10 Years of AERI Data from the DOE ARM Southern Great Plains Site

R. O. Knuteson, F. A. Best, R. G. Dedecker,
W. F. Feltz, H. E. Revercomb, and D. C. Tobin
University of Wisconsin-Madison
Space Science and Engineering Center
Madison, Wisconsin

Introduction

As of January 2004, the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) data archive contained a 10 year record of downwelling infrared (IR) spectral emission measurements at the surface from the atmospheric emitted radiance interferometer (AERI) instrument. The authors have generated a monthly "climatology" of AERI spectral radiances for the 120 months from January 1994 through December 2003 for the DOE ARM Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) central facility (CF) in North Central Oklahoma. This AERI climatology addresses three primary objectives: 1) the investigation of the interplay among clouds, aerosols, and water vapor on the temporal and spectral variability of downwelling IR emission at the surface over multiple seasonal cycles, 2) the characterization of the data quality, accuracy, and completeness of the AERI archival data stream, and 3) the generation of a data product of monthly mean and standard deviations in spectrally averaged bins that will facilitate comparison with climate and weather model output. By confronting models with ARM observations, we can provide validation of improved cloud and radiation parameterizations in climate models. Comparison of the relative spectral content of AERI observations and model output is a particularly good way to distinguish among the competing processes that can lead to an increase (or decrease) in the ability of the atmosphere to trap outgoing thermal radiation (Ellingson et al. 1991; Ellingson and Wiscombe 1996).

Background

The first ground-based uplooking high spectral resolution IR measurements with good absolute radiometric calibration were obtained in 1988 as a part of the successful high-resolution interferometer sounder (HIS) instrument program within the University of Wisconsin Space Science and Engineering Center (UW-SSEC) (Smith et al. 1990). The development project for the AERI instrument began at the UW-SSEC in 1990 with an ARM science team grant and continued as part of the ARM Instrument Development Program (IDP) (Revercomb et al. 1991). The UW-SSEC engineering effort for the AERI instrument combined a reliable commercial interferometer from ABB/BOMEM, Inc. with automated calibration and data processing hardware and software developed at Wisconsin. The design of an operational AERI instrument was one of the key developments resulting from the early ARM IDP (Stokes and Schwartz 1994). The UW-SSEC built and provides ongoing calibration of all of the AERI systems deployed across the ARM sites. One prototype and eight operational AERI instruments were built for the DOE ARM Program. The AERI prototype instrument was first deployed to the DOE ARM SGP CF in March 1993. Site facility upgrades lead to nearly continuous data collection with the AERI prototype instrument by the beginning of 1994. The main limitation of the AERI prototype instrument was the use of a liquid nitrogen detector dewar (12 hour hold time) that required manual filling. In practice, the AERI prototype was only able to operate for less than 12 hours per day, mostly during the day-time, due to the need for operator intervention. However, there were several three-week intensive operating periods when the AERI prototype was operated in a quasi-24/7 mode. The data record for the AERI prototype instrument from April 1994 through July 1995 has been reprocessed to correct for an instrument misalignment that was discovered through inter-comparison with its replacement system. The AERI prototype data correction procedure is well documented in an ARM technical report (ARM TR-001.1); however, the AERI data record before July 1995 contains higher uncertainty than subsequent observations because of this data correction (Knuteson et al. 1999). The first truly automated AERI instrument (AERI-01) was installed as a replacement for the AERI prototype in July 1995. The AERI-01 system and all subsequent instruments use a mechanical cooler (Stirling cycle) to cool the IR detectors. The cooler requires replacement only at 1-2 year intervals. The data record from July 1995 to the present is a remarkably continuous 24 hours per day/7 days per week and stands as a testament to the robust engineering design of the AERI instruments.

The AERI is designed to have an absolute radiometric calibration of 1% (3-sigma) of ambient temperature radiance using "internal" reference sources built at UW-SSEC with traceability to National Institute of Standards and Technology standards. The AERI internal reference sources are viewed by the instrument every 10 minutes using an automated procedure to provide a continuously updated radiometric calibration. The calibration reference sources are designed to be easily removable to allow for periodic recalibration of the reference sources to monitor long-term calibration stability. The AERI measurement of the downwelling IR spectrum is at "1 wavenumber" (~0.48 cm^{-1} unapodized) spectral resolution from 520 cm^{-1} to 3020 cm^{-1} (3.3 to 19.2 μm). A total of 5000 spectral channels per spectrum were recorded at 8-10 minute intervals for the 10 year period. The spectral calibration (wavelength scale) is known to better than 0.3 ppm (3-sigma). The sky dwell of the standard zenith sky view is about 3.5 minutes within a conical beam of 15 mrad half angle. Further details of the design and calibration of the AERI systems can be found in Knuteson et al. 2004.

