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## **Improvement of Irradiance Computations from ReIB1 to ReID1 CCCM Products**

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## CCCM Flux Computations

- CCCM algorithm combines CALIPSO, CloudSat, and MODIS information for better describing cloud/aerosol vertical profiles and optical properties for flux computations (Kato et al. 2011).
- ReIB1 CCCM product was released in 2014, and ReID1 CCCM product will be released soon. The ReID1 product has been generated with new versions of CERES (Ed4), MODIS (Ed5), CALIPSO (V4), and CloudSat (R05) products.

## Input Parameters Used For RelB1 and RelD1 CCCM Flux Computations

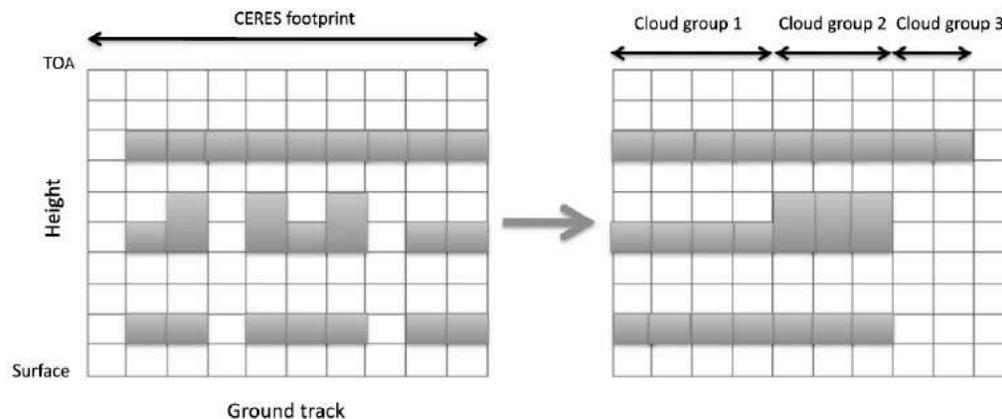
	Release B (RelB1)	Release D (RelD1)
CERES-Derived Flux "Obs"	Edition 2 Angular Distribution Model (ADM)	Edition 4 ADM
MODIS Cloud Algorithm	Edition 3 Beta MODIS Clouds (Smooth hexagonal single habit ice model)	Edition 5 Beta MODIS Clouds (Two-habit ice model)
CALIPSO	V3	V4 Also water clouds below 4 km detected with non-single shots are excluded.
CloudSat 2B-CWC 2B-CLDCLASS	Release 4 (R04)	Release 5 (R05) (Liquid 2B-CWC has been significantly changed but not the ice phase)
CloudSat 2C-ICE (Radar+Lidar combined ice cloud retrievals)	Not used	Implemented, and used as a first choice
MATCH	Daily	Hourly
Solar Constant	1365 W m <sup>-2</sup> Fixed Value	SOLCE Database (~ 1361 W m <sup>-2</sup> for July 2008)
Sea/Ice Albedo	Climatology	Pre-Processed Surface Albedo History (SAH) Map

## RT Inputs for CCCM Flux Computations

- Modified Fu-Liou Model by LARC
- GEOS-5.4.1 T & q Profiles (MOA-5.4.1)
- MATCH hourly Aerosol + CALIPSO Aerosol + MODIS Aerosol
- Surface History Map for Sea/Ice Surface, Climatological Albedo for ocean, MODIS BRDF for land surface albedo
- Cloud properties are combined from CALIPSO, CloudSat, and MODIS products

## CALIPSO-CloudSat (CC) Cloud Groups in each CERES Footprint

- Within a CERES footprint, **CALIPSO and CloudSat cloud boundaries** are merged at a CALIPSO horizontal resolution (every 333 m) along the track. Then the patches with the same cloud top and base heights are grouped.
- Up to 16 cloud groups are generated in one CERES footprint. Each cloud group has up to 6 overlapping layers.
- For each cloud group, cloud properties from CALIPSO, CloudSat, and MODIS are combined, and the radiative transfer simulation is performed. These are weighted by cloud group areas. CCCM product only keeps irradiances for each CERES footprint.

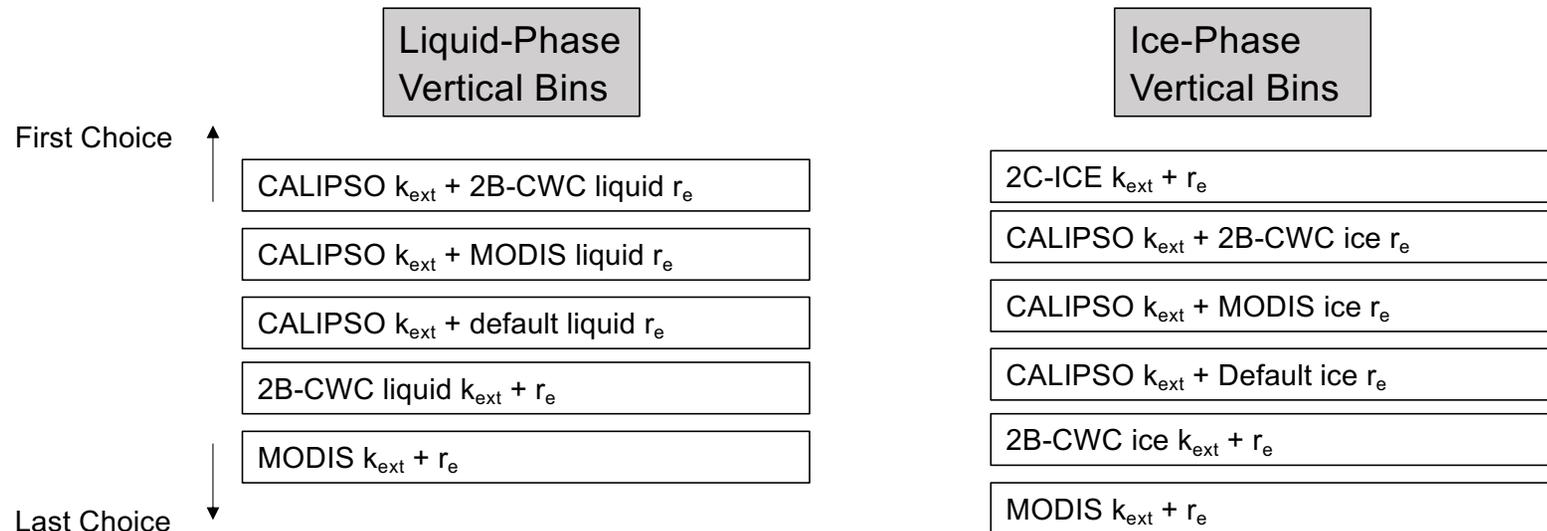


**Figure 2.** Schematic of the cloud grouping process. Cloud profiles that occur within a CERES footprint and have the same cloud boundary heights are grouped together. The group number of 1 is assigned to the cloud group having the largest cloud fraction over a CERES footprint.

