# Developing a Three-Dimensional Cloud Product over the ARM Sites Using Geostationary Meteorological Satellite Data

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## Introduction

Determining the three-dimensional (3D) structure of clouds over large areas from satellites is a daunting task given the limitations of "seeing" through clouds and measuring their properties with satellite imager visible, infrared, and microwave data. One of the greatest problems in multi-layered cloud detection is detecting low-level clouds underneath thick high clouds. Typically, satellite imager-based multi-layered cloud detection methods require that the upper-level cloud is optically thin with an infrared (IR) emissivity of 0.85 or less. Thick ice clouds prohibit detection of low-level clouds when passive visible (VIS) and IR imager data are used (Pavlonis and Heidinger 2004). The addition of a microwave radiometer to that instrument complement can be used to detect low-level water clouds under thick ice clouds (Huang et al. 2005) but is very unreliable over land surfaces. Thus, when the thick ice clouds are present over land, the detection of low-level clouds is indeterminate using passive satellite data.

Ceilometer data could help determine when those clouds are present but they are taken at a limited number of locations and require uncertain interpolation. High-temporal resolution numerical weather prediction analysis data provide a more continuous 3D picture of potential cloudiness that might be useful for filling out the low levels when the VIS-IR methods are unable to discriminate between single and multi-layered clouds. In this paper, a VIS-IR multi-layer cloud detection technique is applied to Geostationary Operational Environmental Satellite (GOES-8) over the Southern Great Plains (SGP) and compared with Atmospheric Radiation Measurement (ARM) SGP Active Remote Sensing of Cloud Layers (ARSCL) data (Clothiaux et al. 2000) and ceilometer data from the Automated Surface Observing System (ASOS). Numerical weather prediction data are used to estimate cloud-base height underneath high-level clouds and validated using the ASOS data. This study is the first step in a process that eventually will provide a more accurate set of vertically defined cloud properties over a large domain covering the SGP for use in single-column modeling and broadband heating rate profile studies.

# Data and Methodology

GOES-8 4-km VIS (0.65 um), solar-infrared (3.9 um), IR (10.8 um), and split-window (12.0 um) bands are used as input to the Visible Infrared Solar-Infrared Split-window Technique (VISST; Minnis et al. 1995). Visible Infrared Solar-Infrared Split-window Technique derives cloud temperature, top and base heights, optical depth (OD), particle phase, effective ice particle diameter (De), ice water path, effective liquid drop radius (Re), and liquid water path for sunlit conditions from GOES-8 data (Minnis et al. 2002). Various cases of daytime March-October 2000 GOES-8 imagery likely to have scenes of cloud overlap (specifically, ice clouds overlying water clouds) were selected for processing via VISST at a 0.5° resolution. Over the SGP domain (32°-42°N; 91°-105°W) VISST uses temperature and relative humidity profiles from 40-km, hourly Rapid Update Cycle (RUC-2; Benjamin et al. 2004) analyses.

The likelihood of cloud overlap for the VISST cases is determined via the Cloud Property Multi-level (CPM) Cloud Detection Method. VISST single-level cloud properties for each cloudy pixel are tested to determine if the clouds in a pixel are single-layered, multi-layered, or indeterminate using a split window method first pioneered by Kawamoto et al. (2001). It is similar to the method of Pavlonis and Heidinger (2004), but relies on cloud phase and OD and radiances, rather than radiances only, to detect multi-layered systems. The radiances used are in the form of the 10.8 – 12 μm brightness temperature difference (BTD). For each cloudy pixel several tests are applied. For a pixel to be classified as overlapped clouds, BTD must be greater than 1.0 K and OD > 10; additionally for water, Re > 16 μm and, for ice, the De < 75 μm. If these tests are not met, the pixel is declared indeterminate if the phase is ice and OD > 10. Otherwise, the pixels are categorized as single-layered.

Indeterminate pixels are further compared with RUC-based cloud probabilities to classify any cloud layers under the high cloud as overlapped or single-layered. When overlap cases are found in the VISST data, it is necessary to determine the probability of an underlying cloud beneath the viewed cloud. This cloud probability is estimated for each-25 hPa layer using the empirical formulae of Minnis et al. (2005) that rely on the RUC temperature, relative humidity, and vertical winds. It is assumed that the cloud fills the layer. Thus, a 3D cloud probability field is built from this RUC-based parameterization.

Two ground-based instrument capabilities are used to validate this 3D cloud probability field. ASOS ceilometers are scattered throughout the SGP domain. Hourly mean cloud base heights (CBH) are from ASOS are interpolated into 0.5° grid boxes to match the VISST results. However, ASOS is limited to 7.6 km cloud heights at the highest, so to provide some validation for higher clouds at fine vertical resolution, ARSCL cloud boundaries over SGP Central Facility are also used. Discrete layers of ARSCL cloud boundaries were defined within 20-minute windows centered at GOES retrieval times.

# Results

## Initial Active Remote Sensing of Cloud Layers Comparison Summary

Out of 27 daytime March-October 2000 cases selected for likely multi-layer clouds, the CPM classed 67% as indeterminate. For these same cases, the breakdown for ARSCL's classifications were 48% deep convective, 15% with some overlap, and 4% single-layer ice clouds. An optically thick cloud classified by the CPM, therefore, corresponds to a deep convective cloud roughly 72% of the time. For the 33% of cases that CPM classified as having some overlap, ARSCL classified 26% as overlapped, and 7% as deep convective. This translates to a 79% success rate.