The AERI observes the downwelling atmospheric emission spectrum between 3.3 and 19.2 μm in two broad spectral bands, the "longwave" spectral band (LW: 520-1800 cm^{-1}) and the "shortwave" spectral band (SW: 1800-3020 cm^{-1}). Since thermal emission decreases with increasing wavenumber beyond about 500 cm^{-1}, splitting the measurement of the IR spectrum into two bands allows the signal to noise to be optimized for each measurement region. As a part of the operational AERI software developed by the University of Wisconsin, a number of summary variables are generated in real-time for each spectral band and included in the archival data stream. The results of a preliminary analysis of the AERI "summary" data products obtained from the ARM data archive are presented in the next section.

Results

One set of AERI summary products from the ARM archive includes wavenumber averages over very narrow regions of the IR spectrum; three in the LW band (675-680 cm^{-1}, 700-705 cm^{-1}, 985-990 cm^{-1}) and three in the SW band (2295-2300 cm^{-1}, 2282-2287 cm^{-1}, and 2510-2515 cm^{-1}). These wavenumber ranges are a measure of near surface air temperature, elevated air temperature, and IR window temperatures, respectively. Both radiance and equivalent blackbody brightness temperature are included in the ARM data archive for these summary products. The 675-680 cm^{-1} brightness temperature product is near the center of the carbon dioxide absorption band at 15 μm. The 2295-2300 m^{-1} brightness temperature product is similarly located within the 4.3 μm carbon dioxide absorption band. The 15 μm and 4.3 μm wavelengths are nearly opaque, making them good measures of the mean temperature within the first 30 meters of air above the instrument. In contrast, the 985-990 m^{-1} (10 μm) brightness temperature product is in a micro-window between absorption lines and is sensitive to the total column water vapor (through the gaseous water vapor "continuum" emission), the downwelling emission from water and ice clouds, and the contribution from the thermal emission of aerosols. In contrast, the 2510-2515 cm^{-1} (4 μm) micro-window has a strong sensitivity to aerosols and clouds during day-light hours due to the scattering of sunlight down into the zenith-looking AERI view, while water vapor emission has a relatively reduced impact. These summary products can be found in the "daily" ARM archive files. The variable names of the observed brightness temperature products in the ARM netCDF files are given in Table 1 for both the AERI prototype (January 1994-July 1995) and AERI-01 data files (July 1995-December 2003).

Table 1. Variable Names in the ARM netCDF Files for a Set of 5 cm^{-1} Width Products

AERI Prototype Product Name	AERI-01 Product Name
'wave_num_avg_BT_675'	'surfaceLayerAirTemp675_680'
'wave_num_avg_BT_700'	'elevatedLayerAirTemp700_705'
'wave_num_avg_BT_985'	'longwaveWindowAirTemp985_990'
'wave_num_avg_BT_2295'	'surfaceLayerAirTemp2295_2300'
'wave_num_avg_BT_2282'	'elevatedLayerAirTemp2282_2287'
'wave_num_avg_BT_2510'	'shortwaveWindowAirTemp2510_2515'

The time series of brightness temperature observations from the 15 μm and 10 μm (675-680 cm^{-1} and 985-990 cm^{-1}) summary products for the entire 10 year record of AERI observations is shown in Figure 1. This figure contains a plot of more than half a million unfiltered observations collected during the 10 year period between January 1994 and December 2003. Close inspection of Figure 1 shows a few gaps (due to instrument maintenance or power outages) and some obvious outlier points (requiring additional quality control). However, the most important first conclusion is that the AERI record from the ARM SGP CF site is remarkably complete and well suited for the development of a long-term spectral radiance climatology.

The seasonal cycle in near surface temperature is captured nicely in the 15 μm AERI brightness temperature product with a peak-to-peak variation of about 40 K from the coldest winter days to the warmest summer days. The 10 μm AERI brightness temperature has considerably more information content since it is a transparent window channel and "sees" the emitting temperature of the clouds, aerosols, and water vapor passing overhead. The upper envelope of the 10 μm time series also follows the seasonal cycle found in the near surface air temperature but without the large temperature extremes found in the 15 μm brightness temperature. The highest 10 μm temperature values are obtained from

