Infrared Land Surface Emissivity in the Vicinity of the ARM SGP Central Facility

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Introduction

The University of Wisconsin Space Science and Engineering Center (UW-SSEC) has developed, under National Aeronautics and Space Administration (NASA) funding, a model for the infrared land surface emissivity (LSE) in the vicinity of the U.S. Department of Energy's (DOE) Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) Central Facility (CF) in North Central Oklahoma. The UW-Madison LSE model is part of the ARM best estimate validation product developed under the NASA atmospheric infrared sounder (AIRS) science team project of H. Revercomb and is being used in the validation of both Atmospheric Infrared Sounder (AIRS) and moderate-resolution imaging spectroradiometer (MODIS) satellite products (Tobin 2003, Revercomb 2003). This paper describes the development of the UW-Madison LSE model for the ARM SGP site and a preliminary comparison to satellite observations from the NASA Aqua platform.

Background

The remote sensing of land surface temperature from satellite requires a detailed knowledge of infrared LSE. Roughly speaking, a 2% error in the knowledge of the land surface emissivity near 10 microns leads to an error in the derived surface temperature of about 1 Kelvin. Since the emissivity of bare soil can vary across the infrared spectrum by 10% or more, errors in the remote sensing of surface temperature from satellites can be substantial. In order to improve our knowledge of the spectral dependence of the infrared land surface emissivity in the vicinity of the ARM SGP CF, the UW-SSEC developed a model of the LSE across the infrared window regions (from 3.3 to 14 μm) at high spectral resolution (1 wavenumber). The current LSE model was created in April 2001 based upon a long series of UW aircraft and ground-based measurements near the ARM CF site extending back to 1996.

Theory

This paper will follow the theory outlined in Knuteson 2003. The cloud-free radiative transfer equation, neglecting solar radiation and scattering effects, for a downlooking infrared sensor viewing a homogeneous surface is

$$I_\nu = \int_0^Z B_\nu[T(z)]\frac{\partial\tau_\nu(z,Z)}{\partial z}dz + \varepsilon_\nu \cdot B_\nu(T_S)\cdot\tau_\nu(0,Z) + (1-\varepsilon_\nu)\cdot\tau_\nu(0,Z)\int_\infty^0 B_\nu[T(z)]\frac{\partial\tau_\nu(z,Z)}{\partial z}dz,$$

where I_ν, ε_ν, B_ν, T_S, $\tau_\nu(z_1,z_2)$, Z, and $T(z)$ are observed spectral radiance, spectral emissivity, spectral planck function, the surface temperature, spectral transmittance at wavenumber ν from altitude z_1 to z_2, sensor altitude and air temperature at altitude z, respectively. The first term of the equation is the emission from the atmosphere above the surface, the second term is the direct emission from the surface that reaches the sensor, and the third term is the downwelling atmospheric emission reflected off the ground under the approximation of a lambertian surface. The radiative transfer equation applies at monochromatic resolution and has been accurately implemented in several line-by-line radiative transfer models. The equation has also been applied successfully to observations of infrared emission at high spectral resolution (Bower 1999, Knuteson 2003).

Results

The UW LSE model for the vicinity of the ARM SGP CF was developed using three key elements; (1) UW on-site ground surveys of land cover and land use, (2) UW ground-based surface emissivity measurements, and (3) UW aircraft-based surface emissivity measurements.

