

A COMPARISON OF CLOUD-TOP HEIGHT ESTIMATIONS FROM SATELLITE AND NWP ANALYSIS DATA

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1. Introduction

The accurate forecast of cloud locations is a major need for Department of Defense (DoD) aviation and satellite reconnaissance operations. Traditionally, the position and depth of a cloud area was diagnosed by arbitrarily relating model variables such as temperature and humidity from a numerical weather prediction (NWP) model with the presence of clouds. Most current mesoscale models such as the Penn State/National Center for Atmospheric Research (PSU/NCAR) Mesoscale Model (MM5; Grell et al. 1995) and the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS; Hodur 1997) explicitly predict clouds in the form of cloud liquid and ice concentrations. These models now carry four moisture variables (cloud water, raindrops, ice crystals, and snowflakes) in addition to water vapor, however only water vapor is a standard analysis variable that is input into NWP models. In the absence of any initial information on cloud liquid water or ice content, it can take several hours for a model to create clouds on its own.

Several attempts have been made to address the problem of initializing cloud fields in NWP models. Kristjánsson (1992) used a scheme that assimilated cloud water by adjusting cloud water produced from a previous forecast with vertically integrated cloud water estimated from Special Sensor Microwave/Imager (SSM/I) and Advanced Very High Resolution Radiometer (AVHRR) data. One drawback to this procedure is that if the model is not producing a cloud where the satellite sees one then no adjustment can be made. In addition, no attempt is made to alter the vertical gradients of the cloud water and ice. Zhao (1993) developed a technique to initialize cloud water and ice for the Eta model run at the National Center for Environmental Prediction. In it a first guess field is produced during the 12 hours prior to initialization time by assimilating both the Air Force's real-time nephanalyses (Hamill et al. 1992) and precipitation analyses fields. The vertical structure is determined using an arbitrary function. During the assimilation period the model is integrated and the cloud mixing ratio is adjusted so that the model produced precipitation matches up

with the observed precipitation. Wu et al. (1995) initialized cloud water and ice using cloud top heights estimated from satellite data and prescribing a parabolic profile of cloud water. Raymond et al. (1995) used a statistical relationship to relate SSM/I radiances with vertical cloud water and ice distributions. Huang (1996) was able to decrease the spin up time to produce reasonable cloud water and rainfall by using digital filtering. This was accomplished by backward and forward integration of the model about the initialization time and is fairly computationally intensive.

The Local Analysis and Prediction System (LAPS), developed at the Forecast Systems Laboratory (FSL) and used for providing initial fields to the mesoscale forecast model (MM5) used by the Air Force, is capable of producing a three-dimensional cloud analysis (Albers et al. 1996). The cloud analysis uses surface observations and pilot reports to generate cloud profiles at the observation locations which are then matched up with cloud top height fields generated from satellite data. The cloud analysis is then augmented with available radar data. This results in a three-dimensional cloud cover field. The equivalent potential temperature profile is then used to estimate the cloud type and mean volumetric drop (MVD) size. The cloud water and ice concentrations are determined, using the estimated MVD size, via the Smith-Feddes model (Haines et al. 1989). Zhang et al. (1998) used LAPS as the basis for the cloud analysis scheme employed in the ARPS Data Analysis System (ADAS). Among the modifications made by Zhang et al. were a change in the cloud top height specification from infrared satellite data and the use of the lifting condensation level (LCL) for determining the cloud base. Both of these changes originated from the work of MacPherson et al. (1996).

While LAPS and ADAS represent the state of the art in cloud analysis systems, they were both designed to run over the data rich continental United States. Many DoD applications take place in extremely data poor regions and/or in situations where available observations are not transmitted freely. Since both LAPS and ADAS use surface observations of cloud base heights in their cloud analyses they would have trouble running in their present form for many DoD applications.

2. Theater Cloud Analysis Procedure

The Weather Technology Unit of the Air Force Research Laboratory has undertaken an effort to develop a regional cloud analysis system that would work in data constrained DoD operating environments. A schematic of how the process would work is offered in Fig. 1. The system is to be called the Theater Cloud Analysis Procedure (TCAP). TCAP would use as input conventional NWP analysis fields (i.e. temperature and humidity) as well as satellite data. The satellite input would be the output from cloud product processing algorithms. The thermodynamic profiles from the NWP analysis would be interpolated to the satellite data locations and combined with satellite derived cloud cover and cloud top temperature retrievals to estimate the vertical boundaries of the clouds. Given the cloud's vertical boundaries the cloud liquid water profiles are then estimated at the satellite pixel locations. These profiles would then be objectively analyzed to the model grid points using cloud liquid water content values from a prior forecast as a first guess. The objective analysis will make use of the

