Validation of Satellite Retrieved Cloud Amounts Over the Continental United States with Automatic Sciences Research Center Ceilometer Data

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Introduction

The National Aeronautics and Space Administration (NASA) Langley cloud and radiation retrieval products are produced near real time over the continental United States (CONUS) by combining satellite-based cloud retrievals from Geostationary Operational Environmental Satellite (GOES) multi-spectral images (Minnis et.al. 2005). A subset of these data is available from the Atmospheric Radiation Measurement (ARM) Data Archive. Currently, validation of real time cloud properties is performed only over the ARM Climate Research Facility (ACRF) Southern Great Plains (SGP) site and during selected intensive operation periods. Surface measurements routinely taken at the SGP site provide an excellent source of validation data and can be used as a quality control dataset (e.g., Nordeen et al. 2005), but the measurements do not cover the entire CONUS and may not be available real-time. However, it is critical that the satellite retrievals be free of regional, diurnal and seasonal biases before they can be integrated into forecast models. Quality control must be performed on a large spatial network of observations to eliminate regional cloud retrieval biases. Fortunately, the Federal Aviation Administration (FAA) Automated Surface Observing System (ASOS) stations continuously operate lidar ceilometers in support of runway safety providing a spatially appropriate source of quality control measurements for, at a minimum, cloud fraction and cloud base height. There are over 900 FAA and National Weather Service ASOS stations distributed over the CONUS. These datasets are used in this paper to perform a preliminary validation of the ARM cloud detection algorithms applied GOES over the CONUS.

Data

This study uses the GOES-10 and GOES-12 half-hourly, 8-km real-time NASA Langley cloud and radiation products for March 2004. These products are currently available on the satellite imagery and cloud products page located at http://www-angler.larc.nasa.gov/satimage/products.html (Palikonda et al. 2005). To determine if a pixel is clear or cloudy, the Clouds and the Earth's Radiant Energy System (CERES) ARM cloud mask (CACM) uses reflectance and brightness temperature (BT) and brightness temperature difference (BTD) thresholds based a set of clear-sky visible reflectance (Sun-Mack et al.

2004) and spectral emissivity (Chen et al. 2004) maps derived for the (CERES) project (Trepte et al. 1999). The surface skin BTs are estimated for the GOES 3.9, 10.8 and 12-µm channels using the surface emissivities along with the hourly Rapid Update Cycle (Benjamin et al. 2004) surface temperatures and an empirical correction for the difference between surface air and skin temperatures. The clear-sky BTs are estimated from the surface spectral BT by computing the atmospheric effects on the upwelling radiance using the Rapid Update Cycle profiles of temperature and humidity. The 4-channel (0.65, 3.9, 10.8 and 12 or 13.3-µm) Visible Infrared Solar-infrared Split-Window Technique (VISST; Minnis et al. 1995) produces daytime pixel-level retrievals for clouds including amount, phase, particle size, water path, optical depth, emittance, top, base, effective height, and estimated outgoing longwave radiation and shortwave reflected flux. The Solar-Infrared Infrared Split-Window Technique (Minnis et al. 1995), using only the three infrared bands to retrieve a subset of the VISST cloud properties is applied to nighttime and near-terminator scenes. The retrievals are performed over the CONUS to include the region bounded by 55°N-20°S and 130°W-65°W. Satellite cloud amounts corresponding to an individual ASOS station are determined from the 3 x 3 pixel matrix centered on the station. An individual imager pixel is considered either clear or cloudy. The dominant cloud phase, liquid or ice, is also saved.

FAA ASOS laser beam ceilometer station cloud amount means from the FAA ASOS stations (http://www.faa.gov/asos/) are obtained in real-time from the Man computer Interactive Data Access System (http://www.ssec.wisc.edu/mcidas) and matched with the corresponding CACM/VISST cloud amount and phase. The agreement may not be perfect since the ceilometer is a vertical-pointing surface instrument that obtains cloud amount over a 30-minute time window, whereas the satellite gives a spatial snapshot of cloud amount from space. The cloud amounts are usually comparable given homogenous cloud cover and uniform advection. The ceilometer also provides up to three cloud base heights and employs 0.9-µm lidar technology. The older ASOS stations have a lidar vertical extent of 3.6 km above ground level, whereas the newer ones can detect bases up to 7.6 km above ground level. Clouds above the limits are frequently not detected by the ceilometers. The station cloud amount categories are clear, scattered, broken, and overcast and are assigned cloud amounts of 0, 25, 75, and 100%, respectively.