## Initial Automatic Surface Observing System Comparison with Cloud Property Multi-level Analysis

VISST cases from 1545-1945 Universal Time Coordinates (UTC) on 17 June 2000 were selected to compare with ASOS cloud base heights. First, the pixel-level cloud properties were classified, binned, and averaged into half-degree resolution grids. The grid box averages were determined to have the classification (single-layer, multi-layer, or indeterminate) of the majority of pixels in the box. Then, the cloud base heights in a box with 80% single-layer water cloud or 100% ice cloud (including single- and multi-layer, as well as indeterminate layer) are compared with the ASOS ceilometer cloud base height data shown in Figure 1. VISST single-layer low water clouds (Figure 1a) with a range of optical thicknesses are well-characterized in terms of cloud base height, although the thinner water clouds might represent slightly larger deviations from ASOS cloud base height. The error or bias is just 0.1 km and the standard deviation of cloud base height differences is 0.7 km for VISST single-layer water clouds. But when overlapped or thin cirrus are observed, the errors are much greater (4.0 km) as indicated in Figure 1b. Multi-layered cloud base heights from VISST are mostly too high (almost 2 times) because the lower-level cloud is not correctly identified. Some single-level ice clouds show misclassification of cloud base height, but most cases are multi-layer or indeterminate.

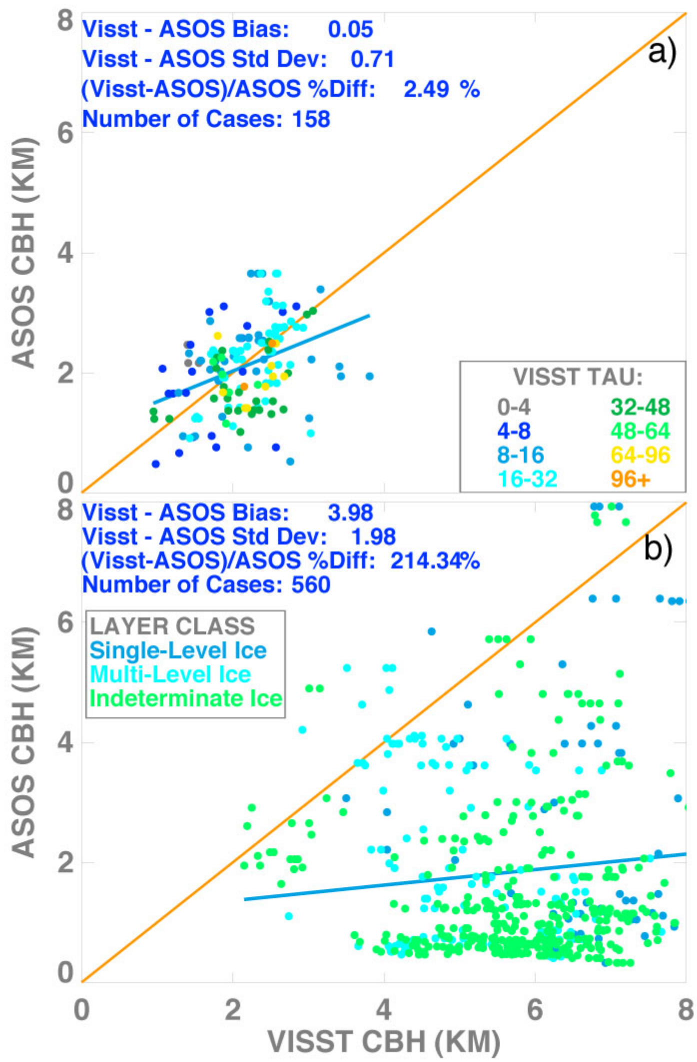


**Figure 1**. Comparison of ASOS and VISST cloud base heights for 17 June 2000 1545-1945 UTC for a) single-layer water clouds, 80% cloud amount or greater, and b) 100% ice clouds.

Surface, satellite, and RUC data at the SGP CF during 17 June 2000 are shown in Figure 2 for 1815 UTC (Figure 2a) and 1945 UTC (Figure 2b). The CPM classifies both these two cases as indeterminate. The VISST retrieved cloud (red line) is too low and thin for the higher cloud level defined by ARSCL (solid green line), and does not detect the low cloud evident in the base detected by the MPL, ARSCL, and ASOS. The maximum RUC cloud probabilities are seen in the heights corresponding to the thick high ARSCL cloud layer (bounded by solid green lines). The dotted green lines are lower cloud determined by ARSCL. The RUC cloud probability (CP) is also greater than 50% at the location of the low clouds seen by ARSCL, ASOS, and MPL indicating that the use of CP could greatly enhance the satellite retrieval of cloud base. For multi-layered clouds, the RUC could aid interpretation of the layering.

