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IMPROVED CLOUD DETECTIONS IN CERES EDITION 3 ALGORITHM AND COMPARISON WITH THE CALIPSO VERTICAL FEATURE MASK

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1. INTRODUTION

For climate and Earth energy budget studies, understanding the presence and distribution of various clouds is a very important first step in any analysis. The Cloud and Earth's Radiant Energy System (CERES) project has produced a 10-year dataset (Edition 2) that has proven valuable for these types of studies. In this dataset, clouds are detected by the CERES cloud mask algorithms using Terra and Aqua MODIS data (CERES-MODIS Cloud Mask, CMCM) as well as other ancillary data sets.

An improved cloud mask will be employed for the CERES Edition 3 dataset, expected to begin in late 2010. Compared with CERES Terra Edition 2 (TEd2) and Aqua Edition 1 (AEd1), many improvements have been made in the Edition 3 cloud detection algorithm (CMCM_Ed3). These improvements include detecting more daytime ocean cumulus clouds and thin cirrus clouds, better discrimination between dust and clouds as well as between polar clouds and snow surface and a smoother transition from non–polar to polar regions.

Comparisons between the CERES cloud mask and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) Vertical Feature Mask (VFM) provide a powerful tool to validate and improve CERES cloud detection globally as well as to understand strengths and limitations of cloud retrievals between active and passive satellite sensors. This paper describes changes in the CERES cloud mask and uses the CALIPSO VFM to illustrate the validity of those improvements.

2. DATA AND METHODOLOGY

2.1. Observations

MODIS

The CMCM uses Terra and Aqua MODIS calibrated radiances data at 0.65, 1.38, 2.1, 3.75, 6.72, 8.55, 11.0, and 12.0 μm. For this study, two types of MODIS date are used: 1) whole swath Terra and Aqua MODIS data, sub-sampled to 2x4 km as used in operational CERES cloud analysis and 2) 200-km swath width of Aqua MODIS 1 km data centered at CALIPSO orbit for matched comparisons.

CALIPSO

Level 1 lidar attenuated backscattering at 532 nm and level 2 Vertical Feature Mask (VFM) at 330 m resolutions are used.

Matching Aqua MODIS 1km Data with CALIPSO

Subsetted Aqua MODIS data are collocated with CALIPSO data as illustrated below. There are three

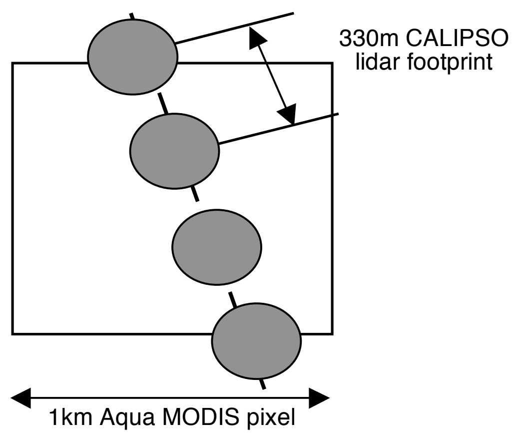

Fig. 1. Collocate CALIPSO 330m VFM with Aqua MODIS ikm data.

CALIPSO (330 m) shots in each MODIS 1-km pixel. Within each 1-km box, CALIPSO cloudy is defined as two or more shots that detect clouds at any level. CALIPSO clear is defined as one or no shots detecting clouds. CMCM returns cloudy or clear in each Aqua 1km pixel.

2.2. Ancillary Data for CMCM

The ancillary data consist of 3-hourly GMAO (Goddard Modeling and Assimilation Office) surface skin temperature and atmospheric profiles, daily snow and ice maps from the National Snow and Ice Data Center (NSIDC), as well as water percentage map, elevation map and IGBP surface-type map.

2.3. Methodology

The CERES cloud mask consists of six components: daytime, twilight, and nighttime masks for polar and non-polar respectively. Table 1 shows the polar and non-polar mask selection criteria. The CERES non-polar cloud detection technique for TEd2 and AEd1 was documented in Minnis et al. (2008). The CERES polar cloud and snow detection method was documented in Trepte et al. (2003).

Day/Night Latitude	Daytime (SZA < 82)	Twilight (82 < SZA < 88.5	Nighttime (SZA > 88.5)
60N - 90N 60S - 90S	Daytime Polar Mask	Twilight Polar Mask	Nighttime Polar Mask
50N - 60N 50S - 60S	Polar Mask if Snow, Ice or IGBP indicates snow or ice Non-polar mask otherwise		
50N - 50S	Daytime Non-polar Mask	Twilight Non-polar Mask	Nighttime Non-polar Mask

Table 1. CMCM polar and non-polar masks selection.