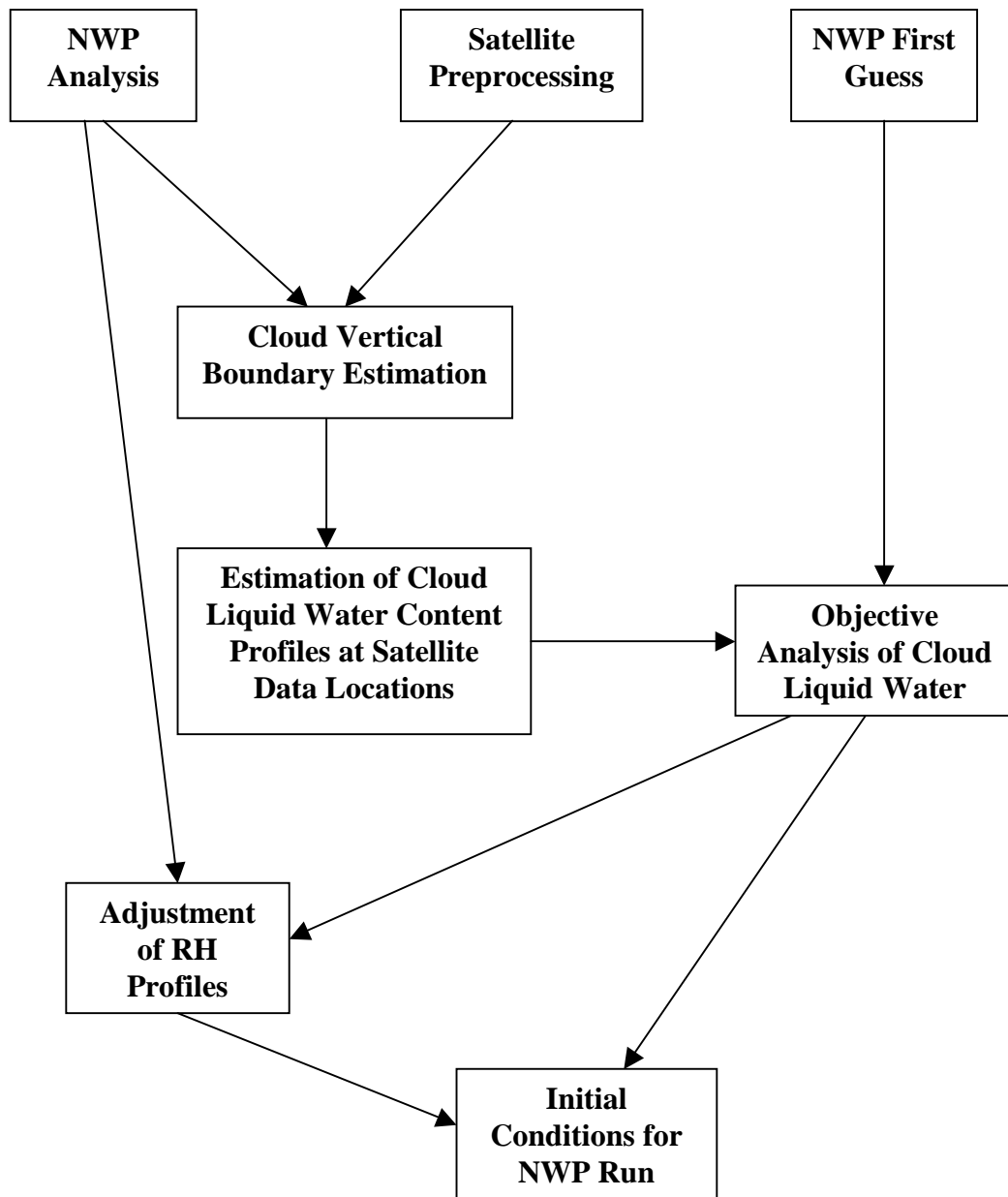


Figure 1. Flowchart of the Theater Cloud Analysis Procedure (TCAP)

optimal interpolation technique laid out by Nehr Korn et al. (1997). The objectively analyzed cloud liquid/ice content values would then be used directly in the initial conditions for the theater-scale NWP model run. In addition the analyzed cloud/ice water content values would be used to adjust the water vapor profiles to insure consistency between the initial relative humidity and cloud/ice water content fields.

Currently the development of TCAP is ongoing in several areas. The first involves the detailed analysis of multi-platform cloud data to derive the statistical relationships between cloud observables (i.e. vertical boundaries, cloud-top temperature) and cloud liquid water and ice concentrations. Another area of work involves the modification of the Theater Analysis Procedure developed by Nehr Korn et al. (1997) to analyze cloud water/ice content. Neither of these areas will be discussed further here. What will be discussed in the rest of this paper is evaluation of candidate techniques for the Satellite Preprocessing and Cloud Vertical Boundary Estimation modules of TCAP.

3. Candidate Techniques

a) Satellite Preprocessing Algorithms

There are two candidates for the satellite preprocessing module. The first is the version of the nephanalysis component of the Cloud Depiction and Forecast System (CDFSII-NEPH) that is currently being installed at the Air Force Weather Agency (Gustafson et al. 2000). CDFSII-NEPH is actually a series of algorithms that ingest raw satellite data from both geostationary and polar orbiting platforms. CDFSII-NEPH performs pixel by pixel cloud detection. Layering algorithms are then used to compute total cloud amount and mean cloud-top temperature (among other products) for windows of 3x3 arrays of 16th mesh grid points centered over the point of interest. This version of CDFSII-NEPH is based on the algorithms developed under the Phase I program of the Support of Environmental Requirements for Cloud Analysis and Archive (SERCAA) (Gustafson et al. 1994). Subsequently upgrades have been made to SERCAA under a Phase II program (Gustafson et al. 1996). Upgrades include improved cloud detection including the ability to detect thin cirrus. As a part of the improvements in cloud detection abilities, cloud-phase classifications (i.e. liquid-water droplets or ice crystals) are made on a pixel-by-pixel basis. Cirrus effective temperature (which is related to cloud-top height) and emissivity are then retrieved for ice-phase clouds using a radiative-transfer algorithm that simultaneously accounts for the competing effects of cirrus temperature and emissivity. At this time the CDFSII-NEPH will not include the Phase II upgrades. However, the SERCAA Phase II set of algorithms will be considered as the second candidate for the satellite preprocessing module of TCAP.

b) Cloud Vertical Boundary Estimation Algorithms

1) Modified ADAS cloud analysis height estimations

The modified ADAS cloud analysis system consists of a stripped down version of the ADAS scheme as described by Zhang (1998). All the aspects of the technique that relied on

data sources other than satellite or NWP analysis thermodynamic profiles have been removed. The modified technique works by determining which pixels have a cloud fraction (computed from SERCAA algorithms) greater than 0.6 and retrieving the satellite derived cloud top temperature. For all cloudy pixels, the LCL is computed using the NWP analysis thermodynamic profile beginning 180 m above the surface and is taken to be the cloud base height. If the satellite retrieved cloud top temperature is less than 253 K, a simple matching of the cloud top temperature with the profile temperature is used to estimate the cloud top height. If the retrieved cloud top temperature is greater than 253 K, the cloud top height is computed by taking a parcel at the estimated cloud base and raising it moist adiabatically until it reaches a temperature that corresponds to a temperature on the analyzed profile. The SERCAA (and CDFSII-NEPH) algorithms have the capability, under certain circumstances, to depict multiple (up to four) cloud layers. In those situations heights of the cloud bases and tops are computed for each level by starting from the bottom up and computing the LCL of the upper cloud layers from just above the top of the next lowest layer.

2) Fuzzy logic approach

A fusion method for satellite-derived cloud analysis and NWP products was developed by Mozer and Ayer (1998) that incorporates a fuzzy-logic decision algorithm. The fuzzy-logic rules determine cloud-top altitudes by weighing and scoring certain NWP parameters for each cloud-filled pixel in a satellite image. This method handles various satellite analysis products, including SERCAA output, by mapping each pixel location onto the NWP grid. A typical rules set examines relative humidity, temperature difference between the satellite and the NWP grid, and cloud liquid water amount.

3) Statistical cloud thickness estimation

Conover and Bunting (1977) developed a number of statistical relationships between satellite infrared and visible image data and cloud thickness. While they did not report a relationship for cloud thickness based solely on infrared brightness temperatures they did present the original data which allowed a linear regression equation to be computed. The resulting equation is

$$dz = -0.1677*BT+47.1621 \quad (1)$$

where dz is the total cloud thickness in km and BT is the infrared derived cloud brightness temperature in K. It is important to note that cloud thickness is for the total of all the cloud layers, that is from the top of the highest level to the base of the lowest level. While this technique does not explicitly estimate the cloud base or top height it can be used with a technique that does estimate one of the boundaries in order to estimate the other.

4. Experiment Design

The candidate modules were evaluated using data collected during the Air Force's Contrail Field Program (Jackson et al. 2000), which took place during September 1995 in eastern Massachusetts. The input NWP analyses were from MM5 analyses prepared as part of the Contrail Field Program by personnel from NCAR (Gao et al. 1998). While they produced a number of analysis products for the experiment, the ones used in this study are the analyses constructed solely from conventional data. The analyses were then output to a grid with 45 vertical levels and horizontal spacing of 18 km. The satellite data was from the Geostationary Operational Environmental Satellite (GOES 8) and was collected and processed at the Air Force Interactive Meteorological Processing System located at Hanscom AFB, MA.

