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Continuation of Data Analysis Software Development for the Atmospheric Emitted Radiance Interferometer (AERI) Progress Report 1998

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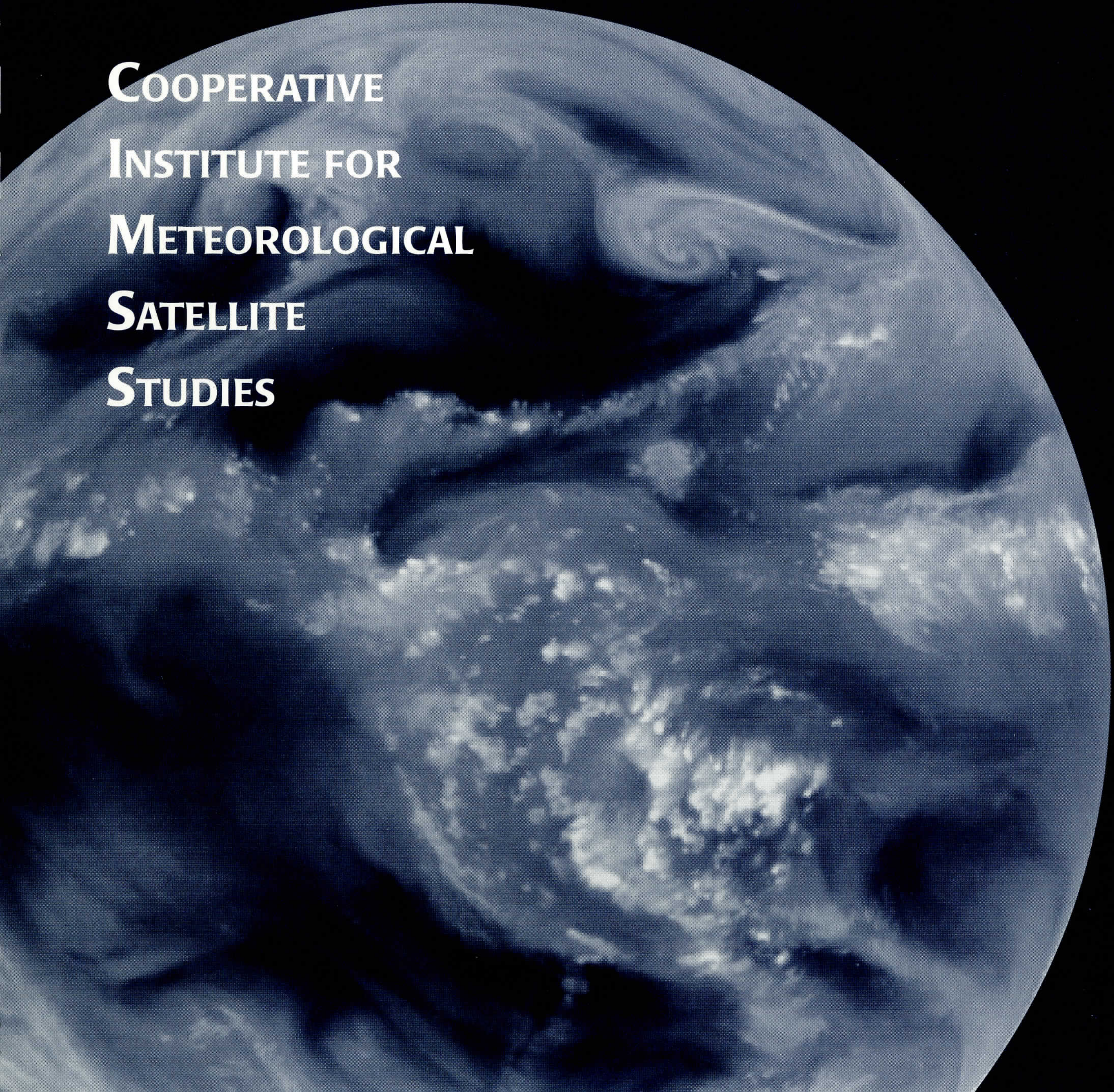

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Continuation of Data Analysis Software Development for the Atmospheric Emitted Radiance Interferometer (AERI) Progress Report 1998

Continuation of Data Analysis Software Development for the Atmospheric Emitted Radiance Interferometer (AERI) Progress Report 1998

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1. Introduction

Significant progress has been made towards the goals funded under DOE Award DE-FG-02-98ER61365. The Atmospheric Emitted Radiance Interferometer (AERI) has been operating routinely at the Southern Great Plains Cloud And Radiation Testbed (SGP CART) site since 1995 and systems have since been installed at the North Slope of Alaska (NSA) and the Tropical Western Pacific (TWP) ARM sites. The downwelling infrared radiance data collected by the AERI systems have been used for 1) improving clear sky radiative transfer in temperate and arctic climate regimes, 2) retrieving thermodynamic profiles of temperature and water vapor, and 3) deriving cloud microphysical properties. The progress towards the above three goals will be discussed within this report.