The land cover of the region containing the ARM SGP CF is dominated by agricultural land use. The local landowners balance cattle ranching with the cultivation of wheat and other grain crops. This land use combines with the relatively small quarter-mile to half-mile square dimensions of farm fields to produce a very heterogeneous land cover distribution. In an attempt to understand and characterize the land cover distribution, the UW conducted in situ ground surveys in November 2000, March 2001, June 2002, and November 2002 (Osborne 2003). Figure 1 shows the survey region, a nine-mile (15-km) square grid including the ARM CF. Visual observations of vegetation cover and land type were used to generate distributions according to land use classifications. The comparison of the June 2002 survey to the 1992 U.S. Geological Survey (USGS) database of this region is also shown in Figure 1. Several important generalizations were drawn from these site surveys. First, the two dominant land cover types in this region are pasture and grains (25% and 64% respectively in June 2002). The cattle ranchers maintain pasture lands that are multi-year grasslands. Since grassland covers the underlying soil (when not subject to overgrazing), the grassland areas are effectively 100% vegetated all year round. In contrast, the grain production is dominated by winter wheat cultivation. Winter wheat is planted in the autumn (September-November), rapidly grows to a height of 3 to 6 inches but goes dormant over winter (December to March) and continues growth in the spring (April-May) ending up with a harvest in mid summer (June-August) at which point the cycle repeats. This growth cycle leads to a period in the autumn of each year when large areas of bare soil are exposed for planting. During the winter, the dormant wheat plants are too small to completely cover the underlying soil. This leads to a fairly constant fractional vegetation cover from November through March. From April through early summer the entire spatial domain is largely covered with vegetation. This understanding of the land use in the region of north central Oklahoma is the basis of the coarse model of fractional vegetation cover by season shown in Figure 2. This coarse model of time variation was introduced in April 2001 at the time the UW LSE model was created with the intention of replacing eventually replacing it with a model based on satellite observations. Refinements to this model are the subject of active research.

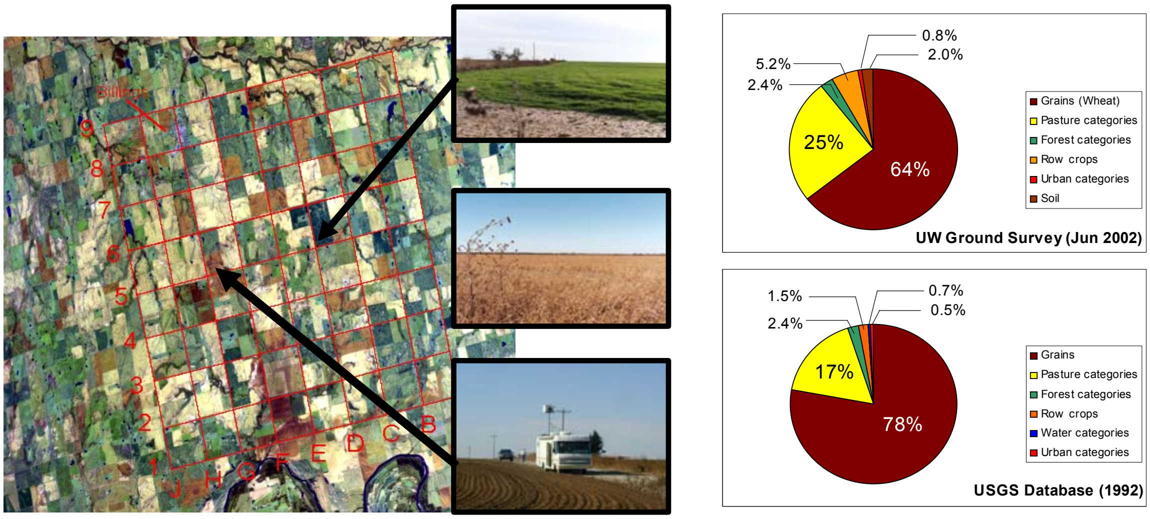


Figure 1. On site surveys have been conducted by UW-SSEC personnel in order to characterize the distribution of land cover in vicinity of the ARM SGP CF near Billings, Oklahoma. The survey grid is superimposed on a MODIS Airborne Simulator image from March 31, 2001 (North is down on the image). The June 2002 survey results are compared to the 1992 USGS database. Pasture land and wheat fields are the two dominant land cover types.