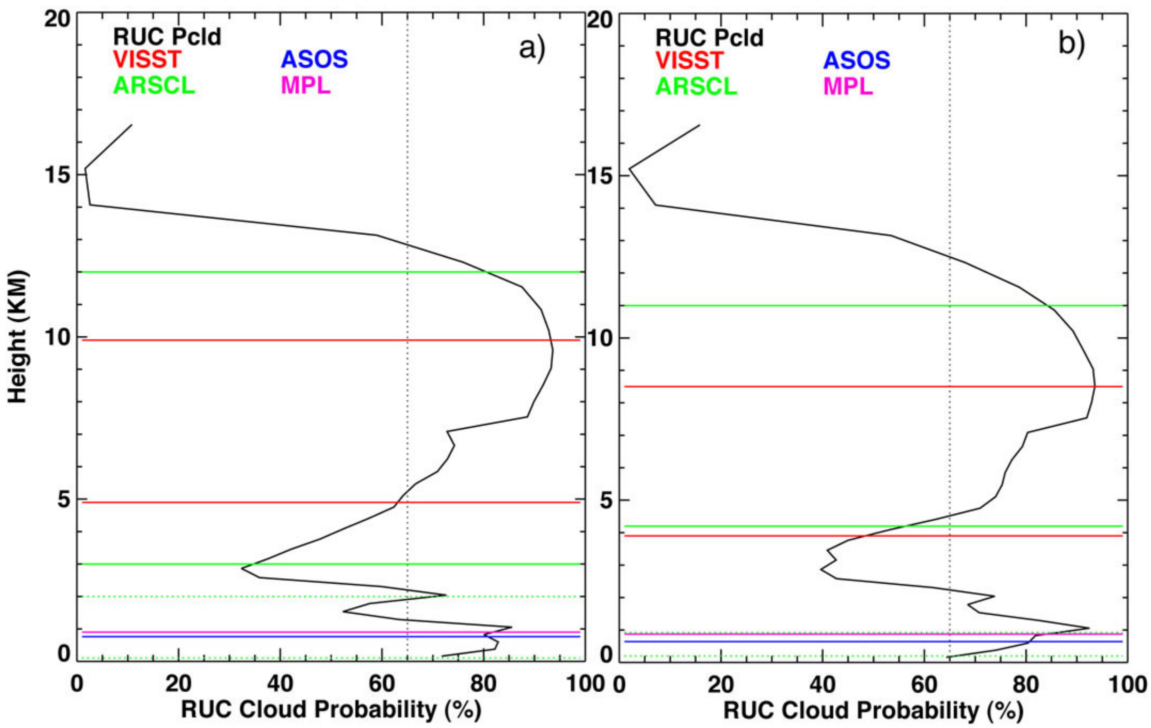


**Figure 2**. Comparison of surface, satellite, and RUC data at SGP CF, for a) 1815 UTC and b) 1945 UTC, 17 June 2000.

## Examples Exploring Potential of Merging Rapid Update Cycle with Cloud Property Multi-level/Visible Infrared Solar-infrared Split-window Technique Results

Figure 3 shows VISST cloud parameters (phase, optical depth and BTD) at 1815 UTC, 17 June 2000. The multi-layer cloud classifications were derived (Figure 4) for cases 1815 UTC and 1945 UTC, 17 June 2000 by applying tests outlined above. Automatic surface observing system classifications are binned into ten classifications based on cloud fraction, cloud height, and separation between cloud layers (DZ), and these observational keys are overlaid onto the VISST multi-layer cloud detection classifications. The classifications include: 1) Clear, Single-layer; 2) Scattered; 3) Broken; 4) Overcast, Multi-layer DZ < 4 km 5) Scattered; 6) Broken; 7) Overcast, and Multi-layer DZ > 4 km; 8) Scattered, 9) Broken; and 10) Overcast. Ceilometer results show that clear areas are identified fairly well, and multi-layered and scattered results are generally seen under the ice multi-layer cases. The ceilometer data can be used to provide information about the low-level clouds, but the higher-level clouds need to be validated using ARSCL and other means. To provide comparisons to VISST over the entire SGP domain, the ASOS data need to be interpolated and gridded.