2. Clear Sky Radiative Transfer

A) Water Vapor Continuum Formulation

The use of AERI data has been instrumental in the effort to generate a new formalism for the water vapor continuum (CKD_3.0). Observations taken during the Surface Heat Budget of the Arctic Ocean experiment (SHEBA) using an AERI instrument with extended spectral coverage (AERI-X) from 380 cm^{-1} to 3000 cm^{-1} have been compared with Line By Line calculations using LBLRTM with the CKD_2.2 water vapor continuum (Tobin et al.). As a result of the low temperature and low water vapor amount conditions, the spectral windows between lines in the wings of the pure rotational band of water vapor (300-600 cm^{-1}) become transparent. Comparisons under clear sky conditions between measurement and model have led to improvements in the air broadened water vapor continuum. For this foreign-broadened continuum, data from the extended AERI has been utilized in a least squares procedure (see Figure 1) to obtain spectral-line-based functions that are used to compute continuum coefficients in any spectral region. This least-squares procedure also made use of laboratory-generated foreign-and self-broadened continuum coefficients in the ν_2 band of water vapor (Tobin et al., 1996). The combination of these two data sources has led to a significantly different continuum formulation, which will improve model accuracy for remote sensing and radiation applications. In the fitting effort for both the foreign- and self-broadened continua, the results of AERI-LBLRTM QME provide an important constraint on the behavior of candidate functions in key spectral regions.

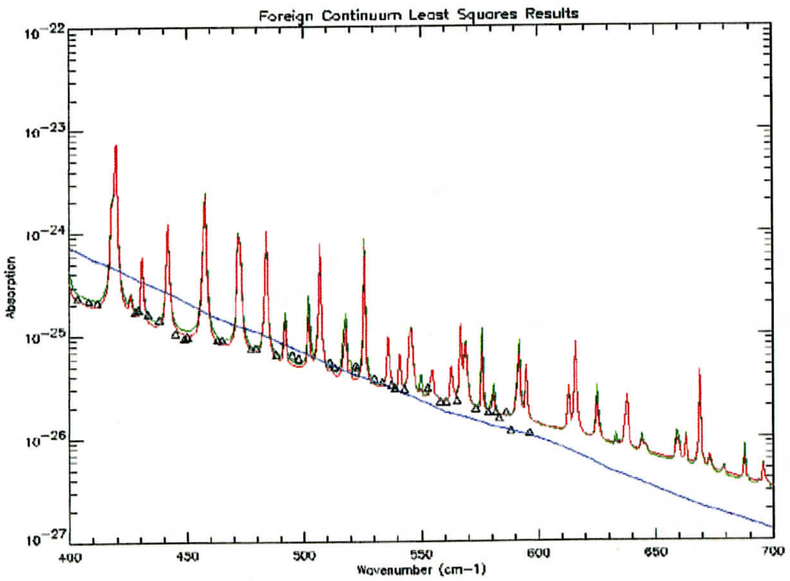


Figure 1. For the spectral region 400-700 cm^{-1}, two candidates for the CKD_3.0 foreign continuum (red and green curves) are compared to data obtained with the extended AERI (triangles) deployed at the SHEBA ice station. Also shown is the CKD_2.2 foreign continuum.

B) Studies of Downward Flux at the Surface using the AERI/LBLRTM QME

The AERI/LBLRTM QME studies continue to critically assess the radiative transfer modeling capability for general circulation models. Several key input elements of the experiment are being reprocessed, including the Micropulse Lidar (MPL) and the Microwave Radiometer (MWR), as improvements to the data quality are implemented. QME analyses of the past four years have demonstrated the ability to model clear sky downwelling direct flux to within 2 W/m^2 of observations. Use of the MWR integrated water column to scale the radiosonde profile has proven to be very robust over a wide range of water vapor amounts, reducing the residuals to 2 W/m^2 from 10 W/m^2, as shown in Figures 2 and 3. Figures 4 and 5 demonstrate that the data quality of the MWR has not changed over the time period of study in its use as a column water measurement. Periodic calibration of the MWR has proven to be useful in correcting any gradual drift over time in the instrument calibration. In addition, studies of AERI/LBLRTM residuals have shown that the MWR scaling technique has also been successful in removing the diurnal variation in radiosonde processing of water vapor measurements. A paper is to be submitted to JGR within the next several months regarding the radiative transfer modeling work supported in part under this grant.