3. RESULTS

3.1. CERES AEd1 vs. CERES Ed3 Mask

Increased Low Cloud Detection over Sun-glint Ocean

Detecting low clouds in sun-glint ocean has always been a challenge. In CMCM_Ed3, MODIS reflectance ratio tests were added and the thresholds of visible, IR and NIR tests were fine tuned. Cloud mask comparisons between CMCM AEd1 and Ed3 over the Indian Ocean are shown in Fig. 2. The Ed3 mask picked up many low clouds that were missed by AEd1, both in sun-glint and non-glint regions. Ratios of 2.1-to-3.7-μm reflectances are tested for regions classified as “all B clr” in the AB Summary (Minnis et al., 2008) to determine if any clear pixels are actually cloudy. MYD06 cloud fraction (from MODIS team analysis; see Ackerman et al., 1998) is between that of the CERES AEd1 & Ed3 amounts.

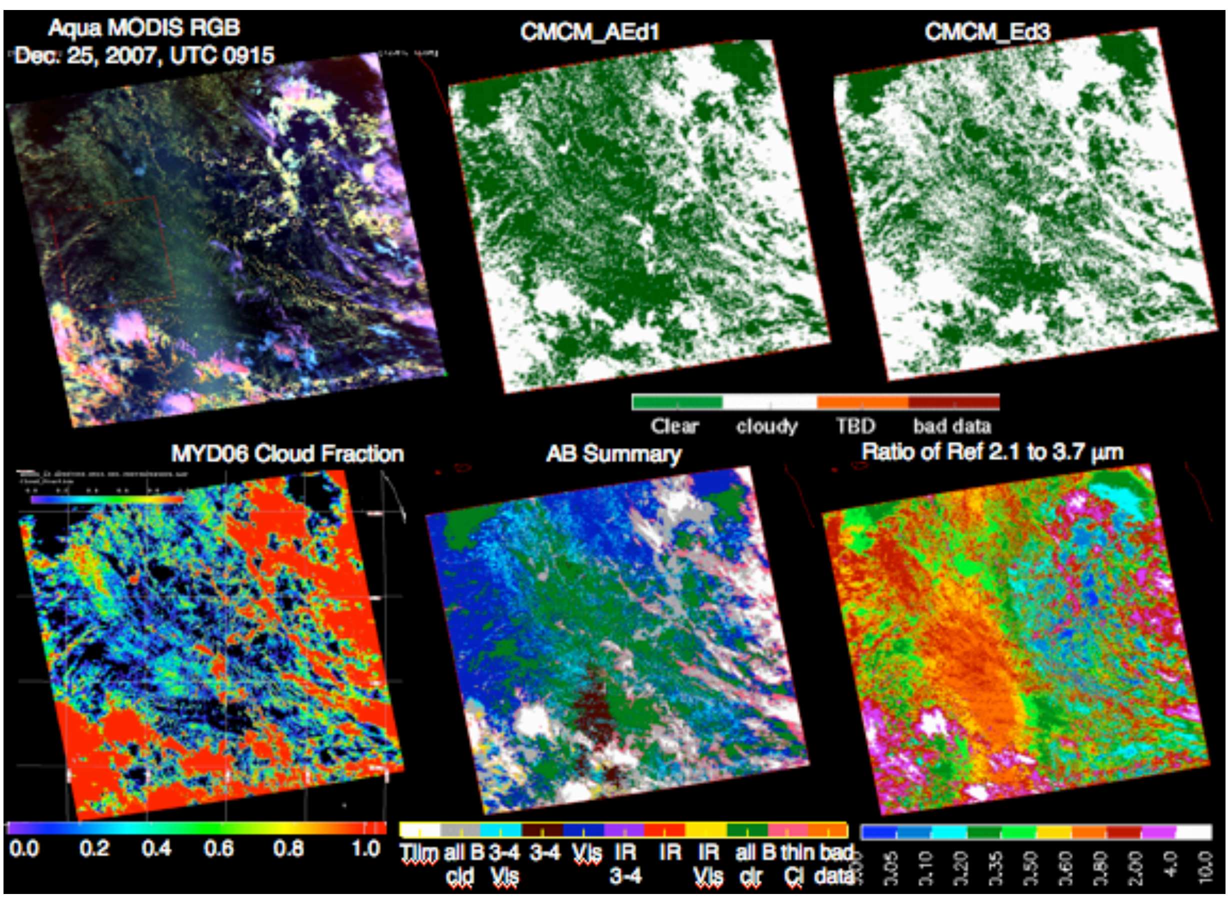

Fig. 2. Comparison of low clouds detection between CMCM AEd1 and Ed3 over Indian Ocean on Dec. 25 2007, UTC 0915.