Subjective validation of the cloud base and top heights was accomplished using surface observations and radiosonde soundings at five locations in eastern Massachusetts. The locations of the stations can be seen in Fig. 2. During the field program, radiosondes were launched every three hours each day from 1200 to 0000 UTC. For this comparison, only the radiosonde observations at 0000 and 1200 UTC were used since they correspond to the times of the MM5 analyses. The presence of clouds and cloud amount were determined from the hourly cloud observations archived at each radiosonde site. Cloud base heights were estimated using the standard surface observations which report cloud base height and by determining areas of high relative humidity from radiosonde soundings. Cloud top heights and temperatures were estimated using the relative humidity and temperature soundings from the radiosonde data. For nearly every case in this study, when clouds were present, a very rapid decrease in humidity with increasing height accompanied by a temperature inversion clearly indicated the cloud top height.

5. Results

There were 48 radiosonde soundings of a variety of cloud conditions for which comparisons could be made between the observed cloud cover and the estimated cloud fraction from the SERCAA algorithms. Table 1 shows how the satellite derived cloud fractions compared with the observed cloud amounts for both the SERCAA Phase I and II set of algorithms. In 31% of the 48 cases the estimated and observed cloud amounts matched up exactly for SERCAA Phase I. For SERCAA Phase II 73% of the cloud fraction estimations are correct. It can be seen that for the SERCAA Phase I results there were many cases where the estimated sky cover was opposite of what was observed. In addition, there was a diurnal aspect in these incorrect estimations. In the morning there was a tendency by the SERCAA Phase I algorithms to estimate clear skies when conditions were overcast. Likewise in the early evening there was a tendency to estimate overcast skies when they were actually clear. Most all of these cases took place when relatively high cloud top temperatures were retrieved from the satellites. Apparently in these cases the satellite algorithm is having problems

Table 1. Observed cloud fraction versus that estimated from the SERCAA Phase I and Phase II sets of satellite preprocessing algorithms. The categories are $CLR < 0.1$, $0.1 \leq SCT < 0.6$, $0.6 \leq BKN \leq 0.9$, and $0.9 < OVC$.

SERCAA PHASE I	OBSERVED				SERCAA PHASE II	OBSERVED			
	CLR	SCT	BKN	OVC		CLR	SCT	BKN	OVC
CLR	10	1	3	8	CLR	19	3	0	2
SCT	0	0	0	3	SCT	2	0	2	0
BKN	0	0	0	3	BKN	0	0	1	2
OVC	12	2	1	5	OVC	1	0	1	15

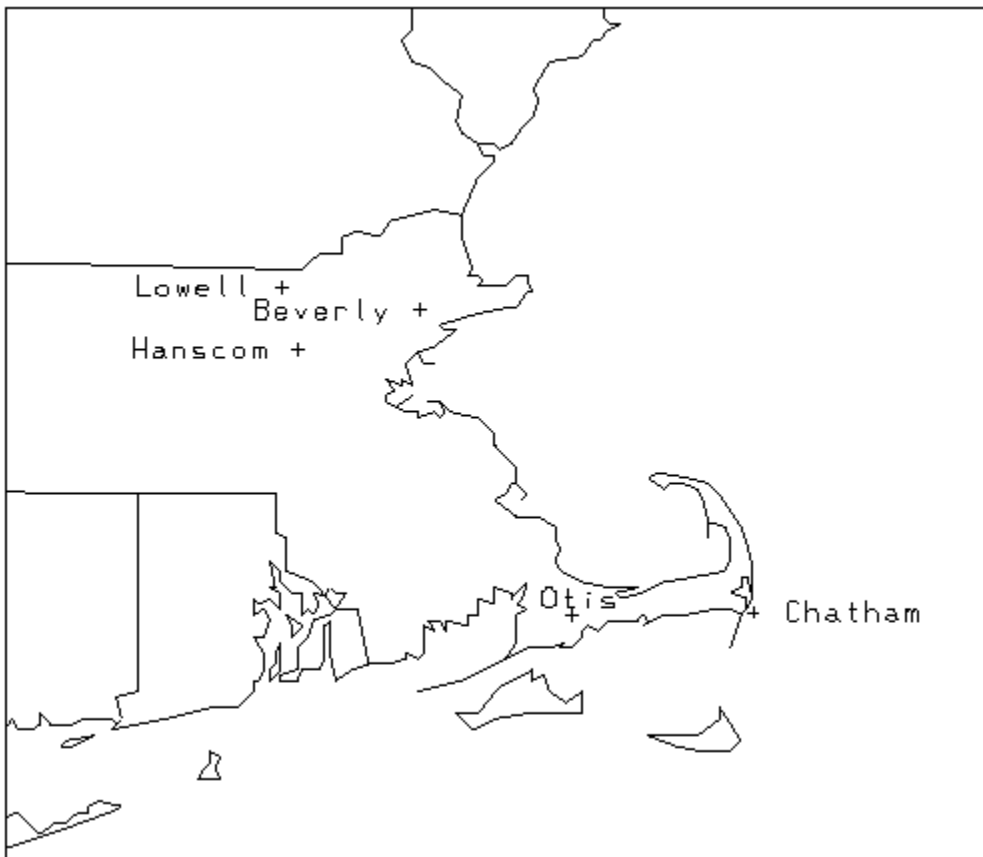


Figure 2. Locations of the launch sites for the radiosondes used in this study.

Table 2. Errors in cloud top temperatures from SERCAA Phase I and II algorithms compared with those observed from radiosonde.

	SERCAA Phase I	SERCAA Phase II
BIAS	2.5 K	-17.5 K
RMS	17.9 K	28.8 K

distinguishing between the ground and low-level clouds. This problem is not apparent in the SERCAA Phase II results.

The plots of the retrieved cloud top temperature from the SERCAA Phase I and II set of algorithms for the 18 observed overcast cases are shown in Fig. 3. In examining the case by case comparisons, the SERCAA Phase II estimations were closer to the observed cloud top temperatures than those from SERCAA Phase I for half of the cases. However for the other half, the magnitude of some of the errors in the Phase II estimations were substantial. One of the changes in the Phase II set of SERCAA algorithms is that it is more sensitive to thin cirrus. However, this improvement does seem to come at a price. Perhaps the cirrus detection algorithm is overly sensitive at this stage of its development. Statistics comparing the cloud top temperatures from SERCAA Phases I and II are given in Table 2. The SERCAA Phase II algorithm has a higher negative bias and larger RMS error than the Phase I algorithm. The cause for this is the apparent false detection of cirrus which results in much colder retrieved cloud top temperatures.

The modified ADAS cloud analysis algorithm was run on the 15 cases where the SERCAA Phase II algorithm correctly estimated the presence of overcast cloud cover. The SERCAA Phase II algorithms were used to retrieve the cloud top temperature. The cloud base height estimations shown in Fig. 4 versus the observed cloud base heights show limited skill. Most of the cloud base height estimates are between 500 and 700 m regardless of the observed cloud base height. The observed and estimated cloud base heights show no correlation with each other as evidenced by a computed correlation coefficient of 0.02. For the cases where the SERCAA Phase II cloud top temperatures were above 253 K, the cloud top height estimations are plotted versus the observed cloud top heights in Fig. 5. The modified ADAS scheme does show some skill here with the observed and estimated cloud top heights being highly correlated but it also shows a bias towards underestimating the height of the cloud tops. The fact that the technique shows some skill is surprising given the fact that it relies on the cloud base estimates in Fig. 4. In Fig. 6 the ADAS cloud top height estimates are plotted against the observed cloud top heights for the cases where the SERCAA Phase II cloud top temperatures are lower than 253 K. While these estimations are also well correlated with the observations, it can be seen for these cases that the estimates tend to be biased to over estimating the cloud top heights.