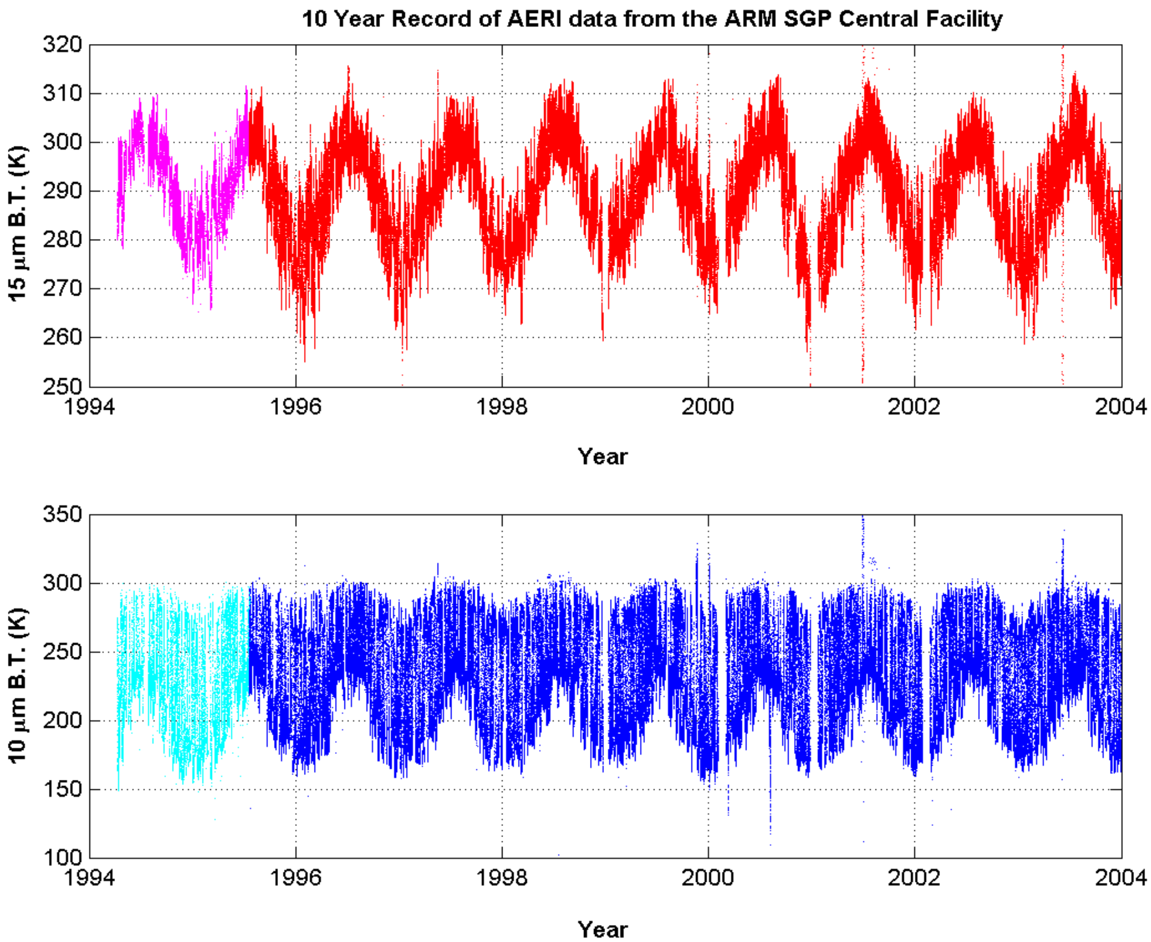

Figure 1. 10 years of unfiltered AERI observations, over half a million samples, from selected high spectral resolution channels at 15 μm (upper panel) and 10 μm (lower panel).

the base of low opaque clouds which often lie near the top of the atmospheric boundary layer at a height of only 1-2 km above the surface. The lower envelope of the 10 μm brightness temperature time series also shows a seasonal cycle with warmer brightness temperature in summer and colder temperatures in winter. The lowest 10 μm brightness temperatures at any time of the year are found during periods of cloud-free conditions where the only contributions to the emission are from the atmospheric emission of absorbing gases. The spectral region chosen for this 10 μm AERI summary product carefully avoids all significant atmospheric line structure so that the dominant emission source at the ARM SGP site is coming from the self-broadened water vapor continuum emission. Since the transmission in this spectral region is relatively high, the 10 μm AERI observed brightness temperature is sensitive to the emitting temperature of the entire column of atmospheric water vapor. The dramatic increase in the minimum observed 10 μm brightness temperatures at the ARM SGP site in the summer months compared to the winter months is caused by a large increase in column water vapor, a dominant part of the seasonal cycle at the ARM SGP site. Between the maximum and minimum observed brightness temperatures at 10 μm, the AERI brightness temperature observations show tremendous variability down to very short time scales. This is the impact of clouds passing over the narrow zenith field of view of the AERI instrument. The 10 μm downwelling radiance can go from maximum to minimum values from one eight minute sample interval to the next due to presence or absence of low opaque clouds (e.g., cumulus) in the AERI field of view. This can be clearly seen in an expanded view of the brightness temperature time series shown in Figure 2 for a 3-month period including the overlap of the AERI prototype and AERI-01 instruments in July 1995. Figure 2 also clearly shows the diurnal cycle of near surface air temperature in the 15 μm observed brightness temperature. Clouds in the middle and upper troposphere also contribute to the 10 μm downwelling radiance but with emission comparable to the colder temperatures of the atmosphere at the cloud base altitude. In summary, the upper and lower extremes of the observed downwelling 10 μm AERI brightness temperature are determined by the temperature of cloud base at the top of the atmospheric boundary layer and the effective emitting temperature of the water vapor emission during cloud-free conditions.