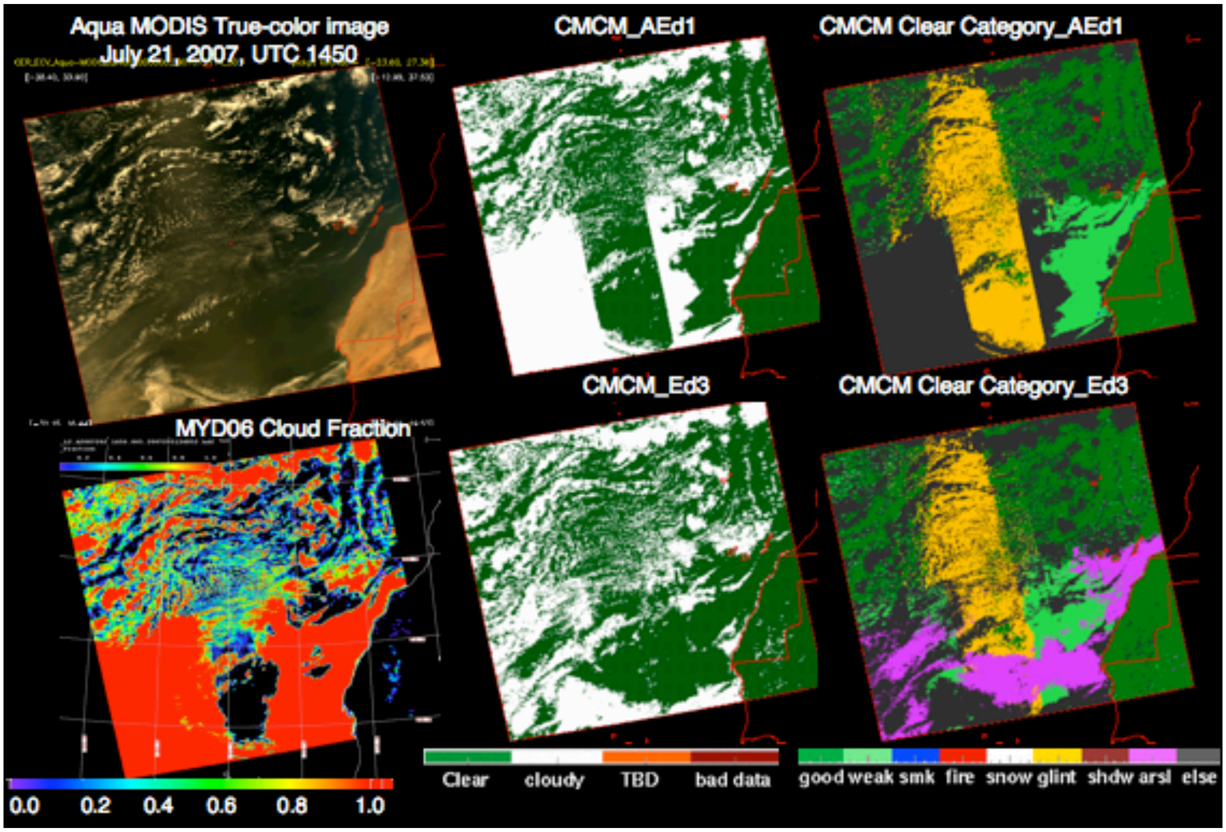

Fig. 3. Comparison of cloud and dust detection between CMCM AEd1 and Ed3 over Atlantic Ocean off North Africa,1450 UTC, 21 July 2007.