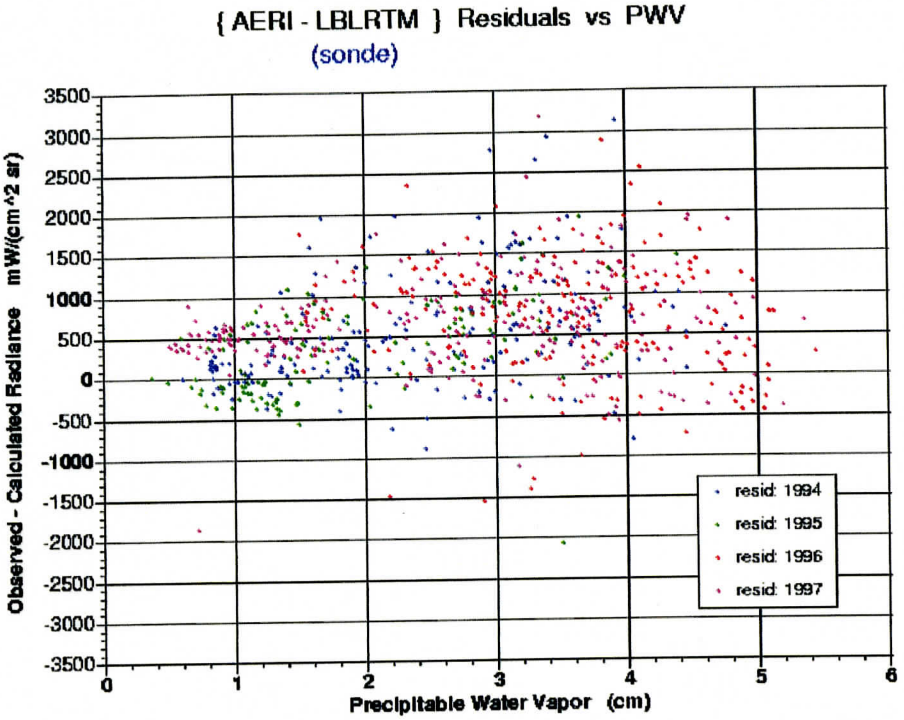


Figure 2. Integrated residuals between AERI measurements and LBLRTM calculations, using original sonde water vapor profiles as input, for transparent spectral elements in the 800-1200 cm^{-1} window as a function of column water vapor. The differing colors distinguish each year in the study.

C) O_3 Characterization Work

Based upon studies at shorter wavelengths using the Denver University Absolute Solar Transmittance Interferometer (ASTI) and SUNY-Albany Rotating Shadowband Spectroradiometer (RSS), there are indications that the characterization of ozone in the radiating path used in the AERI/LBLRTM QME is inaccurate. The current O3 profile was obtained from a three layer (stratosphere, troposphere, and boundary layer) retrieval of a single AERI observation using a standard minimum variance method. This work preceded the discovery of the water vapor characterization issue (as described above). Shortwave studies provide a constraint on the column ozone amount that was not available for the original retrieval. This constraint will be utilized in developing new climatological ozone profiles for the QME using AERI data.

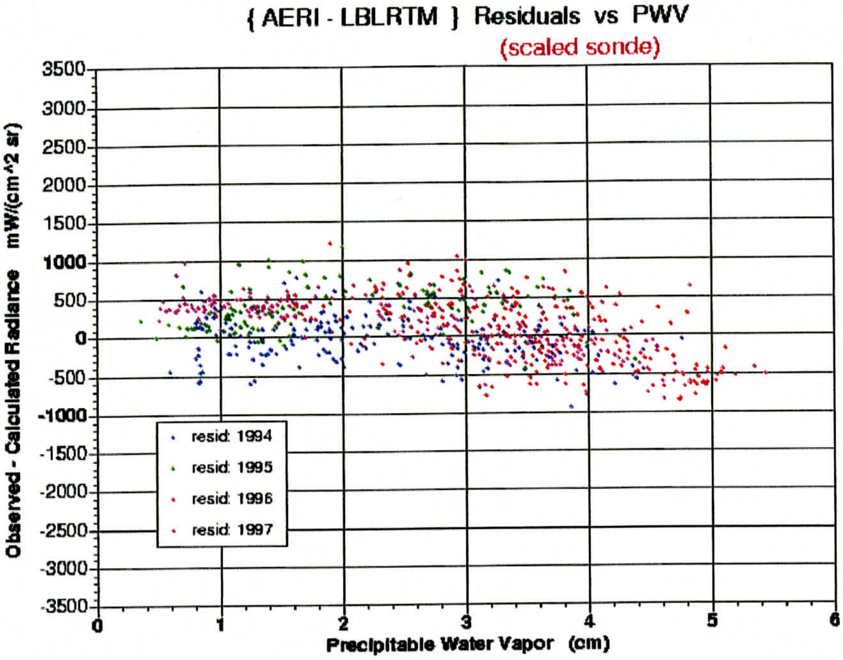


Figure 3. Integrated residuals between AERI measurements and LBLRTM calculations, using MWR-derived scaled sonde water vapor profiles as input, for transparent spectral elements in the 800-1200 cm^{-1} window as a function of column water vapor. The differing colors distinguish each year in the study.