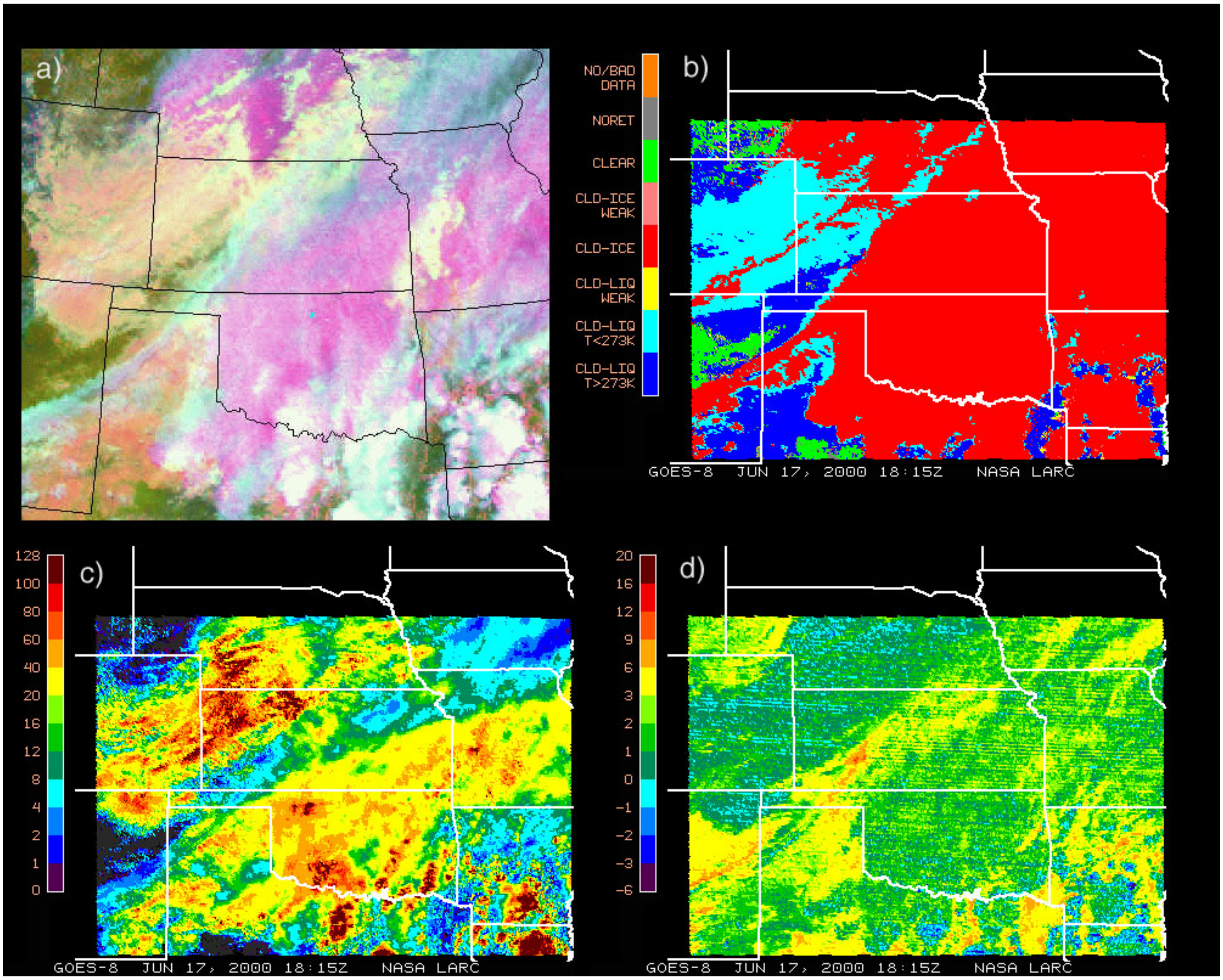


**Figure 3**. VISST cloud parameters from 1815 UTC, 17 June 2000, for a) RGB image, b) cloud phase, c) optical depth, and d) 10.8 μm – 12 μm brightness temperature difference.

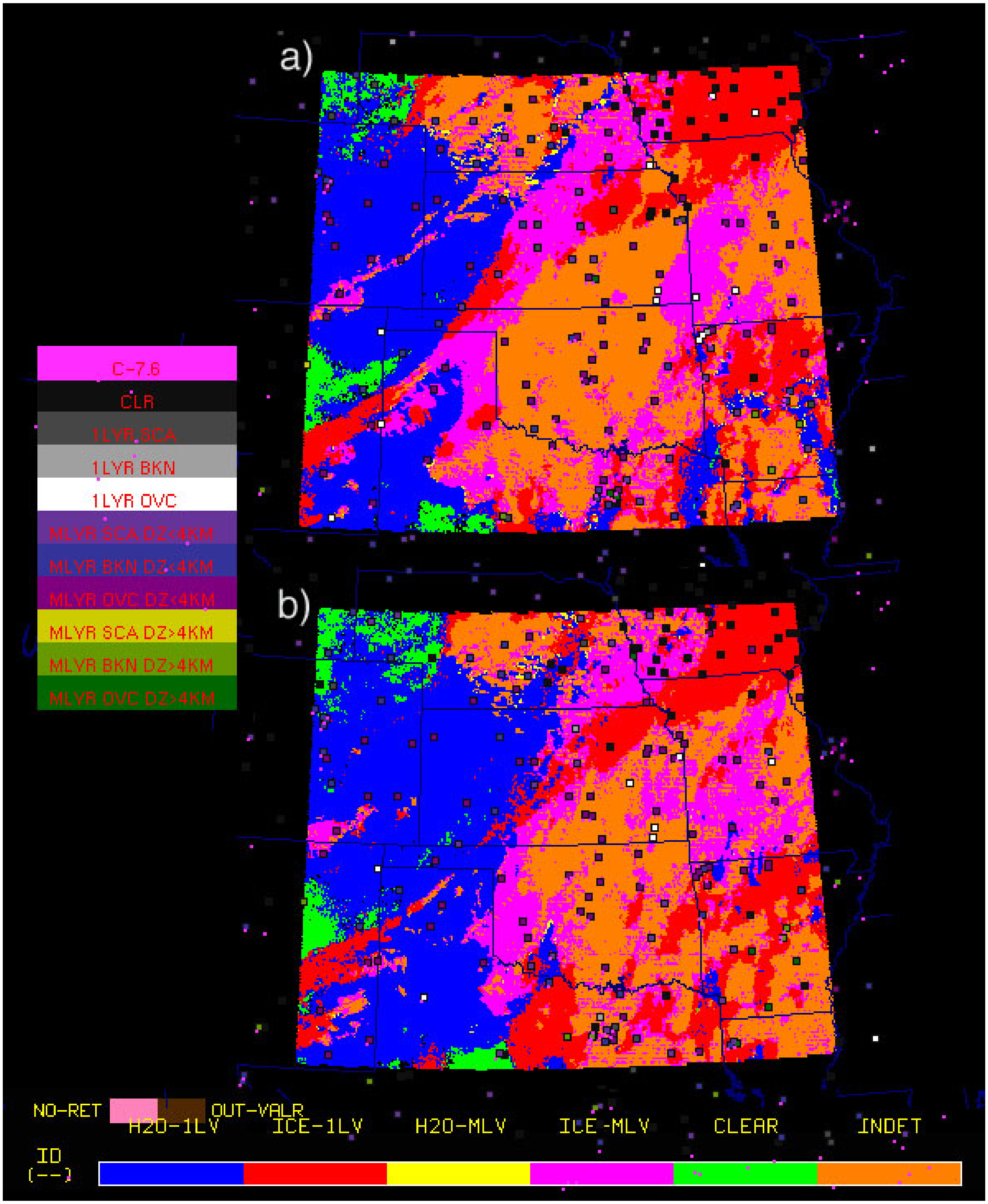


**Figure 4**. Multi-layer cloud detection classifications, overlaid by ASOS observations, for a) 1815 UTC and b) 1945 UTC, 17 June 2000.

Figure 5 shows the cloud base heights from VISST and ASOS for 1815 UTC and 1945 UTC on 17 June 2000. As shown in Figure 1, the cloud base heights for low, single-layer water clouds are well-retrieved, but the VISST cloud base heights are too high compared to ASOS (almost 4 km high on average) in most areas where high clouds are indicated, except in Iowa and southern Arkansas. The areas defined as indeterminate and overlapped yield the biggest errors.