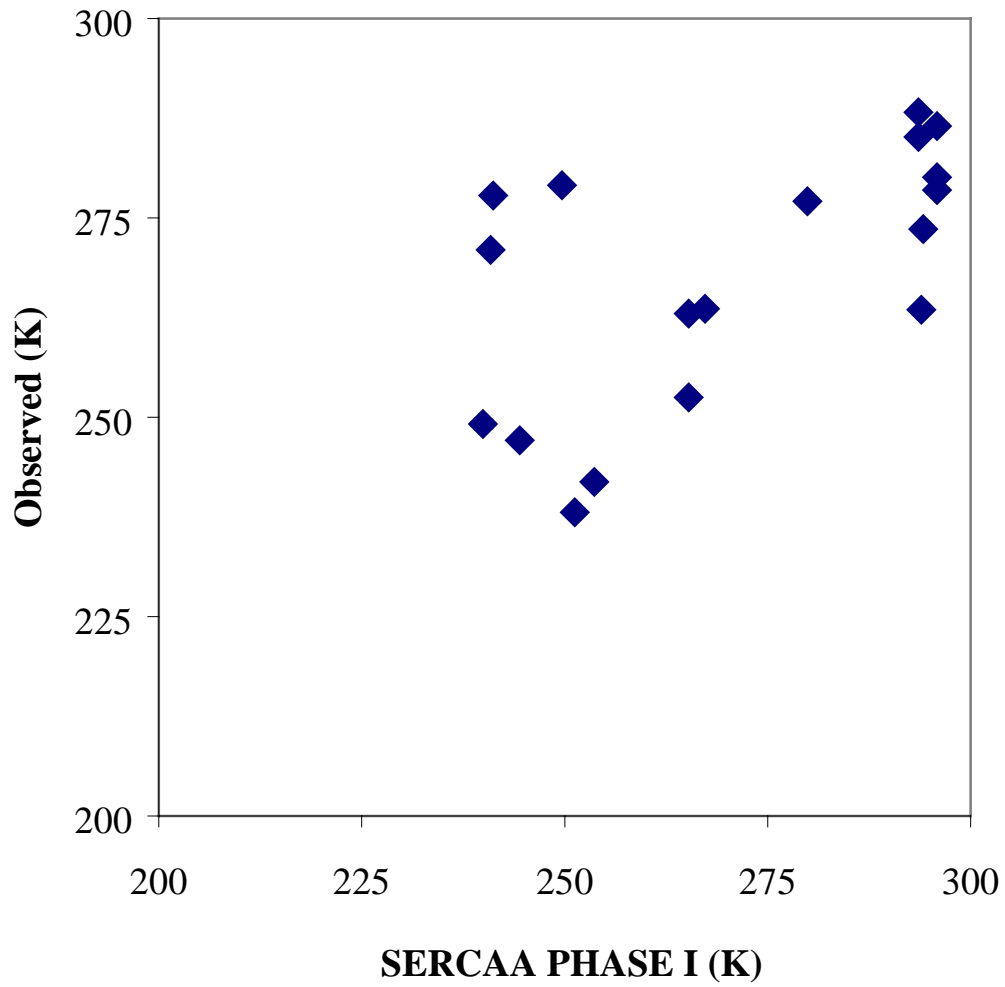


Figure 3. Cloud top temperatures (K) from (a) SERCAA Phase I and (b) SERCAA Phase II versus observed cloud top temperatures from radiosondes for observed overcast cases.

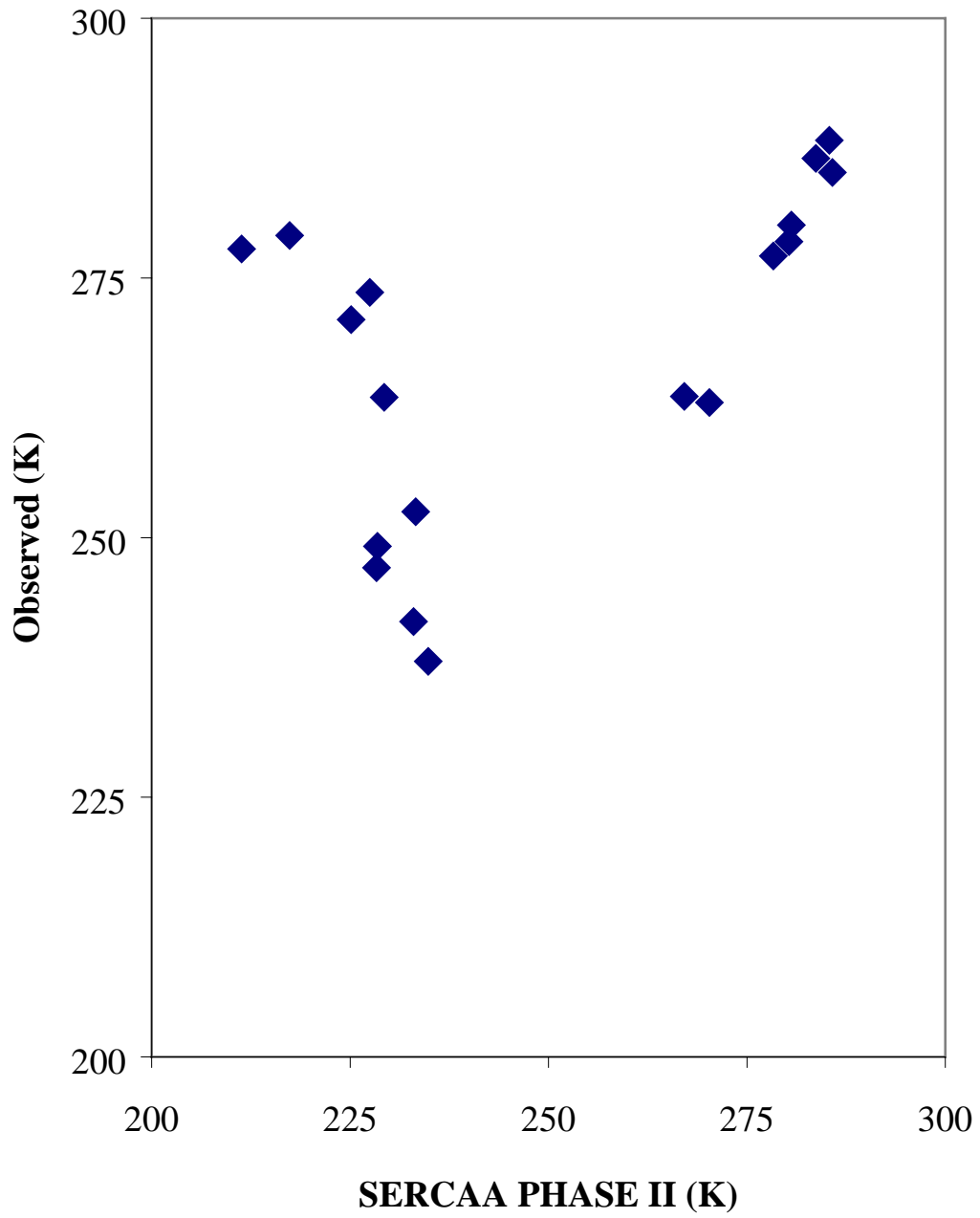


Figure 3b.