Enhanced Dust and Clouds Discrimination in Sun Glint

To better discriminate between dust and clouds, CMCM_Ed3 tests the brightness temperature differences, T_{11}-T_{12}, and T_{85}-T_{11}; the 0.65-*μ*m reflectance; and the 2.1-to-0.65-*μ*m and 0.47-to-2.1-*μ*m reflectance ratios. The subscripts for the brightness temperatures *T* refer to the wavelengths. Figure 3 shows a Saharan dust storm blown over the Atlantic Ocean where sun glint is also present. CMCM_AEd1 classified some dust and sun glint as clouds, showing a strip of false clouds along the sun glint region. In CMCM Clear Category_AEd1, dust off the west coast of the Sahara was called weak clear (light green). MYD06 cloud fraction also misidentified heavy dust as clouds. CMCM_Ed3 appears to have significantly improved both the cloud and dust detection over sun glint and non-glint ocean areas.

Monthly Zonal Cloud Amount Comparison

Compared with TEd2 & AEd1, the preliminary CMCM_Ed3 cloud amounts over ocean and land increased at all latitudes (Fig. 4), especially for daytime tropical oceans where the fractional coverage increased by up to 0.15 (Figs. 4a,c). The cloud amounts increased substantially over extratropical land at night (Figs. 4b,d). Smaller increases over the tropical ocean highlight the difficulty of detecting small, low cumulus clouds at night. Nocturnal cloud amounts rose by almost 0.40 over Antarctic waters for both Terra (Fig. 4b) and Aqua (Fig. 4d) and over Antarctic land for Terra using the Ed3 mask. These unusually large cloud amount increases elicit further investigation.

3.2 CMCM_ Ed3 vs. CALIPSO Vertical Feature Mask

Polar Cloud and Snow Detection

Two Aqua MODIS granules, covering part of the Arctic Ocean in daylight, and twilight and nighttime over Alaska, are shown in Fig. 5. All three polar masks were applied in this case. CMCM_Ed3 compares well with the MODIS RGB and 3.7 - 11 images. The polar mask, applied only to polar regions, gives more detailed classifications. There are no discontinuity lines when transitioning from daytime to twilight and from polar to non-polar regions, even though different CMCM_Ed3 algorithms were used. The MYD06 cloud fraction is fairly close to that from CMCM_Ed3, except for a subtle discontinuity line at the terminator.

Figure 5 also shows the CALIPSO scattering profile and V2 VFM along the CALIPSO track, which follows the green line extending the length of the Aqua MODIS image. CALIPSO reveals only a few cloudless areas just north of the Brooks Range and over part of the Arctic Ocean. These correspond to the green areas in the CMCM_Ed3 image.

The matched MODIS and CALIPSO V2 VFM results in Fig. 5 were analyzed and the results are shown in Table 2. The CMCM_Ed3 and CALIPSO agree that it is cloudy for 77.6% of the data and that it is clear for only 6.2% of the data. The total agreement (cloudy + clear) between CMCM_Ed3 and CALIPSO V2 is 83.8%. However, 12.6% of pixels were identified as clear by CMCM_Ed3, but cloudy by CALIPSO VFM. Of these pixels, 91% are high clouds, 9% are low clouds. Presumably many of the high clouds missed by the CMCM are optically thin and produce very little signal for the passive sensor. Detecting very thin clouds is nearly impossible for passive sensors. Only 3.6% of the CERES clouds correspond to clear CALIPSO shots.

Ed3 Cloud Fraction vs. CALIPSO V2 VFM

Figures 6 and 7 show the global distribution of average cloud amounts from 6 months of matched CMCM_Ed3 and CALIPSO V2 VFM data. These results are for August, September, November, and December 2006 and for February and March 2007. For daytime (Fig. 6), the CMCM_Ed3 (top) and CALIPSO V2 VFM (bottom) have similar global cloud distributions. However, over the tropics and the Sahara desert, the CMCM detects less cloud cover than CALIPSO, while over the near-polar oceans, the CMCM has greater cloud amounts, particularly near Antarctica.

The nighttime cloud fraction comparison (Fig. 7) yields results similar to those found for the daytime data. CMCM_Ed3 generally has lower cloud amounts than CALIPSO V2, especially in the tropics, deserts, and polar regions, but has higher cloud amounts than CALIPSO over high latitude oceans. The most noticeable differences in the tropics are in the trade cumulus areas over the Pacific.