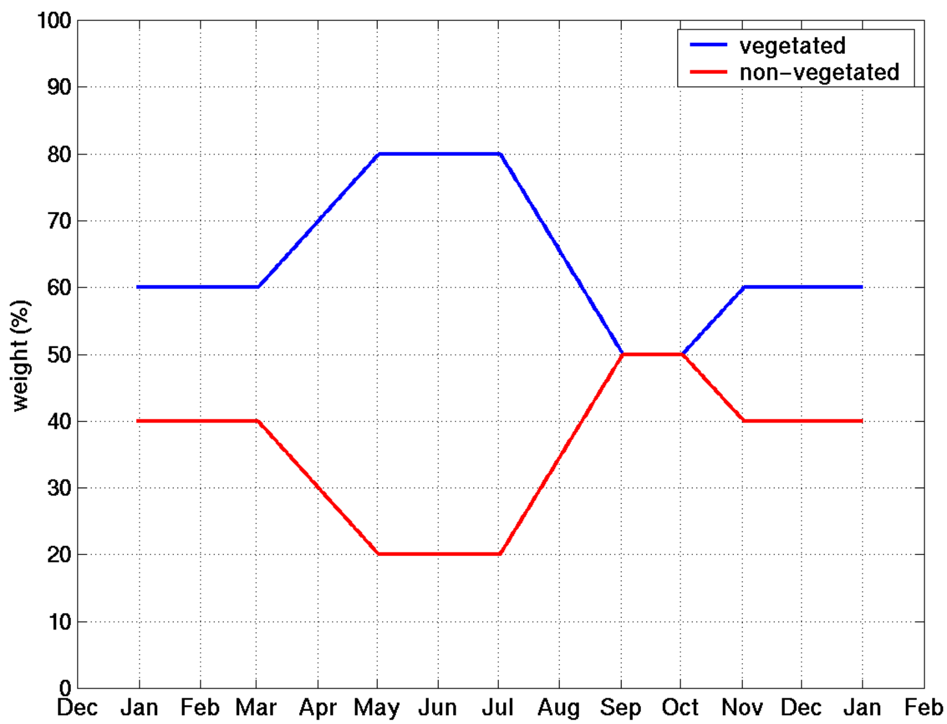


Figure 2. A coarse model of fractional vegetation cover as a function of season used in the UW LSE model (v.APR2001). The time variation is based upon the agricultural growth cycle typical of winter wheat production in North Central Oklahoma. Aircraft observations in November, March, and June were used to estimate the fractional weighting. Improvement of this empirical model is a subject of ongoing research.

