"Water Vapor and Cloud Detection Validation for Aqua Using Raman Lidars and AERI" – Annual Report March 2003

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Summary

This investigation involves the use of Raman lidar, AERI, and radiosonde measurements of water vapor, temperature, pressure and clouds to study and validate Aqua retrievals of water vapor and to develop cloud particle size retrieval techniques. According to the needs of the Aqua activity the first 18 months of this activity have focused on combined ground-based measurements during nighttime overpasses of the Aqua satellite in order to validate Aqua water vapor and temperature profiles.

Two measurement campaigns have thus far been completed. The first of these occurred at NASA/GSFC in Greenbelt, Maryland and spanned September 5 – November 3, 2002 with 26 nighttime overpasses (nominally between 2 and 3 am local) being covered. For each of these overpasses, the NASA/GSFC Scanning Raman Lidar (SRL) was used to acquire profiles of water vapor and clouds. These measurements were supported by launches of Sippican Mark-II radiosondes, which provided measurements of temperature and pressure, and SuomiNet GPS measurements of total precipitable water, which were used as the calibration source for the Raman lidar.

The second of these campaigns occurred at the University of Maryland Baltimore County and spanned January 8 – January 27, 2003. In addition to the previously mentioned instrumentation, the ground-based BBAERI (Baltimore Bomem AERI), the ALEX Raman Lidar and the ELF backscatter lidar made measurements during the overpasses. The results from this second campaign are still being processed. Therefore this report will focus on the results from the first campaign at NASA/GSFC and related efforts including a statistical analysis of cirrus cloud data from earlier SRL deployments, study of GOES, MODIS and AERONET precipitable water measurements using GPS and preliminary comparisons of particle size retrievals from ground-based AERI and Raman lidar.

Comparison of preliminary Aqua water vapor and temperature retrievals to validation data acquired at NASA/GSFC

Water vapor

At the time of this writing, we are in an interactive investigation of the effect of various "tweaks" in the Aqua water vapor and temperature retrieval code on the comparison of these quantities with the validation profiles acquired at NASA/GSFC. This process has provided the opportunity for quick feedback on the effect of various techniques of handling retrieval tuning and error weighting on the quality of the final retrieved product. Figure 1 shows the mean comparison of Aqua water vapor retrievals with the validation profiles using (a) 9 cases deemed "clear" based on the lidar measurements and (b) 8 cases deemed "cloudy" based on the lidar measurements. These are interim retrievals that are presented here as indicative of the interactive work that is occurring to help characterize different versions of the preliminary retrieval code. We expect that the quality of these retrievals will continue to be improved through this interactive process therefore these comparisons should not be taken to represent the eventual quality of the Aqua water vapor and temperature retrievals.

The clear cases shown in (a) indicate that 1) between 200-900 mb, the retrievals have a mean dry bias of ~10-15% with respect to the validation profiles, 2) the untuned retrievals show higher instability than the tuned or error weighted retrievals, 3) all retrievals showed a more rapid increase in moisture than the validation profiles below 900 mb, 4) the wet bias of the retrievals below 900 mb offered compensation for the dry bias of the profiles above 900 mb such that the total precipitable water comparison indicated that the retrievals were between 5 and 9% dryer than the validation profiles.

The cloudy cases shown in (b) indicate that 1) between 450-900 mb there is generally good agreement between the retrievals and the validation profiles with mean differences generally less than +/- 5% although the untuned retrievals again show instability, 2) there is a large wet bias in the retrievals of up to 90% between 200- 400 mb indicative of an upper tropospheric bias to the Aqua retrievals, 3) as in the clear cases, but this time more pronounced, there is a more rapid increase in moisture in the retrievals versus the validation profiles below 900 mb, 4) the mean ratio of the retrieval and validation total precipitable water is between 1.01 and 1.07.

In order to investigate further the large wet bias present in the upper troposphere in the cloudy case comparison shown in figure 1, figure 2 presents two of the individual cloudy case comparisons. Here the source of the wet bias in the retrievals appears to be due to unresolved structure in the water vapor profile below the heights of the clouds which were at altitudes of ~10-12 km in these cases. Examination of previous lidar water vapor data in the presence of cirrus clouds indicates that this highly structured water vapor profile is commonly found. Therefore, the inference from this is that the upper tropospheric wet bias shown in figure 1 could be a frequent and persistent characteristic of the Aqua retrievals over large portions of the globe. If the problem was totally one of resolution, however, one would expect a compensation to be occurring where, for example, above the cirrus cloud the retrieval would be dry in a manner that compensates for the wet bias below the cloud. No such compensation is seen in the mean of the 8 cases studied here implying that large errors in calculations of longwave radiation, and thus modeling of global climate, could occur us ing these Aqua retrievals.

To reiterate, however, the retrieval algorithm development is on-going and the comparisons presented here should not be taken as indicative of the ultimate quality of the Aqua retrievals. Instead these comparisons are motivators to continue the interactive research in studying the behavior of the retrievals as various tretrieval techniques are implemented to improve the overall agreement of the retrievals with the validation profiles.

Temperature

Figure 3 presents the mean temperature comparisons of the Aqua retrieval versus the radiosonde measurements obtained at GSFC during September-November, 2003. As for the water vapor comparisons, the retrievals have been separated into clear (a) and cloudy (b) cases.