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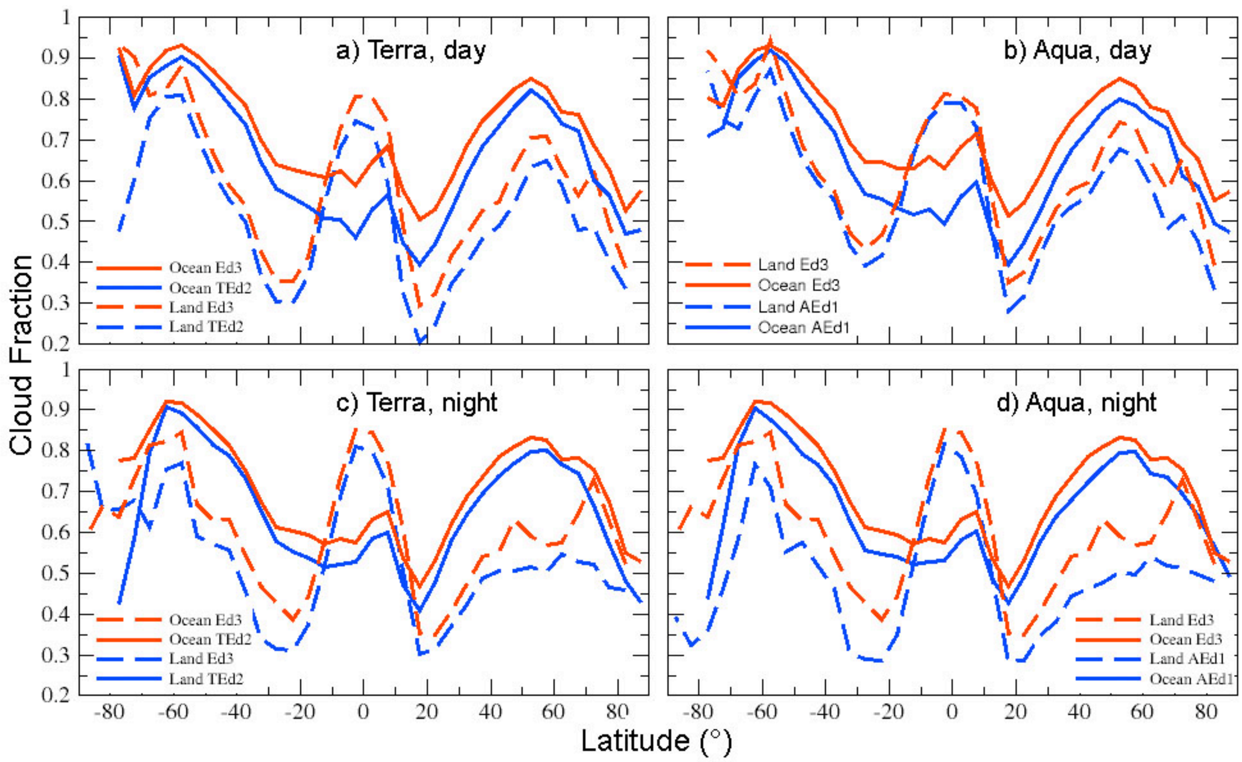

Fig. 4. Monthly zonal cloud amounts from CERES TEd2, AEd1 and Ed3 masks, April 2004.

