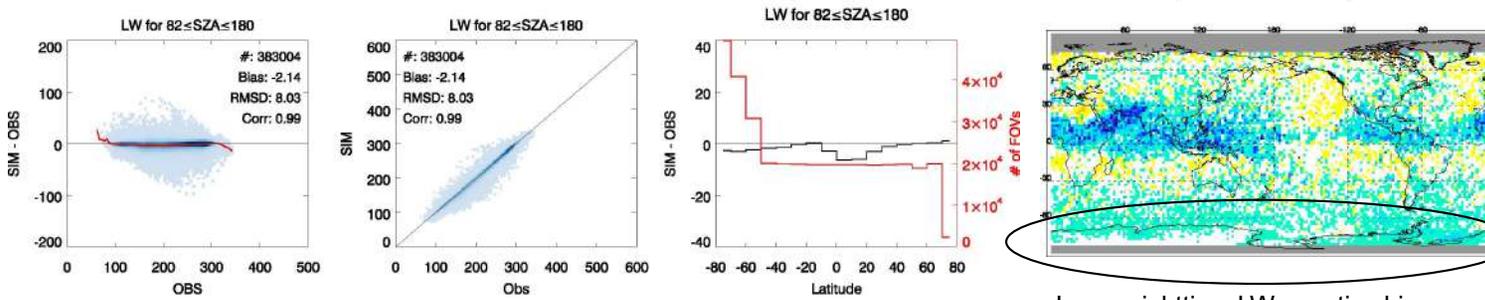
Large negative SW biases for Low cloud regions due to the limitation of TEMIS method.

Large nighttime LW negative biases over the Antarctica are removed by TEMIS method.