The results shown here indicate that for much of the troposphere, i.e. between ~250 and 900 mb, all retrievals agree with the reference profile within approximately +/- 1.5K. Deviations exceed 1.5K both above 200 mb and below 950 mb with all retrievals showing the same general features. The most pronounced differences between the retrievals and the reference profiles occur 1) at the lowest levels where between ~900 – 950 mb, there is a significant cooling of the retrievals with respect to the reference profiles of up to 2K and 2), below 950 mb, where a sharp increase of 2-3K occurs compared to the reference profiles. As the retrieval algorithm work continues we will focus on improving the comparison of the retrieval and reference profiles in both the upper troposphere/lower stratosphere and near the surface where the large differences described above currently are found.

The use of MODIS to study scene variability

One of the factors that can degrade comparisons between a ground-based lidar measurement of water vapor and a satellite-based retrieval is the fact that the two measurements are acquired under very different conditions and over different averaging times. The lidar averaging time for the profile comparisons presented here varies between 30 – 60 minutes. This is done to improve the statistics of the water vapor measurements in the upper troposphere where the random error in the lidar profile can reach 100% by 12-14 km depending on viewing conditions. The requirement for a significant averaging time for the lidar to make its measurement presents the question of how representative the mean atmospheric conditions over the 30-60 minute period of time used for the lidar average is of the instant that the Aqua satellite passed over. We are investigating this possible source of variability between the retrievals and the reference profiles using MODIS data.

Figure 4 presents MODIS 1km cloud product and 5 km total precipitable water product for October 2, 2002 – one of the clear cases studied in figure 1. Independent analysis of the brightness temperatures performed by Gary Jedlovec of MSFC indicates that the 3x3 fov region surrounding GSFC was cloud-free during this measurement period supporting its use in the "clear" comparison statistics. Furthermore the MODIS water vapor product is being used to assess variability of PW within the AIRS scene at the time of the lidar measurement. Analysis of this image showed approximately a 10% variation in TPW over the AIRS scene. However, considering that the lidar averaged over a period of ~45 minutes and that the boundary layer winds were predominantly out of the west, if a static water vapor field propagating with the wind is assumed over this measurement period, the MODIS data support the conclusion that the mean TPW measured by the lidar should agree with the mean of the AIRS scene to within 3%.

Cirrus cloud statistics from CAMEX-3

One of the objectives of this research is to study the influence of cirrus clouds on the water vapor retrievals from Aqua. In support of this effort, we undertook a more thorough examination of the cirrus cloud measurements acquired during the deployment of the Scanning Raman Lidar to Andros Island, Bahamas for the CAMEX-3 hurricane study field campaign in July-Sept, 1998. The results of this study will help to improve the knowledge of cirrus cloud properties in the sub-tropics where measurements of cirrus by advanced sensors such as Raman lidar are limited. Based on these lidar measurements acquired over a period of more than 2 months, the frequency of occurrence of cirrus clouds was greater than 60%. Figure 5 shows the ensemble statistics of cirrus cloud optical depth and extinction to backscatter ratio based on more than 150 hours of cirrus clouds measurements.

On the left is shown the histogram of cirrus cloud optical depth frequency. The plot above shows the entire histogram with optical depths ranging up to 4 while the plot below is an expansion of the optical depth frequency for optical depths less than 0.2. The high frequency of occurrence of very thin cirrus clouds is apparent with the peak frequency of occurrence being for clouds with optical depths between 0.02 and 0.04. Our previous work (Whiteman et. al., 2001) has indicated that standard IR sensors such as GOES have cirrus detection capability down to optical depths of ~0.05 – 0.1 but that the presence of cirrus clouds of these optical depths introduces significant errors in the retrieval of water vapor and temperature from satellite. The statistics shown in figure 5 therefore imply that standard IR sensors would not detect a large number of cirrus clouds in the sub-tropics and that significant biases would be introduced into the retrieved data products.

On the right, is plotted the cloud mean extinction to backscatter ratio (lidar ratio) as a function of cloud temperature, cloud optical depth and cloud height. All three plots show the same trends: a general increase and then decrease in the lidar ratio as the temperature/optical depth/cloud height increases. Such information of the behaviour of the lidar ratio of cirrus clouds can be useful for improving our general understanding of the optical properties of cirrus in the sub-tropics as well as for estimating cirrus cloud optical depth from space-based lidar systems such as the recently launched GLAS system or the upcoming CALIPSO.

Precipitable water comparisons of MODIS and GOES versus ground based GPS

As an extension of our EOS validation activity, we undertook studies of the precipitable water measurements from 1) GOES (MSFC retrievals, 2) MODIS (near-IR), and 3) AERONET sunphotometer at GSFC using ground based SuomiNet GPS as the reference. Figure 6 shows the comparisons.

The regression comparison with GOES shown in (a) reveals a positive offset (~0.5 cm) but a generally linear sensitivity to increases in PW (slope = 0.96). The occasional large positive biases in the GOES retrievals are thought to be due to undetected cirrus clouds. The tendency toward a dry retrieval for small PW values is under study. The MODIS regression comparison shown in (b) yields a slope of 1.06 and an offset of –0.1 cm. The comparison of the MODIS retrievals with GPS are in agreement with other studies that show ~7% moist bias in the regression. This is similar to the results shown for AERONET (c) which shows a 5% moist bias to the regression line and a very small offset. Both MODIS and AERONET make use of the 940 nm region of the water vapor spectrum for their inversions so that uncertainties in the spectroscopy in this part of the spectrum are thought to bias both retrievals slightly moist. Based on the work shown in (c), which according to the AERONET group at GSFC is the best PW comparison ever performed with an AERONET system, consideration is being given implementing a parameterization of the PW retrieval for AERONET based on a fit to these GPS data.