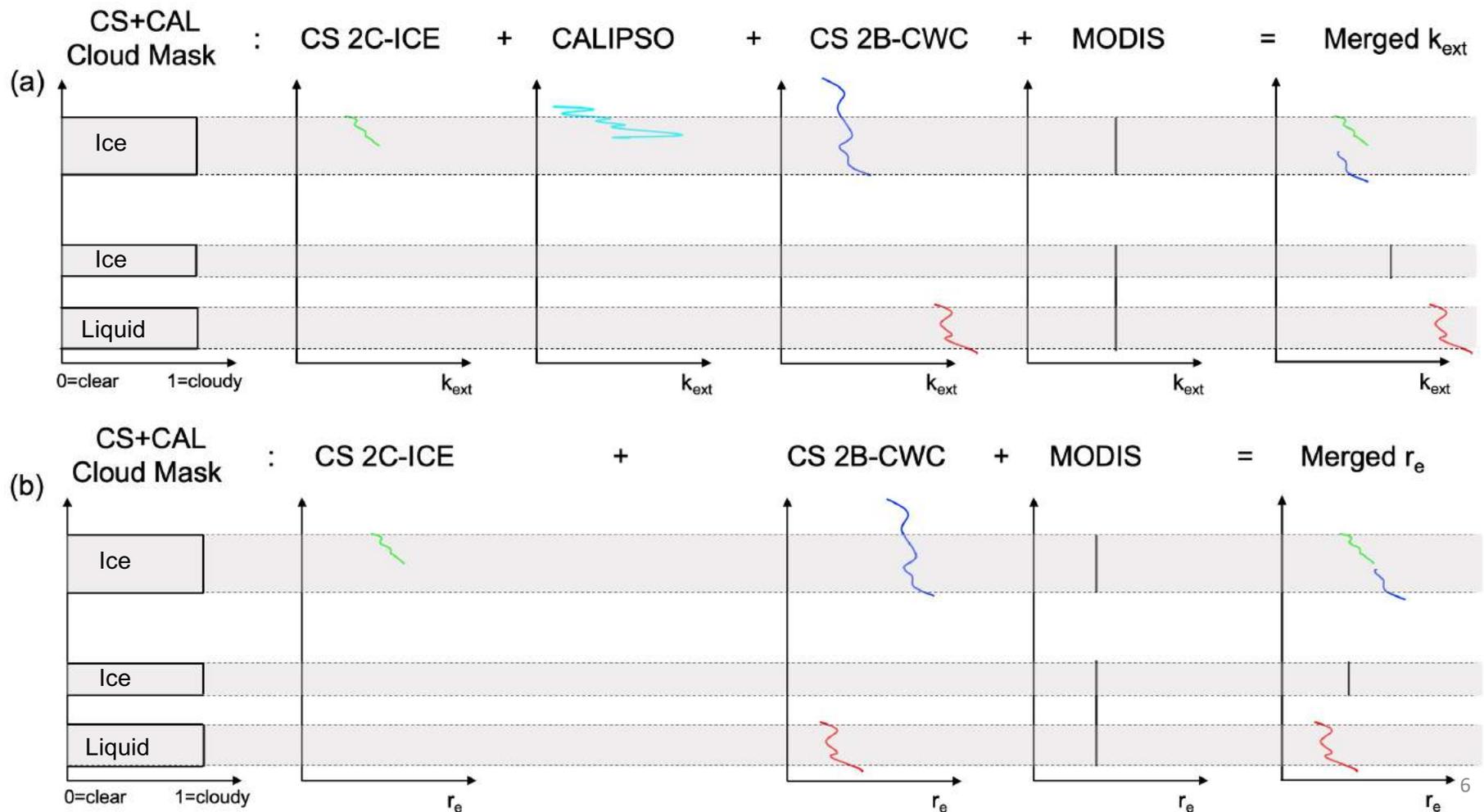
(Kato et al., 2010)

## Merging Multi-Sensor Cloud Information for Each Cloud Group

- For the cloudy vertical bins, cloud phase is determined.
- For  $T(z) > 273.15$  K, liquid phase is assumed.
- For  $T(z) < 253.15$  K, ice phase is assumed.
- For  $T(z)$  between 253.15 and 273.15 K, CALIPSO phase is used if the CALIPSO phase confidence is medium or high. If CALIPSO phase is not available, MODIS column phase is used to assign the phase between 253.15 and 273.15 K.
- We prefer from an order of 2C-ICE, CALIPSO, 2B-CWC, and MODIS cloud properties for ice phase clouds and CALIPSO, 2B-CWC, and MODIS for liquid clouds.



## A Schematic Diagram How $r_e(z)$ and $k_{ext}(z)$ are Merged for Each Cloud Group



## Constraining of the Merged Cloud Extinction Profiles with MODIS Information: Scaling Factor ( $\alpha$ ) is applied to the merged cloud profiles.

- 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 cloud vertical profiles ( $k_{\text{ext}}, r_{\text{eff}}$ ) from the active sensors, while the merged cloud profiles are normalized/constrained by MODIS cloud column-cloud ( $\tau_M$ ) properties.
- When MODIS cloud optical depth is derived from visible channels ( $\text{SZA} \leq 82^\circ$ ) (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 ( $k_{CCM}(i)$ ).

- When MODIS cloud optical depth is derived from infrared channels ( $\text{SZA} > 82^\circ$ )

$$TEMIS(T_{eff,MODIS}, \tau_{MODIS}) \quad \text{MODIS-estimated thermal IR emission from cloud layers}$$

$$= TEMIS(\alpha k_{CCM}(z), r_{CCM}(z))$$

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

Added  
in ReID1  
(Ham et al.,  
CERES Fall STM  
2020)

## Standard vs Enhanced MODIS Cloud Retrievals for CCCM Algorithm

- **Standard** MODIS Cloud Retrieval: MODIS retrieval is performed using MODIS radiance channels. The way used for the rest CERES products.
- **Enhanced** MODIS Cloud Retrieval (Sun-Mack, 2008 Spring CERES STM presentation) using collocated CALIPSO information: For single-layer and transparent CALIPSO ( $OD < 4$ ) clouds, CALIPSO cloud temperature is used in retrieving cloud optical depth, phase, and particle size → More consistent cloud heights to active sensors and more sensitive to thin ice cloud layers (larger cloud fraction)

Enhanced cloud fraction ( $f_c$ ) is larger than the standard  $f_c$  by including thin clouds.

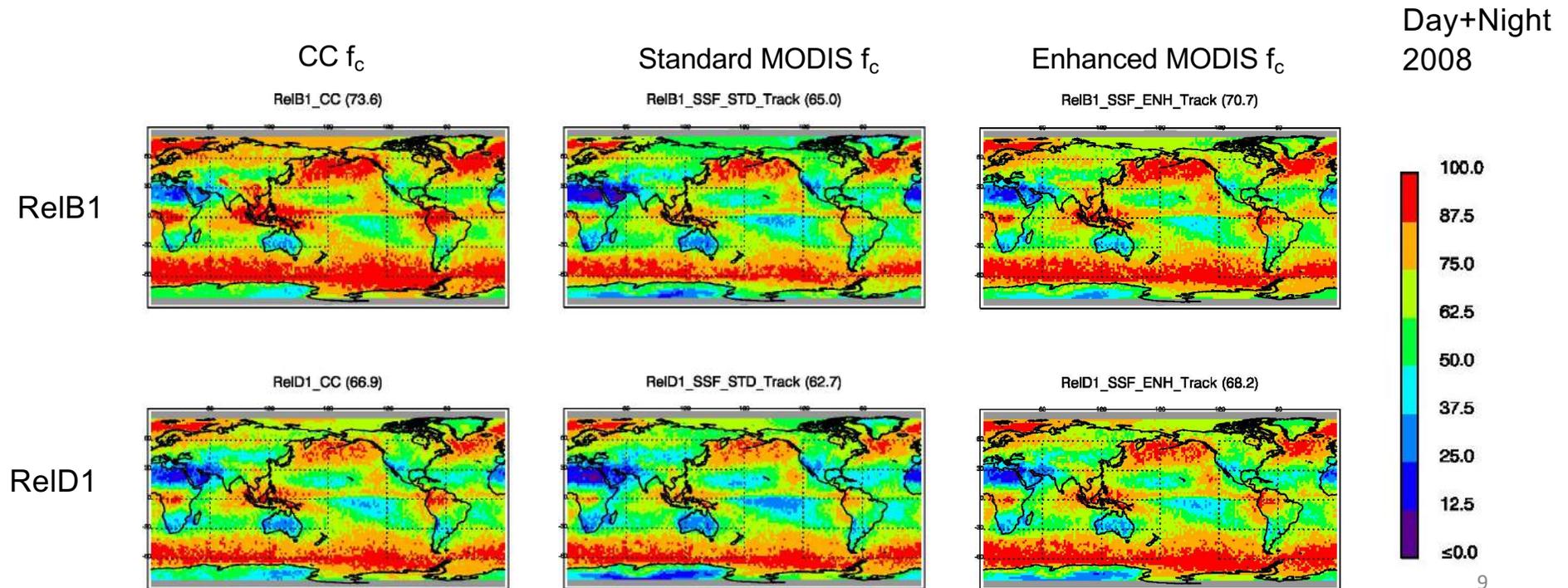
Enhanced cloud height ( $z_c$ ) is higher than the standard  $z_c$ , for cirrus clouds, by implementing CALIPSO information.

Enhanced cloud optical depth ( $\tau_c$ ) is slightly smaller than the standard  $\tau_c$  due to the larger  $f_c$  and higher  $z_c$ .