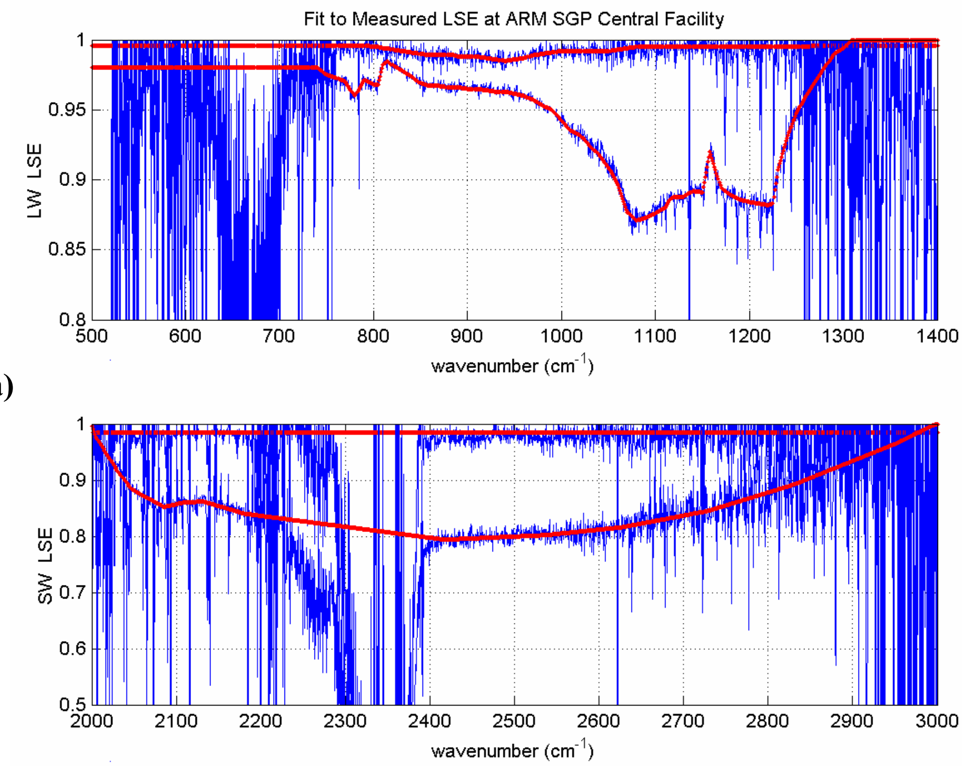
The high spectral resolution infrared LSE measurements used in the UW model were collected during ground surveys conducted by the University of Wisconsin - Madison on October 6, 1997, and November 30, 2000, in the vicinity of the ARM SGP CF and subsequently repeated in 2001 and 2002. The measurements of LSE were made using the Scanning-Atmospheric Emitted Radiance Interferometer (S-AERI) from a mobile research vehicle (AERIBAGO). The ground-based measurements of pure scene type have been described previously (Knuteson 2001a, 2001b). Figure 3 shows the smooth fit to the spectral emissivity measurements of two pure scene types. The vegetation is represented by measurements of pasture, i.e., a dry grass canopy. The bare soil measurements have been repeated at various locations within a 10 kilometer radius of the ARM SGP CF. The fit to (dry) bare soil shown in Figure 3 is representative of the measurements in the vicinity of the CF. Note that the measurements in the shortwave region were made at night to avoid solar contamination effects. One of the important conclusions drawn from repeated measurements of the ground-based surface emissivity measurements at the SGP ARM site is the reproducibility of the bare soil infrared emissivity spectral signature in the vicinity of the ARM SGP CF. The implication of this spatial uniformity in the bare soil emissivity is that the average emissivity viewed from satellites (or high altitude aircraft) can be simply represented as a fractional weighting of emissivity of pure scene types; vegetation (grasses) and bare soil. In other words, the infrared scene in the region of the ARM SGP CF would be fairly uniform if not for the variability in vegetation which blocks emission from the underlying soil surface. The spatially averaged seasonal change in the vegetation cover used in the UW LSE model (April 2001 version) is that shown in Figure 2.

High altitude aircraft observations have been used to estimate the spatially averaged land surface emissivity over a 15 km region centered at the SGP ARM CF. The 15 km spatial domain is chosen to match the satellite footprint of the NASA AIRS instrument on the EOS Aqua platform. Aircraft observations from the UW Scanning High-resolution Interferometer Sounder (similar to the ground-based AERI instrument) as well as observations from the NASA NPOESS Atmospheric Sounder Testbed – Interferometer (NAST-I) have been collected over several field campaigns. A complete analysis of one of these observation cases can be found in Knuteson 2003. Figure 4 shows the result of fitting the UW LSE model pure emissivity scene types to a spatially averaged emissivity obtained from aircraft observation over the ARM SGP site during the TX-2001 experiment in March 2001. Similar results were obtained during the ARM-FIRE Water Vapor Experiment (AFWEX) in November 2000 from both the Scanning HIS and the NAST-I (Tobin 2002). Analysis of these aircraft observations has been used to set the vegetation fraction values in Figure 2. Analysis of aircraft observations from other field experiments, including IHOP in June 2002, will provide further validation of the UW LSE model. Ultimately, satellite observations will be used in place of aircraft observations to characterize the time dependence of the UW LSE model.

Conclusions

The model of infrared LSE developed by UW-SSEC for the ARM SGP CF is being used in the validation of radiance observations by the NASA MODIS and AIRS instruments. Recent results suggest that even the crude time dependence of the current LSE model provide substantially better agreement with observations than assuming unit emissivity. As an illustration of this point, Figure 5 shows an average of six AIRS observations near the ARM SGP CF on November 16, 2002

(a)



(b)