Particle size retrieval comparison

An ancillary goal of our study is the comparison of particle size retrievals using ground-based high spectral resolution passive data and Raman lidar data. The initial comparisons of these two techniques are shown in figure 7 based on measurements of a high cloud event at the ARM CART site on September 27, 1997. The aerosol scattering ratio time series from the lidar is shown in (a) indicating the presence of clouds between altitudes of 7-10 km for much of the measurement period that spanned ~2-12 UT. The time series of particle size retrievals from AERI is shown in (b) with particle radii varying between approximately 5 and 25 microns. At ~6UT the AERI is retrieving particle sizes of ~8-9 microns. The lidar multiple scattering technique for retrieving particle sise (Whiteman et. al., 2001) is illustrated in (c) where the measured lidar signal above the cloud at 6UT is compared to simulations of the multiply scattered lidar signal The best agreement of the lidar data and the simulations is obtained for an assumed particle size of 9 microns in good agreement with the AERI retrievals. Over the remainder of this activity, the lidar particle size technique will be automated and used to study the particle sizes for both the CAMEX-3 cirrus cloud data set as well as the measurements acquired at UMBC in January, 2003 and that are expected to be acquired during January, 2004. The lidar-based retrievals will be compared with those from ground-based AERI as those techniques are further developed and applied to AIRS data.

Publications

Whiteman, D. N., K. D. Evans, B. Demoz, D. O'C. Starr, E. Eloranta, D. Tobin, W. Feltz, G. J. Jedlovec, S. I. Gutman, G. K. Schwemmer, M. Cadirola, S. H. Melfi, F. J. Schmidlin, Raman lidar measurements of water vapor and cirrus clouds during the passage of hurricane Bonnie, *J. of Geophys. Res.*, 106, No. D6, 5211-5225. (2001)

Whiteman, D. N., "New examination of the traditional Raman Lidar technique for water vapor and aerosols I: evaluating the temperature dependent lidar equations", accepted by Applied Optics.

Whiteman, D. N., "New examination of the traditional Raman Lidar technique for water vapor and aerosols I: evaluating the ratios for water vapor and aerosols", accepted by Applied Optics

Sub-tropical cirrus cloud properties derived from Raman Lidar measurements during CAMEX-3, in preparation.

Presentations

"Water Measurements using Raman Lidar", presented at the annual meeting at the American Meteorological Society, February, 2003, Long Beach CA.

"Water Vapor and Cloud Detection Validation for Aqua Using Raman Lidars and AERI – initial validation results", presented at the AIRS Science Team Meeting, February 25-27, 2003, Camp Springs MD.

