Improvements in Near-Terminator and Nocturnal Cloud Masks using Satellite Imager Data over the Atmospheric Radiation Measurement Sites

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Introduction

Cloud detection using satellite measurements presents a big challenge near the terminator where the visible (VIS; 0.65 µm) channel becomes less reliable and the reflected solar component of the solar infrared 3.9-µm channel reaches very low signal-to-noise ratio levels. As a result, clouds are underestimated near the terminator and at night over land and ocean in previous Atmospheric Radiation Measurement (ARM) Program cloud retrievals using Geostationary Operational Environmental Satellite (GOES) imager data. Cloud detection near the terminator has always been a challenge. For example, comparisons between the CLAVR-x (Clouds from Advanced Very High Resolution Radiometer [AVHRR]) cloud coverage and Geoscience Laser Altimeter System (GLAS) measurements north of 60°N indicate significant amounts of missing clouds from AVHRR because this part of the world was near the day/night terminator viewed by AVHRR. Comparisons between MODIS cloud products and GLAS at the same regions also shows the same difficulty in the MODIS cloud retrieval (Pavolonis and Heidinger 2005). Consistent detection of clouds at all times of day is needed to provide reliable cloud and radiation products for ARM and other research efforts involving the modeling of clouds and their interaction with the radation budget.

To minimize inconsistencies between daytime and nighttime retrievals, this paper develops an improved twilight and nighttime cloud mask using GOES-9, 10, and 12 imager data over the ARM sites and the continental United States (CONUS). The algorithm utilizes the 4-km GOES VIS reflectance, 10.8-µm brightness temperature (T), and the brightness temperature differences (BTD) for 3.9-11 µm (BTD1), 6.7-10.8 µm (BTD3), 10.8-13 µm (BTD4 for GOES-12), and 10.8-12 µm (BTD2 for GOES-10), together with the predicted background clear-sky information to detect various types of clouds and snow. The results show significant improvement in cloud amount over the ARM Southern Great Plains (SGP) and the Tropical West Pacific (TWP) sites. The improved near-terminator and nocturnal cloud masks are validated using the Automated Surface Observing System (ASOS) data, the Micropulse Lidar (MPL) observations and the Millimeter-Wavelength Cloud Radar (MMCR) measurements at SGP site.

Data and Methodology

This study uses GOES-9, 10, and 12 radiance measurements taken at 0.65, 3.9, 6.7, 10.8 (11), and 12 µm (or 13.3 µm for GOES-12) from September 2004 to January 2005. GOES provides nearly continuous temporal sampling at a 4-km resolution. The ancillary data used here include the hourly Rapid Update Cycle (RUC; Benjamin et al. 2004) sounding data over U.S. and 3-hourly Global Forecast System (GFS) sounding data over TWP; daily snow and ice maps from the NOAA Satellite Services Division (SSD); Clouds and the Earth's Radiant Energy System (CERES) 10' surface emissivity maps at 3.9 and 11 µm derived from Moderate Resolution Imaging Spectroradiometer (MODIS) data (Chen et al. 2004); CERES clear-sky VIS reflectance maps derived from MODIS (Sun-Mack et al. 2003); International Geosphere Biosphere Program (IGBP) ecosystem map; and water percentage and surface elevation maps. Ground measurements of cloud fraction from ASOS stations over continental U.S. and MPL data over ARM SGP site are used for validation.
The original GOES cloud detection algorithm is based on the Clouds and Earth's Radiant Energy System (CERES) cloud mask, which was developed and tested using MODIS data from *Terra* and *Aqua* and is used as the scene identification method for the operational CERES products (Trepte et al. 1999). Because of spectral differences between GOES and MODIS several threshold adjustments have been made for application to the ARM GOES measurements. The adjusted cloud mask algorithm is designated the CERES ARM Cloud Mask (CACM). The technique is based primarily on a cascade of threshold tests utilizing the radiances taken at 0.65, 3.9, 6.5, 11, and 12.0 or 13.3 µm compared with the predicted clear-sky 0.65-µm reflectance, 11-µm top-of-atmosphere (TOA) T_{11}, and TOA BTD1. Clear-sky albedo maps, directional and bidirectional reflectance models (Sun-Mack et al. 2004) are used to predict the expected clear-sky reflectances. The surface skin temperatures T_s are estimated from the hourly RUC surface temperatures using an empirical correction for the difference between surface air and skin temperatures. Clear-sky TOA brightness temperatures T_{cs} are estimated from T_s for the GOES 3.9, 10.8 and 12-µm channels using the surface emissivities and computing the atmospheric effects on the upwelling radiance using the RUC profiles of temperature and humidity. The clear sky maps are resolved to 10 minutes of latitude and longitude. Thresholds are based on spatial and temporal variation within a 10-minute box. At night, only the IR channels are used. The scenes are classified as clear or cloudy with additional subcategories. Clear categories include strong, weak, smoke, fire, snow, sun-glint, shadow, and aerosol. Cloudy classifications include strong, weak, sun-glint. The strong and weak refer to the certainty of the classification. This version of the CACM is V1.1. It was used for real-time GOES cloud retrievals (Minnis et al. 2004) through April 2005 over the continental United States (CONUS) and environs (55°N-20°S and 130°W-65°W).

Unlike the polar orbiting satellites such as *Terra* and *Aqua*, the geostationary satellites provide continuous temporal sampling over the middle latitudes and Tropics that providing a good opportunity to examine how cloud detection/retrieval algorithms work at all local times. In previous analyses, it was found that as the sun approaches the day/night terminator (solar zenith angle, SZA > 70°), the V1.1 CACM missed low clouds, such as stratus clouds off California coasts and sometimes over central U.S. In the "twilight zone" (82° < SZA < 87.5°), "clear bands" often crossed the CONUS. Also, low warm clouds were underestimated at night.

Several improvements have been made based on evaluations of the CACM V1.1 cloud mask. The newer CACM version, V2.1 developed here, includes the following changes.

1. A new twilight cloud and snow detection scheme that uses VIS reflectance, together with the IR channels and the snow map as outlined below.

   In twilight, a pixel is cloudy if:

   Over land: if $\rho > (\rho_{cs} + 0.10)$ or $T_{cs} - T_{11} > 2.5*\sigma_{11}$,
   where ρ *is VIS reflectance, CS refers to clear-sky, and is the uncertainty in clear-sky estimate.*
   Over water: if $\rho_{0.65} > (\rho_{cs0.65} + 0.05$ and $\rho_{0.65} > 0.20$ or $T_{cs11} - T_{11} > 1.5*\sigma_{11}$
   Additionally for GOES-12: BTD4 < 15 and (BTD1 > 3 or BTD1 < -0.5).

   If no clouds are detected by the above cloud tests, snow tests are applied to the surfaces where T_s < 275 K or snow map > 0. A pixel is clear snow if

   $T_{11} < 277K$ and $\rho > (\rho_{cs} + 3*\sigma_{VIS})$ and $-1.5K <$ BTD1 $< 6K$ and $T_{cs} - T_{11} < \sigma_{11})$.
   σ_{VIS} *ranges from 0.2 – 0.4 and* σ_{11} *ranges from 3 - 7 K for land.*

2. A new BTD1 test that has surface-emissivity, $\varepsilon_{3.9}$, dependent thresholds, DET, to detect clouds near the terminator and nocturnal warm low clouds. In general, DET = 11.1 * $\varepsilon_{3.9}$ - 11.15. If DET > -1.5, then DET = -1.5. A pixel is cloudy if *BTD < DET*.