Methodology

Overlaying ASOS station cloud amounts on an instantaneous CACM image provides a means for assessing the regional agreement between the ASOS and satellite-derived cloud amounts. These validation images also point out the limitations of ASOS in cirrus and fog cases. Several statistics are computed given the cloud height and category limitations of the ASOS station data. Again, ASOS cannot detect high thin clouds and the ASOS cloud categories are coarse. Two null hypothesis statistics are performed to evaluate the CACM/VISST retrievals. The first is when ASOS reports overcast, the CACM should not be reporting clear skies. This statistic is used to evaluate the satellite cloud mask. The second scenario is when ASOS reports clear skies; the CACM should not be reporting overcast low clouds, although high clouds may be present. This statistic is used to evaluate the VISST cloud phase and to a degree the cloud mask. Monthly coincident station cloud amount means and root mean square (RMS) errors are also computed. Means and RMS errors must differ by a minimum two cloud categories to be statistically significant. Since the nighttime Solar-Infrared Infrared Split-Window Technique algorithm relies on just the infrared (IR) channels, statistics are computed separately for day and night. These statistics can then pinpoint regions where topography can influence satellite retrievals or where diurnal or seasonal trends are not accounted for. This is the first step to perform real-time quality control on the GOES cloud property retrievals.

Results

CACM image and ASOS Station Cloud Amount Overlay

Figure 1 depicts the GOES-12 CACM for March 18, 2004, at 1845 Universal Time Coordinates (UTC) (~1:00 p.m. local time) overlaid with individual ASOS station cloud amounts. Stations detecting cloud bases up to an altitude of 3.6 and 7.6 km are plotted. The ASOS stations outline the cloud boundaries of low clouds very well. For example, the VISST liquid-phase cloud decks across Oklahoma, Arkansas, and Texas are surrounded by stations that reported clear sky (black dots) with numerous overcast stations (white dots) underneath the clouds. The cloud system across the Great Lakes is virtually covered with overcast stations with very few reporting clear and scattered. The high clouds (displayed in red) have base heights within the range of the ASOS lidars. The uniformity of reported cloud amounts from the ASOS stations gives credibility to individual station reports.