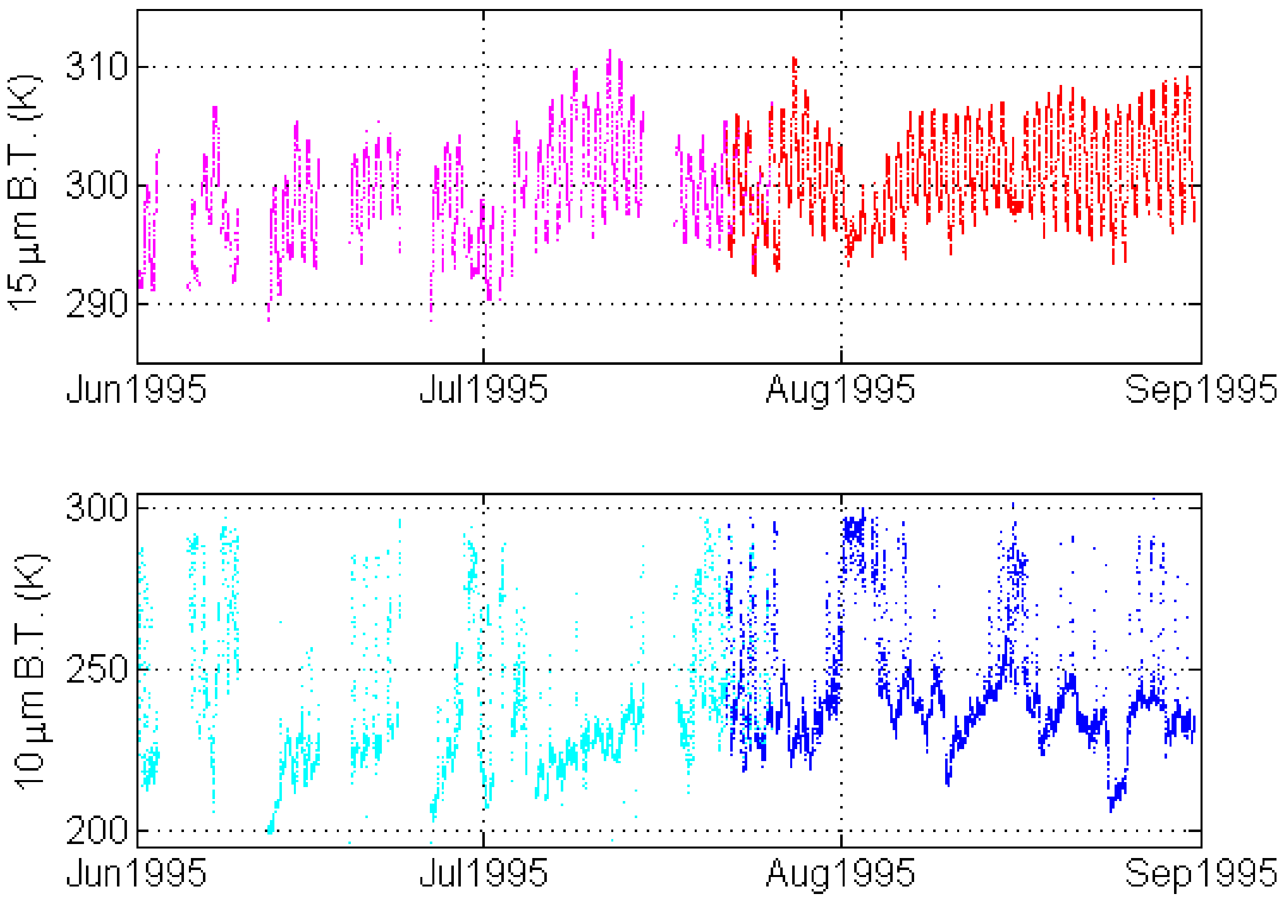

Figure 2. The AERI prototype instrument was replaced by the operational AERI-01 facility instrument in July 1995 leading to more continuous data collection at 10 minute intervals. Note the diurnal change in near surface air temperature seen in the 15 μm AERI observations and the rapid change in the 10 μm observations due the passage of clouds over the AERI zenith view of view.