3. During daytime (SZA < 82°) with high SZAs, BTD1 thresholds were refined to account for the cancellation of the reflected solar component of the 3.9-µm radiance in order to detect more low clouds over ocean and land.

Other changes are noted as the examples are presented.

Results

Stratus Clouds off California Coast near Terminator

Two cases shown below compare the performance of CACM V1.1 and V2.1 in near-terminator conditions off the California coast. The top two panels in Figure 1 are GOES-10 VIS and BTD1 images. The SZAs vary between 65 and 82°. The BTD1 image appears to show fewer stratus clouds than are evident in the VIS image. With no solar illumination, the BTD1 for low clouds is negative. As the SZA decreases (rising sun), the reflected solar radiation at 3.9-µm increases and BTD1 gradually changes

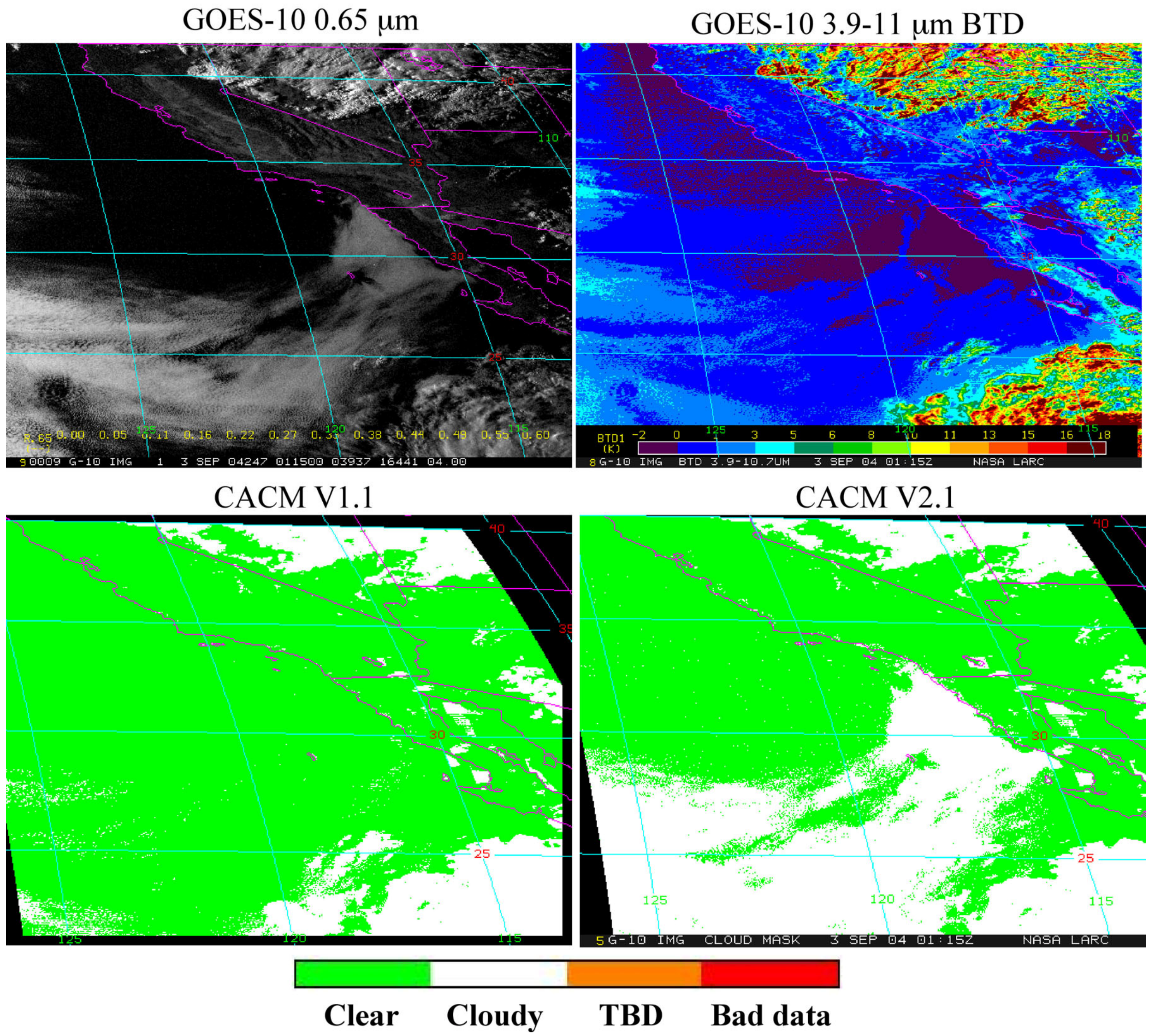

Figure 1. Sunset case, 0115 UTC, 3 September 2004. **Upper right**: BTD1 range for purple is -2 to 0 K. Dark blue is 0 to 1 K, medium blue is 1 to 3 K, etc.

from small negative to large positive values. When the sun is low, BTD1 is close to zero and cannot be used to detect clouds because it is close to the clear-sky estimate. By refining the cloud test for large SZAs, the V2.1 (lower left) detects the warm status that was missed by V1.1. Similar results are seen for the sunrise case in Figure 2 when the solar radiation was reflected in a more forward direction then in Figure 1. The warm stratus clouds produce a weak signal in the 11-µm image, but are more obvious in the VIS band. In both cases, the inclusion of more weight for the VIS reflectance thresholds in the decision results in dramatic improvements in the CACM in low sun conditions.