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Hybrid Approach

Daytime (SZA < 82°) → VSCOD Method

Nighttime (SZA ≥82°) → CC T_c < T_{skin} − 20 K and CC T_c < MODIS T_c − 20K

No → VSCOD Method

Yes → IREMIS Method
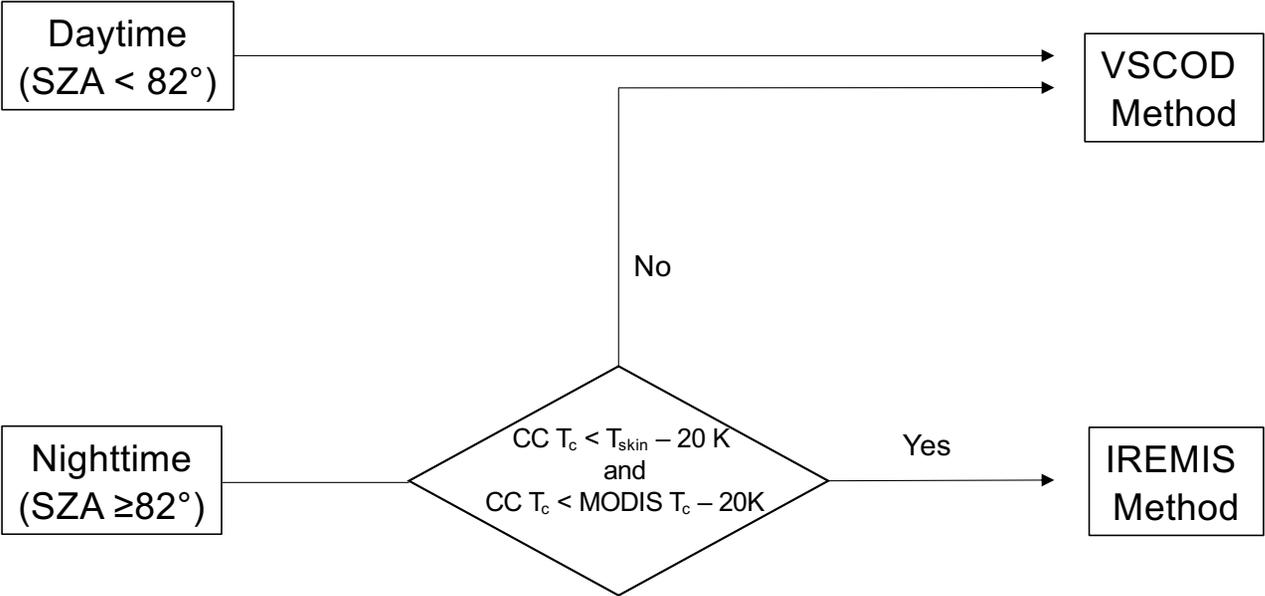
TOA SW and LW Biases to CERES Observations
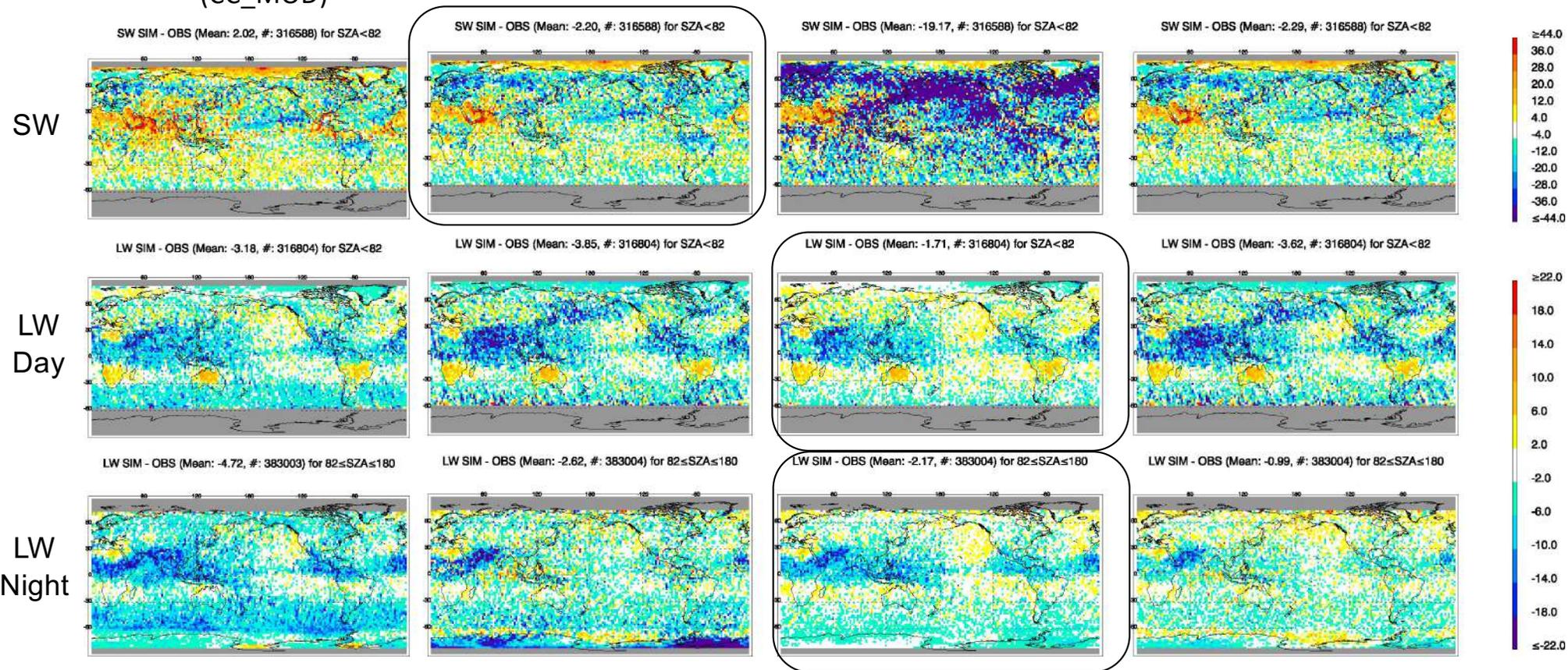
When combining VSCOD and IREMIS, SW and LW biases are reduced.