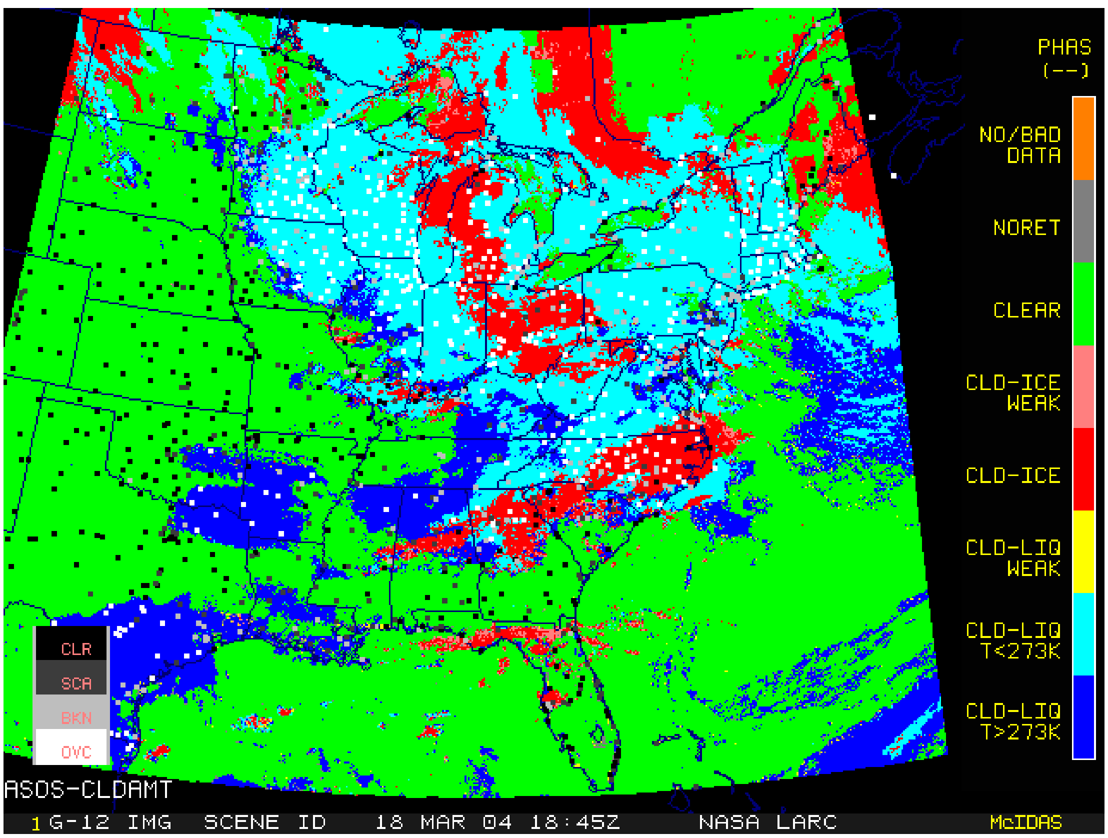

Figure 1. CACM for GOES-12 8-km resolution for March 18, 2004, 1845 UTC and individual ASOS stations gray shaded by cloud amount. CACM/VISST clear-sky, low water, low super-cooled water, and high cloud regions are demarcated by green, blue, cyan, and red, respectively. ASOS stations reporting clear, scattered, broken, and overcast are shown as black, dark gray, light gray, and white filled squares, respectively.