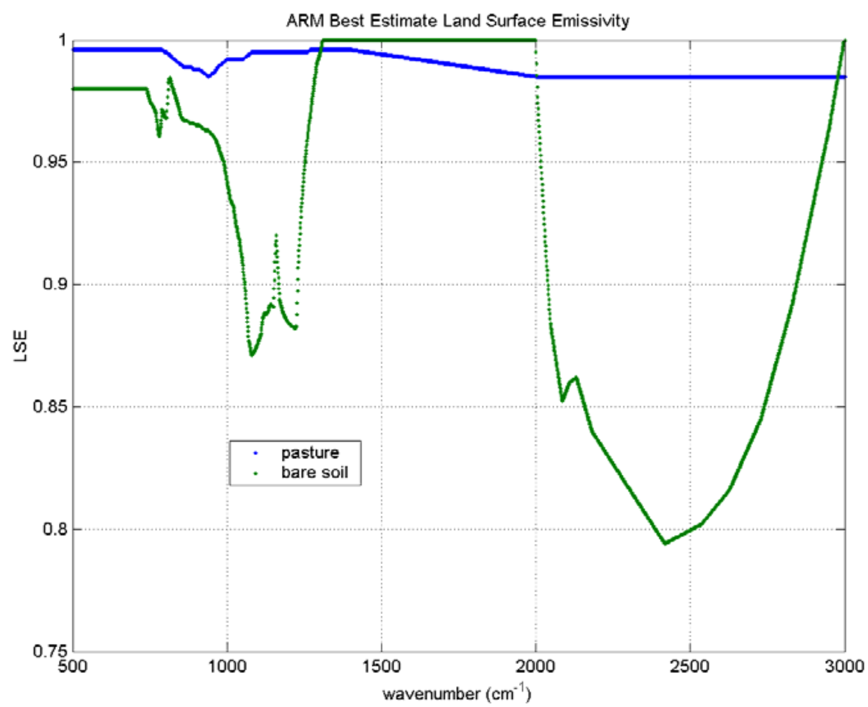


Figure 3. Fit to measured land surface emissivity near the ARM SGP CF (a). The fit (red curve) is to night-time observations of grass vegetation canopy (pasture) and bare soil by the UW Scanning-AERI system collected near the ARM CF on October 6, 1997 and November 30, 2000. The two dominant emissivity types used in the UW LSE model are shown in (b).