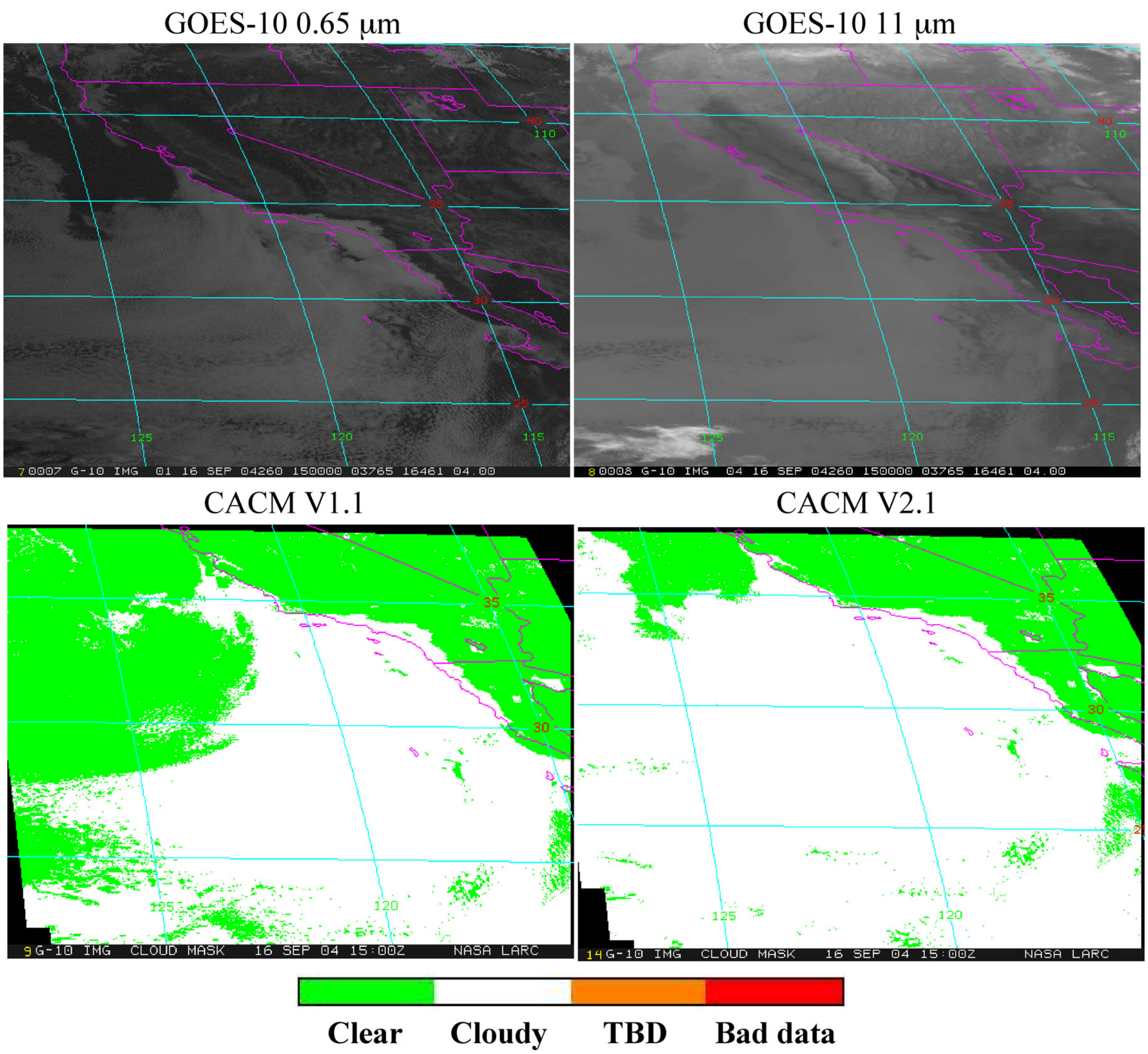

Figure 2. Sunrise case, 1500 UTC, 16 September 2004.

Low Clouds Over Land near Tropical Western Pacific Site at Low Sun Angles

The difficulties detecting low clouds at low sun angles are not confined to marine stratus. Figure 3 shows some low clouds over New Guinea and northeastern Australia that were missed by CACM V1.1 due to their small BTD1 signals are detected by CACM V2.1 (yellow color in Cloud Category). The area of false weak clouds (pink in Cloud Category) over northwestern Australia is reduced in the V2.1 image, however, some noisy pixels are classified as clouds. This problem is addressed using a despeckling technique discussed later in this paper.

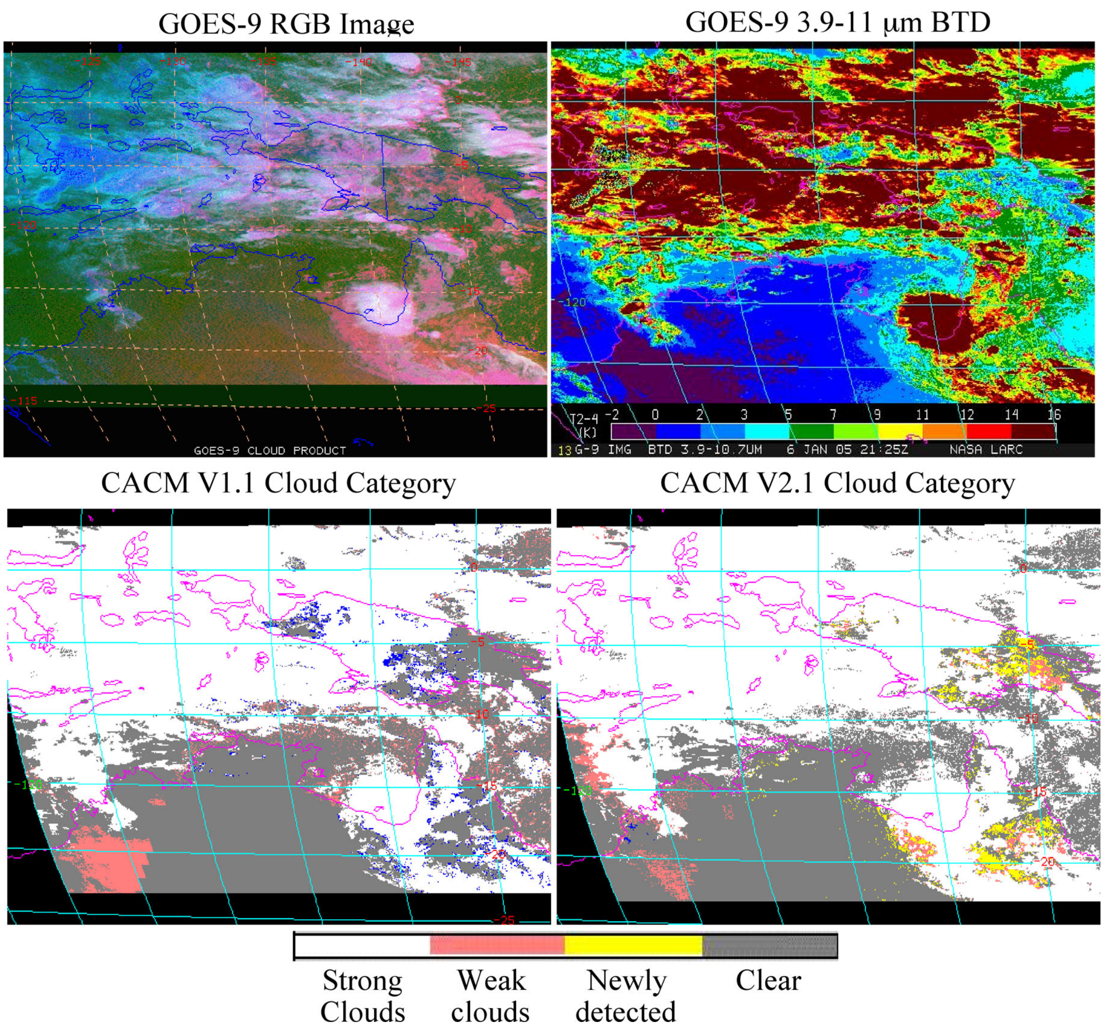

Figure 3. Sunrise case over northern Australia, 2125 UTC, 6 January 2005.

New Twilight Cloud Tests Using Visible Channel

Figure 4 shows a cyclone crossing the midwestern U.S. during the twilight period. The infrared (IR) channels-based V1.1 nighttime mask missed the warm clouds over the northern plains since the IR signals are small. The new twilight cloud tests, applied when 82° < SZA < 87.2°, use the VIS reflectance together with new 10.8-µm and BTD thresholds to significantly improve the twilight cloud mask. One of the problems associated with these conditions is that high clouds can cast long shadows over lower clouds effectively changing the illumination from low- to no-sun conditions. This new test includes the classification of pixels as cloudy if BTD1 is negative and SZA < 87.5°. The change results in CACM V2.1 detecting low clouds over western Wisconsin that appear dark in the VIS image and were missed by V1.1. The BTD1 emission-reflectance cancellation problem discussed earlier is alleviated with the use of the VIS channel resulting in the detection of large areas missed with the V1.1 tests that only considered the IR channel data. If the low clouds are optically thin, use of the VIS channel may not help much. In Figure 4, the VIS channel results in marked improvement.