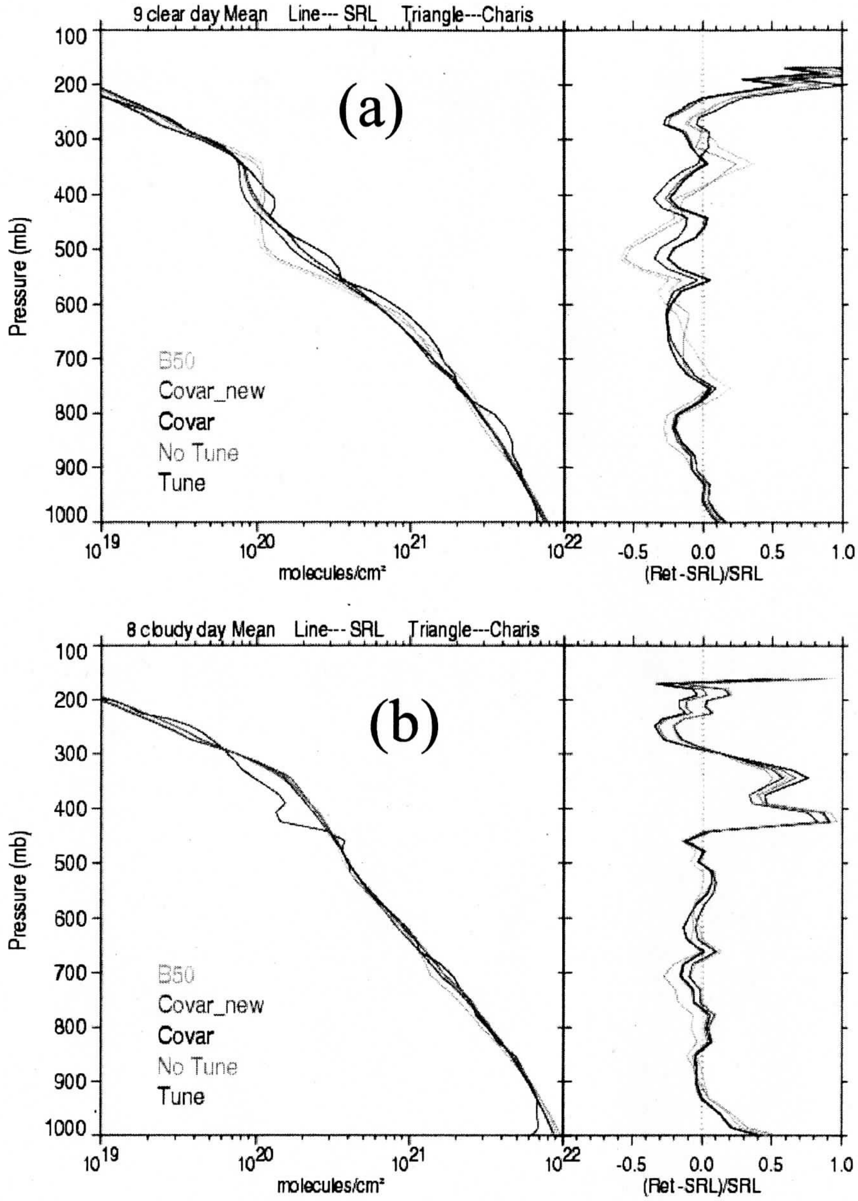

Figure 1 Comparison of preliminary Aqua retrievals using 5 different methods of handling tuning and error weighting versus validation profiles of water vapor acquired at NASA/GSFC in Sept-Nov, 2003. On the left is shown the mean comparison for the 9 available comparisons that were deemed "clear" based on the lidar data. On the right is shown the mean comparison for the 8 available "cloudy" cases. These comparisons reveal instability in this particular treatment of the untuned retrievals under clear conditions. The comparisons under cloudy conditions indicate that there is a persistent wet bias of up to 90% in the retrievals in the upper troposphere. See text for more details.

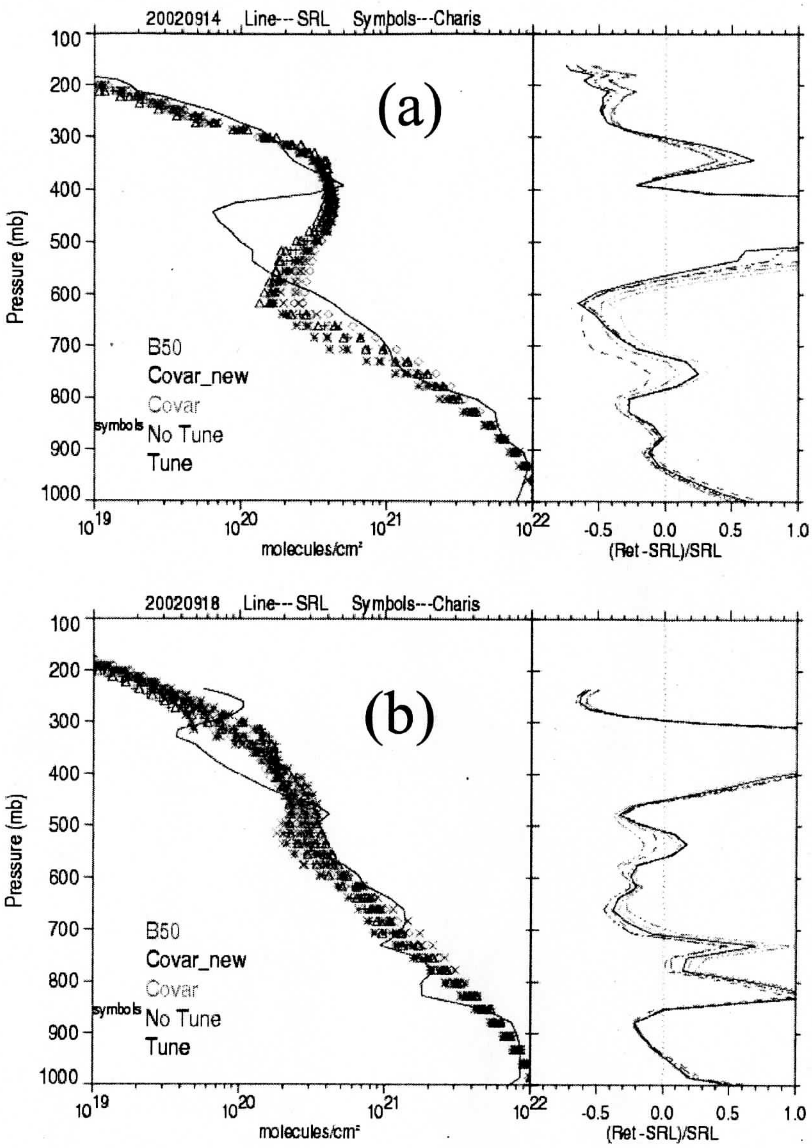

Figure 2 Two examples of retrieval comparisons under cloudy conditions. These are cases when the lidar indicated that cirrus clouds were present between the altitudes of ~10-12 km. Based on lidar data such as these, a rapid increase in water vapor is frequently observed below cloud base. The inability of the retrieval to resolve this structure leads to a large wet bias in the retrieval compared to the validation profile. However, if the wet bias below the clouds were only due to a resolution issue, one would expect a dry compensation above the cloud such that the total precipatable water observed in the upper troposphere agreed with the reference profile. This is not observed in the mean profile comparison shown in figure 1 however. See text for more details.