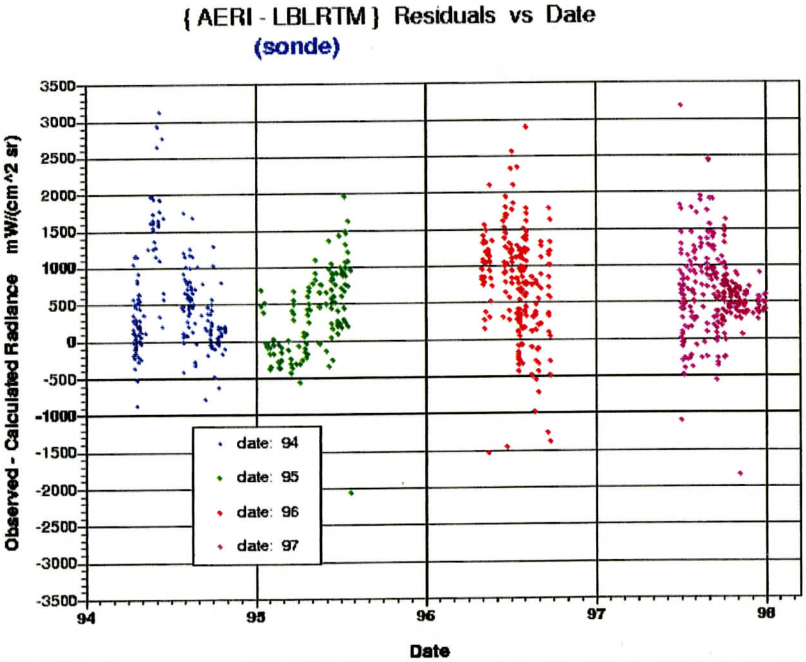


Figure 4. Integrated residuals between AERI measurements and LBLRTM calculations, using original sonde water vapor profiles as input, for transparent spectral elements in the 800-1200 cm^{-1} window as a function of time.

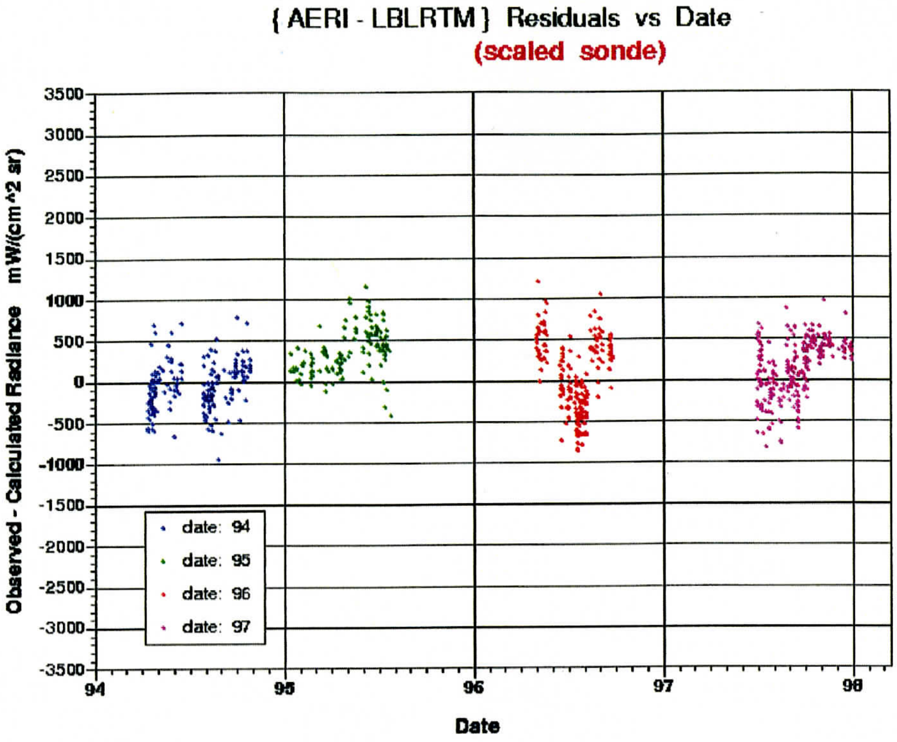


Figure 5: Integrated residuals between AERI measurements and LBLRTM calculations, using MWR-derived scaled sonde water vapor profiles as input, for transparent spectral elements in the 800-1200 cm^{-1} window as a function of time.