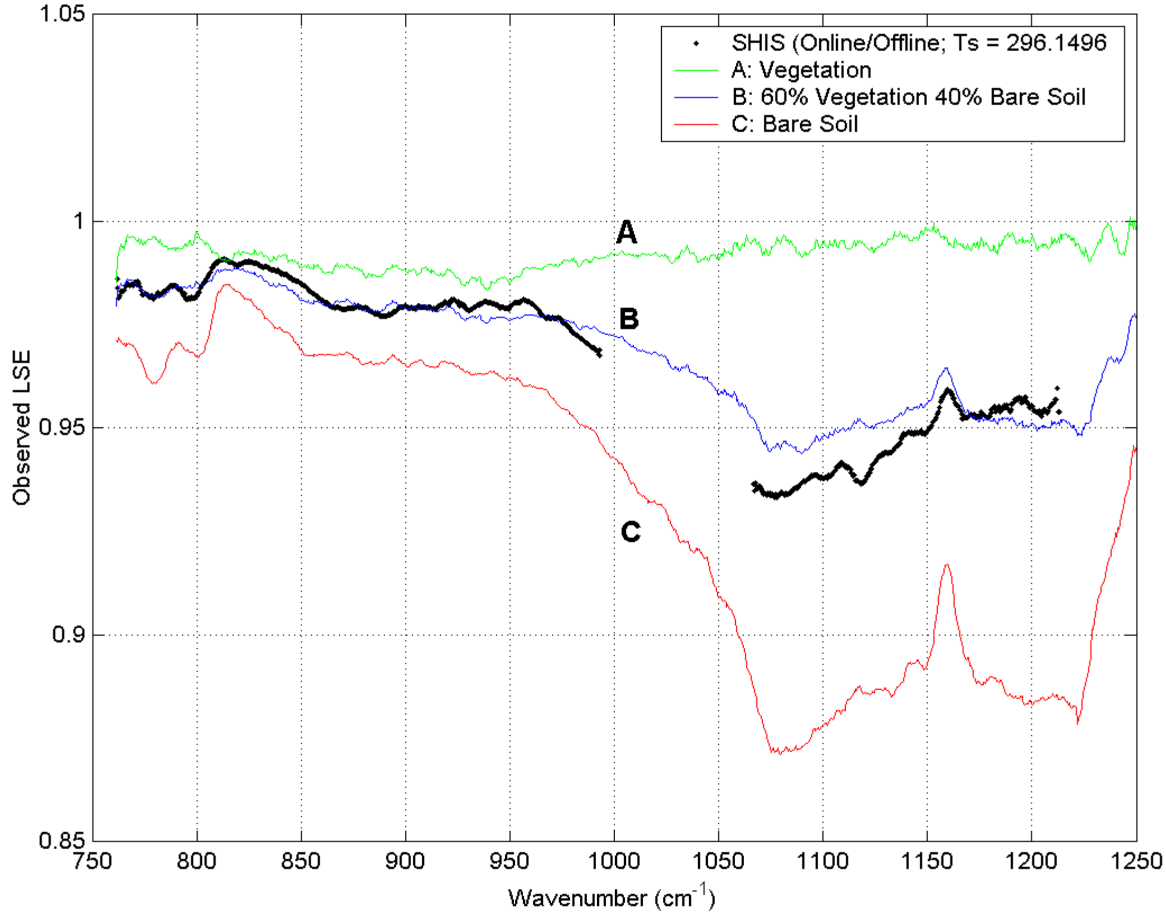


Figure 4. Determination of effective vegetation cover fraction using aircraft observations of upwelling radiance from the UW Scanning HIS interferometer averaged over a 15 km region in the vicinity of the ARM SGP CF. The observations were collected from the NASA high altitude ER-2 aircraft on March 31, 2001, during the Terra Experiment-2001 (TX-2001) (Moeller 2001). A 60% vegetation and 40% bare soil weighting was determined for this case. Similar values were obtained from observations during the AFWEX in November 2000. The gap in the Scanning HIS observations from 990 to 070 cm^{-1} is due to contamination by ozone absorption. The UW LSE model is able to reproduce (i.e., "fit") the spatially averaged aircraft measurements to within 1% across the 8 to 14 μm window region using a linear combination of just two pure scene types.

compared to two line-by-line calculations. The observations and calculations are shown in units of equivalent blackbody temperature (brightness temperature) to simplify the interpretation of the results. The first calculation (using LBLRTM v6.01 and HITRAN2000) assumes the surface has unit emissivity (LSE = 1) for all wavelengths. The second calculation uses the UW model LSE as defined by Figure 3 with the weighting of 60% vegetation and 40% bare soil given in Figure 2 for the month of November. The results shown in Figure 5 illustrate that use of the current version of the UW LSE model reduces the brightness temperature errors substantially over calculations that ignore the effect of surface emissivity. Similar improvements have been seen in comparison with NASA MODIS spectral channels. This result has implications both for the interpretation of satellite observations over the SGP CART site and for accurate modeling of upwelling infrared radiation within the ARM Program.