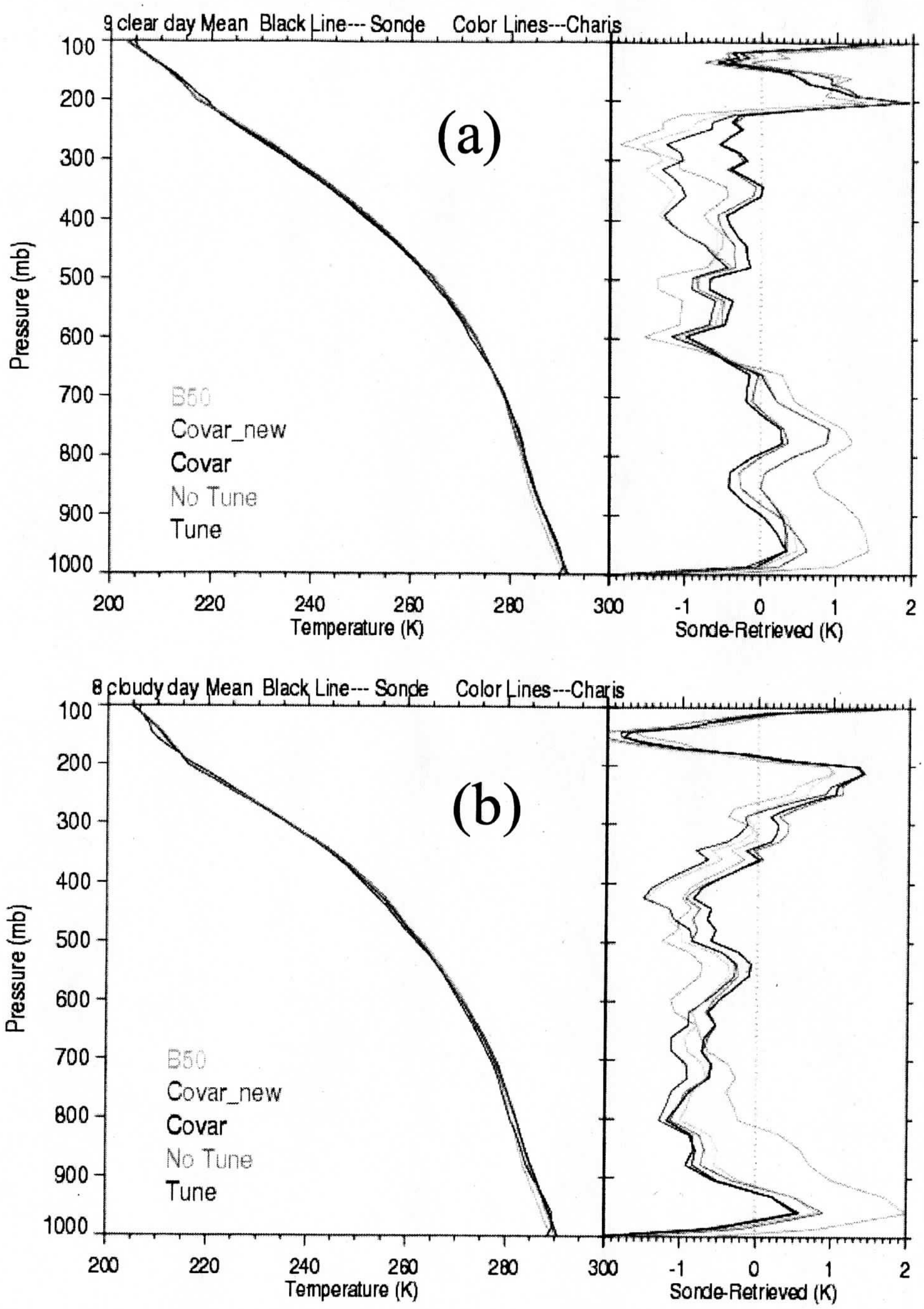

Figure 3 Comparison of 5 Aqua retrieval schemes with the reference temperature profiles provided by radiosonde. The measurements have been separated into clear and cloudy conditions as for the water vapor comparisons. The results shown here indicate that for much of the troposphere, between ~250 and 900 mb, all retrievals agree with the reference profile within +/- 1.5K. Deviations exceed 1.5K both above 200 mb and below 900 mb with all retrievals showing the same general features. The most pronounced differences between the retrievals and the reference profiles occur at the lowest levels where between ~900 – 950 mb, there is a significant cooling of the retrievals with respect to the reference profile and then, below 950 mb a sharp increase of 2-3K when compared to the reference profile. See text for more details.