D) Improvement in Water Vapor Spectral Line Parameters and Retrieved Column Water Vapor

Progress has been made in the effort to characterize and utilize weak water vapor lines in the 8-12μm atmospheric window. The goal of this work is to improve the absolute accuracy of column water vapor derived from AERI-X and AERI radiances by improving our knowledge of the spectral parameters of these spectral lines and by creating an algorithm which properly accounts for the line-by-line transmittance forward model in the column water vapor retrieval. This work may also extend the vertical range of retrieved water vapor since these weak water lines see higher into the atmosphere. Such studies are also important for surface temperature/emissivity retrievals from down-looking AERI radiances and for satellite based retrievals. To date, we have begun to use AERI-X and AERI radiances to assess the absolute accuracy and relative consistency of the line strengths and Lorentz widths of these lines (using the HITRAN and JPL-extended databases) using selected stable, clear sky cases from the 1997 WVIOP. In doing so, we have identified a calibration anomaly in the AERI-X data and have developed a correction algorithm based upon comparisons with coincident AERI radiances. Assuming the column water vapor is known for these cases, we can also determine revised line parameters (strength, width product and line center) from the radiances. A preliminary algorithm for retrieving integrated column water vapor using these lines and the LBLRTM forward model has been developed. Studies to determine the sensitivity of the retrieval to baseline and continuum-like errors and ways to characterize the percentage of the total column the retrievals are sensing are underway.

3. Thermodynamic Profiling

Temperature and water vapor profiles within the planetary boundary layer calculated from AERI radiances at the SGP CART site central facility have been operational at Pacific Northwest National

Laboratory (PNNL) since July 1995. Retrieval differences for one year compared to radiosondes are approximately 1 K for temperature and 10% of absolute water vapor. Details about the retrieval technique have been published with this DOE grant support in Feltz 1998 and Smith 1999.

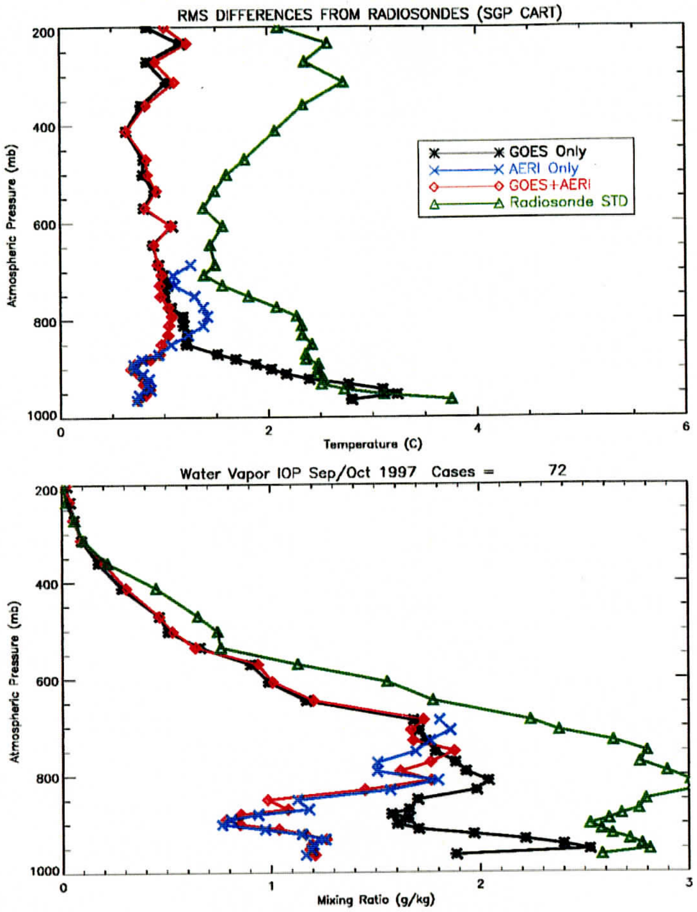


Figure 6: Rms differences from 72 radiosondes for AERI retrievals (X), GOES retrievals (black *), and AERI+GOES retrievals (light diamonds) for temperature (upper panel) and mixing ratio (lower panel) respectively during the 1997 Water Vapor IOP. The line with the triangles indicates a measure of meteorological variability of the temperature and water vapor. This is obtained by calculating the standard deviation of the radiosondes used within the statistics.

A significant improvement in retrieval accuracy above two kilometers has been achieved this year with the synergistic combination of Geostationary Operational Environmental Satellite (GOES) radiance derived soundings with ground based AERI radiances. Hourly GOES 3X3 retrievals (Hayden, 1988, Ma et al. 1998, Menzel et al. 1998) are routinely collected over the CART site at the Cooperative Institute for Meteorological Satellite Studies (CIMSS) and input to the ARM data stream. An AERI is located at the central facility in the CART site domain, measuring downwelling atmospheric infrared radiation from 3-20 μm at 0.5 cm^{-1} resolution every ten minutes. The GOES sounder radiances (Menzel and Purdom, 1994, Menzel et al., 1998) contain important information about the temperature and water vapor structure in the upper- and mid-tropospheric regions every hour. The AERI radiances have been used to successfully monitor the thermodynamic state of the Planetary Boundary Layer (0-2.5 km above the earth's surface) at the CART site (Feltz, et al., 1998). Because AERI profile sensitivity decays rapidly with altitude and GOES provides the highest quality space based meteorological information from geosynchronous orbit, a natural synergy is to combine their information to improve the sounding retrieval product.