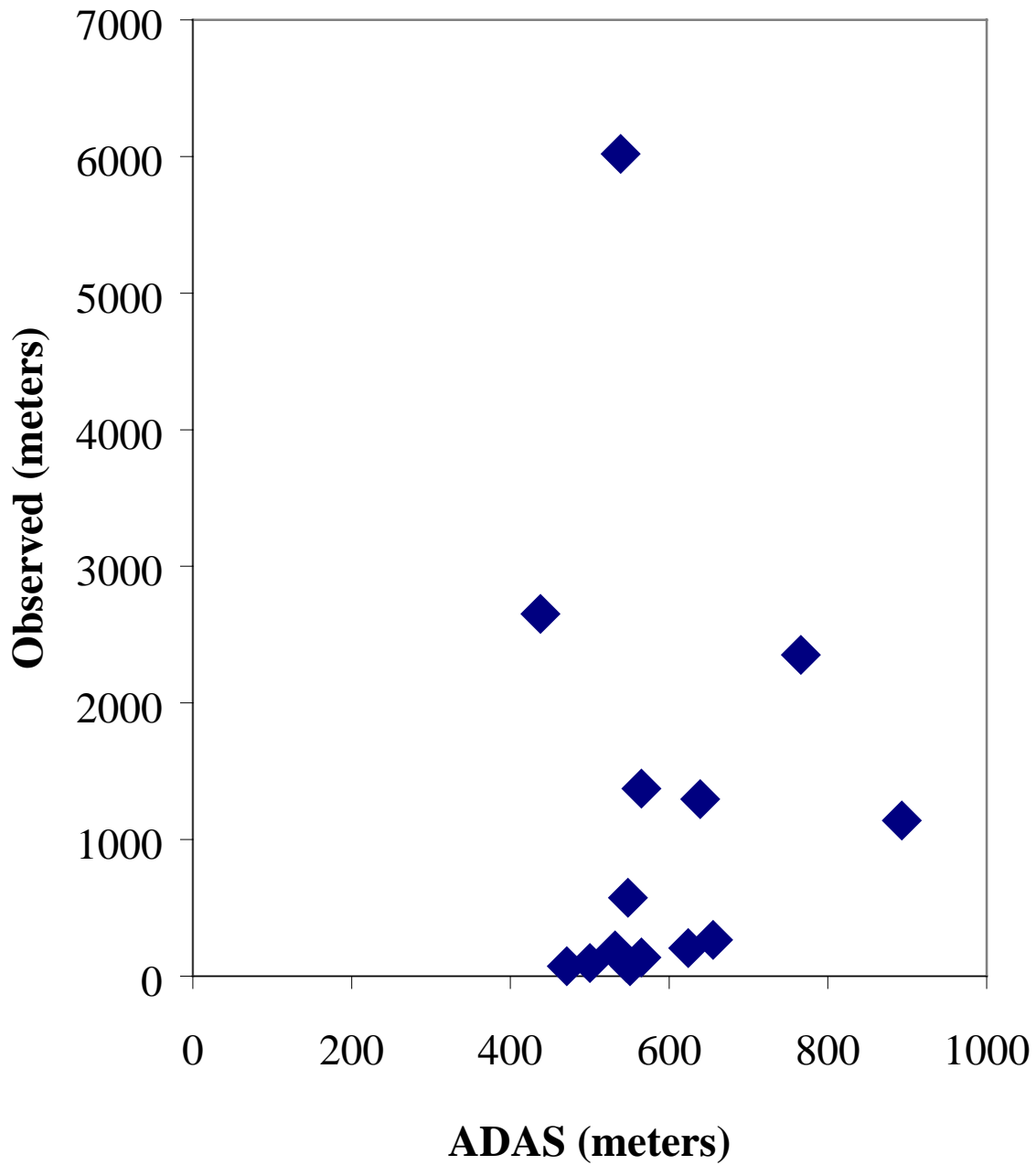


Figure 4. Estimated cloud base height estimations from the modified ADAS technique compared the those determined from radiosondes for cases where the SERCAA Phase II algorithm correctly identified overcast cloud cover.