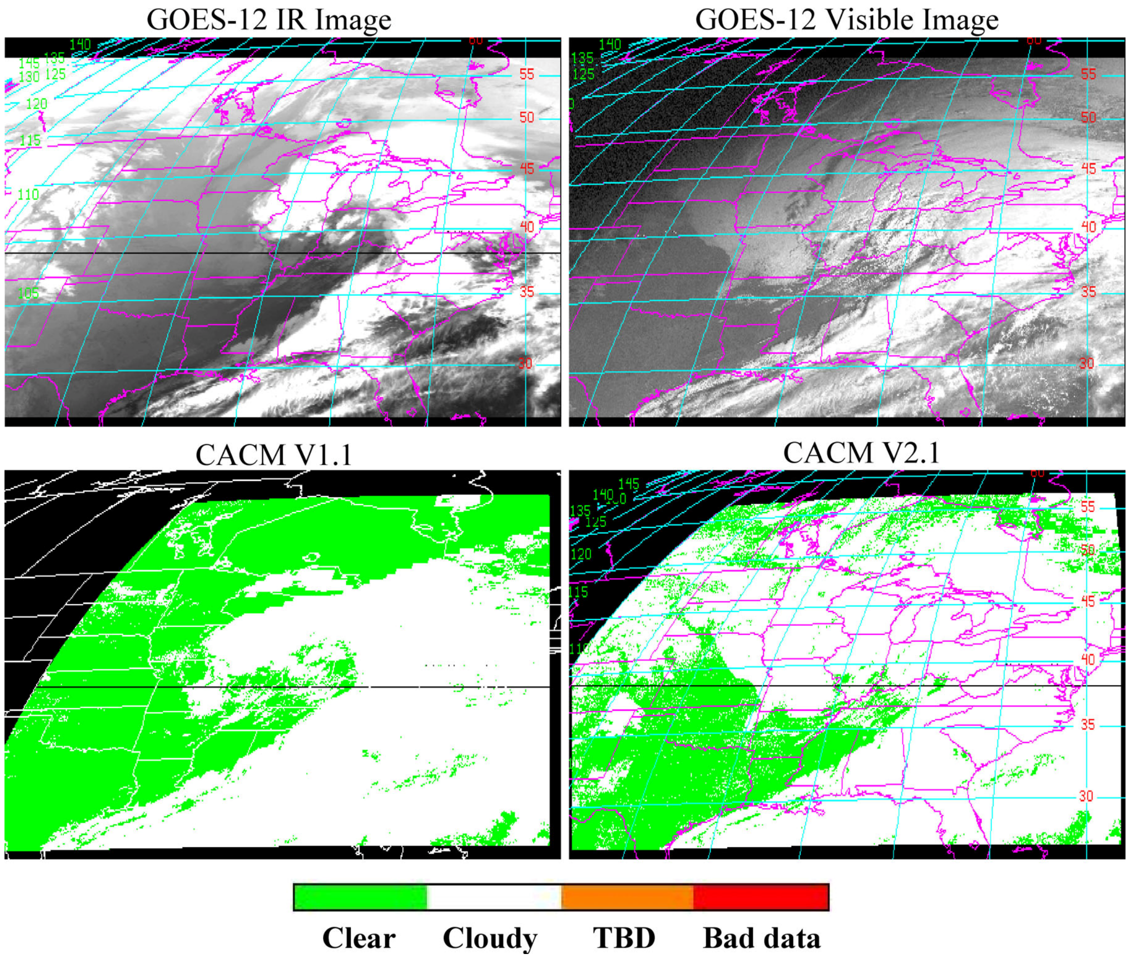

Figure 4. Sunset case over eastern CONUS, 1415 UTC, 7 December 2004.

Nighttime Low Cloud Improvements over United States

Warm low clouds at night have minimal IR signal as seen in the IR and BTD1 images in Figure 5. In V1.1, a fixed BTD1 threshold was used in an attempt to detect low clouds that were missed by the 11-µm threshold. It underestimated the cloud cover in some locations. The V1.1 threshold value is very conservative to prevent false cloud detection for areas with smaller values of $T_{3.9}$. By taking account of the spatial variability of $T_{3.9}$, DET is much tighter than the V1.1 threshold. In V2.1, this $_{3.9}$-dependent threshold added to the BTD1 test improves the detection of low clouds considerably as seen over the southern Appalachians, Texas, and Oklahoma.

$_{3.9}$-dependent test improves low clouds detection at night, but also results in misclassification of noisy pixels in the BTD1 as clouds causing "speckling" problems. To eliminate the false clouds, a prototype "despeckling" procedure is applied to a tile of 16 x 16 pixels that has at least 40% clear pixels from V2.1 cloud mask. In this procedure, all pixels with T_{11} > the warmest clear pixel and DET-1.5 K < BTD1 < DET are reclassified as clear. Figure 6 shows the retrieved cloud particle phase before and