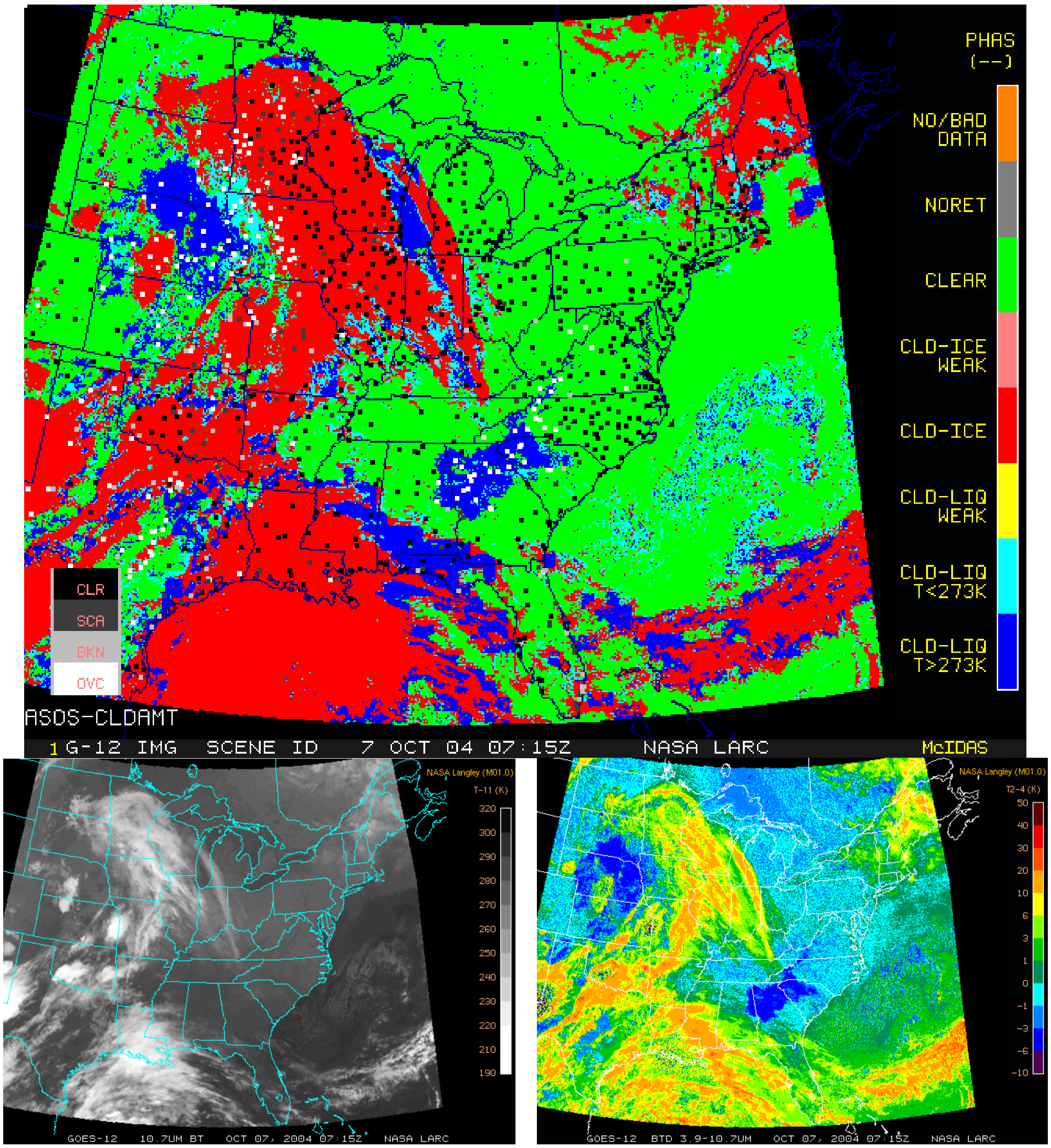

Figure 2. Top, GOES-12 8-km resolution cloud mask for October 7, 2004 at 0715 UTC overlaid with individual ASOS stations gray shaded by cloud amounts in Figure 1. Lower left: GOES-12 8-km IR (10.7 µm) temperature. Lower Right: GOES-12 8-km 3.9 µm-10.7 µm temperature difference.

Figure 2 shows the GOES-12 cloud mask for October 7, 2004, at 0715 UTC (~3:00 a.m. local time). Again, ASOS stations measuring cloud base to both a 3.6 and 7.6 km altitude are overlaid on the image. This image was chosen for its extensive high cloud coverage. In this case, numerous ASOS stations report clear in the high cloud decks across Wisconsin/Illinois, Arkansas, and Louisiana. The IR image (Figure 2 lower left panel) confirms the presence of high clouds. The ASOS stations encompassed by the low cloud decks across Nebraska and Georgia reported overcast conditions. The low cloud decks are clearly defined (dark blue areas) by the 3.9-10.8 µm GOES-12 temperature difference image (Figure 2 lower right panel). Note that where the cloud mask identifies low clouds across southern Alabama, the ASOS stations are reporting clear skies. In this case, the GOES cloud mask has identified cloudy pixels; however, the phase was not determined properly. If it were truly a low cloud region it would be apparent as a negative value in the 3.9-10.7 µm BTD image. Instead, it is either an area of thin cirrus clouds (IR image) or thin cirrus over a low cloud deck. This difference would cause a less than desired clear-sky agreement because of the incorrect VISST cloud phase retrieval.

Lastly, some discrepancy exists between ASOS and CACM in the Appalachian valleys in North Carolina and Virginia. In this case, ASOS stations are reporting localized fog associated with radiational cooling. The ASOS Meteorological Terminal Air Report (METAR) station reports indicate fog when the visibility is obscured as measured by the visibility instrument. In some cases, the ASOS stations report clear-sky if the fog is shallow and/or thin enough to be unobserved by the lidar. In other cases, the fog is thick enough to report overcast or obscured conditions. CACM results for the comparisons are from a 3 x 3 pixel matrix to account for parallax and navigation errors. Since fog must cover the majority of the nine pixels, small patches of fog are easily missed. Further south in Appalachians, the CACM detected foggy areas, where the 3.9-10.7 µm BTDs were negative for adjacent pixels. Imager pixels over complex terrain will have an IR temperature somewhere between the mountaintop and valley temperature, but unfortunately it is not valid for either location. Together with the possibility of sub pixel fog conditions challenges even the best of cloud mask algorithms using 4-km data. For these reasons, all ASOS stations reporting fog are eliminated from the ASOS and CACM comparisons. This type of mismatch between ASOS data and satellite retrievals for foggy conditions is also a problem over coastal California where fog associated with the marine layer is prevalent. Evaluation of fog detection will be performed in future studies.