Figure 6 indicates the AERI+GOES vs radiosonde differences for the ARM Second Water Vapor Intensive Operational Period (WVIOP). Retrieval root mean square (RMS) differences for GOES only (black), AERI only (blue), and GOES+AERI (red) are plotted for temperature and water vapor mixing ratio. During this period a radiosonde was launched once every three hours providing relatively high temporal profile validation. The standard deviation of the radiosonde temperature and mixing ratio are plotted in green as a measure of atmospheric variability of these two parameters. RMS differences, with respect to radiosonde observations, for GOES+AERI temperature retrievals have been shown to be approximately one Kelvin from the surface to 200 hPa from 72 concurrent radiosonde launches during the September/October 1997 WVIOP (Figure 6 upper panel). Notice that the combined product is an improvement over the AERI retrievals above 900 mb and over the GOES temperature retrieval between the surface and 900 mb. The combined product also improved the water vapor mixing ratio product of the GOES by greater than 1 g/kg during the WVIOP (Figure 6 lower panel).

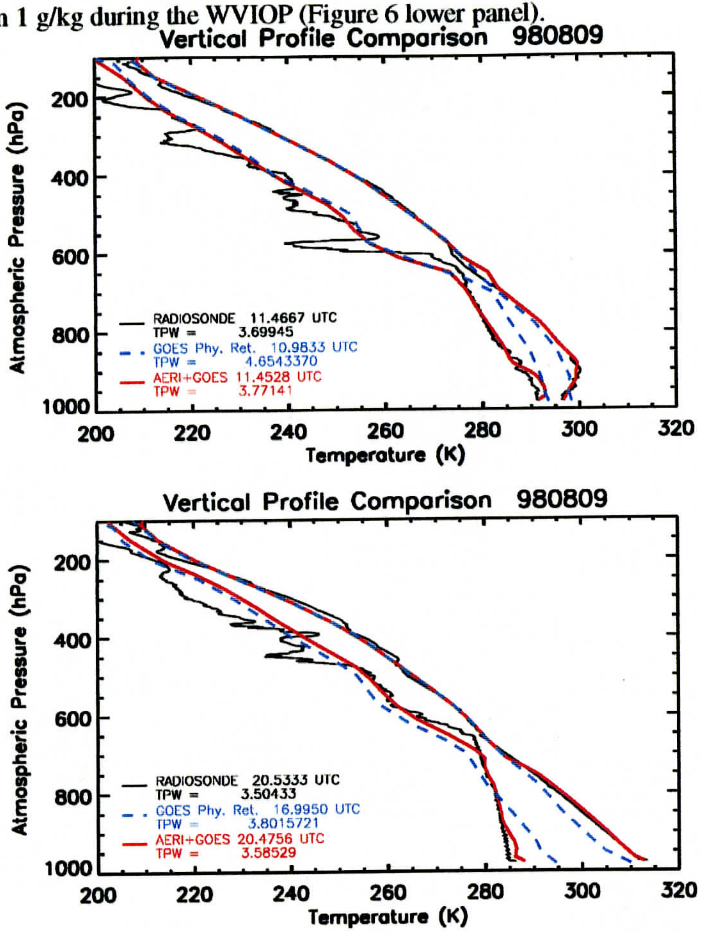


Figure 7: Two comparisons of a GOES and AERI+GOES physical retrieval to radiosonde over the ARM SGP CART on August 9, 1998.

Figure 7 gives an example of the improvement AERI offers to the GOES physical retrieval on August 9, 1998 at approximately 11:30 and 21 UTC over the ARM SGP CART site. The AERI radiance significantly improves the GOES retrieval in the planetary boundary layer (altitudes below 700mb) when compared to coincident ARM radiosonde observations. Whereas the radiosonde sounding is available at most every three hours the AERI+GOES product provides temperature and water vapor vertical profiles on a continuous, automated basis.

The CART Raman Lidar is offering an excellent source of validation for the AERI retrieval water vapor product since it is of similar time resolution and higher vertical resolution. Figure 8 shows a time cross section of water vapor from the CART Raman Lidar and AERI. A dryline passage occurred between 8 and 12 UTC indicating a similar drying within the boundary layer from top to bottom for both the passive and active retrieval techniques. Continual validation of the retrieval product has been conducted throughout the last year.