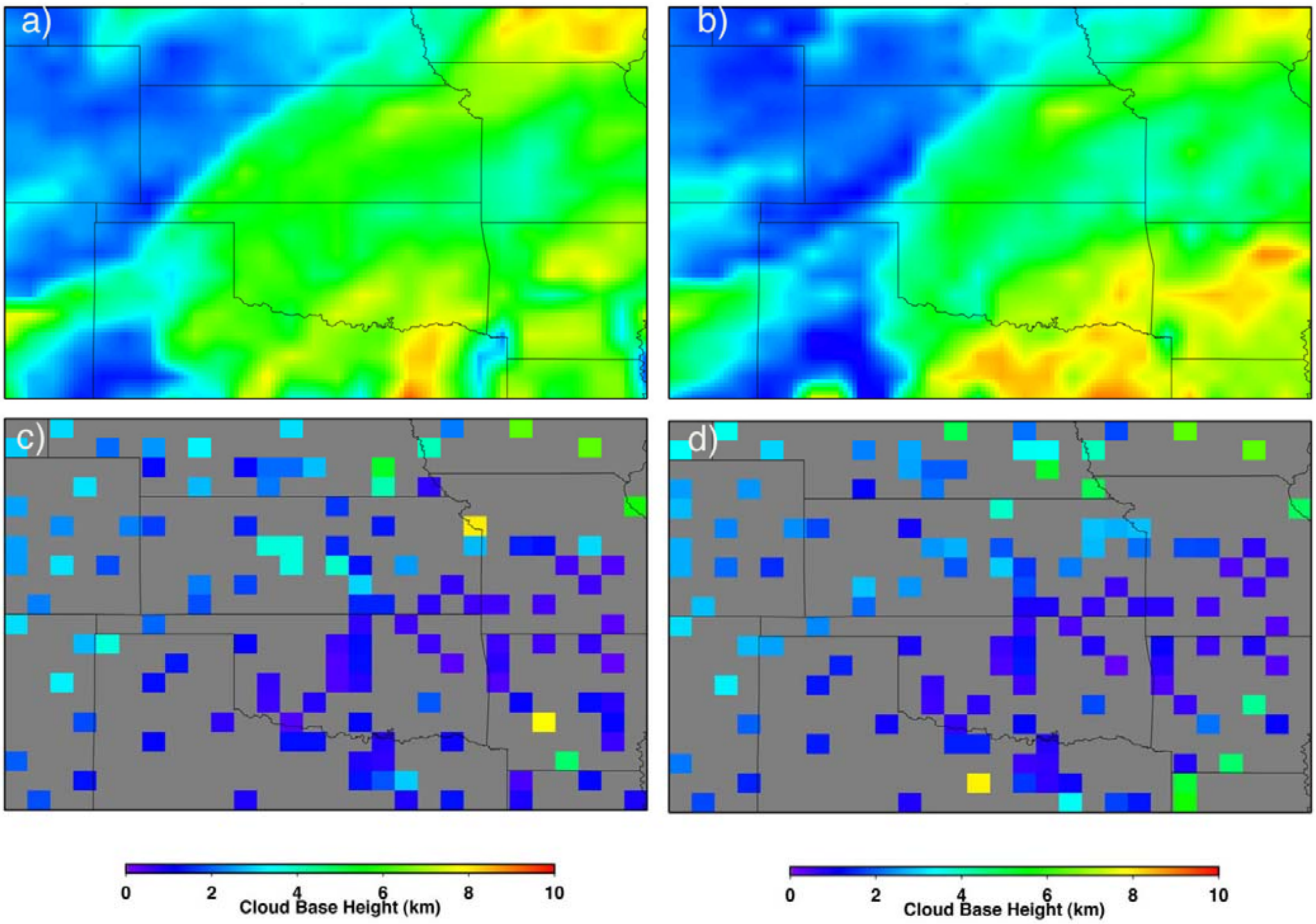


**Figure 5**. Cloud base height for 17 June 2000, for VISST a) 1815 UTC and b) 1945 UTC, and ASOS a) 1815 UTC and b) 1945 UTC.

The RUC cloud base heights derived from various cloud probability cutoffs are examined for their potential to correct the VISST cloud base heights in areas defined as indeterminate and overlap. For a given CP threshold, for example 67%, the RUC CBH is defined as the lowest height where the RUC CP exceeds the threshold. The CP threshold is a somewhat arbitrary number, so tests are required to establish a physically sound threshold. Figure 6 shows the sensitivity of the RUC cloud base heights to the chosen RUC CP threshold; a threshold of 67% is employed in Figure 6a. With the higher RUC CP threshold (67% or P67 in Figure 6a), several areas have no cloud base heights. If the CP threshold is decreased to 50% (P50, Figure 6b), some of the clear areas (gray in Figure 6a) are filled in. In Figure 6a, many of the RUC high CBHs agree well with the VISST heights. Lowering the threshold tends to drop the CBH significantly.