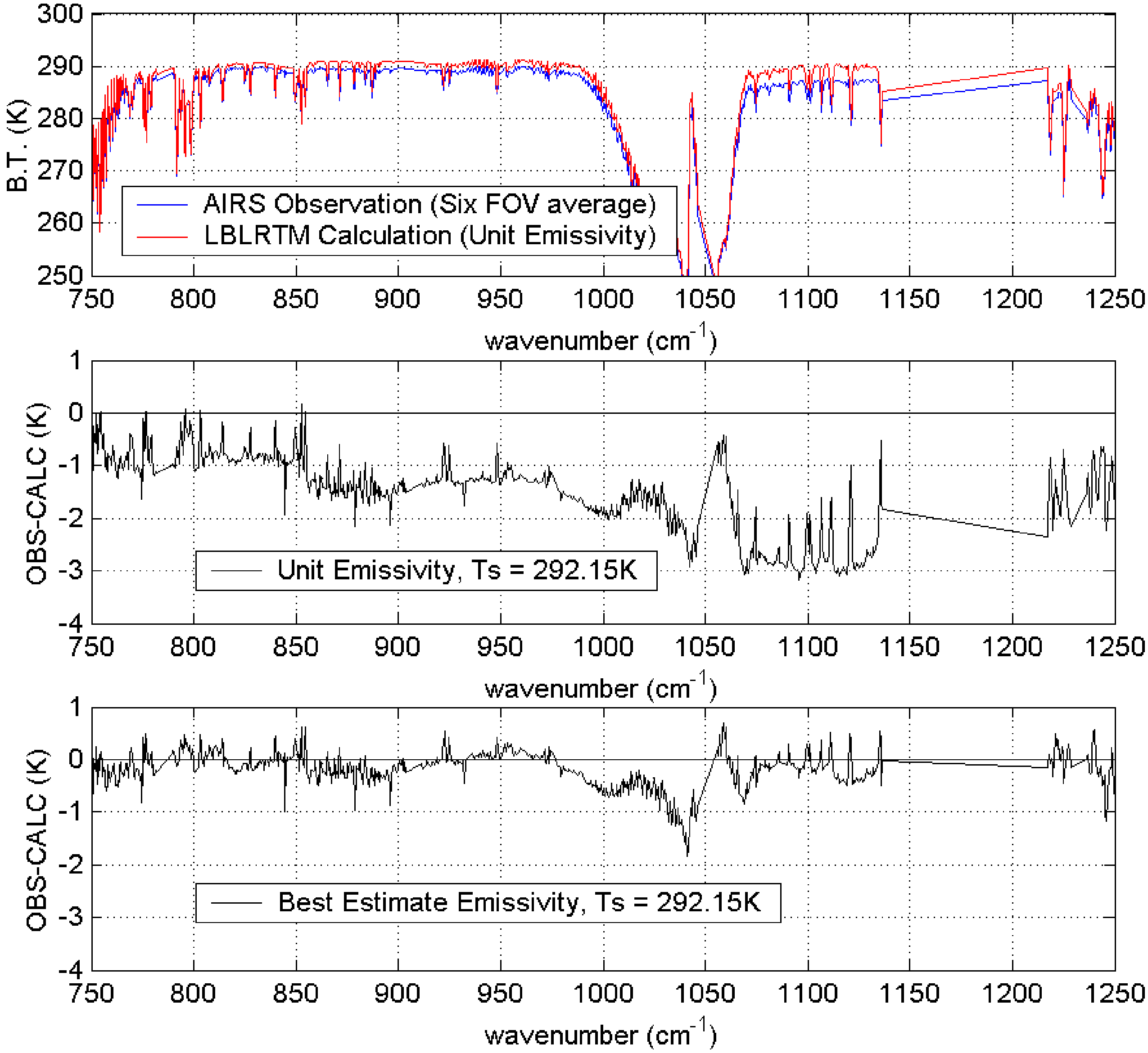


Figure 5. Mean of six observations from the NASA AIRS instrument near the SGP ARM CF on November 16, 2002 (19 UTC overpass) compared to two line-by-line calculations. The calculations use the same atmospheric profile and surface skin temperature but make different assumptions about the surface emissivity. The error in the residual in the range 990-1070 cm^{-1} is caused by the use of a climatological ozone profile in the line-by-line calculations that does not match the observations perfectly. The gap between 1140 and 1220 cm^{-1} is a region that is not measured by the AIRS instrument. The use of the UW LSE model ("Best Estimate") is superior in accounting for the wavelength dependence of the infrared spectral residual compared to calculations that ignore the effect of land surface emissivity. This has implications both for the interpretation of satellite observations over the SGP CART site and for accurate modeling of upwelling infrared radiation within the ARM Program.

The launch of the NASA Aqua platform in 2002 with the AIRS sensor has opened a new era of high spectral resolution infrared observations that will continue with the operational advanced sounders on the NOAA and EUMETSAT polar orbiting platforms. Future work includes the analysis of the AIRS observations over the SGP ARM site to obtain spatial maps of the surface emissivity over the larger SGP site domain (350 sq km).

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