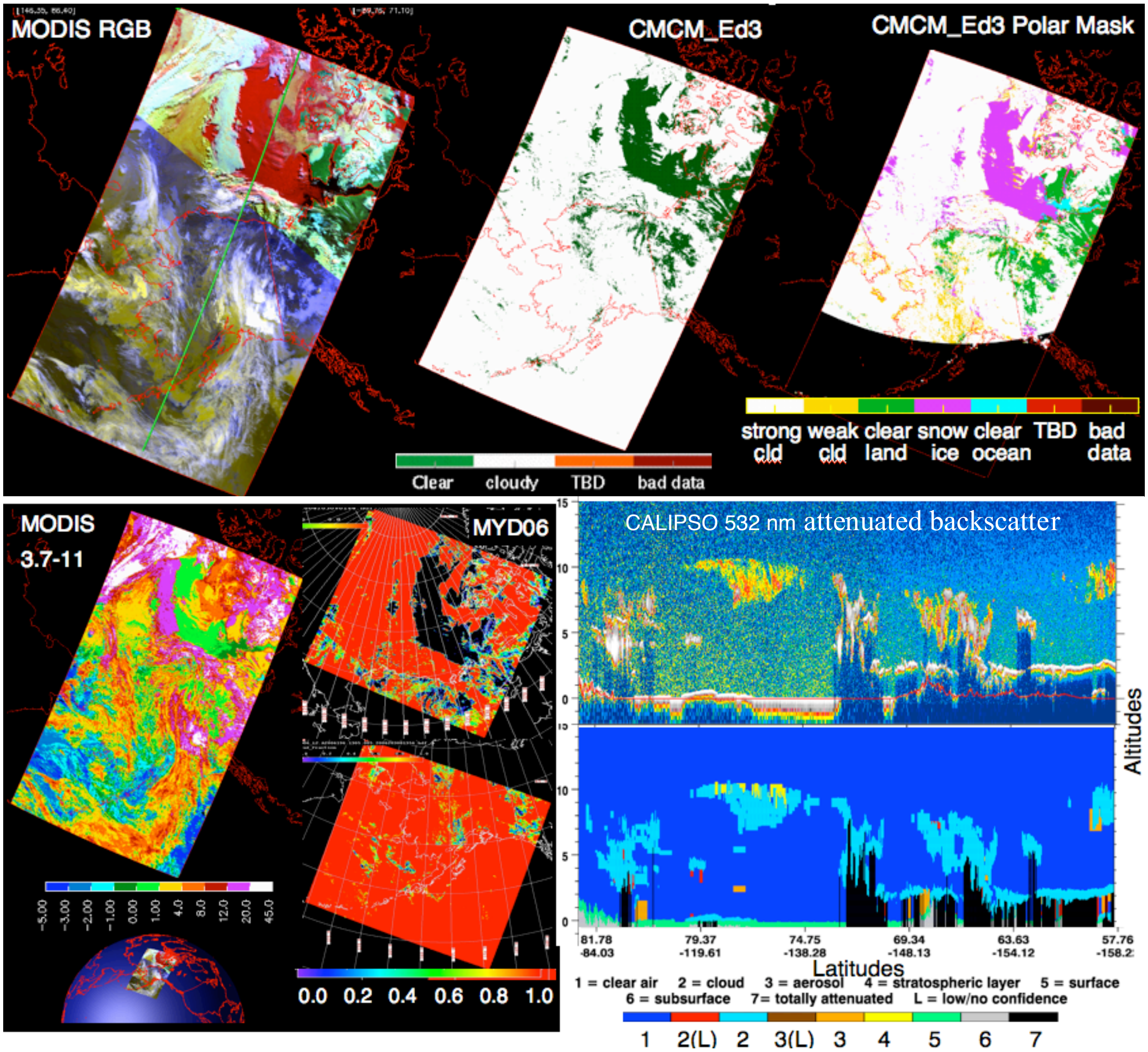

Fig. 5. Comparison of CMCM_Ed3 polar cloud mask with MYD06 cloud fraction and CALIPSO lidar and VFM images for July 15, 2006, UTC 1300–1305.

Table 2. Matched CMCM_Ed3 and CALIPSO VFM for the polar case shown in Fig. 5. Top: cloudy and clear agreements. Bottom: percentage of high and low clouds from 12.6% of CMMC_Ed3 Clear and CALIPSO Cloudy pixels.

	CMCM_Ed3 Cloudy	CMCM_Ed3 Clear
CALIPSO Cloudy	77.6%	12.6%
CALIPSO Clear	3.6%	6.2%

	Percentage	Averaged height
High Clouds (> 5km)	91%	10 km
Low Clouds (< 5km)	9%	2.2 km

The mean CMCM_Ed3 and CALIPSO polar cloud fractions are shown in Figs. 8 and 9. The daytime (Fig. 8) cloud patterns are similar for CMCM_Ed3 and CALIPSO over the Arctic regions, but CMCM yields slightly less cloud cover than CALIPSO. Over Antarctica, CMCM_Ed3 has noticeably greater cloud amounts than CALIPSO.

Nighttime polar cloud detection is challenging due to lack of thermal contrast between clouds and snow/ice surfaces, Clouds can be warmer than the surface under strong inversions. Over Antarctica, the CMCM_Ed3 and CALIPSO cloud distributions are similar (Fig. 9), but the CMCM cloud cover tends to be greater than that from CALIPSO. Over the Arctic, the patterns are also similar, but the Ed3 cloud amounts are typically less than their CALIPSO counterparts.