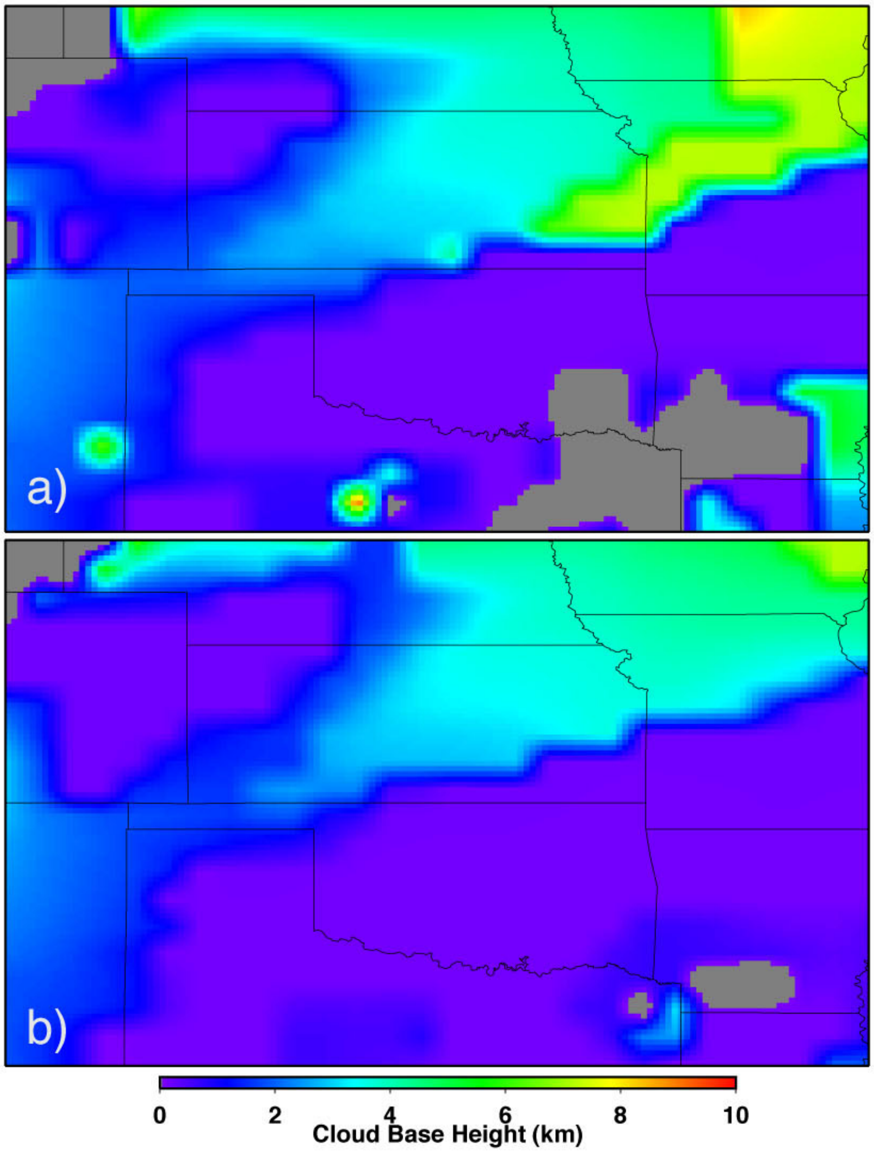


**Figure 6**. Sensitivity of cloud base height to RUC cloud probability for 1800 UTC on 17 June 2000 for a) 67% threshold and b) 50% threshold.

Figure 7 compares the cloud base heights for RUC P50 and ASOS for a) 1815 UTC and b) 1945 UTC, 17 June 2000. RUC P50 tends to underestimate CBH resulting in many clouds close to the ground. This indicates that RUC P67 or P80 (cloud probabilities of 67% and 80%, respectively) might be more appropriate for assigning CBH for some regions.