To better illustrate the seasonal changes in downwelling radiation at the ARM SGP, the monthly mean and standard deviation of the 15 μm and 10 μm AERI summary products have been computed. A preliminary set of quality control flags was used to filter out bad or missing data and to remove cases where the instrument view port to the sky was closed due to precipitation. Figure 3 shows the same 10 year AERI time series found in Figure 1 but as a climatology of the mean and standard deviation of observed brightness temperature over each calendar month. The number of AERI observations used in the monthly statistics is shown in Figure 4 as a time series. Figure 4 shows that the number of useable observations approximately doubled from about 2500 to over 5000 per month after the AERI prototype instrument was replaced by the operational AERI-01 instrument in July 1995. The monthly mean 15 μm observed brightness temperature clearly shows the seasonal dependence of near surface air temperature with maxima in the summer months (June-July-August) and minima in the winter months (December-January-February). However, the standard deviation of the 15 μm observed brightness temperature within each month is relatively constant over time with only a weak seasonal variation. The opposite is true for the monthly statistics of the 10 μm observed brightness temperature which shows a strong seasonal dependence in the standard deviation but a somewhat "washed out" seasonal dependence in the mean. In particular, the monthly standard deviation for the 10 μm summary product has a pronounced minimum each summer when the water vapor total column is highest. This is consistent with the discussion describing Figure 1 which indicated that the difference between the maximum and minimum 10 μm observed brightness temperatures is smallest in the moist summer atmosphere and largest in the dry winter atmospheres. This is a modulating effect of the water vapor total column on the downwelling thermal radiation at the ARM SGP site.

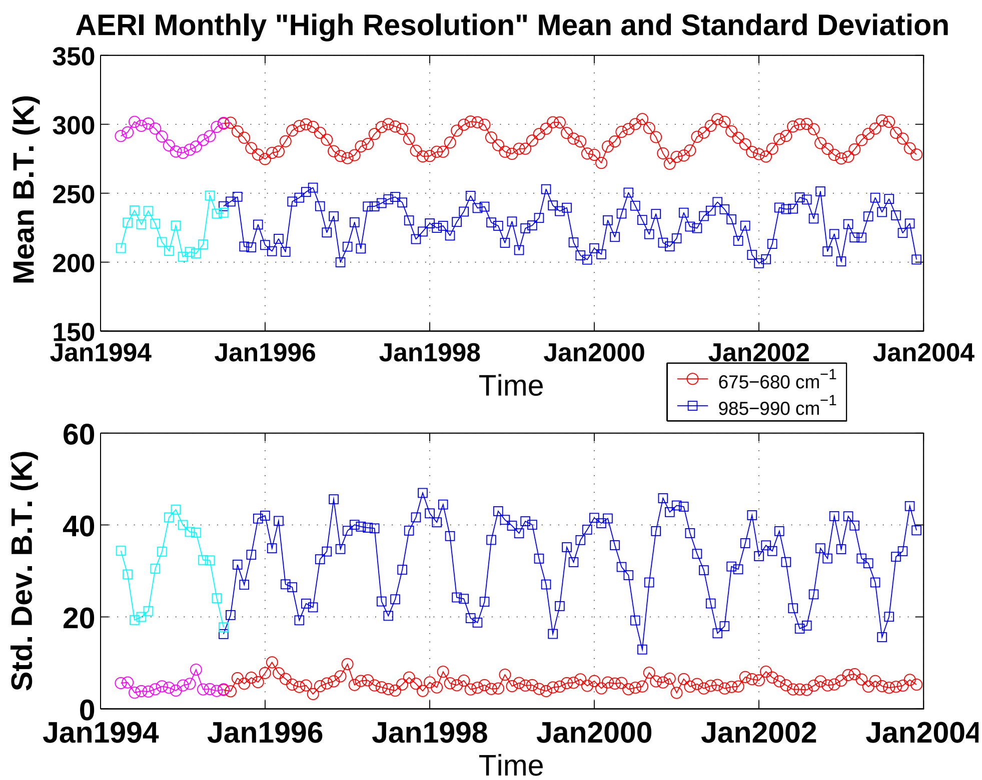

Figure 3. Monthly climatology of AERI observed brightness temperature at 15 μm (675-680 cm^{-1}) and 10 μm (985-990 cm^{-1}) quantifies the strong seasonal forcing of temperature, water vapor, and clouds.