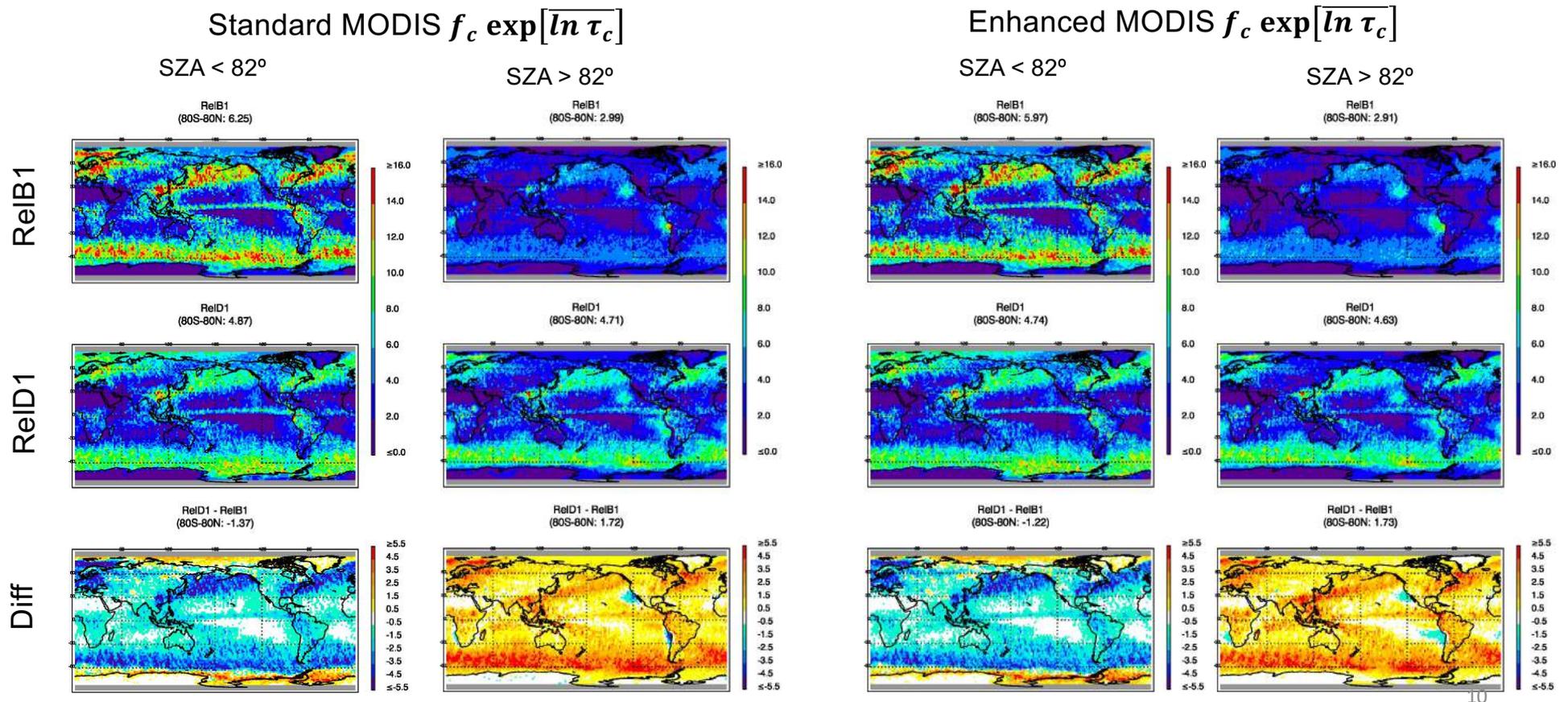
Note that when the enhanced approach is only available for thin single-layered cloud cases. The rest cases are still filled with the standard retrievals (in other words, multi-layered thick clouds, “enhanced” and “standard” MODIS cloud variables are the same.)

## CC (CALIPSO+CloudSat) and MODIS Cloud Fraction Changes From ReIB1 to ReID1

- CC cloud fractions are decreased in ReID1 because CALIPSO water clouds detected non-single shots are removed. Also cloud fractions in CloudSat 2B-CLDCLASS are reduced from R04 (used ReIB1) to R05 (used for ReID1).
- From MODIS Ed3 (used for ReIB1) to MODIS Ed5 (used for ReID1), MODIS cloud fractions are reduced.
- Note that radiative transfer simulations are performed based on CC cloud detections.



- Daytime MODIS cloud optical depth is decreased, and nighttime MODIS cloud optical depth is increased from ReIB1 to ReID1.
- In ReID1, day and nighttime MODIS cloud optical depths are more comparable by implementing neural network (NN) approach for ReID1.



# Improvement of SW Computations from ReIB1 to ReID1

Only fluxes computed with valid CALIPSO+CloudSat are used in 2008.

Standard

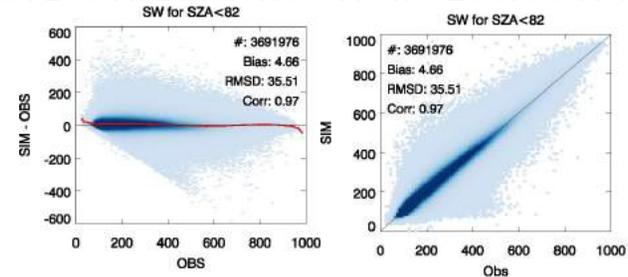
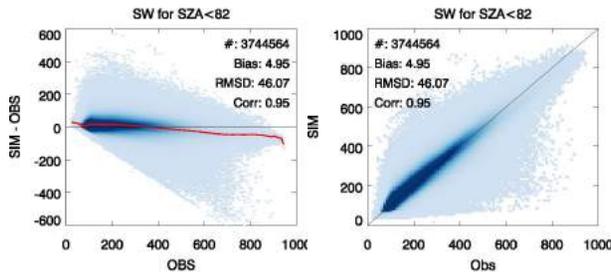
ReIB1



ReID1

STD SW Bias:  $4.95 \text{ W m}^{-2} \pm 46.07 \text{ W m}^{-2}$

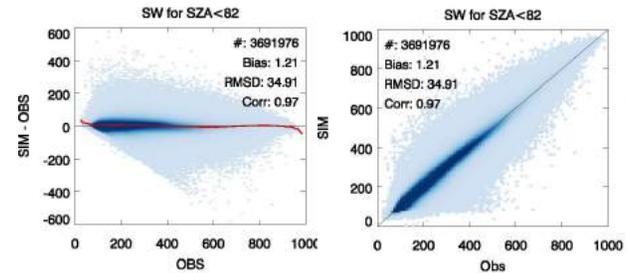
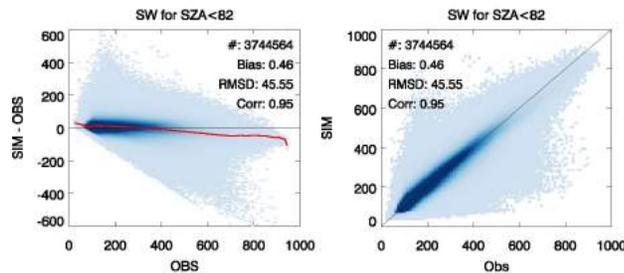
STD SW Bias:  $4.66 \text{ W m}^{-2} \pm 35.51 \text{ W m}^{-2}$