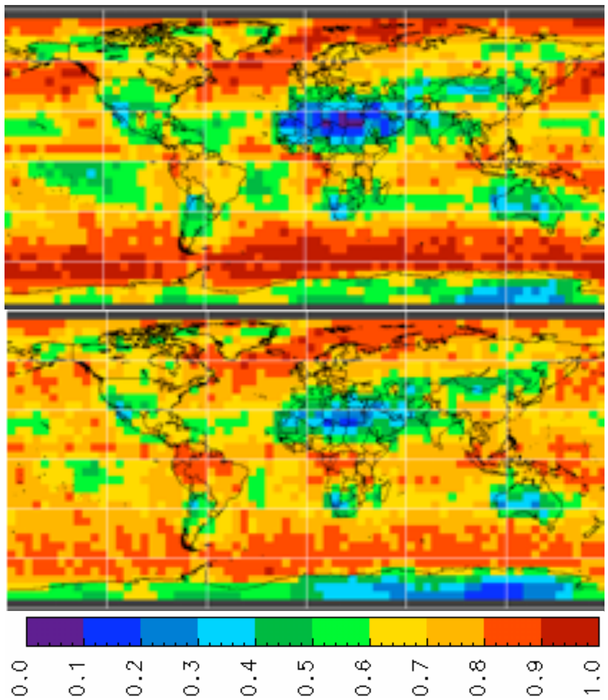

Fig. 6. Daytime cloud fractions from matched CMCM_Ed3 mask (top) and CALIPSO V2 VFM (bottom).

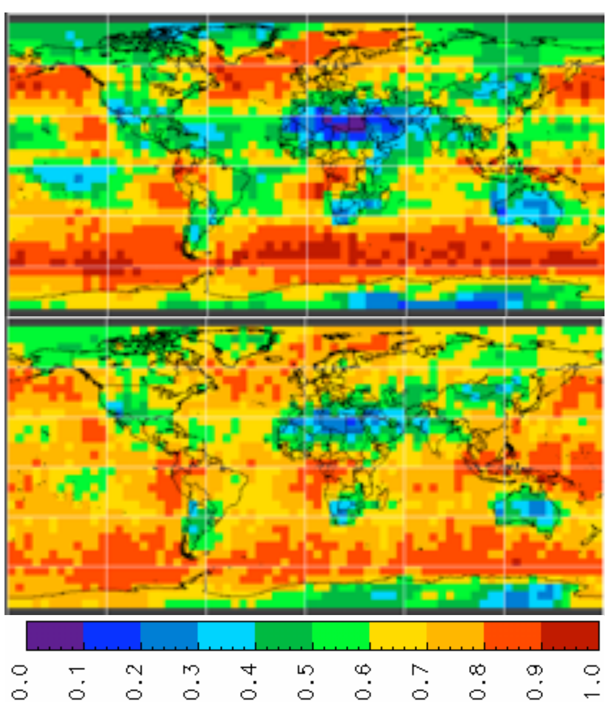

Fig. 7. Nighttime cloud fraction from matched CMCM_Ed3 mask (top) and CALIPSO V2 VFM (bottom).

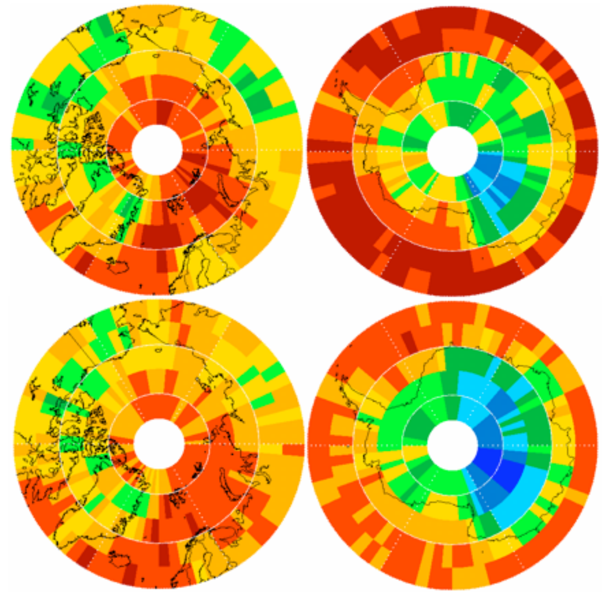

Fig. 8. Polar daytime cloud fraction from six-month matched CMCM_Ed3 mask (top) and CALIPSO V2 VFM (bottom).