SW and LW Surface Downward Irradiances (W m⁻²)   200807

MODIS Only   VSCOD   IREMIS   Hybrid
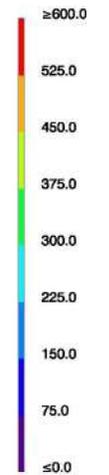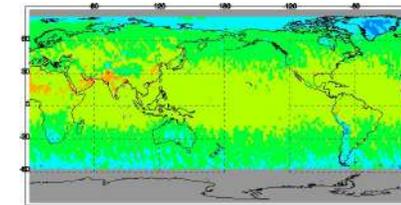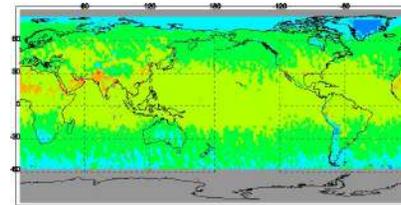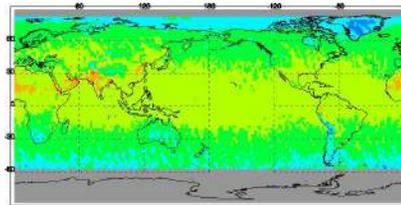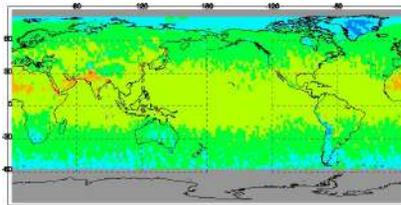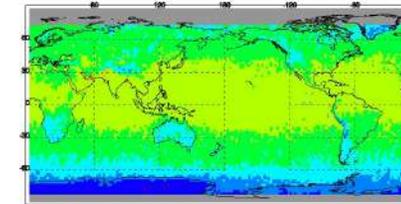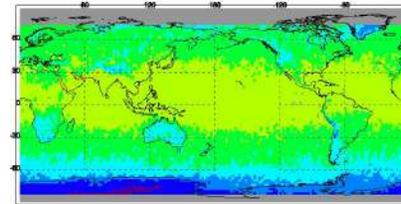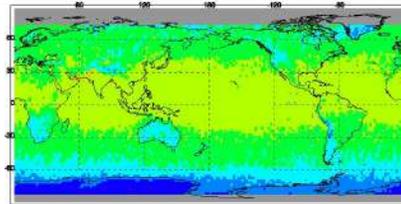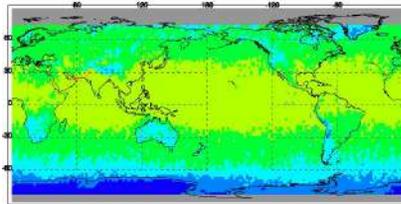
(CC_MOD)

Differences of SW and LW Surface Downward Irradiances (W m^{-2}) from Hybrid Results