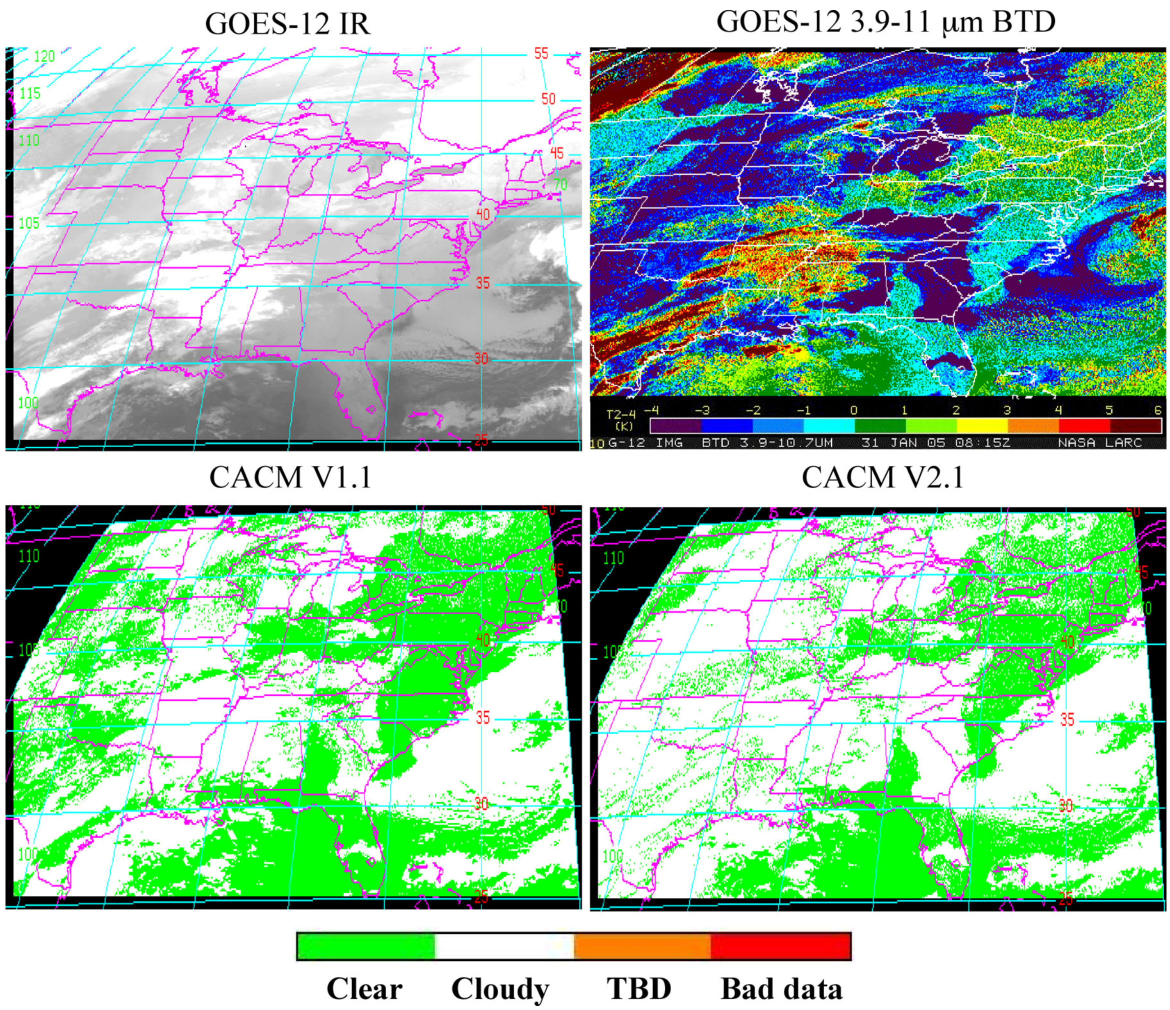

Figure 5. Low clouds over Kansas, Oklahoma, and Texas - 31 January 2005, UTC 0815.

after “despeckling.” The top panels are the GOES-8 BTD1 and T_{11} images. The warm low clouds at the right and bottom part of the GOES-8 images are evident as negative BTD1 values with large values of T_{11}. The speckled clouds in the bottom left panel, resulting from noise in BTD1, are significantly reduced after despeckling procedure (bottom right panel). This preliminary procedure sometimes fails when the surface emissivity is relatively low and the clear-sky BTD1 is more negative than the low cloud case. The Llano Estacado region of west Texas is just such an area. Here, the values of $_{3.9}$, are generally less 0.85 as seen in the emissivity map in Figure 6. The BTD1 image reveals values approaching -4 K in that area with values less than -2 K extending northeastward toward Oklahoma. That pattern is reflected in the V1.1 speckling. Although V2.1 reduces the speckling, some remains in central west Texas. Part of the difficulty is small-scale spatial variability in $_{3.9}$ that is not reproduced by the low-resolution emissivity maps. Thus, better spatial resolution is needed for the input maps. Another problem with surface emissivities, in general, is that they vary with surface moisture and vegetation changes. Accounting for those effects will require a more complex procedure based on much additional research. Another part of the problem is the noisy 3.9-µm channel on GOES. This effect should be smaller in future GOES imagers and in polar orbiting imagers.

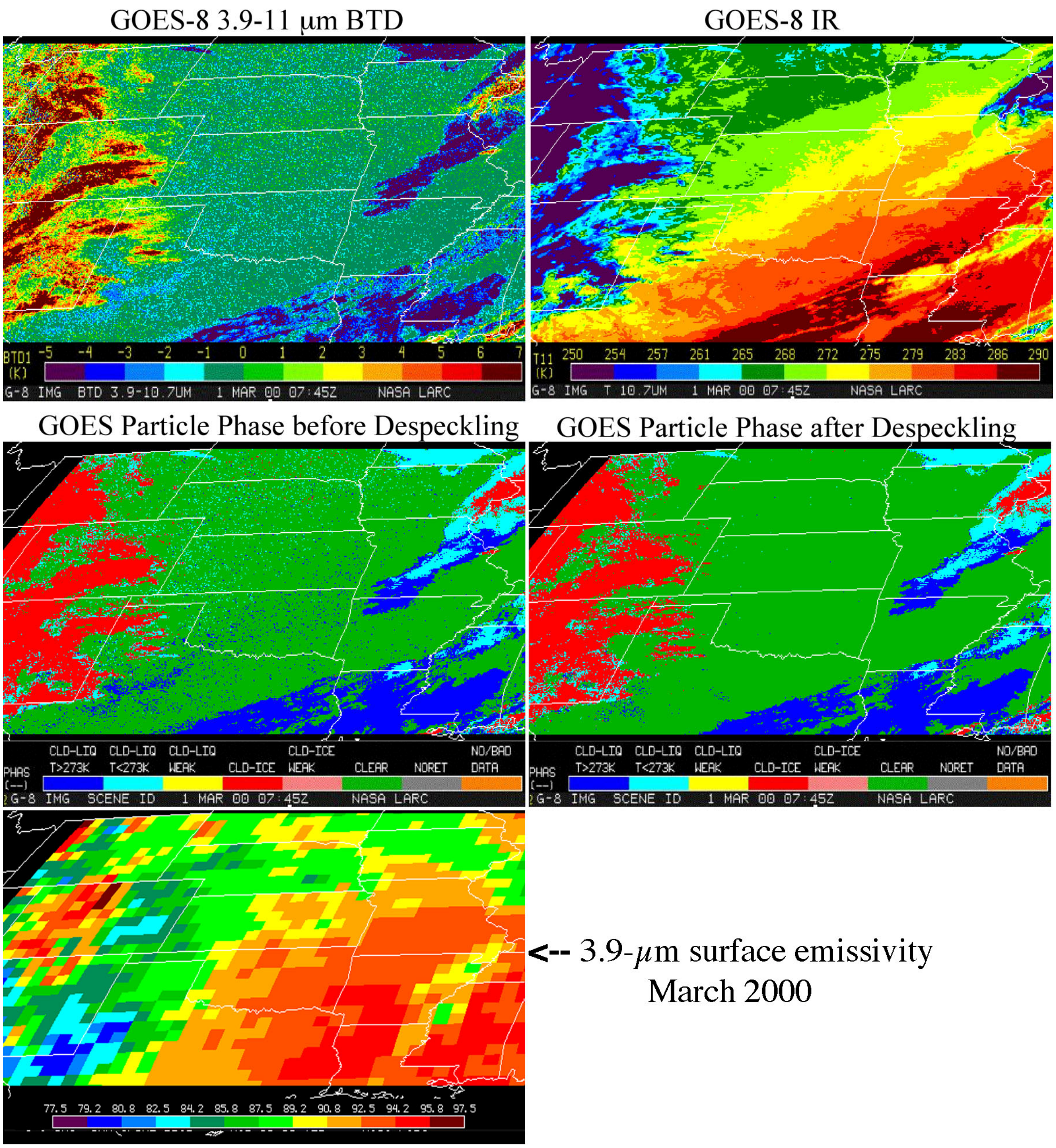

Figure 6. Despeckling procedure for a GOES-8 case, 0745 UTC, 1 March 2000.

Validation

Validation Using Automated Surface Observing System Data

For initial validation, the improved near-terminator and nocturnal cloud masks are compared with the Federal Aviation Administration (FAA) Automated Surface Observing System (ASOS) laser beam ceilometer data. In the following three cases (Figures 7 and 8), the cloud amounts from ASOS stations over the CONUS (square boxes) were superimposed onto the CACM V2.1 cloud mask results. Since the ceilometer can only detect clouds with bases under 3.6 or 7.6 km, depending on the location, an ASOS clear report means no clouds under 3.6 or 7.6 km. Thus, high clouds could be present. The comparisons are summarized as follows.