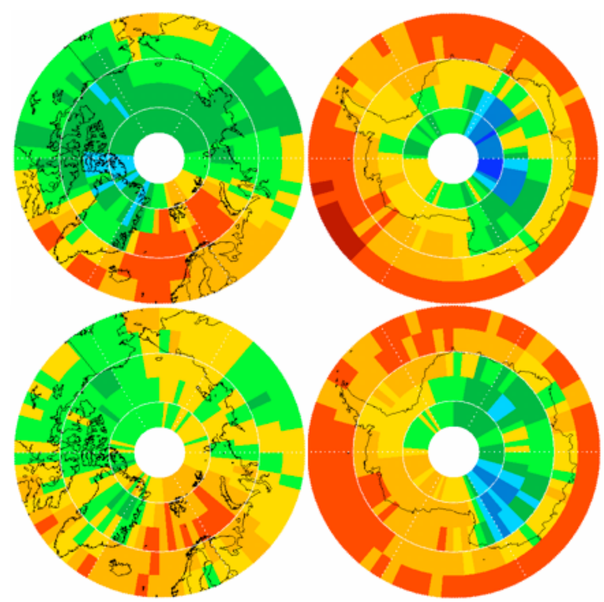

Fig. 9. Polar nighttime cloud fraction from six-month matched CMCM_Ed3 mask (top) and CALIPSO V2 VFM (bottom).

Table 3 lists the combined cloudy and clear agreement between CMCM_Ed3 and CALIPSO V2 from the 6 months of data. The best agreement, 80%, occurs over the daytime polar regions, while the worst agreement, 71%, is for nighttime polar areas.

Table 3. Combined cloudy and clear agreement between CMCM_Ed3 and CALIPSO V2 cloud masks for 6 months of matched data.

	Daytime Polar	Daytime Ocean	Daytime Land
CERES-CALIPSO Agreement	80%	78%	75%
	Nighttime Polar	Nighttime Ocean	Nighttime Land
CERES-CALIPSO Agreement	71%	76%	74%

CALIPSO Version 3 vs. Version 2 VFM.

Newly released CALIPSO Version 3 products show significant improvements (Fig. 10). Compared with Version 2, low-cloud fraction dropped globally, especially in the tropics, where decreases of up to 30% are seen over water. High clouds fell and rose by about 5% around the globe. Increases in high cloud cover are most consistent over the Arctic Ocean. These changes in CALIPSO V3 products should yield better agreement with CMCM_Ed3.

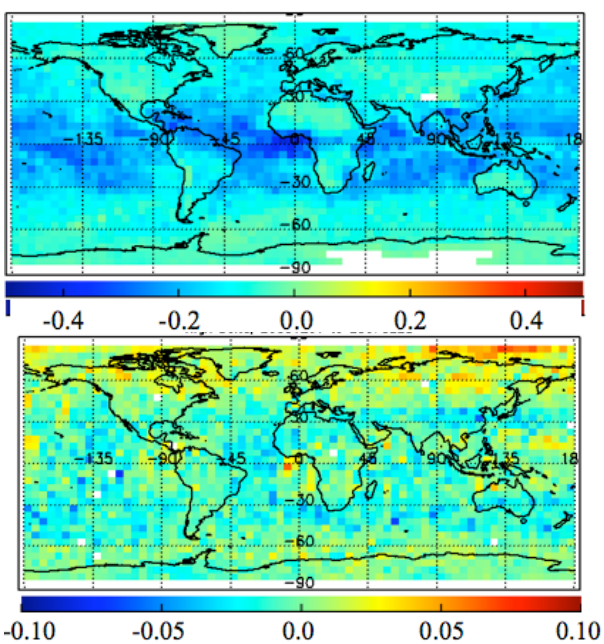

Fig. 10. Cloud amount differences between CALIPSO V2 and V3 VFM from 20061201 to 20070228. Top: low clouds; bottom: high clouds.

4. CONCLUSIONS

Significant improvements have been made in the CERES Ed3 cloud mask compared with the previous CERES Terra Ed2 and Aqua Ed1 algorithms. The improvements include detection of more cumulus clouds over daytime ocean, better dust and cloud discrimination over ocean and land, increased thin cirrus detection, enhanced polar cloud and snow/ice classification, and a smoother transition from non-polar to polar regions.

Six months of matched CMCM_Ed3 and CALIPSO V2 VFM show agreement (cloudy agreement + clear agreement) ranges from 80% for daytime polar to 71% for nighttime polar. Comparison with CALIPSO V3 products will likely show better agreement.

This paper has used a preliminary version of Ed3. Final tuning of the algorithm is underway. Future work in CERES cloud mask includes enhancing nighttime cloud detection, especially over polar and trade cumulus regions, and investigating the regions where the CERES Ed3 mask classified pixels as cloudy that CALIPSO determined to be clear.

5. REFERENCES

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