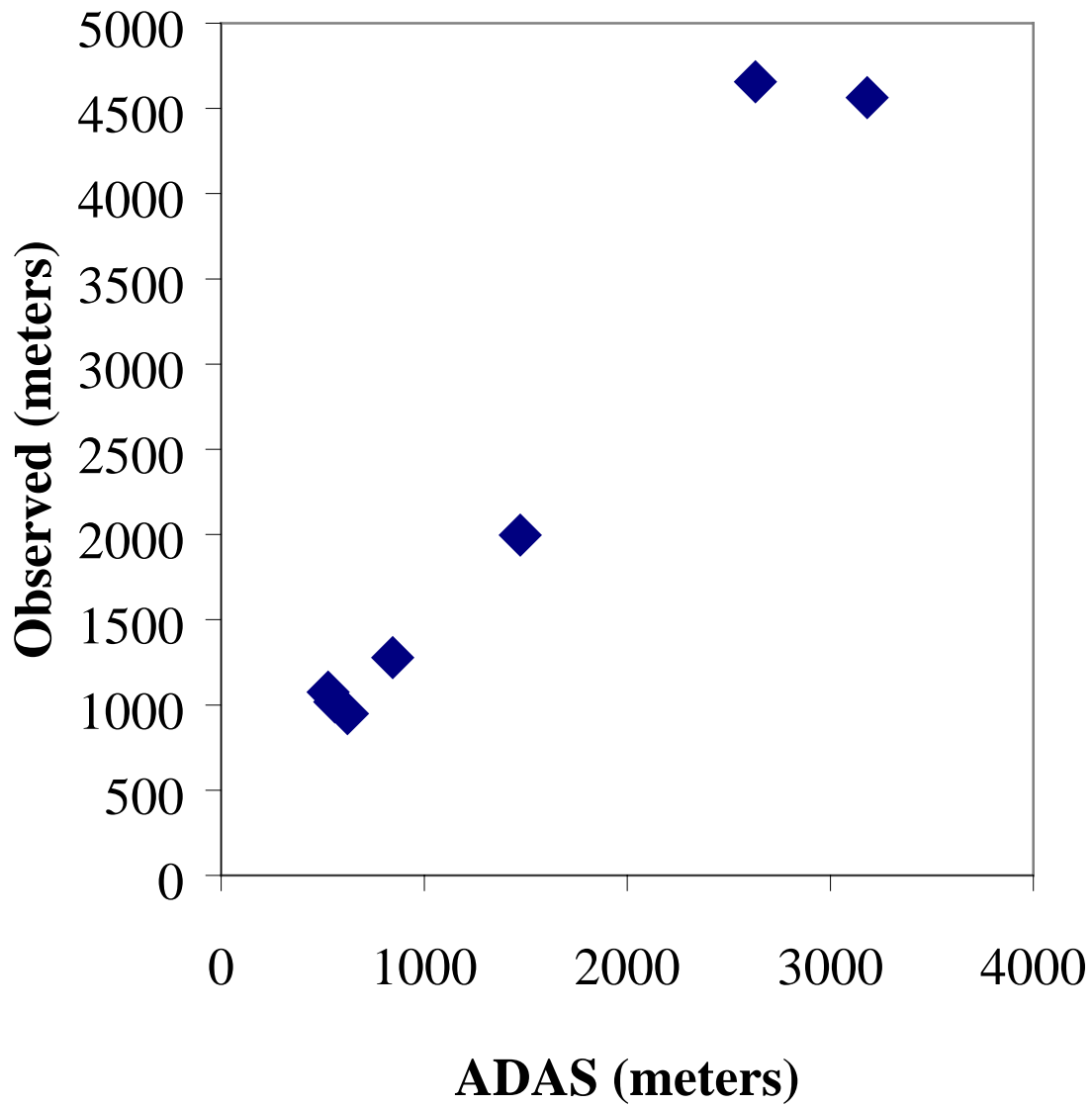


Figure 5. Cloud top height estimations from the modified ADAS cloud analysis technique compared against cloud top heights determined from radiosondes for cases where the SERCAA Phase II algorithm correctly identified overcast conditions and the SERCAA cloud top temperature was greater than 253 K.

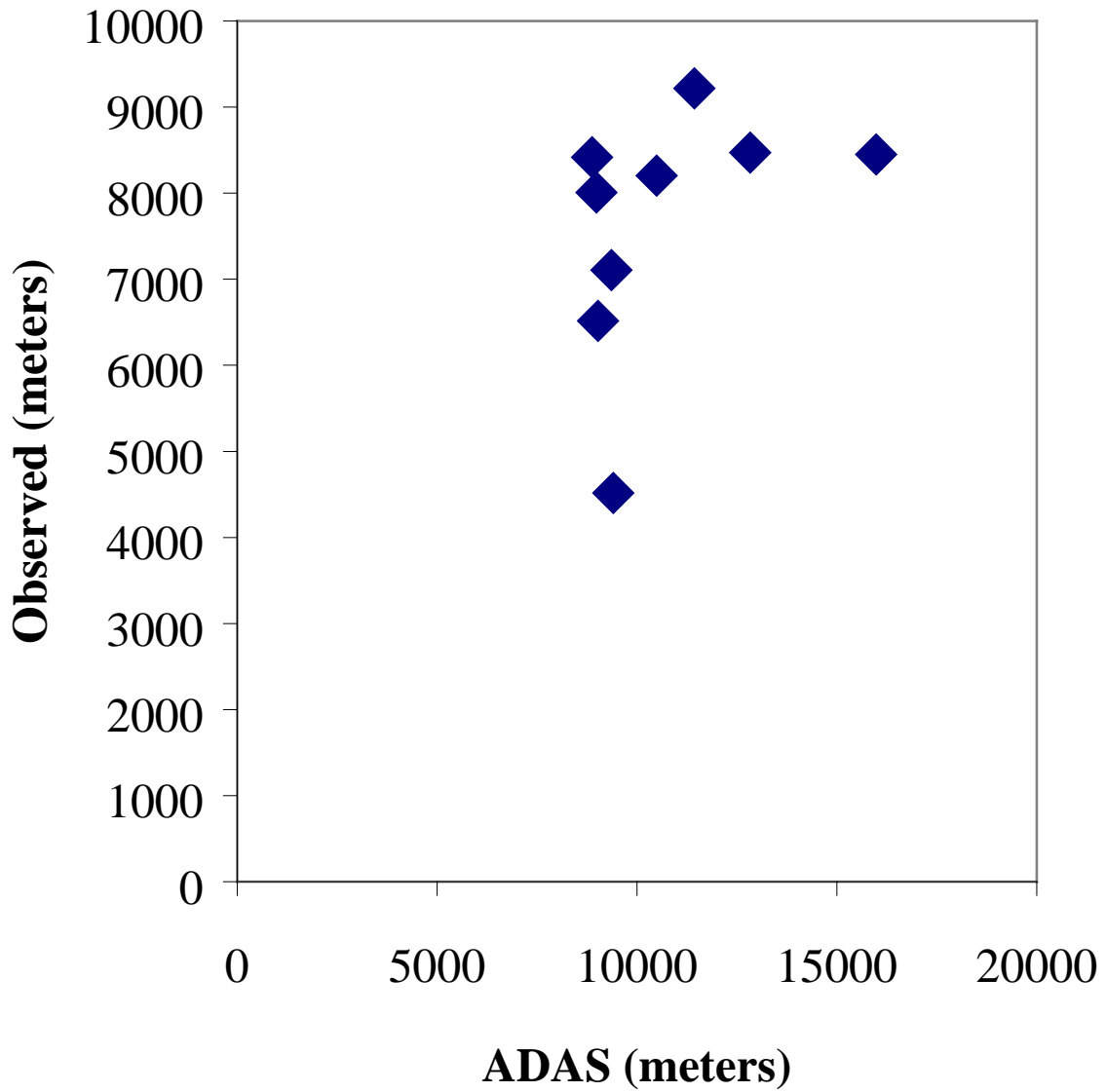


Figure 6. Cloud top height estimations from the modified ADAS cloud analysis technique compared against cloud top temperatures determined from radiosondes for cases where the SERCAA Phase II algorithm correctly identified overcast conditions and the SERCAA cloud top temperature was less than 253 K.

The estimated thickness of the clouds determined by the Conover and Bunting (1977) statistical method compared to the observations are presented for the 15 cases where the SERCAA Phase II algorithms correctly estimated overcast cloud cover in Fig. 7. The SERCAA Phase II cloud top temperature was used in lieu of the satellite brightness temperature in eq. (1). In general, for thicker clouds the estimated thickness are too large and for thinner clouds the estimated thickness are too small. Using the statistical cloud thickness algorithm combined with the modified ADAS cloud top height estimation, cloud base height estimations were made and results are presented in Fig. 8. The combination of techniques tends to produce cloud base heights that are generally too high. In addition, as with the modified ADAS technique, there is no correlation between the observed estimated cloud base heights with the computed correlation coefficient being -0.02 .

The fuzzy logic approach of Mozer and Ayer (1998) was also evaluated against the observations. However due to software considerations the fuzzy logic approach to only run with the SERCAA Phase I set of algorithms including cloud detection and cloud top temperature retrievals. The result is that there are only seven cases where the fuzzy logic technique estimated and observations indicated overcast cloud cover. The results are presented in Fig. 9. The technique shows a tendency to under estimate the actual cloud top heights for all the cases. However the estimates are well correlated with the observations and with the exception of one outlier, the estimated cloud top heights for all the cases are within 1000 m of the observed cloud top height.

6. Conclusions and Recommendations

It was the objective of this work to recommend the modules to handle the satellite preprocessing and cloud vertical boundaries for TCAP. The candidate techniques for the satellite preprocessing modules were the SERCAA Phase I and II set of algorithms. It is believed that the fact that the SERCAA Phase II algorithm has superior cloud detection makes up for its short-comings with retrieving cloud top temperatures. In addition since Phase II represents the most current version, its selection would insure that TCAP is in a position to get the latest upgrades and improvements to SERCAA. Therefore it is recommended that the SERCAA Phase II set of algorithms comprise the satellite preprocessing module of TCAP.