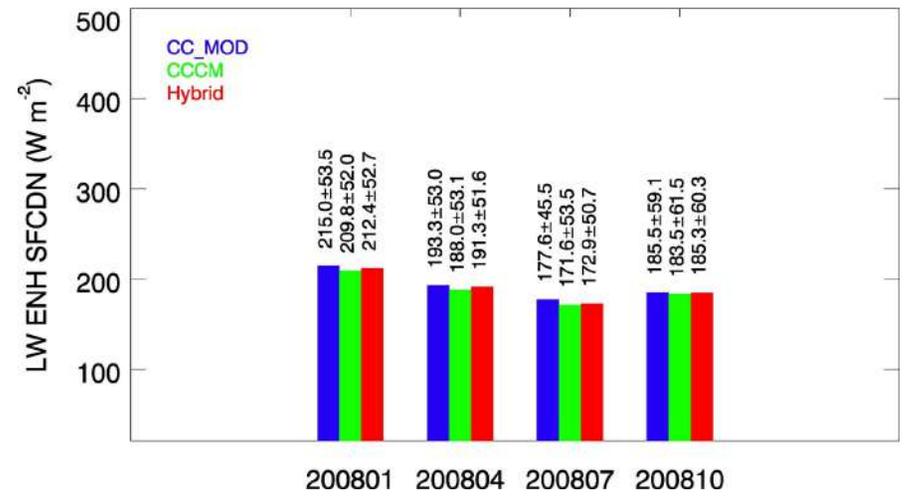**CC_MOD - Hybrid**
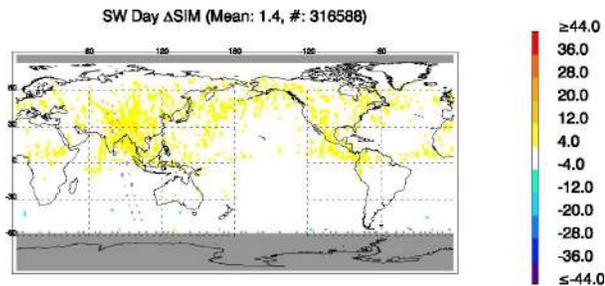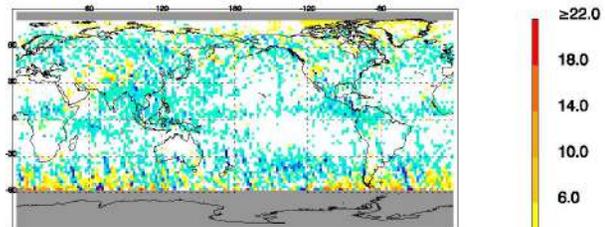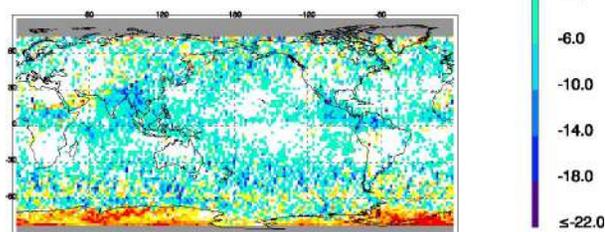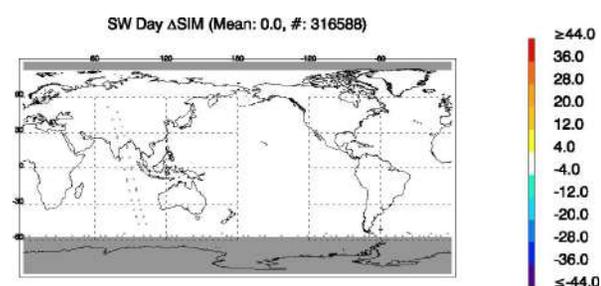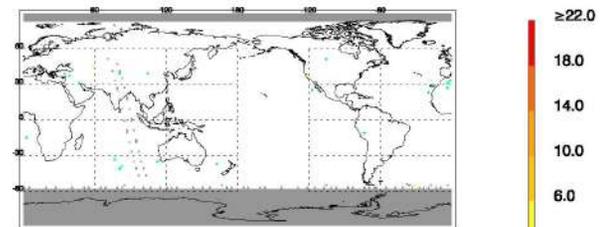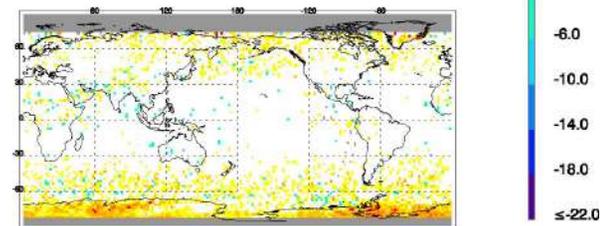
VSCOD - Hybrid