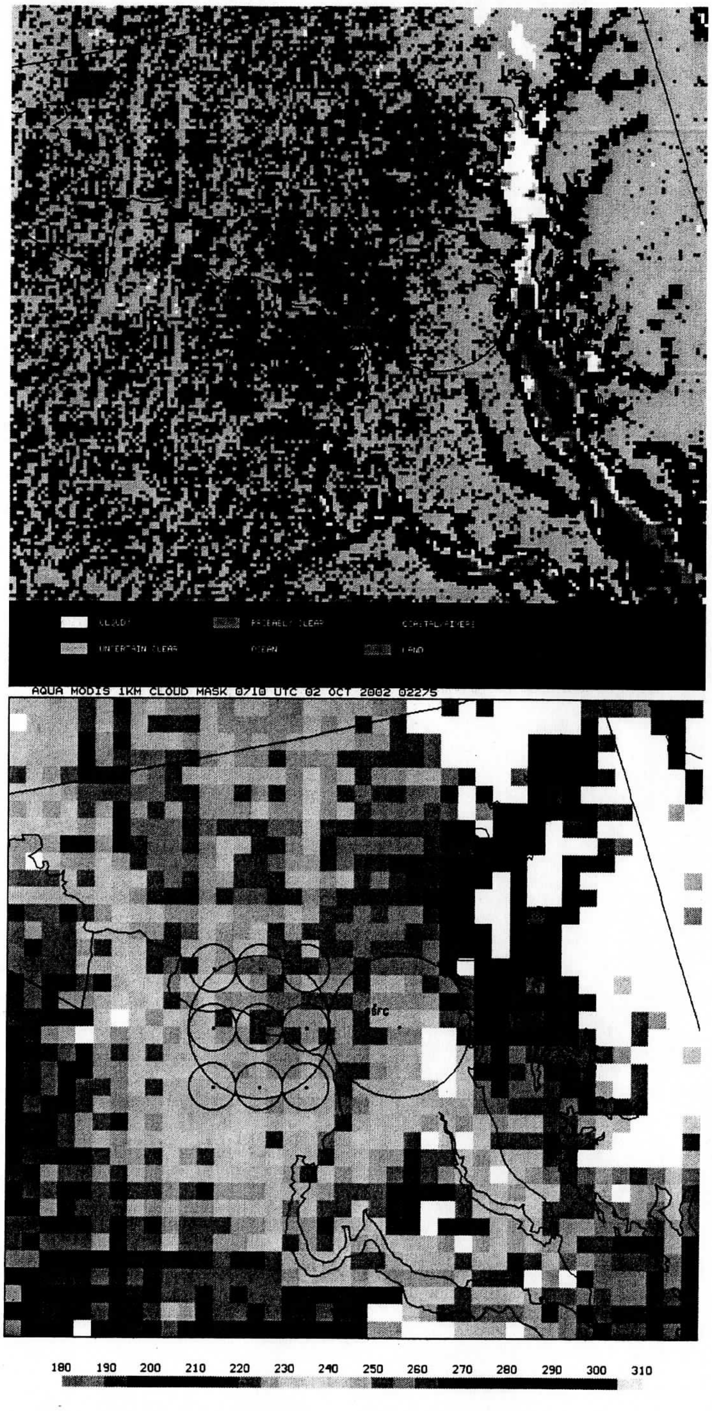

Figure 4 MODIS 1km cloud product (top) and 5 km total precipitable water product (bottom) for October 2, 2002 – one of the clear cases studied in figure 1. Independent analysis of the brightness temperatures performed by Gary Jedlovec of MSFC indicates that the 3x3 fov region surrounding GSFC was cloud free during this measurement period. Furthermore the MODIS water vapor product can be used to asses variability of PW within the AIRS scene at the time of the lidar measurement. Analysis of this image showed approximately a 10% variation in TPW over the AIRS scene. See text for more details.