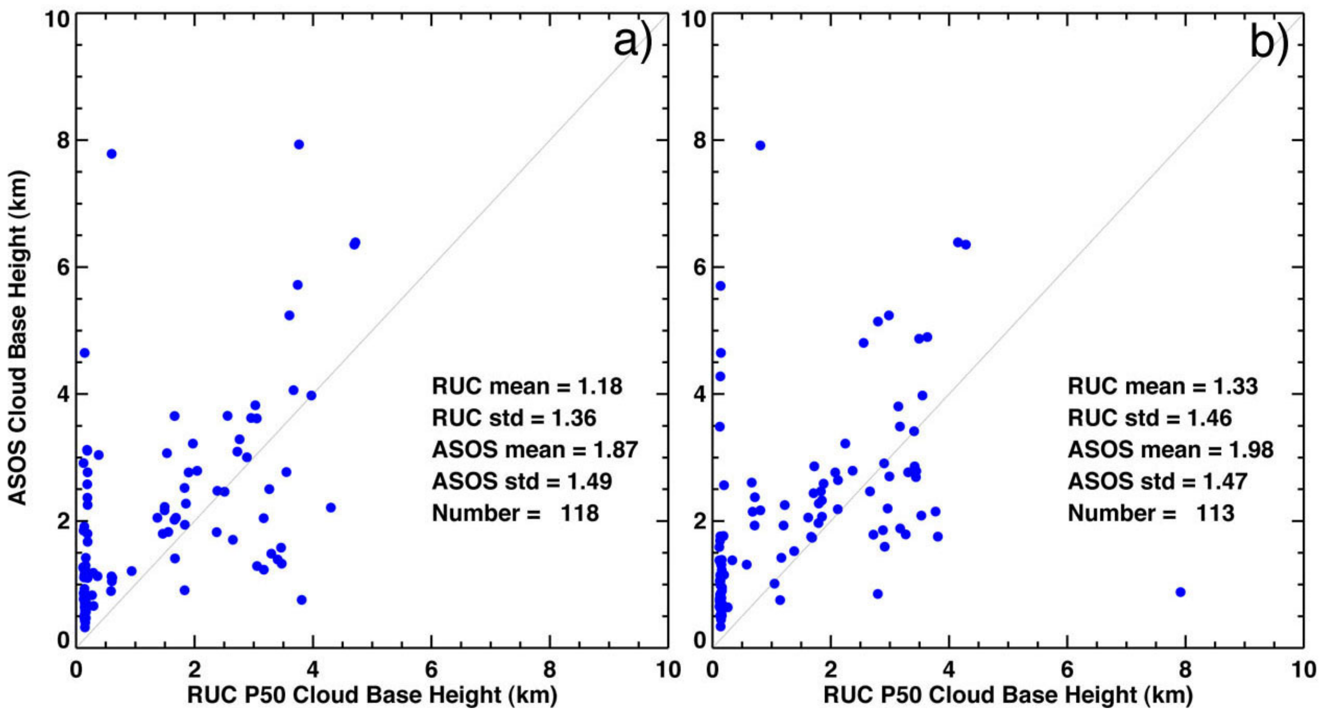


**Figure 7**. Comparison of cloud base height between RUC P50 and ASOS for a) 1815 UTC and b) 1945 UTC, 17 June 2000.

The RUC P50 CBHs are first merged with the VISST cloud base heights in the areas defined as indeterminate (top two panels in Figure 8, green dots in Figure 9) and then in the areas defined as ice-overlapped (bottom two panels in Figure 8, red dots in Figure 9). Comparisons of the merged products with the ASOS CBHs are shown in Figure 9. Merging RUC and VISST produces a distribution of CBHs that is much closer to the ASOS CBHs than VISST alone. Some large errors remain, but the average CBH is reduced by more than 3 km (from 5.63 km to 2.19 km for 1815 UTC and 5.61 km to 2.43 km for 1945 UTC).

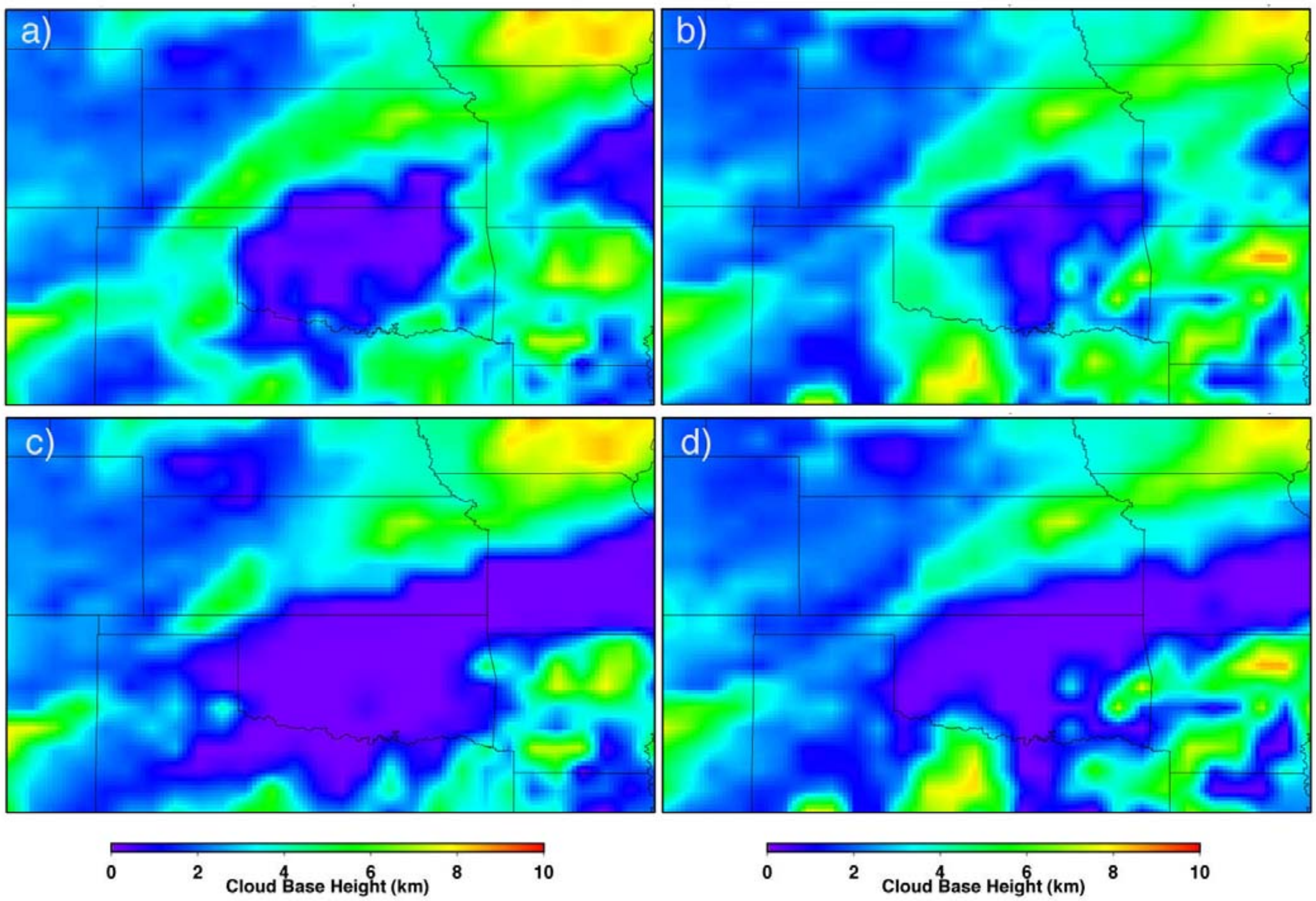


**Figure 8**. Visible infrared solar-infrared split-window technique cloud base heights merged with RUC P50 cloud base heights for 17 June 2000, for areas defined as indeterminate only at a) 1815 UTC, and b) 1945 UTC, and for areas defined as indeterminate and ice overlap at c) 1815 UTC and d) 1945 UTC.