IREMIS - Hybrid
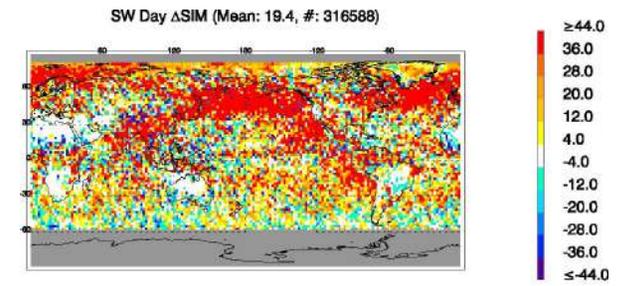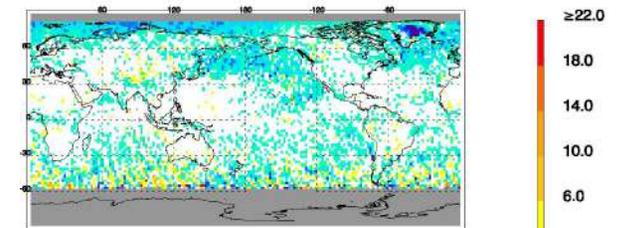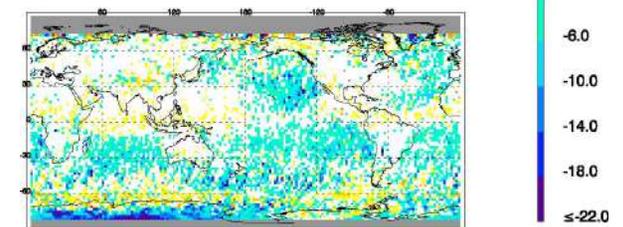
Domain-Averaged LW Surface Irradiances (W m$_{-2}$)

Day+Night Avergeas over the Global Mean
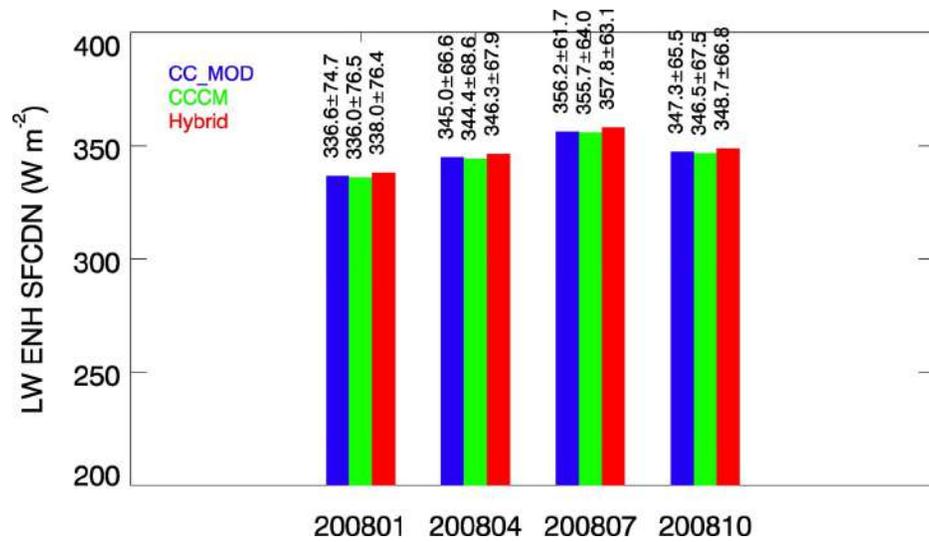
Day+Night Averages over the Antarctic
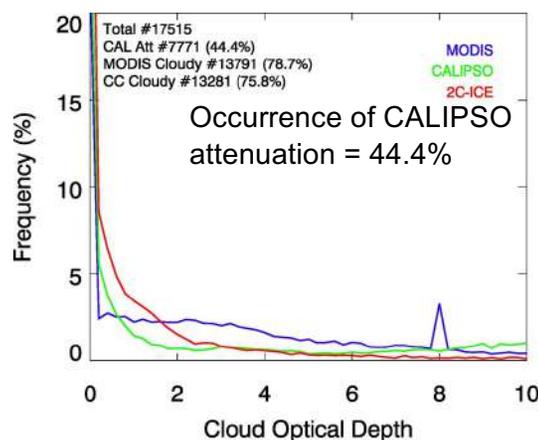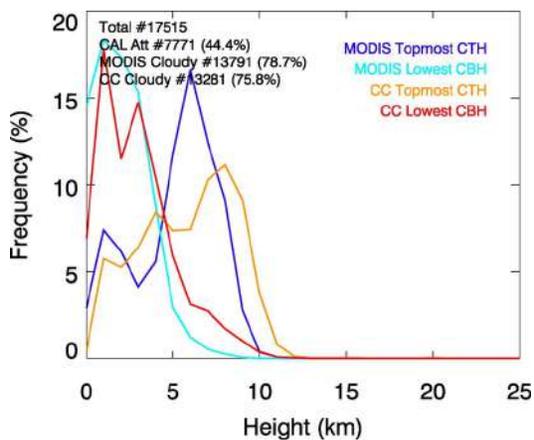
Summary