Enhanced

ENH SW Bias:  $0.45 \text{ W m}^{-2} \pm 45.55 \text{ W m}^{-2}$

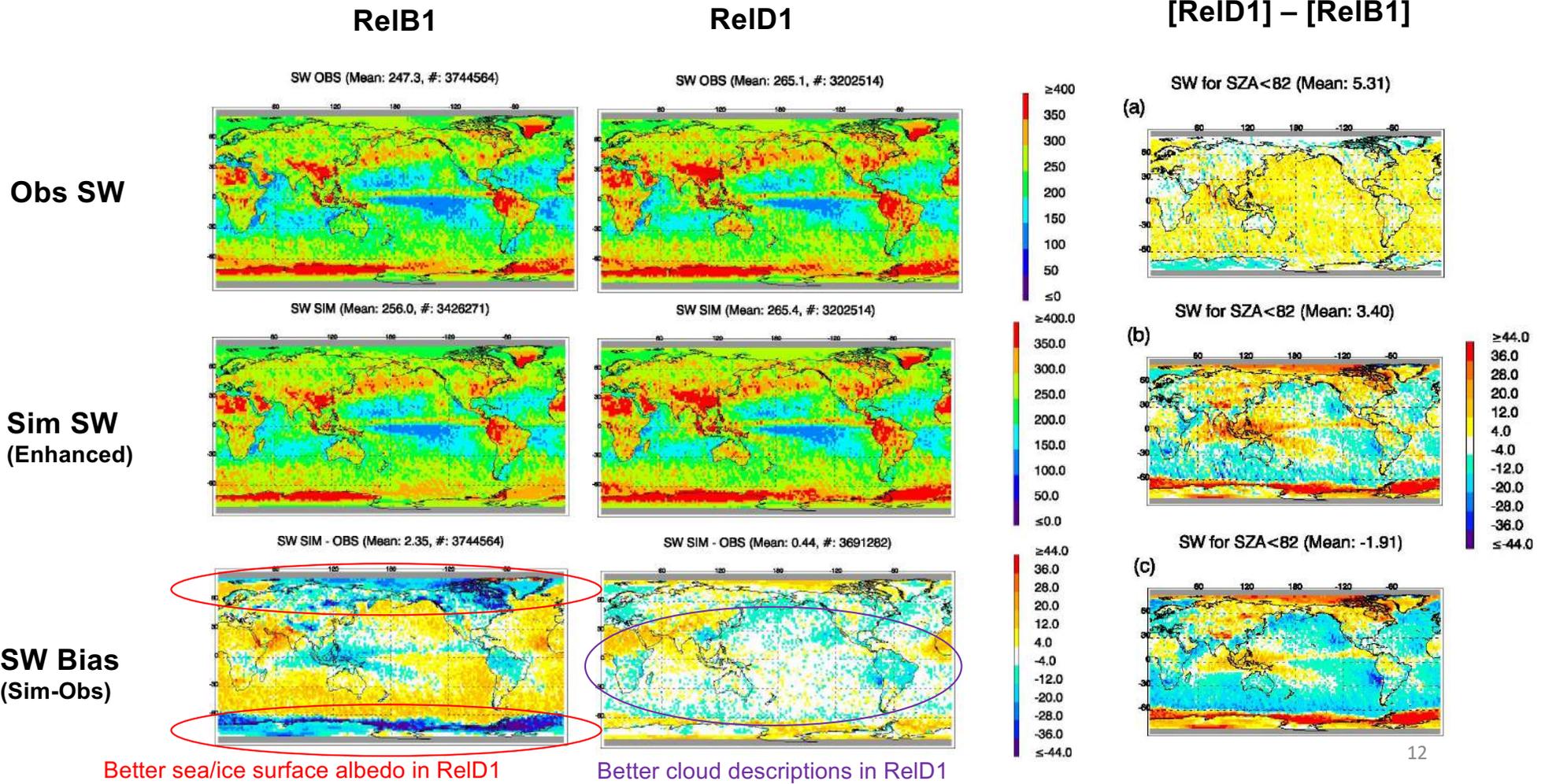
ENH SW Bias:  $1.21 \text{ W m}^{-2} \pm 34.91 \text{ W m}^{-2}$



- Negative SW biases at the high end of SW flux in ReIB1 are removed in ReID1.
- RMSD of SW biases are decreased in ReID1: Better consistency between MODIS cloud retrievals and RT forward computations in ReID1.
- Compared to STD, ENH algorithm provides better agreement with observations in both ReIB1 and ReID1: CC cloud detection and heights are used for MODIS cloud retrievals in ENH algorithm.

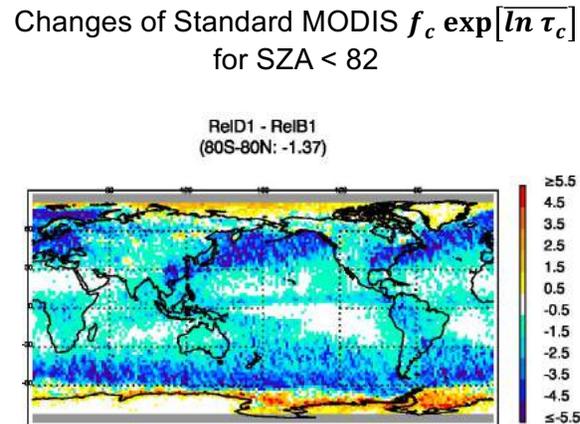
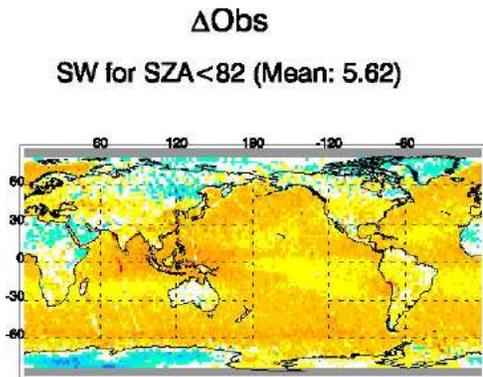
# Both CERES-Derived (Obs) and Computed SW Fluxes Changed in ReID1 from ReIB1

Enhanced CC\_number

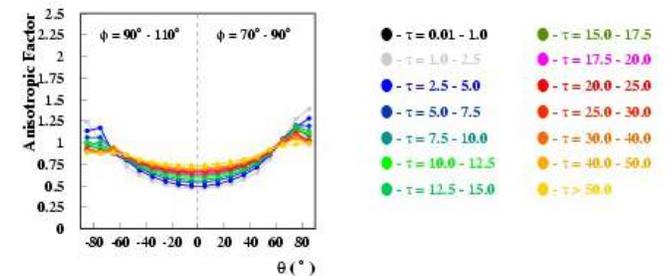


## Changes in CERES-Derived (Observed) SW Fluxes

- CERES flux changes are due to changes of scene identification and cloud ADMs from ReIB1 to ReID1
- One dominant factor is reduction of  $f_c \exp[\overline{\ln \tau_c}]$  from ReIB1 to ReID1. The reduction is due to 1) changes of ice scattering model from smooth hexagonal to THM models, 2) changes of atmospheric correction (Minnis et al. 2011).
- CCCM product only includes near-nadir CERES footprints.
- Note that Ed4 ADM was used with Ed5-beta MODIS cloud retrievals. Further examination is needed.



Water cloud ADMs for SZA=70-80° and RAA=70-90°



As the cloud optical depth is smaller, derived SW flux is larger because anisotropic factor is smaller.

## Improvement of ReID1 Flux Computations for Cloudy Atmosphere

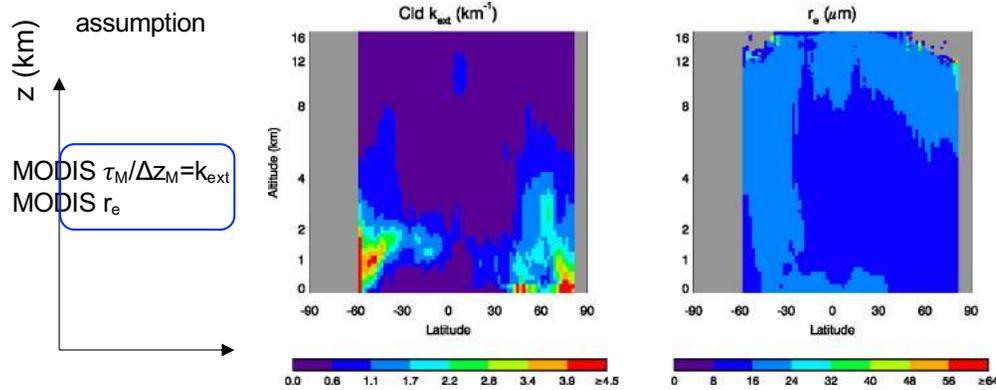
- Implementation of 2C-ICE ice  $k_{\text{ext}}$  and  $r_e$  profiles
- Use of temperature profiles and CALIPSO to determine cloud phase of each vertical bins
- Improved ice scattering model, two habit models (THM), used for MODIS cloud retrievals and RT computations
- Use of wet-bulb temperature at low cloud tops to take into account latent cooling due to entrainment
- Taking into account bidirectional reflectivity effect over ocean surface (Ham et al. 2016)

# Impact of the Description Method of $r_e$ and $k_{ext}$ profiles

(All four methods have the same visible scaled cloud column optical depths)