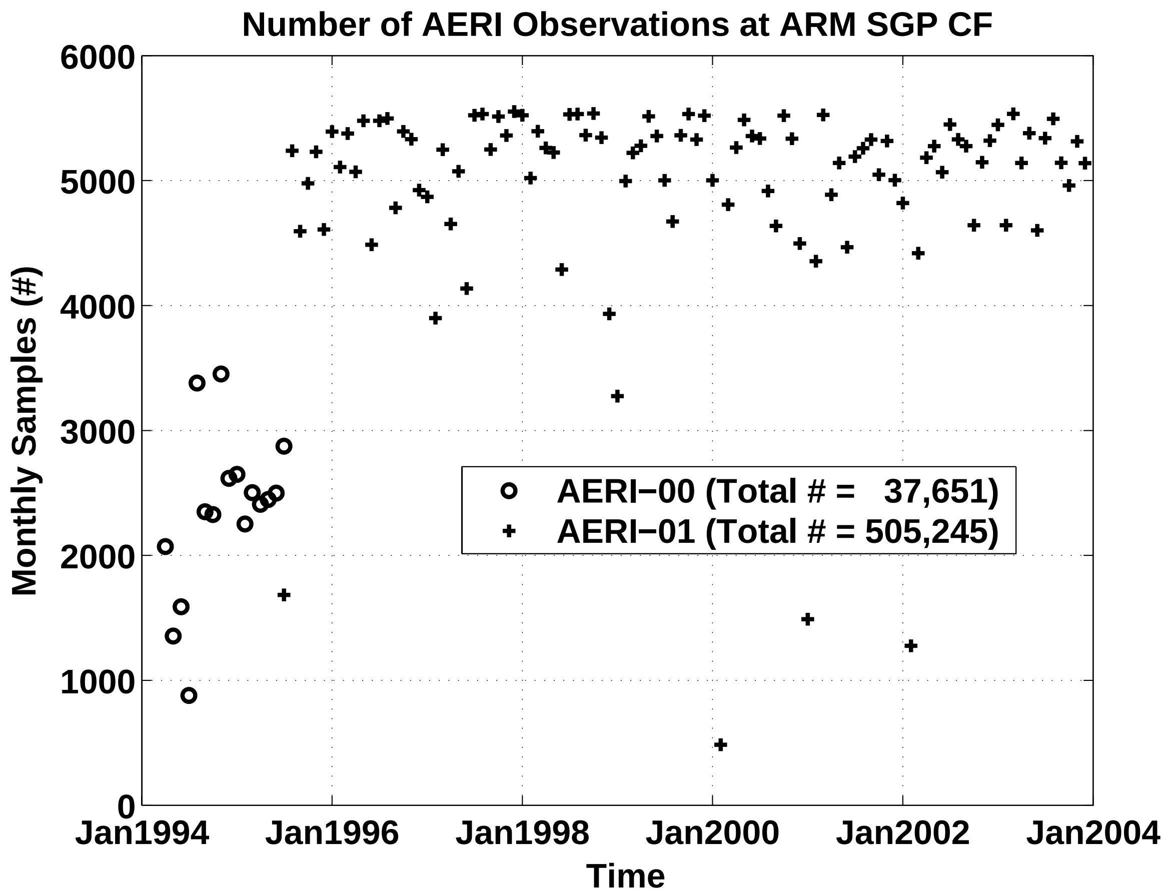

Figure 4. Time series showing the number of AERI observations included in the monthly statistics shown in Figure 3. The operational AERI-01 instrument replaced the AERI prototype (-00) in July 1995.

The previous figures show that the spectral content of the AERI observations can be used to quantify the complex interaction of clouds, water vapor, and aerosols on the downwelling emission at the Earth's surface. However the high spectral resolution of the AERI instrument (resolving power >1000) is beyond the simulation capability of current climate radiation models. In order to bridge the gap between high spectral resolution observations and low spectral resolution climate radiation models we have degraded the spectral resolution of the AERI observations into 25 cm^{-1} "bins," while maintaining the contiguous spectral coverage of the AERI observations from 3.3 to 19.2 μm. In fact, this "binning" capability was built into the operational AERI-01 instrument by the University of Wisconsin as a part of the real-time data processing software and the products are included in the daily summary product file. The ability to produce this spectrally binned radiance product while maintaining the high absolute radiometric accuracy and long-term stability of the radiance product is one of the most important contributions that the AERI instrument can make to the ARM Program. Figure 5 shows the AERI radiance measurements reduced to 25 cm^{-1} wavenumber bins for summer (JJA) and winter months (DJF) averaged over the eight year record of the AERI-01 instrument from July 1995 through December 2003.