- Clear agreement: In both figures, the black squares from ASOS are mostly over the V2.1 gray areas. Some black squares are over high clouds (cloud height in Figure 7).
- Cloudy agreement: The light and dark blue squares agree well with the various cloudy areas in Cloud Category (non gray areas).
- Low cloud improvements: Yellow areas in GOES Cloud Category, the newly detected low clouds by V2.1, agree well with the blue squares.

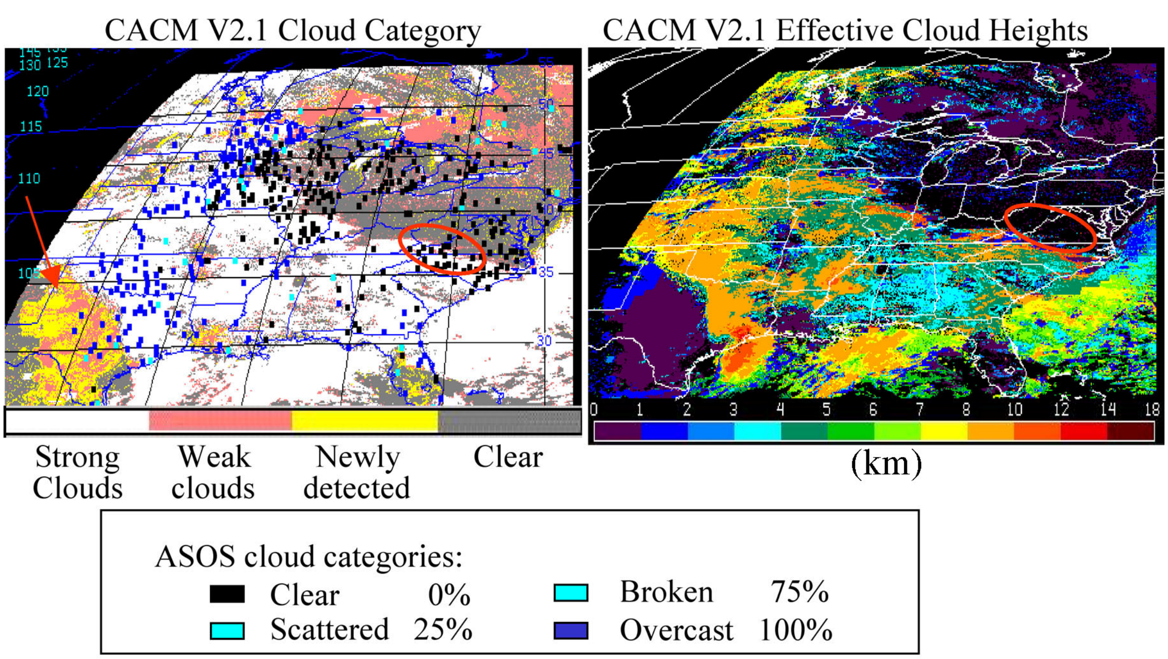

Figure 7. GOES-12, 1015 UTC, 28 January 2005. **(left)** V2.1 cloud mask and ASOS data; **(right)** cloud height.

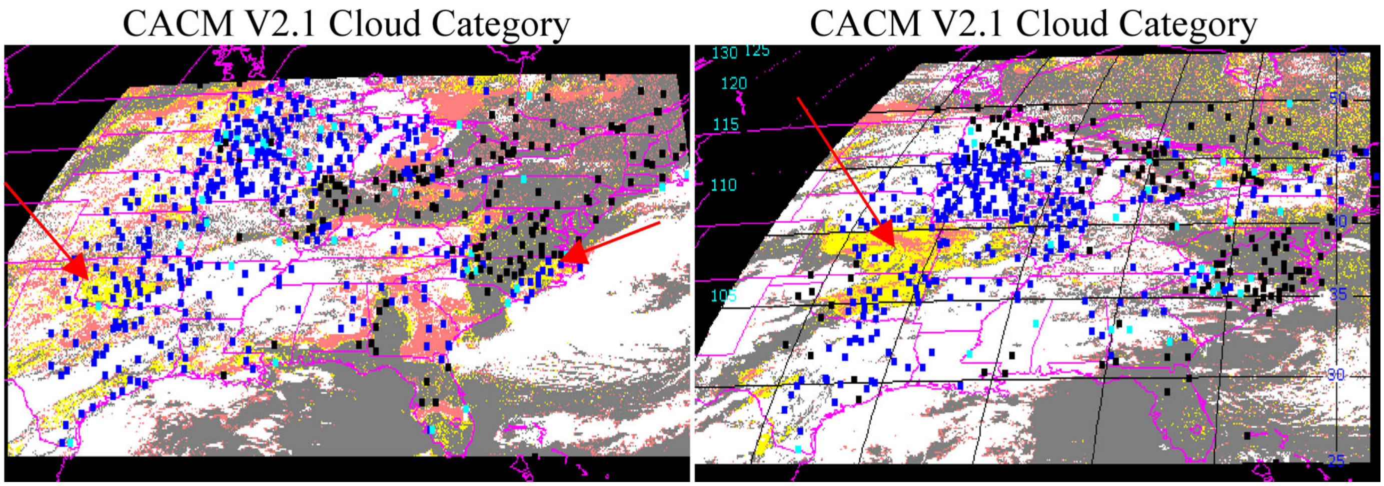

Figure 8. CACM V2.1 cloud mask for GOES-12 and ASOS data **(left)** 0815 UTC, 31 January 2005; **(right)** 0115 UTC, 20 February 2005.

Validation at Southern Great Plains Site

The following figures show a comparison the CACM V1.1 and V2.1 cloud fractions for 31 January and 20 February 2005. The mean CACM retrieved cloud amount was calculated for a 20 km x 20 km box centered at SGP Central Facility using GOES-10 data. Micropulse Lidar (MPL) measurements at SGP site are also plotted for the same time period.

At local twilight and nighttime (00 - 14 UTC), the V2.1 cloud mask increases the cloud amount by 10-90% on 31 January and around 50% on 20 February with some exceptions. The MPL indicates that the cloud cover is relatively heavy throughout the day on the 31st, but around 1345 UTC (twilight) in Figure 9 the V2.1 cloud fraction drops to 0.2 and returns to overcast in the next image. Except for this anomaly, the observations match well with the cloudy and clear portions throughout 31 January. The agreement is relatively good at night on the 20th (Figure 10) but during daytime. The cloud height is extremely variable, even extending up to 20 km suggesting the cloud heights are interpreted form noise in the MPL returns. In Figure 11, the SGP MMCR reflectivity imagery and GOES-10 RGB imagery at four different times show clear skies over the SGP during the daytime (14 - 20 UTC) on 20 February 2005, which agrees well with the V2.1 results. Most of the newly detected clouds from V2.1 are very low in altitude.