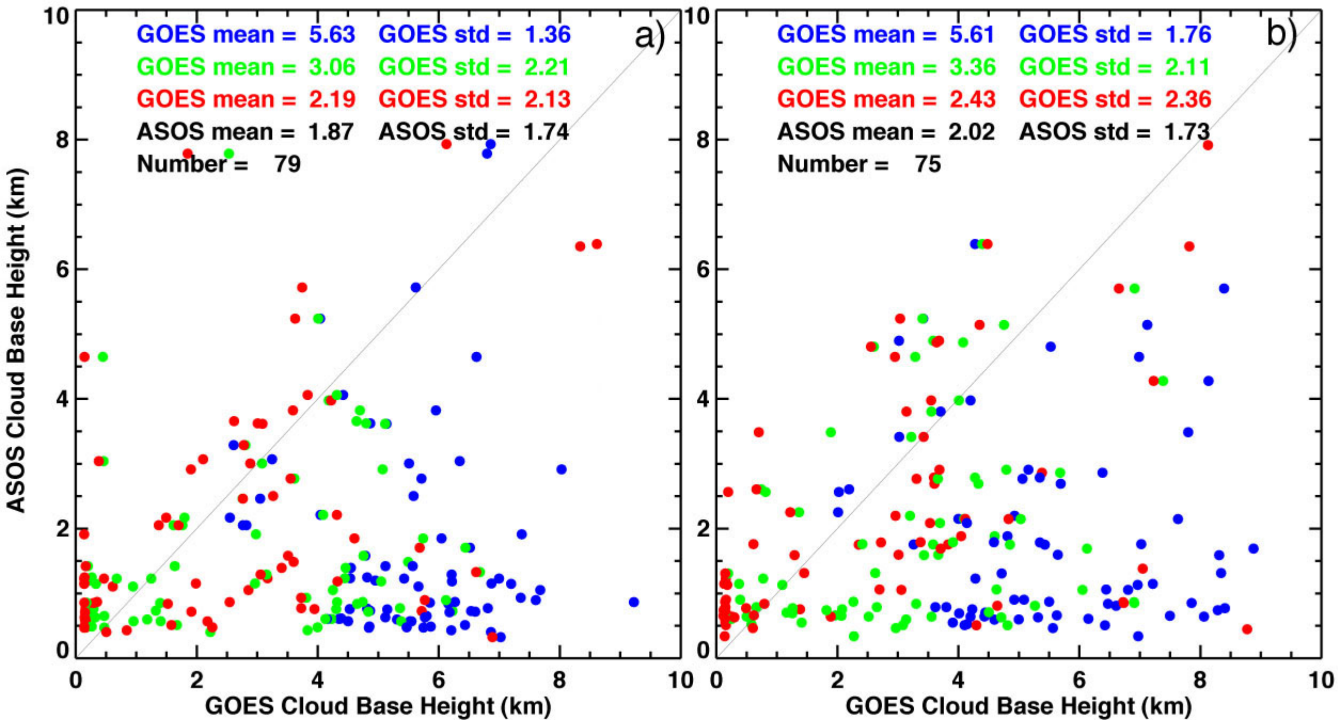


**Figure 9**. Comparison of cloud base heights among VISST, VISST merged with RUC and ASOS for a) 1815 UTC and b) 1945 UTC, 17 June 2000.

## Discussion

In areas classified as overlap, the best way VISST can determine location of low-level clouds is by using any adjacent single-layer low clouds detected, as Figure 1a shows. However, large continuous areas of indeterminate or multi-layered clouds can occur without any nearby single-layer low clouds. In those instances, using the RUC CP parameterization may be better than having no information at all or interpolating. The RUC data could also be tuned using the available single-layered clouds to obtain a more realistic cloud height. Careful analysis is needed to determine the most accurate RUC CP threshold.

Augmentation of GOES low-level cloud detection, by using the RUC CP parameterization, will only be possible if the CPM thresholds classify cloud as multi-layered ice cloud. If VISST retrieved pixels are falsely classified as single-layered ice clouds, they cannot take advantage of the RUC information. Thus, improvements in the CPM thresholds must be considered to ensure that overlap is classified as accurately as possible.

Errors in the comparisons result from differences in sampling by ASOS and GOES, but these should primarily be random. Interpolated ASOS results may be less accurate in areas of sparse instrumentation however, so it would be best to focus on densely populated ASOS concentrations for accurate comparisons with GOES retrievals.

## Conclusions and Future Work

The CPM provides a realistic classification for most cloud types, although additional discrimination for cumulonimbus cloud types is needed, as many of these clouds are being classified as indeterminate. For other cloud types, the results are encouraging. VISST-derived single-layered water cloud base heights agree well with those from ASOS. The RUC cloud probability estimator shows some skill in matching ASOS cloud base heights and greatly reduces errors in CBH for multi-layered and indeterminate layering clouds; however, there needs to be further refinement of probability thresholds. To bring all elements together more seamlessly, additional logic is needed for blending both VISST low clouds and CP.

Analysis indicates the need to refine CPM thresholds to better detect multi-layered clouds, but the prototype method still shows considerable skill. However, this new method relies on having the 12-µm channel, which is not available from GOES-12, the current satellite monitoring the eastern continental United States. Therefore, a different approach to multi-layer detection is needed when the 12-µm channel is unavailable. An additional limitation to this method is found in the GOES-10 BTD data, which exhibits considerable noise.

Future refinements of the CPM can be made in additional areas, to obtain the most accurate 3D cloud field possible. One such addition will include the definition of low-level cloud characteristics from adjacent low clouds. Also, tuning of RUC heights with VISST low clouds can be added, and ultimately VISST will be able to provide retrieval of low and high-level cloud properties for both thin and thick cirrus overlap cases. The ARM microwave radiometer and SGP extended facility data can then be used to validate and improve the resulting 3D cloud probability fields.

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