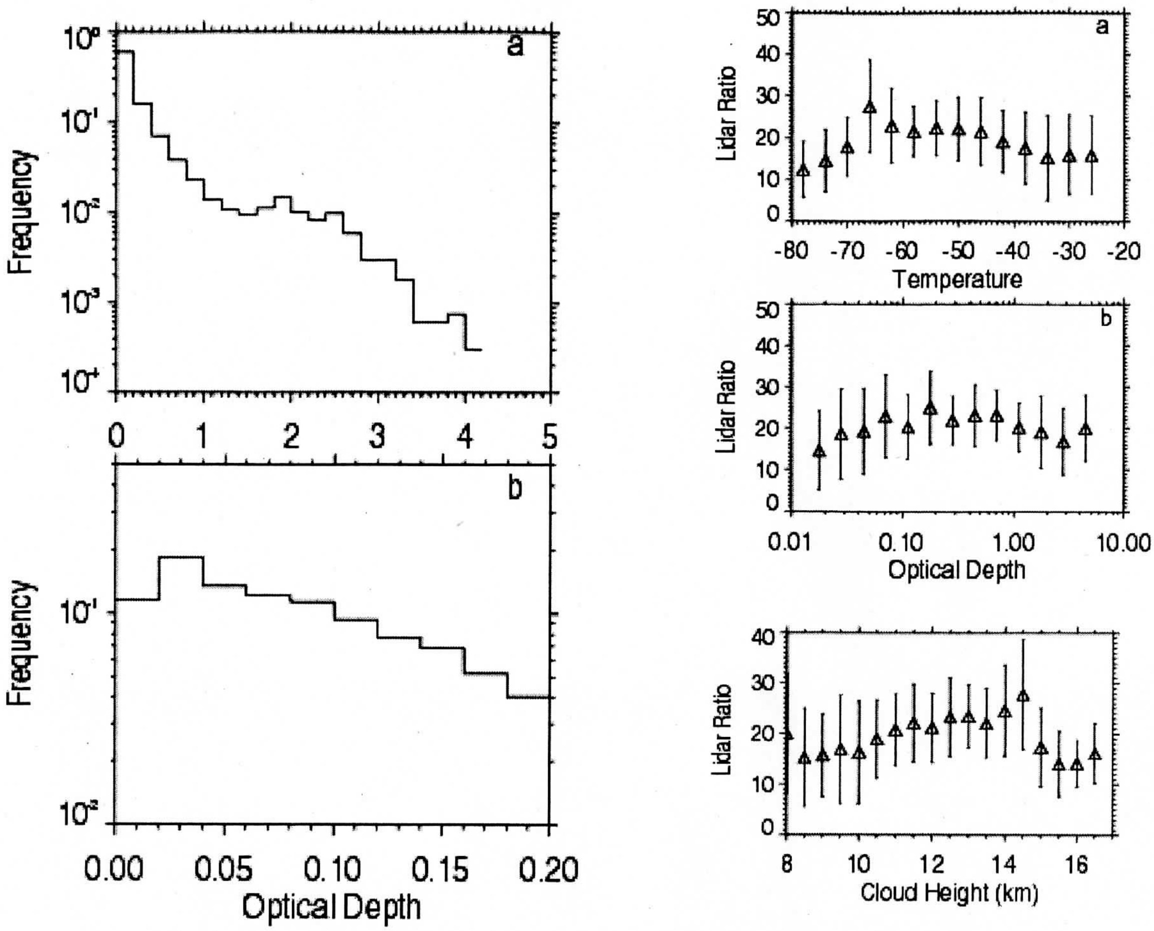

Figure 5 Cirrus optical depth and extinction to backscatter ratio statistics from July – September, 1998 at Andros Island, Bahamas based on 150 hours of cirrus measurements acquired by the Scanning Raman Lidar during the CAMEX-3 hurricane study program. The overall occurrence rate of cirrus clouds was > 60% during the deployment period of the SRL. On the left is shown the histogram of cirrus cloud optical depth. The plot above shows the entire histogram while the plot below is an expansion of the optical depth frequency for optical depths less than 0.2. The high frequency of occurrence of very thin cirrus clouds is apparent. Our previous work has indicated that standard IR sensors have cirrus detection capability down to 0.05 –0.1 optical depth implying that a large number of cirrus clouds will go undetected in the sub-tropics. On the right, is plotted the cloud mean extinction to backscatter ratio (lidar ratio) as a function of cloud temperature, cloud optical depth and cloud height. All three plots show a general increase and then decrease in the lidar ratio as the temperature/optical depth/cloud height increases. See text for further details.

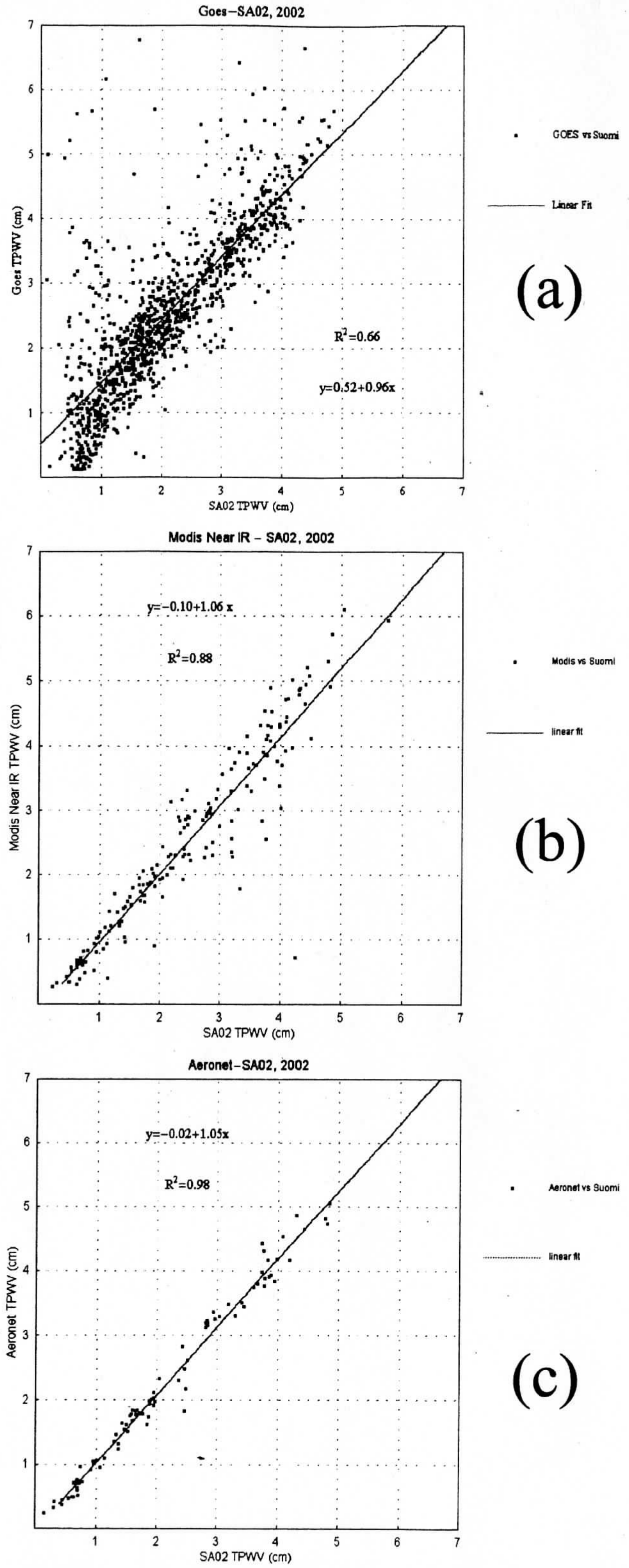

Figure 6 Comparison of SuomiNet GPS precipiatable water (PW) measurements at GSFC with (a) GOES PW from MSFC (b) the operational MODIS near-IR PW retrieval and 3) with the reference Cimel sun photometer that is part of the NASA/GSFC AERONET. The GOES retrievals show a generally linear increase in PW with increasing PW in the GPS. However, there is a 0.5 cm offset to the regression line and a tendency for the retrieval to be too dry for very small PW. The comparison of the MODIS retrievals shown in (b) with GPS are in agreement with other studies that show ~7% moist bias in the regression. This is similar to the results shown for AERONET (c) which shows a 5% moist bias to the regression line. Both MODIS and AERONET make use of the 940 nm region of the water vapor spectrum for their inversions so that uncertainties in the spectroscopy in this part of the spectrum are thought to bias both retrievals slightly moist. See text for more details.