ASOS and CACM Overcast Agreement

The most reliable ASOS and satellite overcast agreement statistic is the frequency when ASOS ceilometers report overcast and the CACM yields clouds. This statistic is computed for individual stations to pinpoint geographic regions in need of cloud mask improvement. Both the 3.6 and 7.6 km maximum cloud altitude ASOS stations are used along with measurements of either broken or overcast skies. Cases with the corresponding CACM cloud amounts greater than 75% or less than 25% are used for the cloud matching. The overcast agreement is defined to be the ratio of positive cloud returns for both ASOS and CACM to all positive returns from ASOS. Figure 3 shows the results for both day and night during March 2004. During daytime, the eastern United States has excellent agreement (>90%) for overcast clouds while most of the western U.S. stations show good agreement. At night, the overcast agreement is slightly less than that during the daytime over the eastern United States. However, for some mountainous regions over the western United States the agreement is less than 50%. Coastal California at night is also problematic at night due to stratus clouds over the water (See CACM Image and ASOS Station Cloud Amount Overlay section). Using this technique, regional trends can be easily identified.

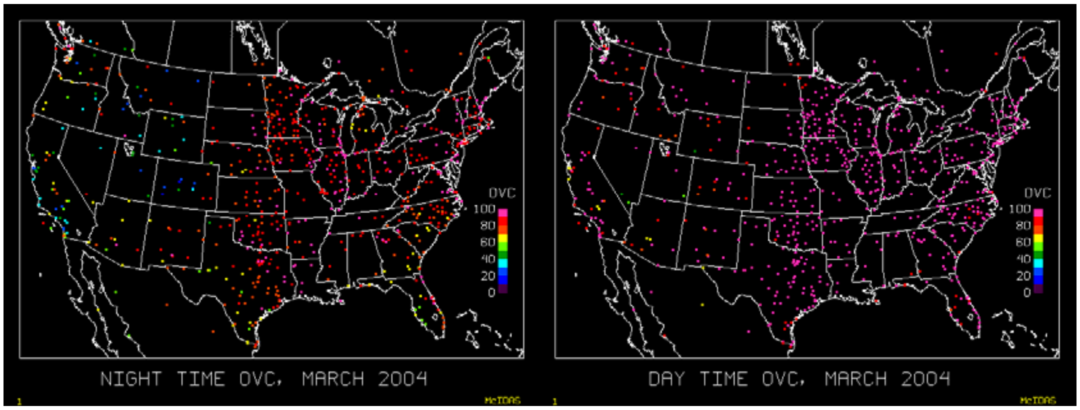

Figure 3. Left: Nighttime ASOS and CACM overcast agreement in % for March 2004. Right: Daytime agreement.

ASOS and CACM Clear-Sky Agreement

The ASOS and CACM clear-sky agreement statistic is the frequency when ASOS reports clear skies and the CACM pixels are also clear. Only the 7.6 km maximum cloud altitude ASOS stations are used for this statistic. Also, an ASOS METAR report of fog excludes the observation from the comparison. VISST ice clouds are also excluded since the base height may be above the reach of the ASOS lidar. ASOS clear-sky observations with no fog and cloud height restrictions along with cases where CACM cloud amounts were less than 25% and above 75% were used. Clear-sky agreement is defined as the ratio of positive clear-sky returns by both ASOS and CACM to all positive clear-sky ASOS returns. Figure 4 shows both day and night results for March 2004. The stations reporting cloud base height up to 7.6 km represent a significantly reduced subset of all the ASOS stations. The results are not as good as for the overcast cases, but are generally encouraging. The clear-sky agreement is better than the overcast in the western United States, revealing that the CACM underestimates cloud amount in those areas at night. California coastal and valley daytime cloud coverage also appears to be overestimated by the CACM. It should be noted that not all ASOS stations report continuously and occasionally under-report clear-sky events.

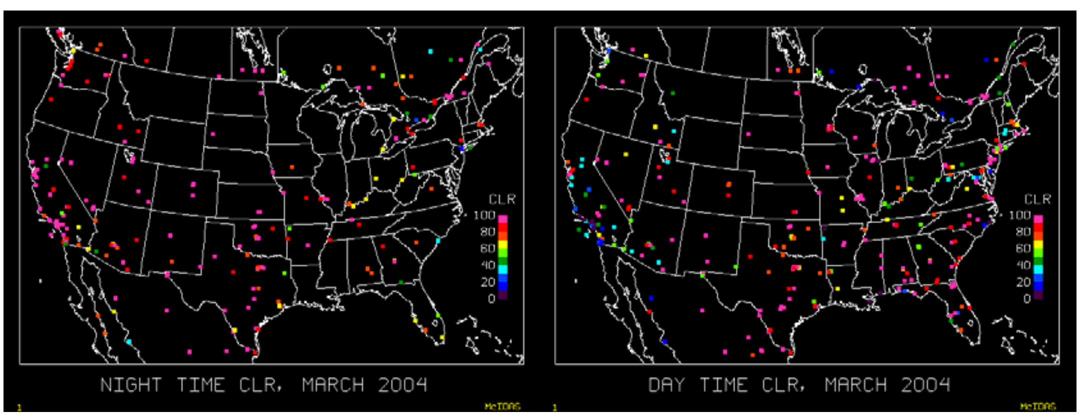

Figure 4. Left: Nighttime ASOS and CACM clear-sky agreement in % for March 2004. Right: Daytime agreement.