- VSCOD method is shown to improve SW simulations by increasing $\alpha k_{CCM}(z)$ 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. In this case, MODIS Tc is warm-biased and MODIS τ is positively biased. The biases are more significant in wintertime over the Antarctica when polar stratospheric clouds (PSCs) appear. MODIS algorithm often detects this type of clouds as low clouds.

- IREMIS method is shown to improve 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.

- A hybrid method is considered by combining VSCOD and IREMIS methods.

- The impact of which method is used is relatively small for TOA LW simulation, but the impact of surface LW radiation can be more noticeable, especially over the Antarctica. From CCM approach, surface LW downward is reduced by 3-5 W m-2 over the Antarctic. In the rest regions, CCM approach gives larger LW surface downward due to the lower cloud base.
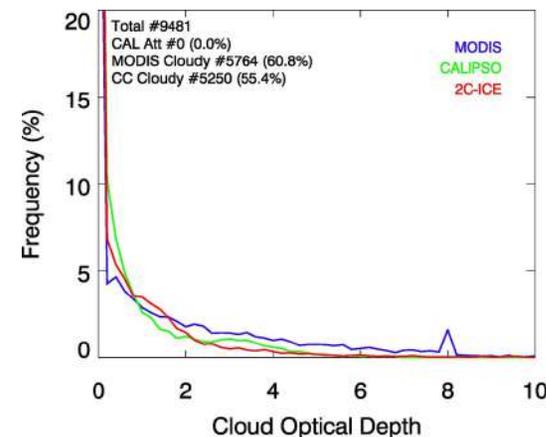
Optical Properties of PSC II

- Small cloud optical depth (or cloud extinction coefficient)
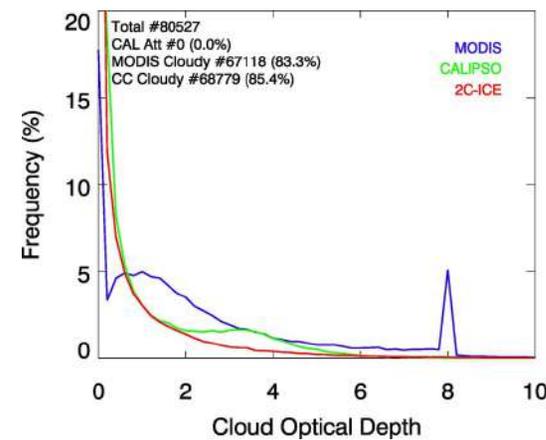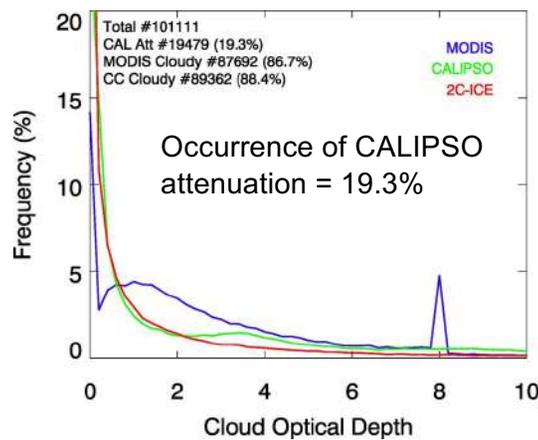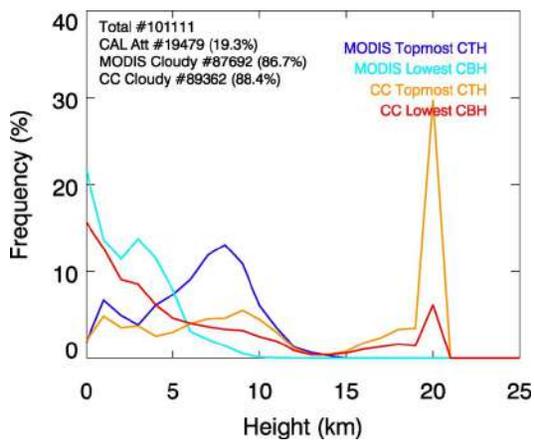- High altitude above tropopause (~ 11 km) located between 10-20 km