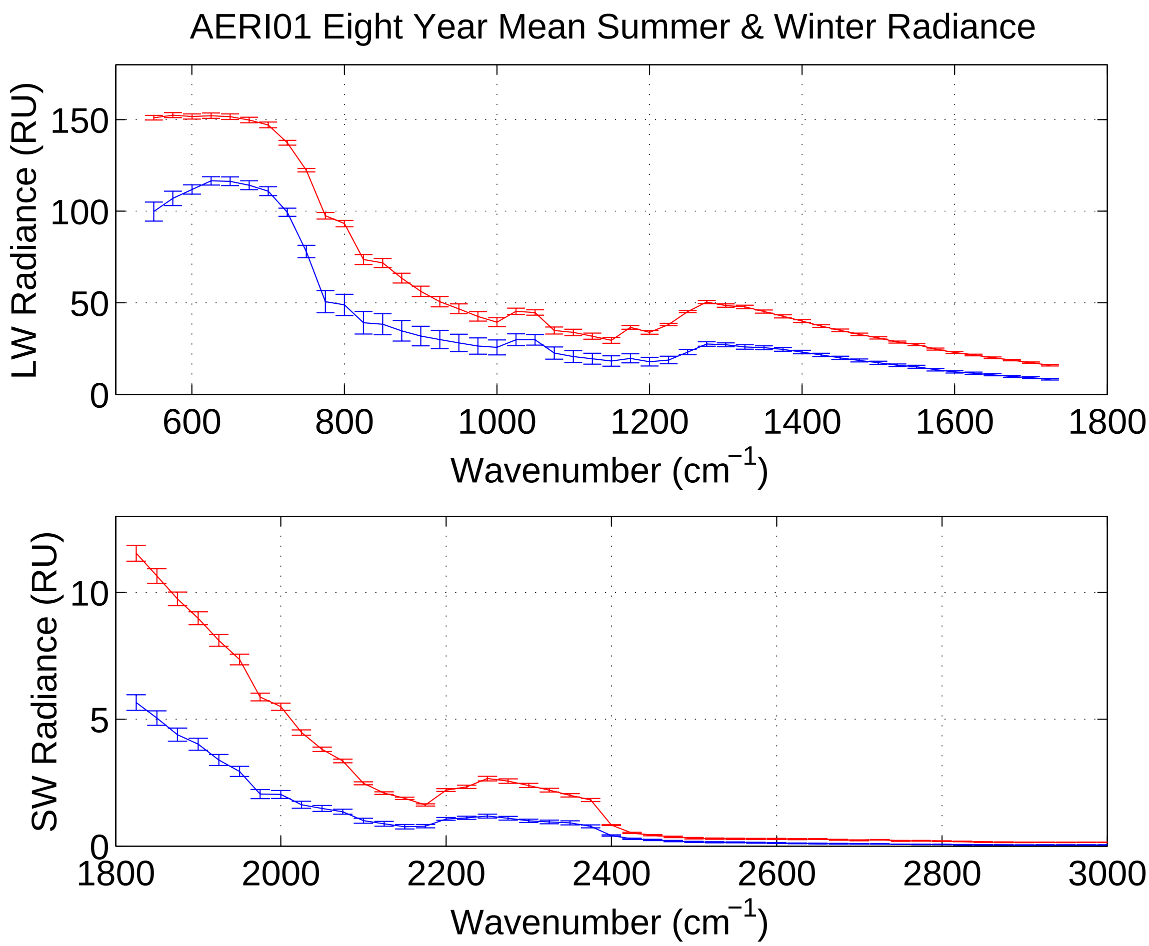

Figure 5. AERI-01 spectral observations spectrally reduced to 25 cm^{-1} wavenumber bins for the summer (JJA) months (shown in red) and the winter (DJF) months (shown in blue) at the ARM SGP CF site. The error bars are the standard deviation among the eight summers (and eight winters) from 1995 through 2003.

The error bars shown in Figure 5 are the inter-annual variation of the summer months and similarly for the winter months over this 8 year period. It is worth noting that the summer and winter (3 month) averages have a relatively small inter-annual standard deviation in radiance, indicating that the summer and winter mean downwelling radiance at the ARM SGP site is fairly consistent from year to year. Figure 5 also shows that the mean summer radiance is about a factor of 1.5 to 2 times larger than the mean winter radiance. The fractional change in AERI observed radiance relative to the 8 year mean AERI observed radiance is shown in Figure 6 as a time series from July 1995 through December 2003. The points in Figure 6 are computed by integrating the “binned” radiances over the AERI spectral bands. The 8 year mean AERI-01 radiance has a spectrally integrated value of 61.3 W/(m^2 sr) for the spectral ranges shown in Figure 5 (LW: 59.3 W/[m^2 sr] and SW: 2.0 W/[m^2 sr]). As shown in Figure 6, the peak-to-peak seasonal variation in the spectrally integrated LW band is approximately 50% of the 8 year mean value. The fractional variation is larger in the SW band as a percentage although the total