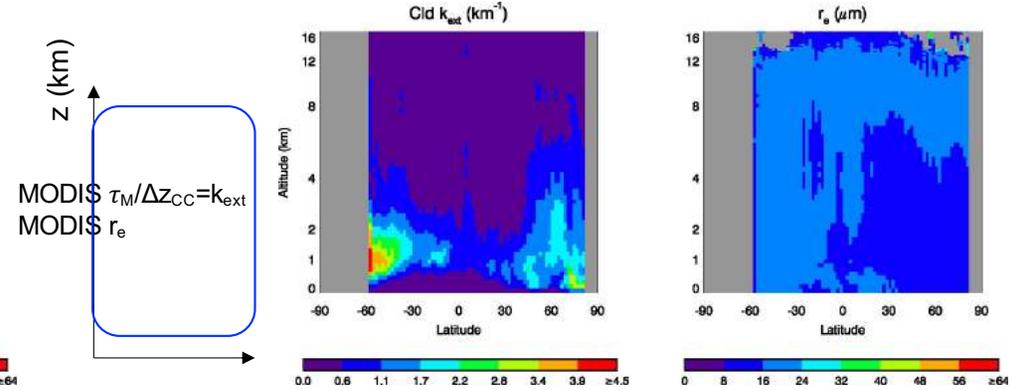
Method 1 (MODIS Only):

MODIS cloud height, MODIS phase, MODIS  $r_e$  with a single layer assumption



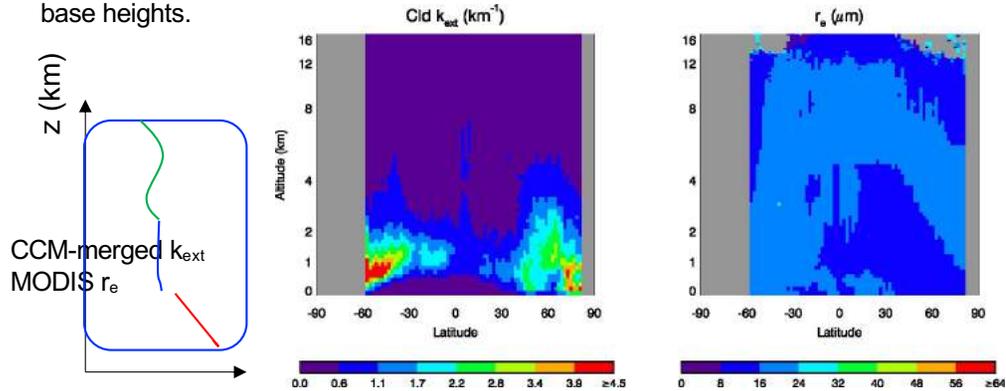
Method 2 (MODIS cloud properties + CC boundary):

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



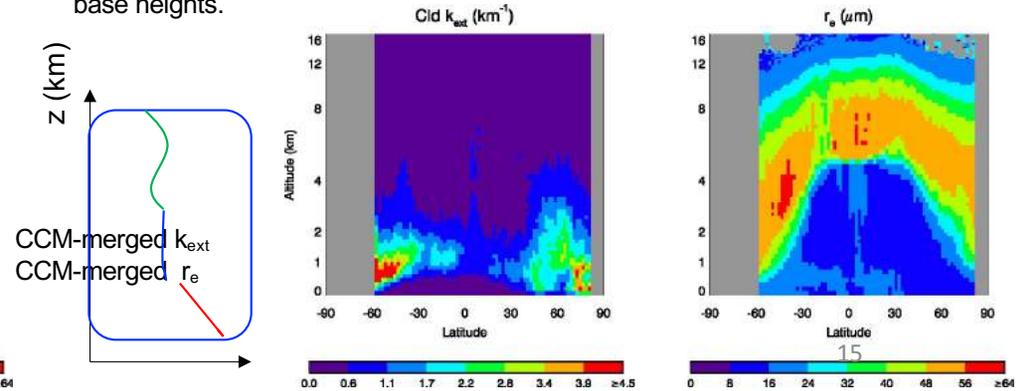
Method 3 (CCM  $k_{ext}$  + CCM phase + MODIS  $r_e$  + CC boundary):

Merged  $k_{ext}$  profile is assumed but with a constant MODIS  $r_e$  between CC-detected cloud top and base heights.

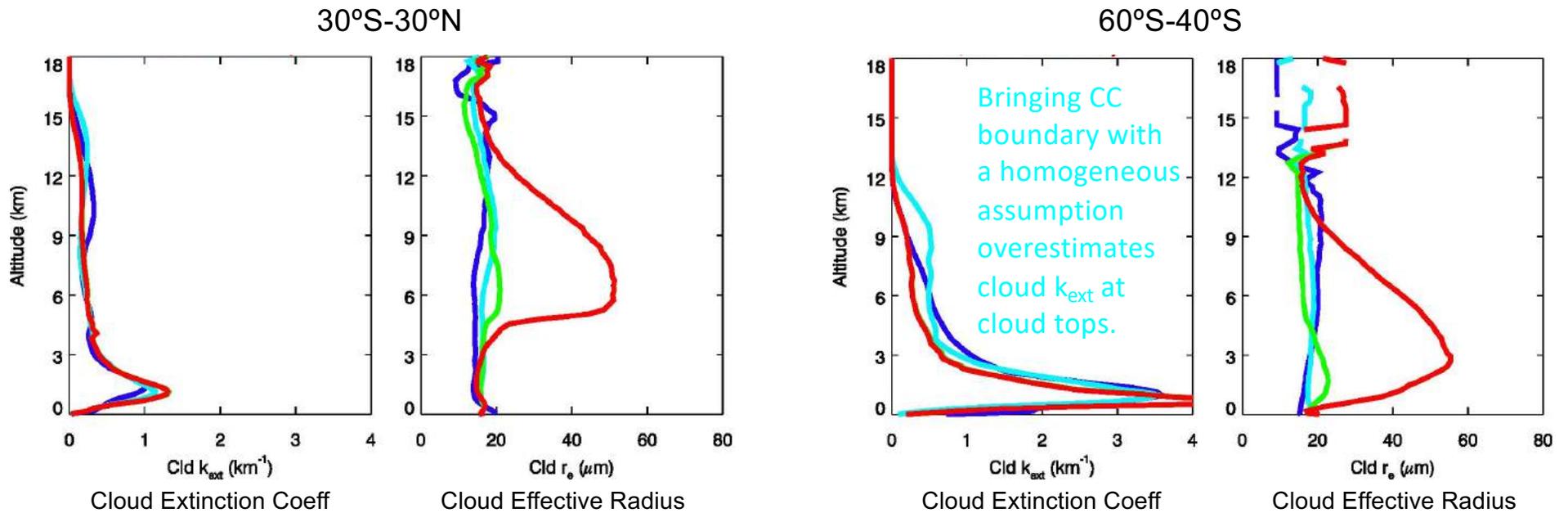


Method 4 (CCM  $k_{ext}$  + CCM phase + CCM  $r_e$  + CC boundary):

Merged  $k_{ext}$  and  $r_e$  profile is assumed between CC-detected cloud top and base heights.



## Domain-Averaged Cloud Extinction ( $k_{\text{ext}}$ ) and particle effective radius ( $r_e$ ) profiles for the Four Methods



Method 1: MODIS reff/tau/hgt

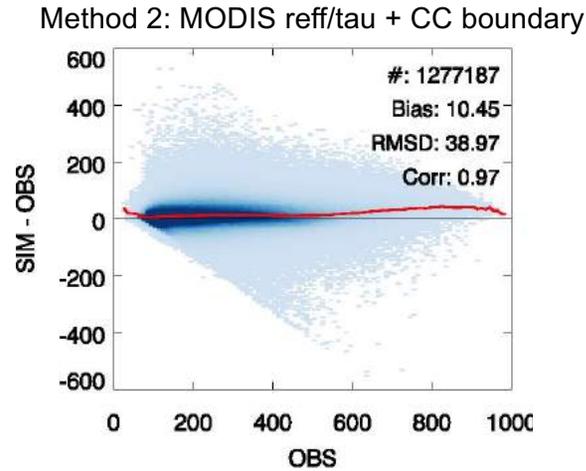
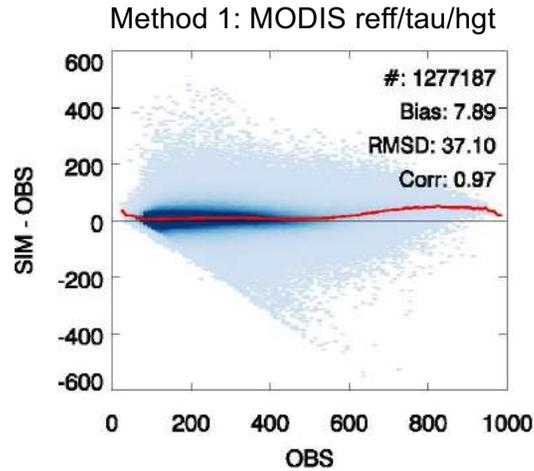
Method 2: MODIS reff/tau + CC boundary