For the cloud-top height estimations two techniques were evaluated, the modified ADAS approach and the fuzzy logic technique of Mozer and Ayer (1998). Both techniques proved to be positively correlated with the observations. Given the small amount of data to test the algorithms it is difficult to base a decision on the results alone, however it would appear that the fuzzy logic approach has the edge. An additional aspect to consider is the fuzzy logic technique was designed from the beginning to ingest just satellite and NWP data to produce cloud top heights whereas the ADAS approach was originally designed to work with many other data sources and has essentially been stripped bare to work in this scenario. Likewise the fuzzy logic approach is more sophisticated in that it can employ many relationships between the input data and the desired predictands and it is expected to be further modified and improved. Based on this additional sophistication and flexibility, it is

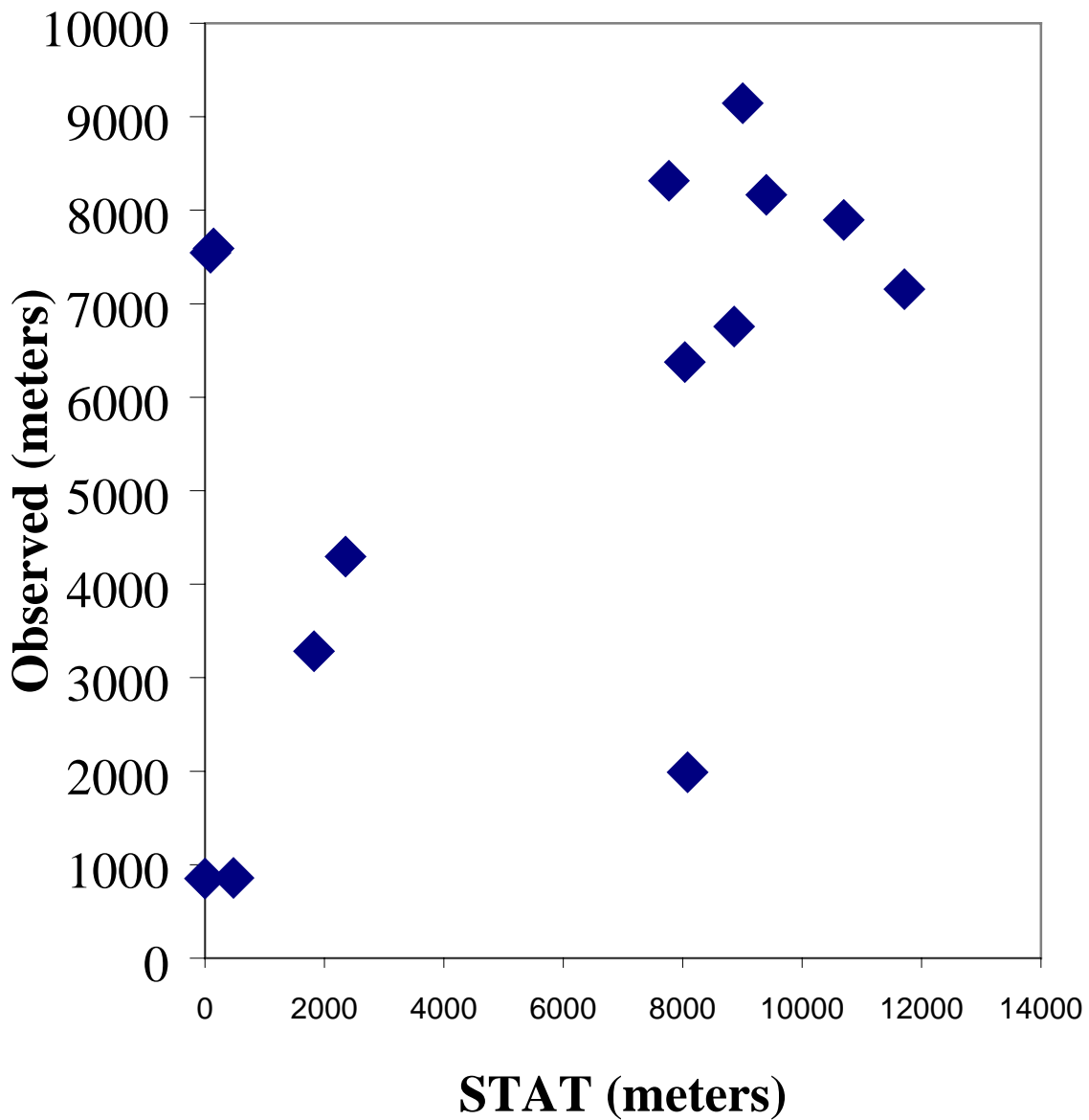
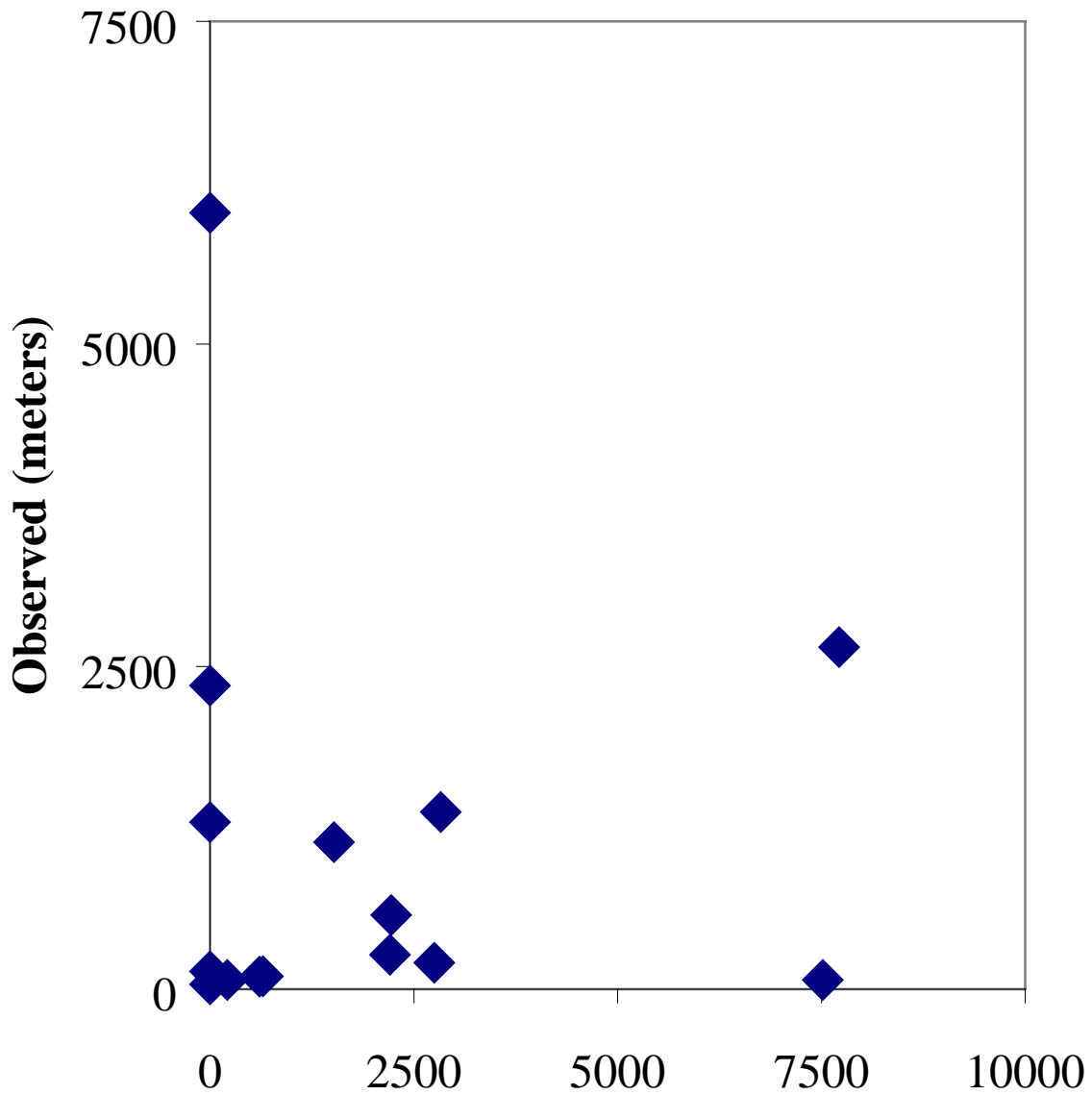