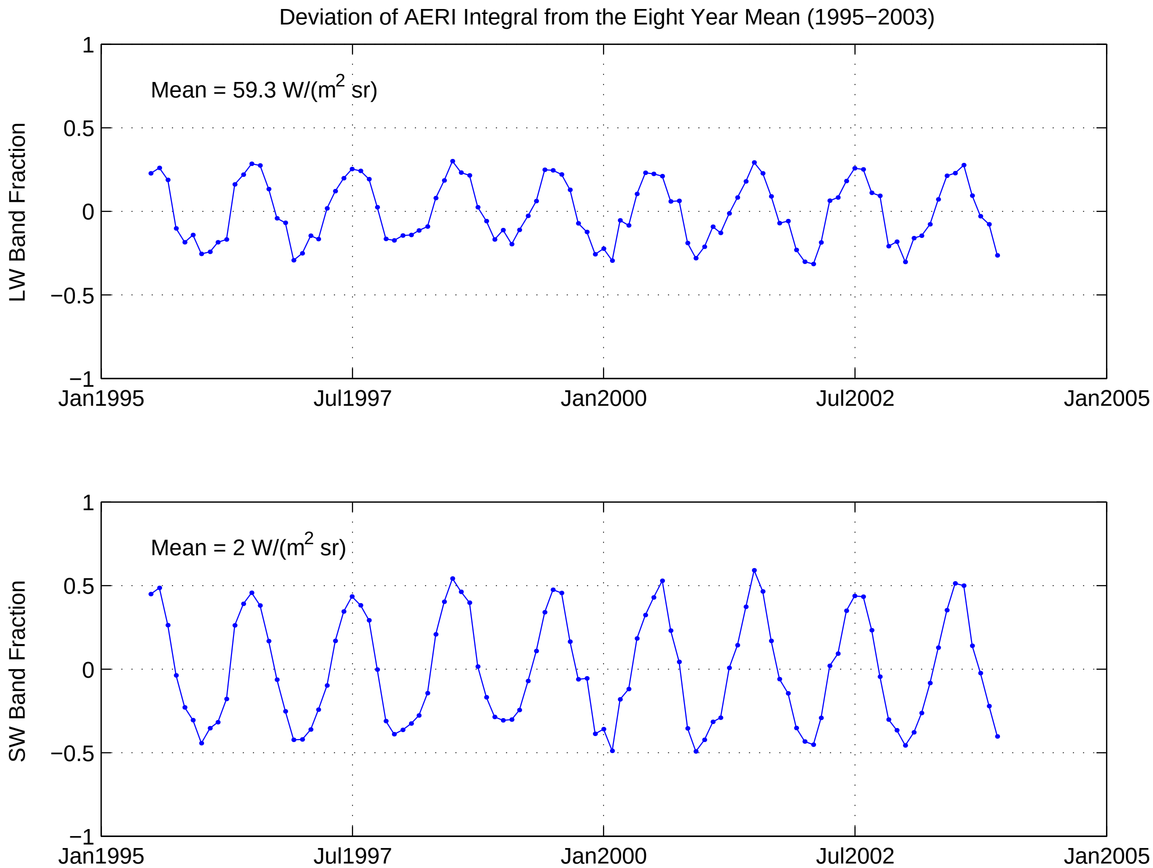

Figure 6. The spectral integral for the AERI LW band (upper panel) and SW band (lower panel) plotted as a fractional deviation from the eight year mean (1995-2003).

integrated radiance contribution is fairly small, i.e., 2 W/(m^2 sr) out of 61.3 W/(m^2 sr). There is no obvious long-term trend in the AERI data from the ARM SGP site over this 8 year period, though this will be quantified in subsequent analysis.

Conclusions

The AERI was one of the first instruments developed under the DOE ARM IDP to be deployed to the first CART SGP CF site near Lamont, Oklahoma. A prototype AERI was deployed in March 1993, where it collected data until the first AERI operational instrument replaced it in July 1995. The ARM archive contains AERI data from the ARM CART SGP CF site from January 1994 to the present. More than half a million AERI spectral radiance observations were collected at the ARM SGP CF during the 10 year period from January 1994 through December 2003. The AERI record allows a "climatology" to be developed that provides unique insight into the atmospheric distribution of energy by wavelength. In particular, the seasonal dependence of the IR window radiation clearly shows that the cloud forcing at the surface (as measured by the monthly standard deviation) is reduced by the presence of high water vapor amounts during the summer.

The following preliminary conclusions can be drawn from analysis of the AERI time record at the ARM SGP CF in North Central Oklahoma:

- The monthly mean brightness temperature at 15 µm shows a seasonal dependence with a peak-to-peak variation of about 40 K from the warmest summer days to the coldest winter days. This wavelength is sensitive to the near surface air temperature (lowest 30 meters).

- The minimum brightness temperatures at 10 µm show a strong seasonal dependence with high values each summer and low values each winter. This is due to the increase in column water vapor during the summer months, which leads to increased continuum emission in summer and reduced emission in winter.

- The monthly standard deviation of the 10 µm brightness temperature is large (20-40 K) and shows a strong seasonal dependence with the minimum variance in the summer and maximum in the winter. This is due to the greater impact of downwelling cloudy radiance in the relatively dry winter atmosphere than in the moist summer months where water vapor emission provides a large downwelling emission even during clear sky periods.

- AERI high spectral observations have been reduced to 25 cm^{-1} wavenumber bins which cover the IR spectral region from 3.3 to 19.2 µm. This spectrally binned radiance product is designed to facilitate comparison with radiation codes used in climate models.

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Corresponding Author

R. O. Knuteson, Robert.knuteson@ssec.wisc.edu

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