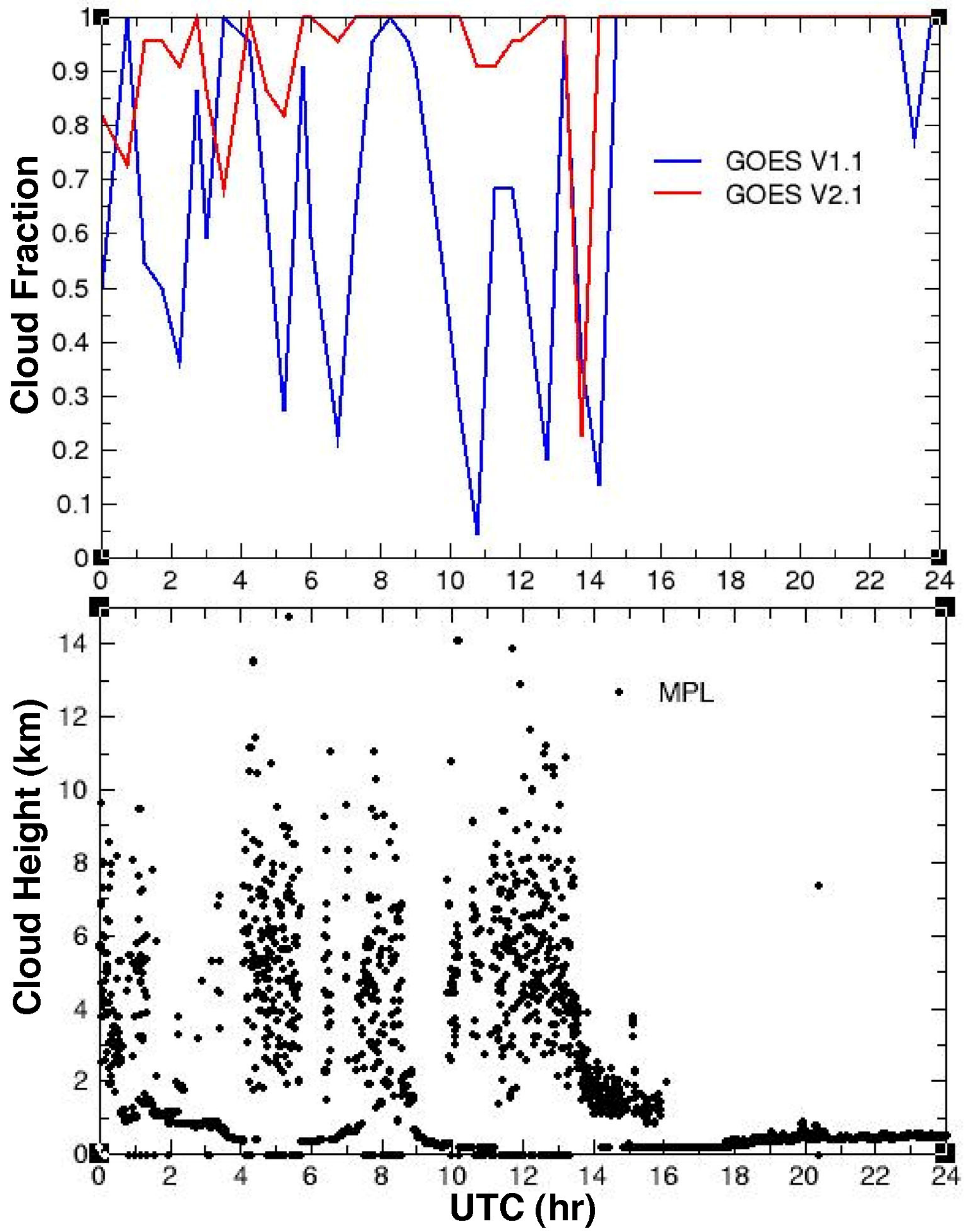

Figure 9. Top: Comparison of cloud fraction at SGP site between CACM V1.1 and V2.1, 31 January 2005; Bottom: MPL measurements of cloud heights.

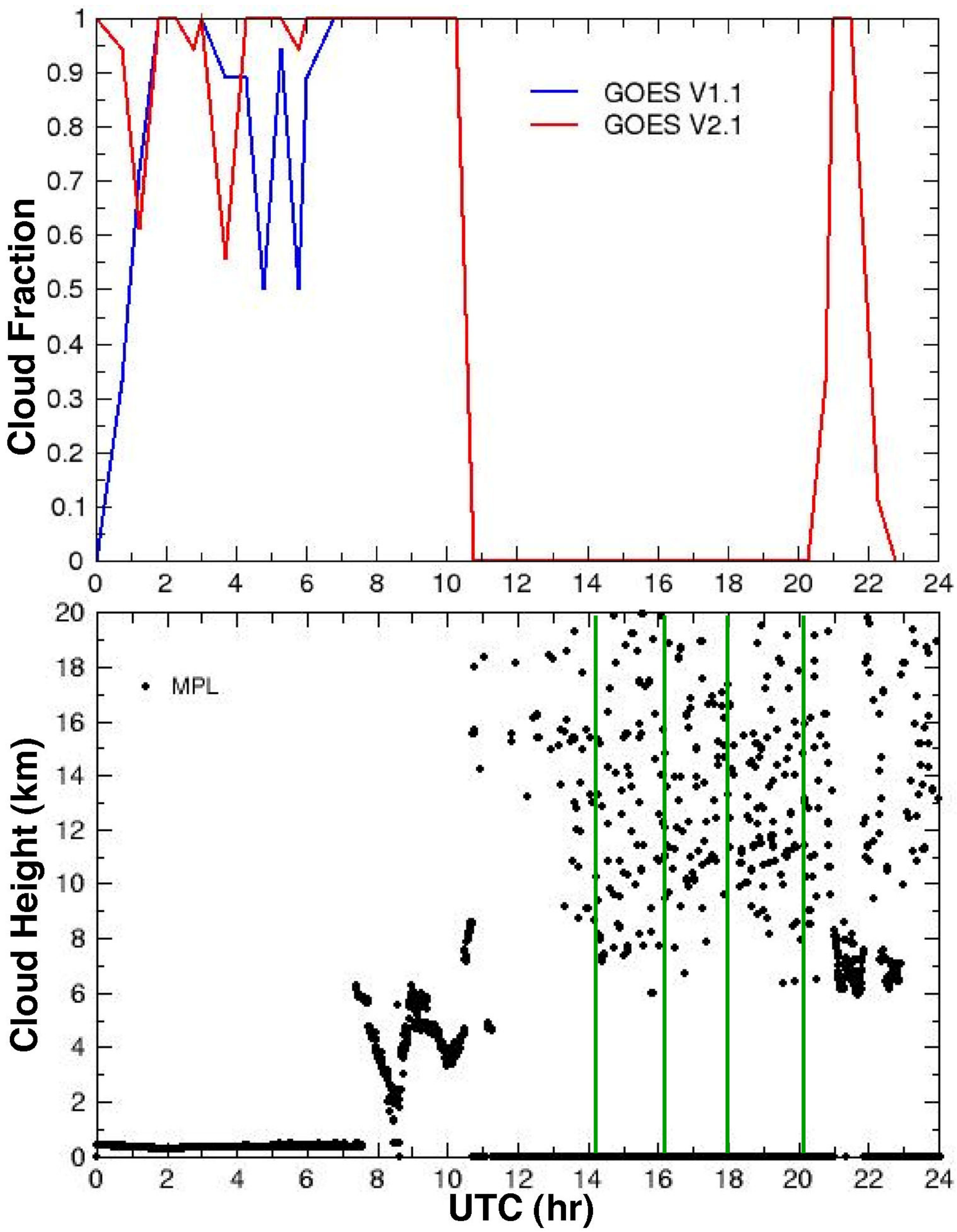

Figure 10. **Top**: Comparison of cloud faction at SGP site between CACM V1.1 and V2.1, 20 February, 2005. **Bottom**: MPL measurements of cloud heights.