Cases with no CALIPSO attenuation

January 2008

Occurrence of CALIPSO attenuation = 44.4%

July 2008

Occurrence of CALIPSO attenuation = 19.3%

CC_Tc from weighted mean
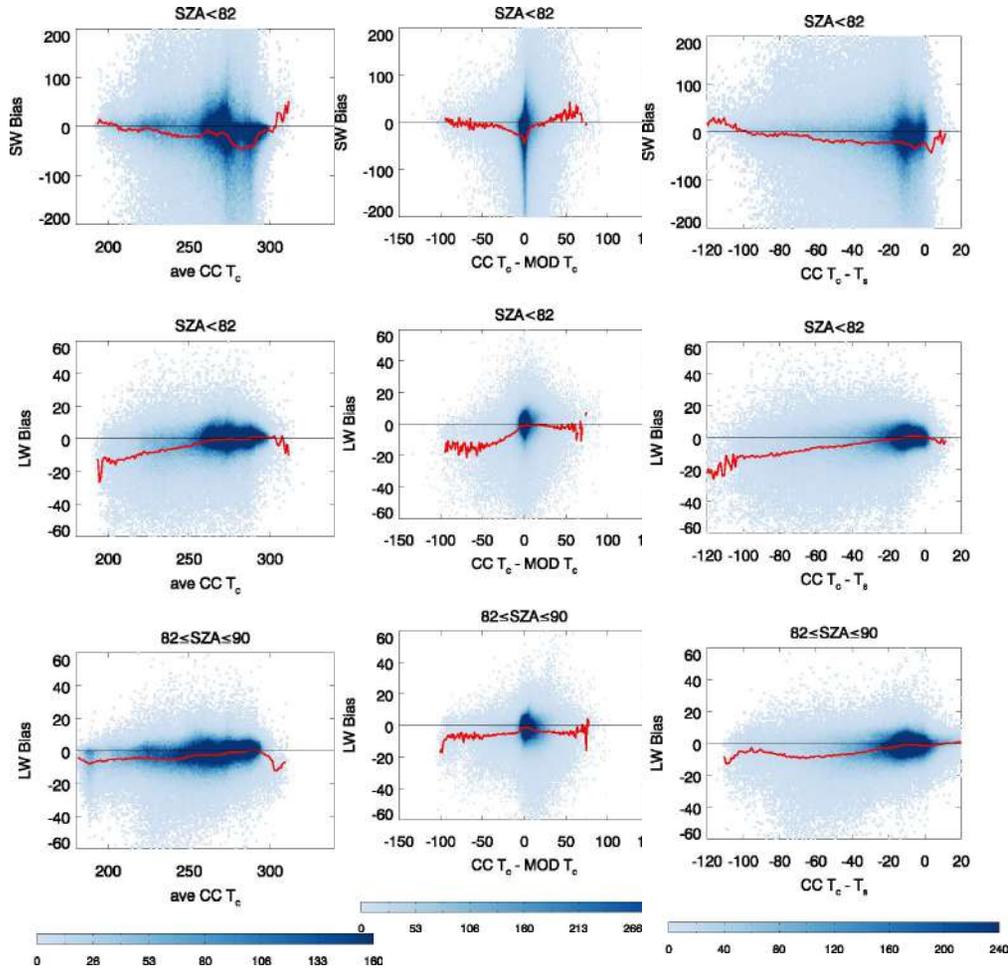
CC_Tc from temperature at cloud top