Coincident ASOS and CACM Cloud Amount RMS Difference

The cloud amount RMS difference is a comparison of ASOS measurements with the corresponding CACM cloud amounts over the course of the month. Only ASOS stations reporting clouds up to 7.6 km are used and if the ASOS report is either clear or scattered, only fog-free observations are included. Any station where the CACM reports the ice cloud phase is excluded from the comparison. Essentially, this is the same as the clear-sky agreement limitations. An RMS cloud amount error is computed for each station between all the coincident CACM and ASOS station cloud amounts. Since ASOS only reports 4 cloud categories, a RMS of error of 2 or more cloud categories is significant, or ~40 % in terms of the cloud amount. Figure 5 shows the day and night results for March 2004. Most daytime stations have RMS errors less than 40%. Note the excellent agreement around the Great Lakes. Coastal California stations as expected, and coastal Florida have large discrepancies. The assumption of homogenous clouds advecting over a station may not be valid in this case. Small popcorn cumulus clouds not associated with synoptic events are more typical in Florida. As expected, RMS cloud amount errors are greater at night, especially over Texas and Washington State.

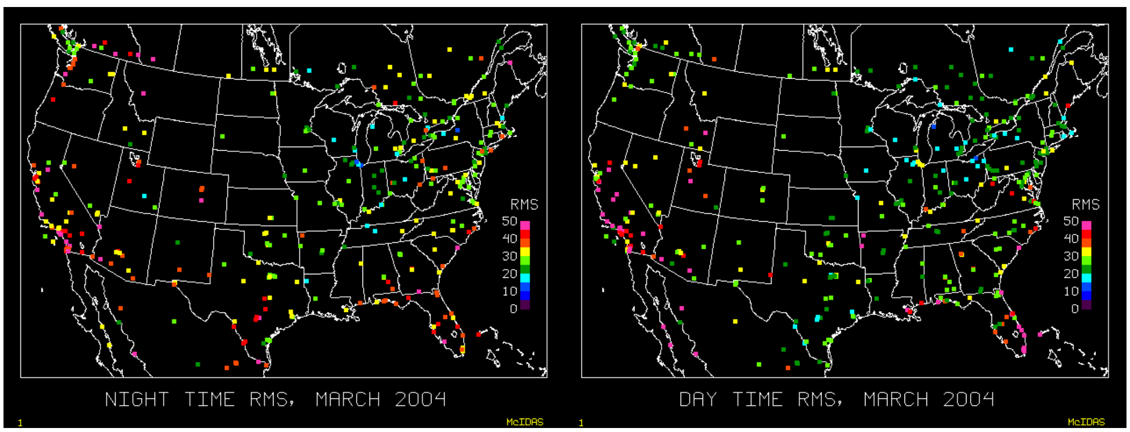

Figure 5. Left: Nighttime coincident ASOS and CACM cloud amount RMS difference in % for March 2004. Right: Daytime RMS difference.

ASOS and CACM Monthly Cloud Amount Comparisons

The mean coincident station cloud amounts for both ASOS and CACM are computed for the month. Since not all ASOS clear-sky measurements are really clear, they cannot be used to derive the "true" cloud amount for the station. Individual ASOS and CACM monthly-mean cloud amounts are plotted on a scatter diagram in Figure 6. The individual points are color coded by the coincident RMS cloud amount error. Encouragingly, most stations fall along the diagonal or line of agreement. For both day and night results, the stations with the highest RMS errors (red dots) are usually not along the diagonal. Although it appears that the CACM overestimates cloud amount during the day, the areas with the greatest bias are also those with the greatest RMS, which is most likely to due persistent strong cloud amount gradients at those stations (e.g., coastal sites). For ASOS to report clear or overcast all returns in