Method 3: MODIS reff+ CCM kext + CC boundary

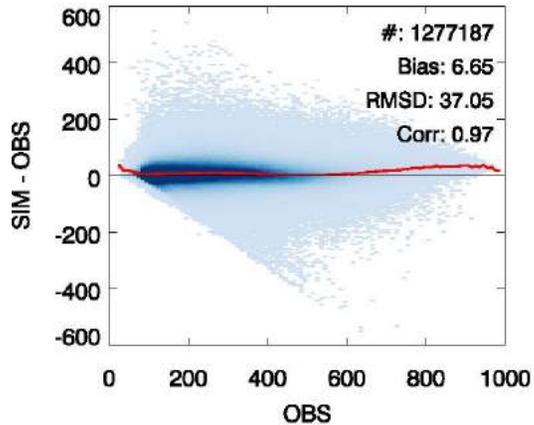
Method 4: CCM reff + CCM kext + CC boundary

- Note that Method 2 (homogenous assumption between CC cloud boundary) brings larger cloud extinction coefficient at the cloud top parts, compared to MODIS only (Method 1) method.
- CCM-merged  $k_{\text{ext}}$  (Methods 3 & 4) has larger weights at cloud bottom than Method 2.
- MODIS  $r_e$  (Methods 1, 2, & 3) is in a narrow range, especially compared to active-sensor measured  $r_e$  (Method 4).

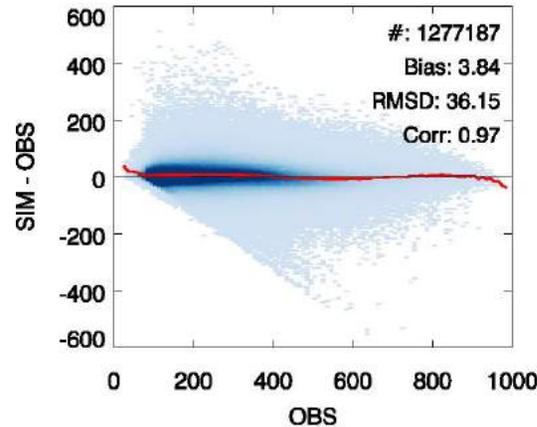
## Standard ReID1 SW Biases for Jan/Apr/Jul/Oct in 2008



Method 3: MODIS reff+ CCM k<sub>ext</sub> + CC boundary

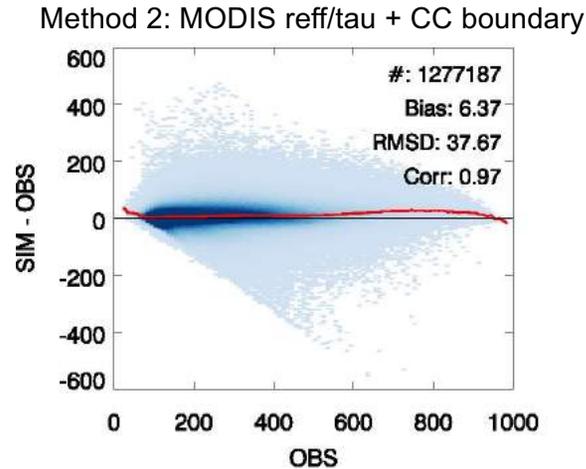
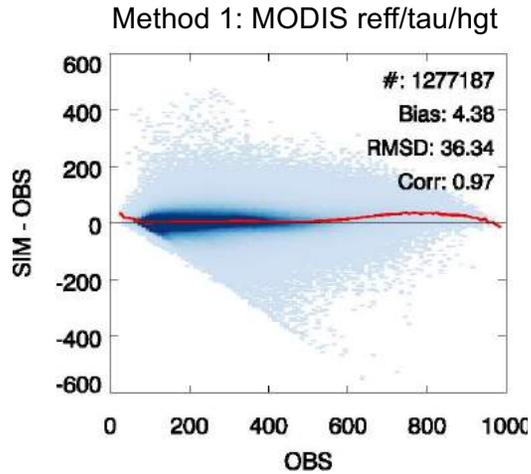


Method 4: CCM reff + CCM k<sub>ext</sub> + CC boundary

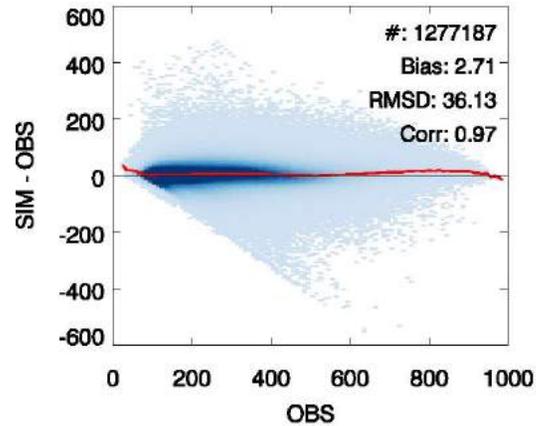


- When only MODIS cloud properties are used (Method 1), positive biases occur for deep convective clouds.
- The positive biases even increased when CC cloud boundary with a homogeneous assumption. This is due to overestimated  $k_{\text{ext}}$  at cloud tops.
- CCM-merged  $k_{\text{ext}}$  reduces SW biases, and the use of CCM-re further reduces SW biases.
- The sensitivity tests suggests importance of vertical structures of  $k_{\text{ext}}$  and broader ranges of ice particle size ( $r_e$ ) for SW flux computations.

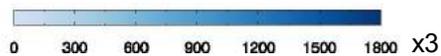
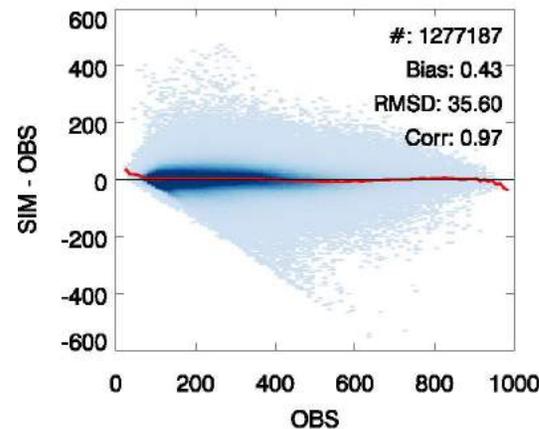
## Enhanced ReID1 SW Biases for Jan/Apr/Jul/Oct in 2008



Method 3: MODIS reff+ CCM kext + CC boundary



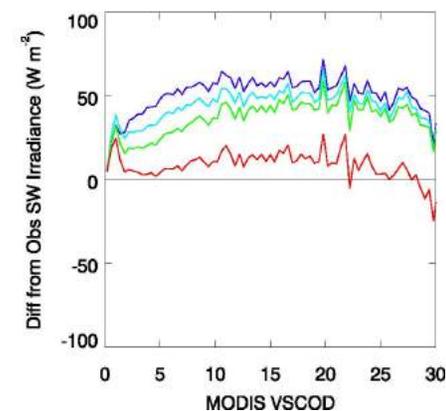
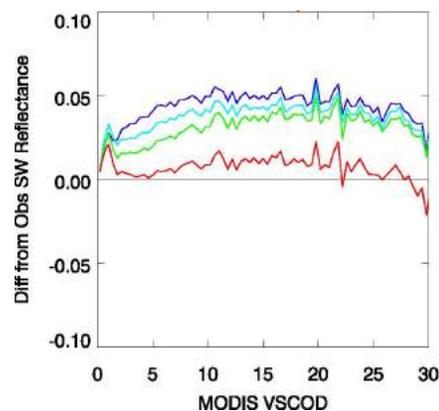
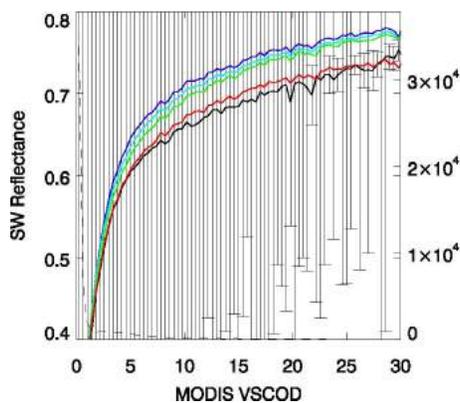
Method 4: CCM reff + CCM kext + CC boundary