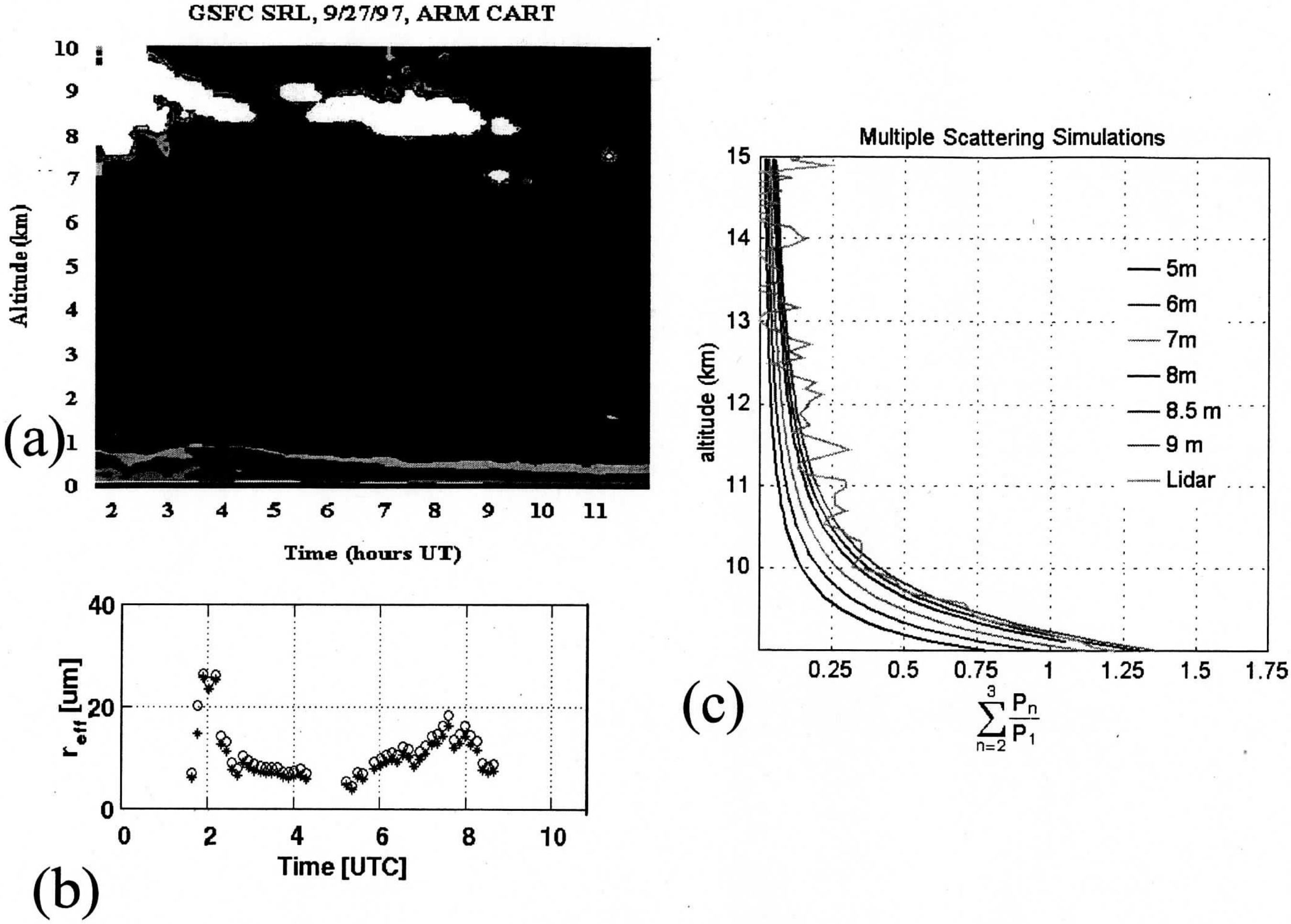

Figure 7 Comparison of particle size retrievals using ground based AERI measurements and Scanning Raman Lidar measurements for a high cloud event at the ARM CART site on September 27, 1997. The aerosol scattering ratio time series from the lidar is shown in (a). The time series of particle size retrievals from AERI is shown in (b) with particle radii varying between approximately 5 and 25 microns. At ~6UT the AERI is retrieving particle sizes of ~8-9 microns. The lidar multiple scattering technique for retrieving particle is illustrated in (c) where the measured lidar signal above the cloud at 6UT is compared to simulations of multiple scattering. The best agreement of the lidar data and the simulations is obtained for an assumed particle size of 9 microns in good agreement with the AERI retrievals. See text for more details.