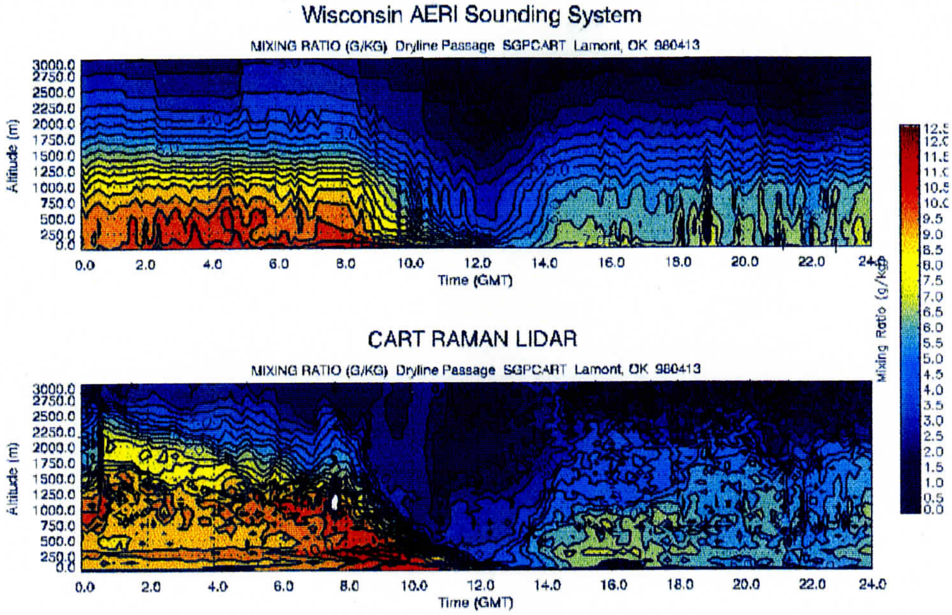


Figure 8: A time cross section of water vapor from AERI retrievals and the CART Raman LIDAR indicating a dry line passage between 8 and 12 UTC on April 13, 1998 at the SGP central facility near Lamont, Oklahoma.

The AERI-GOES retrieval algorithm technique has been implemented at PNNL and will be operational January 1, 1999. Five AERI systems are now in operation over the ARM SGP CART domain and the retrieval algorithm will produce profiles of temperature and water vapor every ten minutes through the troposphere. These data will be provided to the Single Column Model working group during the 1999 Winter SCM IOP at the SGP CART site. Currently a retrieval algorithm is being developed for the ARM NSA site and the Tropical Western Pacific (TWP) ARM site.

4. Cloud Microphysical Properties

The ability to derive cloud microphysical properties from AERI data has improved with the recent addition of cloud boundaries determined from CART micro-pulse lidar (MPL) measurements. A series of 18 microwindows were chosen to measure cloud emission within the infrared atmospheric window (8 to 12 μm) from the AERI data. These spectral regions represent the least contaminated portion of the atmospheric window, while providing ice absorption spectral characteristics which vary from weak to strong absorption across the atmospheric window. The resultant spectral optical depth signature is indicative of particle size, where smaller particles yield a greater variance in optical depth in regions of weak ice absorption. A similar approach can be applied to liquid water clouds. MPL derived cloud boundaries were required to properly invert the radiative transfer equation that represents the column of downwelling radiance measured by the AERI. CART radiosonde data provide atmospheric state measurements that are input to the LBLRTM to calculate the clear sky contribution in the atmospheric column. The remaining radiance represents the cloud contribution, located at a level and temperature determined by MPL and radiosonde measurements, respectively. Thus, the cloud optical depth is known, assuming uniform extinction between the cloud boundaries.

Retrieval of cloud optical depth from AERI measurements has progressed to the point where it is nearly fully automated. The retrieval requires a vertical temperature profile (radiosonde data) and clear sky atmospheric transmission profile (LBLRTM with radiosonde input) to invert the cloud optical depth. The AERI and MPL acquire data over a 24-hour period; therefore, radiosonde measurements and subsequent LBLRTM calculations must be interpolated to the AERI data acquisition frequency (roughly 10 minutes).

Each vertical profile (temperature and transmissivity) is interpolated to 50 m vertical resolution. Each profile is then interpolated in time to match the AERI measurement.