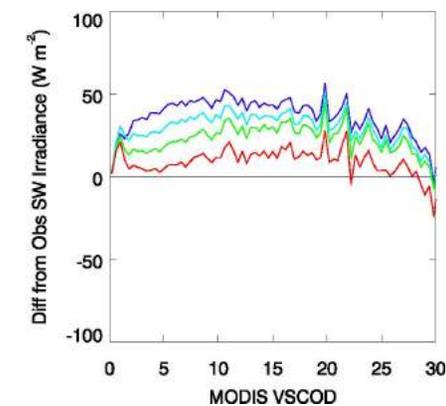
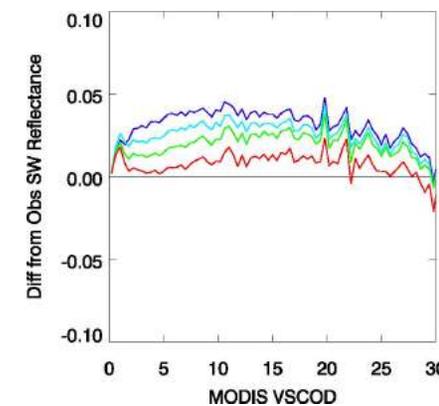
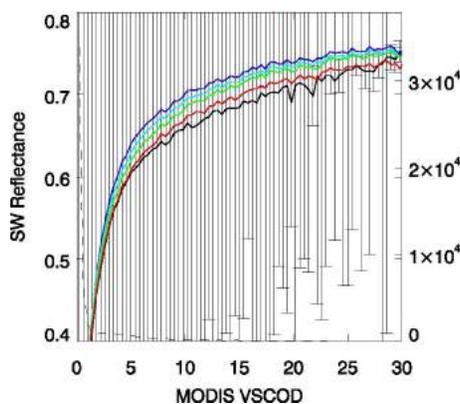
- Compared to standard MODIS algorithm, enhanced MODIS algorithm produces smaller SW biases. This is partly due to higher cloud top used for enhanced MODIS algorithm, inducing smaller cloud optical depth. In other words, standard MODIS cloud optical depth is slightly overestimated due to underestimated cloud height.

# ReID1 SW Biases for Jan/Apr/Jul/Oct in 2008 for Pure-Ice Clouds over 30°S–30°N

Standard Algorithm



Enhanced Algorithm



Obs

Method 1: MODIS reff/tau/hgt

Method 2: MODIS reff/tau + CC boundary

Method 3: MODIS reff+ CCM kext + CC boundary

Method 4: CCM reff + CCM kext + CC boundary

# Daytime LW fluxes are improved from ReIB1 to ReID1, but there still exist negative LW biases

Standard

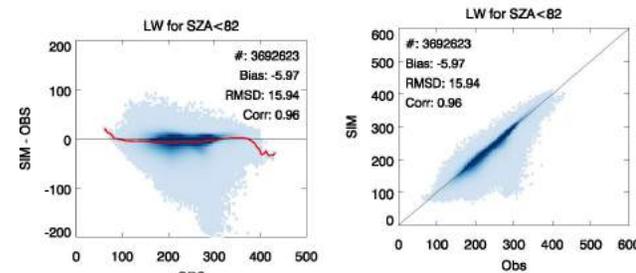
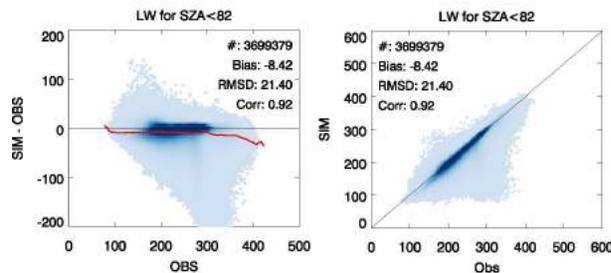
ReIB1



ReID1

STD SW Bias:  $-8.42 \text{ W m}^{-2} \pm 21.40 \text{ W m}^{-2}$

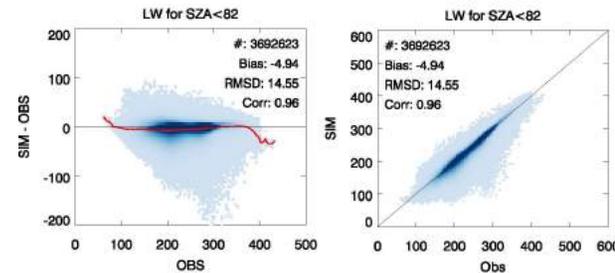
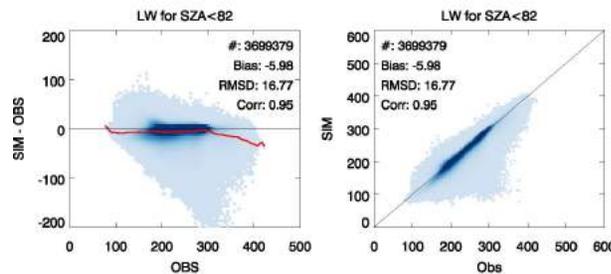
STD SW Bias:  $-5.97 \text{ W m}^{-2} \pm 15.94 \text{ W m}^{-2}$



ENH SW Bias:  $-5.98 \text{ W m}^{-2} \pm 16.77 \text{ W m}^{-2}$

ENH SW Bias:  $-4.94 \text{ W m}^{-2} \pm 14.55 \text{ W m}^{-2}$

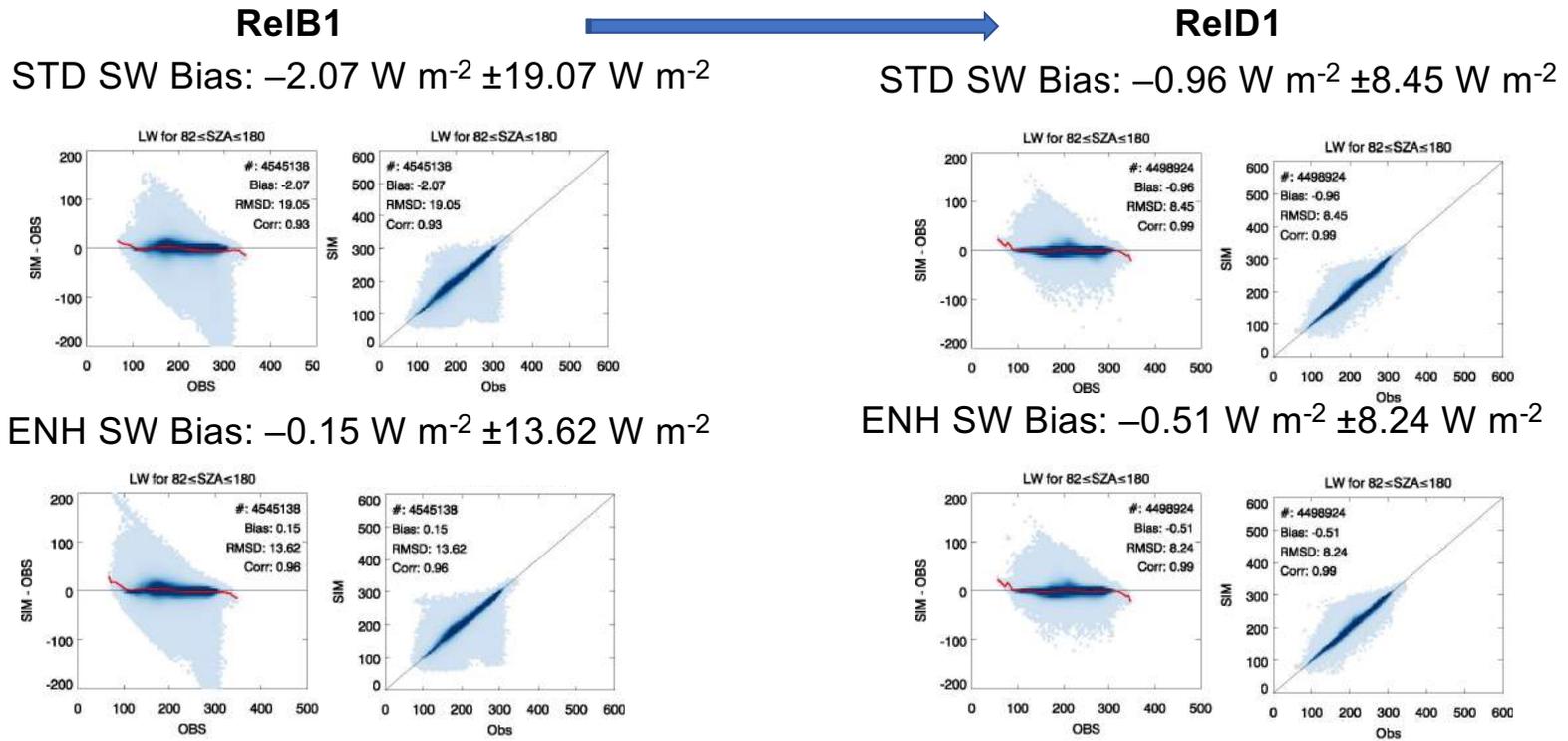
Enhanced



- The negative LW biases are probably due to the overweighted cloud extinction coefficients at the cloud top parts for deep convective clouds.
- While mean biases remain similar, smaller RMSD is noted in ReID1.