Figure 7. Estimated thicknesses of layer from top of highest overcast layer to base of lowest overcast layer from the Conover and Bunting (1977) statistical technique compared to thicknesses determined from radiosonde observations for cases where SERCAA Phase II algorithms correctly identified overcast cloud cover.



ADAS Tops - STAT Thickness (meters)

Figure 8. Cloud base height estimations, computed by subtracting the cloud thickness determined from the statistical technique from the ADAS cloud top heights, plotted against cloud base heights determined from radiosondes for the cases where the SERCAA Phase II algorithm correctly identified overcast cloud cover.

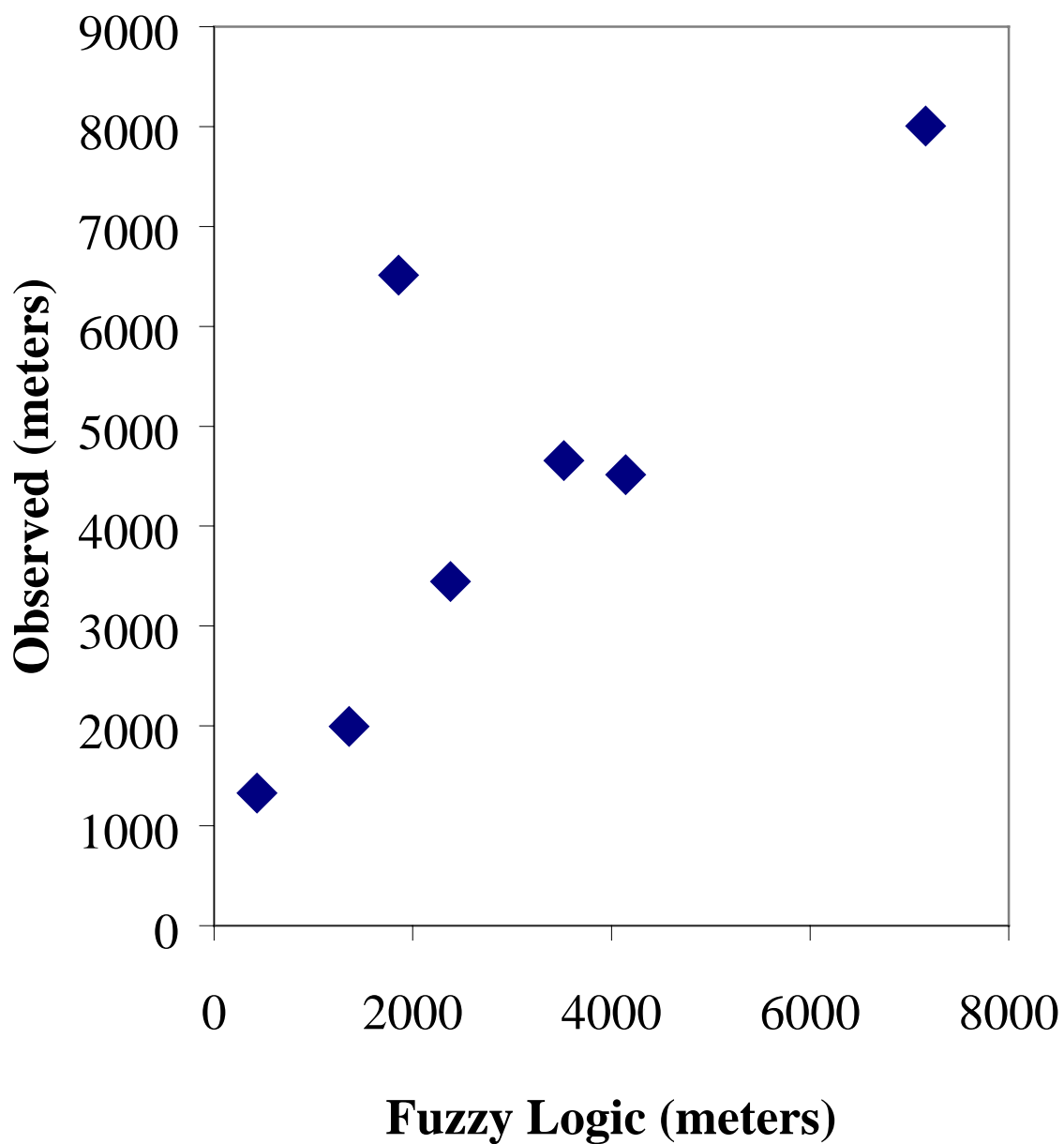


Figure 9. Cloud top height estimations from the fuzzy logic technique compared to cloud top heights determined from radiosondes for the cases where the algorithm detected clouds over the radiosonde site.

recommended that the fuzzy logic approach be selected for the cloud top height estimation module of TCAP.

Neither of the candidate techniques for estimating the cloud base heights provided especially satisfying results. Neither technique was well correlated with observations. The performance of the modified ADAS technique may improve as the NWP analyses become more accurate and highly resolved. It is also possible that the Conover and Bunting (1977) statistical approach might be improved by adding emittance (a SERCAA Phase II product) to the regression equation. Given that both techniques currently have significant short-comings, it is recommended that a decision on the approach for cloud base height estimation to be used in TCAP be deferred until more testing can be done.

The authors realize that the above recommendations are made on limited data and the challenge of estimating cloud vertical boundaries with satellite data and NWP analyses is substantial. Expansion of the data sets used for evaluation of the proposed techniques is recommended. Cloud radars should be used when possible to provide the ground truth of the cloud vertical boundaries. The use of cloud radars would help take out the subjective nature of interpreting radiosonde profiles to determine the cloud vertical boundaries. Given that improved methods for the determining the cloud vertical boundaries may be developed in the future, it is recommended that the developers of TCAP try to maintain as much flexibility as possible in its design. The amount of flexibility should be sufficient to allow modules to be upgraded as the techniques in the modules are improved and also to be swapped out in favor of other techniques that are shown to be superior.

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