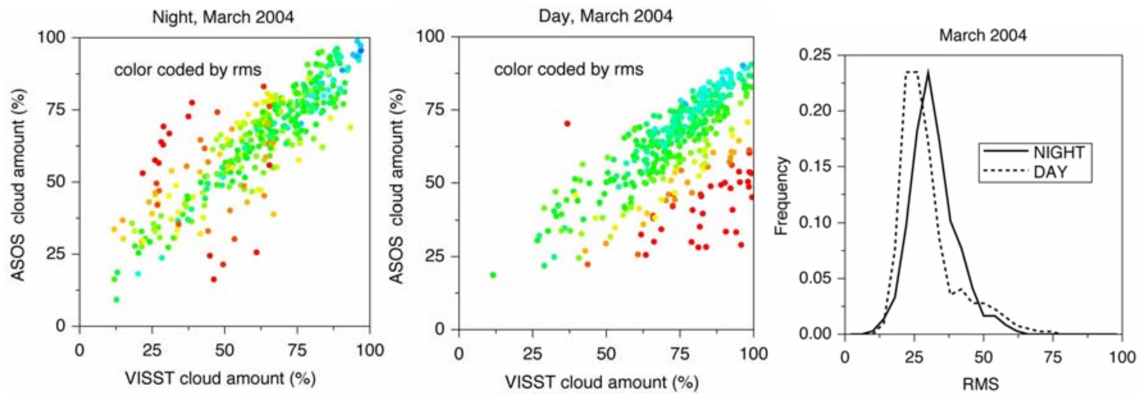

Figure 6. Left: Nighttime ASOS station and CACM monthly-mean cloud amount scatter plot for March 2004. Individual stations are color-coded by coincident ASOS and CACM cloud amount RMS difference. Color-coding is same as Figure 5 except for magenta, which corresponds to the dark red points in this figure. Center: Daytime differences. Right: panel Histogram of ASOS and CACM cloud amount RMS differences.

the half hour have to be clear or cloudy, respectively, which may skew some station results. It is not apparent in the scatter plots that the daytime results are better than at night. However, the frequency distributions of RMS station cloud amount differences (Figure 6, right) reveal that the daytime peak occurs at a lower RMS than the nighttime peak.

Conclusions and Future Work

Although ASOS ceilometers are limited to detecting clouds primarily below 8 km, the cloud METARS provide an excellent quality control dataset. ASOS data are one of the many datasets being used to validate the CACM and can ultimately lead to improvements in the cloud property algorithm. Four comparison techniques have effectively evaluated the VISST retrievals for all but high ice clouds. Based on ASOS observations over the United States, CACM daytime overcast agreement was better than 90% and clear-sky agreement better than 80%. Regional discrepancies were easily identified. As predicted, nighttime CACM results are not as good as those during the day and efforts are underway to rectify the situation (Trepte et al. 2005). Since the ASOS data are available in real-time, comparisons can be made to assure that quality CACM/VISST retrievals derived from the real-time analyses are being put into the archive. This procedure can be repeated when new domains are analyzed. Adding VISST-derived cloud properties to numerical weather prediction models or Value Added Products requires that the properties do not introduce any satellite-based artifacts. Comparisons to the ASOS database help build that confidence. Additional comparisons will be performed using ASOS cloud amounts and later improved CACM results.

The ASOS database also includes cloud base heights, which will be used to validate and improve VISST cloud-base height estimates. Unlike the cloud microphysical properties, cloud bases are usually not directly retrieved, but are instead inferred by parameterizations based on cloud-top properties and surface observations. The parameterizations derived for the ACRF SGP site (Chakrapani et al. 2002) will be validated and improved using ASOS station cloud base heights beginning with single layer events. Several multi-layer cloud algorithms (e.g., Huang et al. 2005) need to be validated and enhanced using the multi-layer cloud height database from ASOS station METAR reports. Presently, NASA Langley cloud and radiation parameters are used in the ARM Broadband Heating Rate Profile product. The Broadband Heating Rate Profile algorithm tries to incorporate all reliable datasets to improve radiative heating profiles based on measurements (Mlawer et al. 2005). The validation and improvements of CACM cloud amounts, VISST cloud base heights, and multilayer parameters, when implemented, will eventually increase the accuracy of the Broadband Heating Rate Profile product. Accurate satellite cloud base and top heights will also aid in forecasting aircraft icing events in super-cooled liquid water clouds.

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