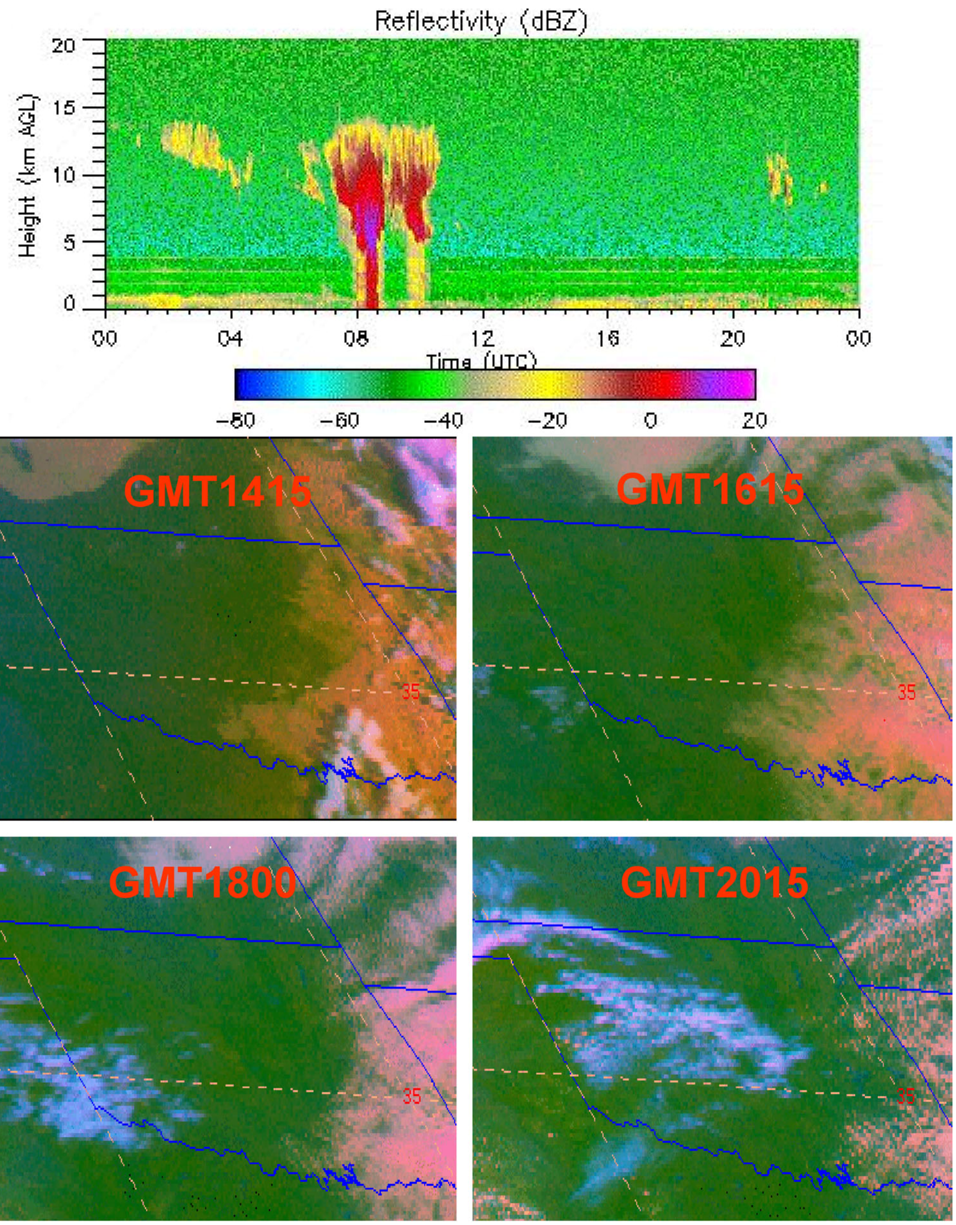

Figure 11. Top: MMCR reflectivity. Bottom: GOES-10 RGB imagery at GMT 1415, 1615, 1800, and 2015 corresponding to the green vertical lines in Figure 10.

Conclusions and Future Work

The CACM V2.1 improves the low cloud detection near the day/night terminator where the observed BTD1 signals are weak due to cancellation of the reflected solar component of 3.9-µm and the lack of contrast in the 11-µm channel for warm low clouds. Twilight cloud tests, which utilize the GOES visible and IR channels, smooth the transition between daytime and nighttime cloud retrievals. The new surface-emissivity-dependent BTD1 cloud test significantly improves low cloud detection at night. The cloud fraction from the improved GOES cloud mask agrees well with surface measurements from ASOS, MPL and MMCR data.

Additional enhancements are needed for the CACM over snow-covered mountains, shadows of high-over-low clouds, sunglint ocean, smoke over the Gulf of Mexico, and clouds over bright desert regions. More highly resolved GOES-based estimates of clear sky visible, skin temperature, and surface emissivity are also necessary for further gains in cloud detection accuracy, especially at night. These future changes in the cloud mask will be intensely scrutinized with observations at all of the ARM surface sites.

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References

Benjamin, SG, D Devenyi, SS Weygandt, KJ Brundage, JM Brown, GA Grell, D Kim, BE Schwartz, TG Smirnova, TL Smith, GS Mankin. 2004. "An hourlyassimilation-forecast cycle: The RUC." *Monthly Weather Review* 132(2): 495-518.

Chen, Y, S Sun-Mack, P Minnis, DF Young, and WL Smith, Jr. 2004. "Seasonal surface spectral emissivity derived from Terra MODIS data." In *Proceedings of the Thirteenth AMS Conference Satellite Oceanography and Meteorology*, Norfolk, VA, September 20-24, CD-ROM, P2.4.

Minnis, P, L Nguyen, WL Smith, Jr., MM Khaiyer, R Palikonda, DA Spangenberg, DR Doelling, D Phan, GD Nowicki, PW Heck, and C Wolff. 2004. "Real-time cloud, radiation, and aircraft icing parameters from GOES over the USA." In *Proceedings of the Thirteenth AMS Conference Satellite Oceanography and Meteorology*, Norfolk, VA, September 20-24, CD-ROM, P7.1.

Pavolonis, M, and AK Heidinger. 2005. "Preliminary Global Cloud Comparisons from the AVHRR, MODIS, and GLAS: Cloud Amount and Cloud Overlap." Poster session (number 5658-32) from Passive Optical Remote Sensing of the Atmosphere and Clouds IV sponsored by the SPIE (International Society for Optical Engineering).

Sun-Mack, S, Y Chen, RF Arduini, and P Minnis. 2004. "Clear-sky narrowband albedo variations from VIRS and MODIS data." In *Proceedings of the Thirteenth AMS Conference Satellite Oceanography and Meteorology*, Norfolk, VA, September 20-24, CD-ROM, P6.34.

Sun-Mack, S, P Minnis, Y Chen, and RF Arduini. 2003. "Clear-sky narrowband albedos derived from VIRS and MODIS." In the *SPIE Tenth International Symposium Remote Sensing Conference Remote Sensing Clouds and Atmosphere*, Barcelona, Spain, September 8-12, 101-109.

Trepte, Q, Y Chen, S Sun-Mack, P Minnis, DF Young, BA Baum, and PW Heck. 1999. "Scene Identification for the CERES Cloud Analysis Subsystem." In *Proceedings of the AMS Tenth Conference Atmospheric Radiation*, Madison, Wisconsin, June 28 - July 2, 169-172.