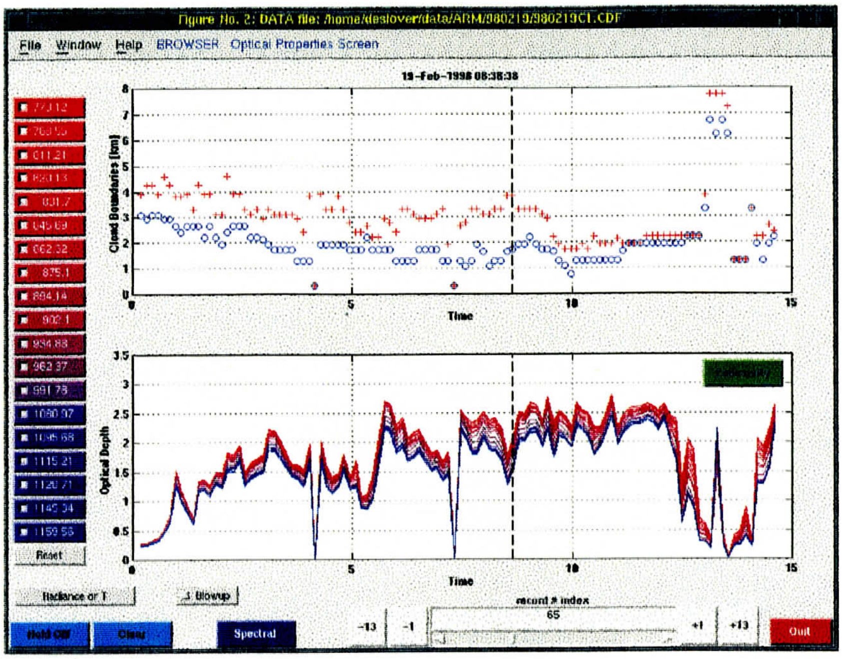
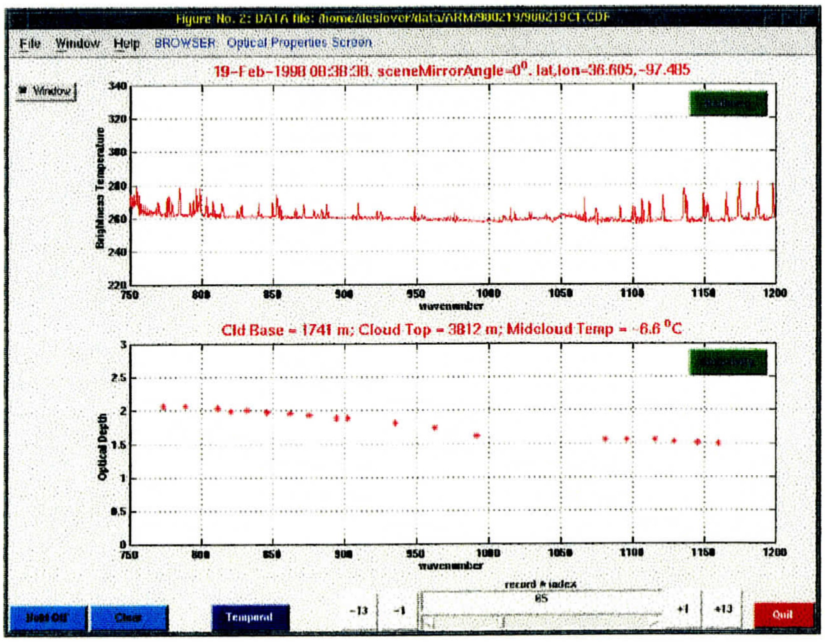


Figure 9: Micropulse LIDAR derived boundaries in upper plot and resultant AERI optical depths from 18 spectral microwindows in lower plot for February 19, 1998 at the SGP CART central facility.



19-Feb-1998 08:38:38, sceneMirrorAngle=0°, lat,lon=36.605,-97.485

Cld Base = 1741 m; Cloud Top = 3812 m; Midcloud Temp = -6.6 °C

Figure 10: AERI spectral data in upper plot was used to derived the optical depths shown in figure 9 for 0838 UTC. Lower panel indicates AERI/MPL derived optical depths for 0838 UTC.

Figure 9 illustrates the result of this procedure for data acquired over the SGP CART central facility on 19 February 1998. The upper plot shows MPL derived cloud boundaries (red cross, top; blue circle, bottom) as a function of time. The lower plot provides the resultant optical depth for each of the 18 spectral microwindows, which are color-coded in the legend (wavenumber, cm^{-1}). The figure was captured from a Matlab graphical user interface developed to easily observe the data. Figure 10 represents the spectral version of the data given by the dashed line in Figure 9, near 0838 UTC. AERI measured radiance is shown in the upper plot, while the cloud optical depth is given in the lower plot. The spectral variation in optical depth is due to particle size.

5. Future Goals

Future clear sky radiative transfer work includes (1) extension of the AERI/LBLRTM QME to the NSA site, (2) finalization and validation of the CKDv3.0 water vapor continuum model, and (3) incorporation of improvements in water vapor line parameters into a line database and the AERI/LBLRTM QME.

Goals planned within the next year for thermodynamic retrieval algorithm development include a) implementing an AERI+TOVS retrieval algorithm for the NSA and TWP CART sites since only polar orbiting satellite instruments can provide data over these areas, b) the addition of a higher resolution vertical forward model based upon LBLTRTM will be added to the retrieval algorithm to fully realize all information within the AERI radiance spectrum, and c) assimilation of the AERI+GOES retrievals into Single Column Models (SCM) are planned for several 1999 IOP periods. With the four additional AERI instruments deployed over the SGP domain, ten minute AERI+GOES retrievals could be used to observe the temporal variation of divergence/convergence of mass and moisture with the aid of wind profilers coincident with the AERI instruments.

The goals for cloud microphysical parameter research is to completely automate the procedure presented in part 4 of this paper and add cloud optical depth measurements to the ARM data stream as a value-added-product. The process required to make this transformation will begin during FY99. A discrete ordinance theory (DISORT) model will be used to generate an estimate of particle size. This procedure has been successful in determining effective radius from similar data acquired from aircraft (Sungii et al. 1998).

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