Only fluxes computed with valid CALIPSO+CloudSat are used in 2008.

# Nighttime LW fluxes are significantly improved from ReIB1 to ReID1, especially over polar regions



- New constraining method using thermal emission term (TEMIS) produces closer LW TOA fluxes to CERES observations (Ham, 2020 Fall CERES STM). However, the constrained cloud optical depth using MODIS TEMIS for nighttime is smaller than daytime value, requiring further examinations.

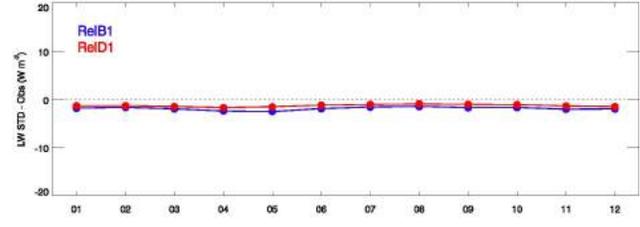
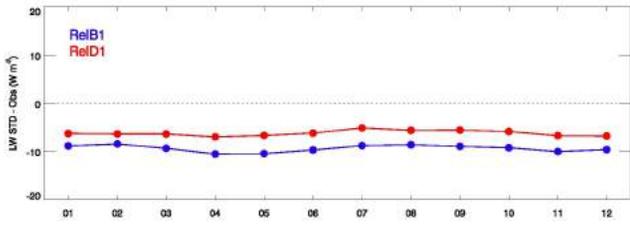
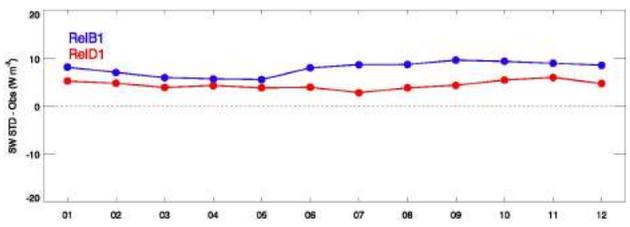
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SW Standard (SZA < 82°)

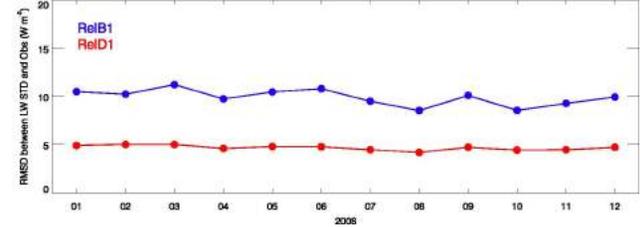
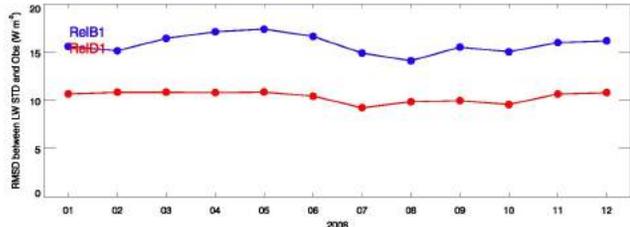
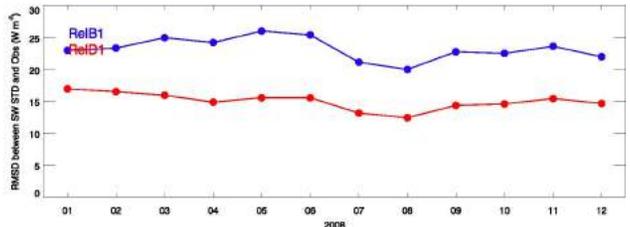
LW Standard (SZA < 82°)

LW Standard (SZA ≥ 82°)

Mean Bias



RMSD



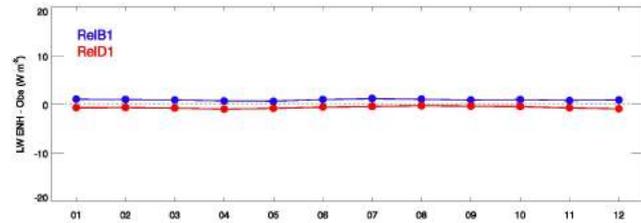
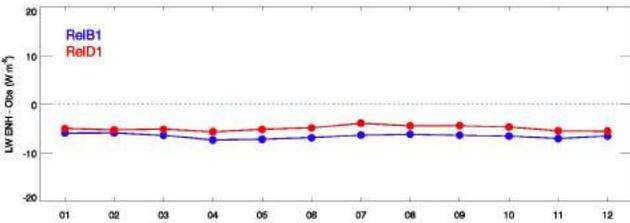
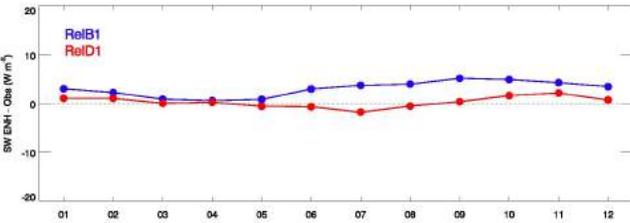
Enhanced\_num\_filter

SW Enhanced (SZA < 82°)

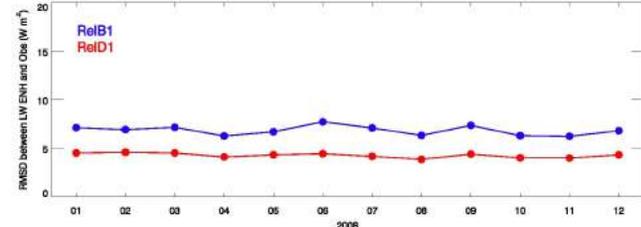
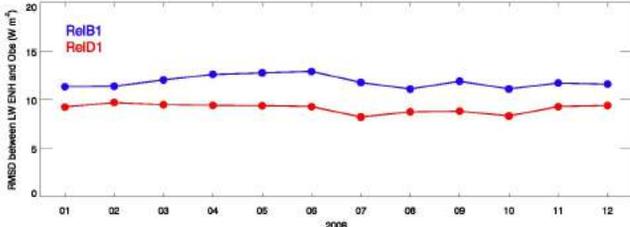
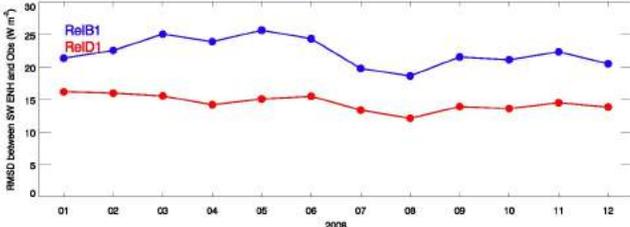
LW Enhanced (SZA < 82°)

LW Enhanced (SZA ≥ 82°)

Sim-Obs



RMSD



## Summary

- Cloud detections from CC and MODIS are reduced in ReID1, compared to ReIB1.
- Better agreement are shown between observed and computed SW fluxes in ReID1 compared to ReIB1.
- SW computations are improved by better sea/ice surface albedo and ice cloud particle information from 2C-ICE product.
- LW computations are improved by new normalization method for SZA > 82 deg and the use of wet-bulb temperature for low clouds.
- Overall, RMSD and mean biases are improved in ReID1 flux computations.