Shortwave Radiometry and Analysis at the Southern Great Plains (SGP) Site

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Here we report the results of three parallel efforts: the recalibration and reanalysis of pyrano-metric data from Southern Great Plains (SGP) to improve its accuracy, use of the multifilter rotating shadowband radiometer (MFRSR) data to derive cloud optical depths and then tests of radiative transfer models to predict shortwave irradiance under cloudy skies, and operational results for the Rotating Shadowband Spectroradiometer (RSS) operated at SGP during the H_2O intensive observation period (IOP) compared to MODTRAN-3.5.

Improved Estimates of Shortwave Bolometric Irradiance at SGP

At the March 1996 Atmospheric Radiation Measurement (ARM) Science Team Meeting, Kato et al. (1996) showed comparisons of clear-sky, solar (shortwave) total irradiance measured with pyranometers at the ARM Enhanced Shortwave Experiment (ARESE) vs. a model with four different aerosol types. There were four separate instruments, all pyranometers. Their most plausible model predicted surface irradiances higher than any of the measurements, and the discrepancies among the measurements were comparable to the disagreement of this model with the highest of the measurements. This was an unsettling result prompting much concern and work within ARM. The following work is described in greater detail by Michalsky et al. (1997).

Following the ARM meeting, Mike Rubes of the National Oceanic and Atmospheric Administration (NOAA) made measurements at the SGP Central Facility in April 1996 with two absolute cavity radiometers (that measure direct-normal irradiance), and four recently calibrated pyranometers; two measured total-horizontal irradiance and two measured diffuse-horizontal irradiance under a tracking disk. The Eppley absolute-cavity radiometers serve as standards for solar irradiance measurement, and exhibit typical errors of Å 0.3%. Likewise, Joe Michalsky went to the SGP site with a recently calibrated Eppley Normal Incidence Pyrheliometer (NIP) and an Eppley Precision Spectral Pyranometer (PSP).

The Baseline Surface Radiation Network (BSRN) and Solar and Infrared Observing System (SIROS) complements of shortwave instruments (those permanently operating at the SGP) include pyrheliometers, unshaded pyranometers, and shaded pyranometers. Thus, during these calibration exercises there were five sets of instruments for measuring direct-normal irradiance (either Eppley NIPs or Eppley absolute-cavity radiometers), five unshaded pyranometers measuring total-horizontal irradiance (all Eppley PSPs), and four pyranometers measuring diffuse-horizontal irradiance under tracking disks (all Eppley PSPs).

Figure 1 is a plot of the total-horizontal irradiance measured by the five unshaded pyranometers on April 23, 1996. There is a 60 W/m^2 spread near solar noon among them. In contrast, Figure 2 shows the diffuse-horizontal irradiances measured by the shaded pyranometers at the same time. The spread is always within Å 10 W/m^2, though of course the diffuse irradiance is a small fraction of the total on this clear day.

Figure 3a is a plot of the direct-normal irradiance for this day. The cavity radiometers of NOAA's Surface Radiation Research Branch (SRRB1 and SRRB2) and the Atmospheric Science Research Center (ASRC) pyrheliometer (calibrated against a different cavity radiometer at ASRC [Albany, New York] the week before) agree to within 2 W/m^2. However, the BSRN and SIROS pyheliometers, which had not been calibrated recently, differed significantly from the active cavity. Consequently, we used this day's data to recalibrate them against the cavity output during the clear morning portion of the day. Figure 3b shows the data of Figure 3a with these new calibration constants applied. Now the five measurements of direct-normal irradiance agree to within 4 W/m^2 throughout the day.

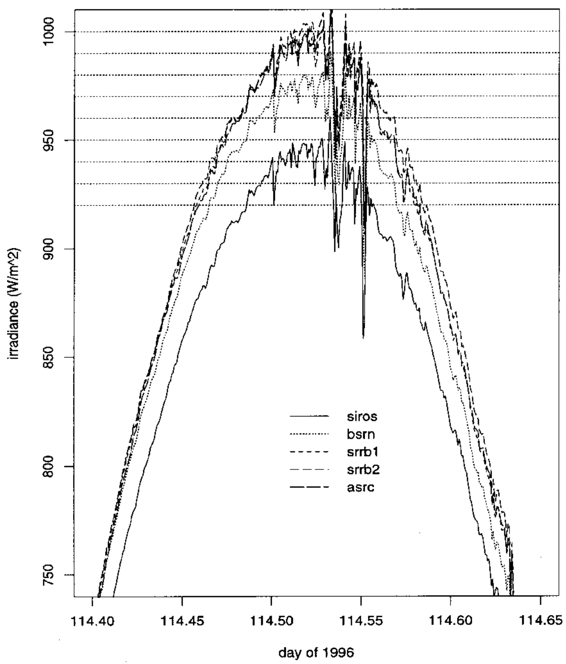

Figure 1. Downwelling shortwave irradiance measured with five pyranometers near solar noon on April 23, 1996. Note spread of 60 W/m^2.

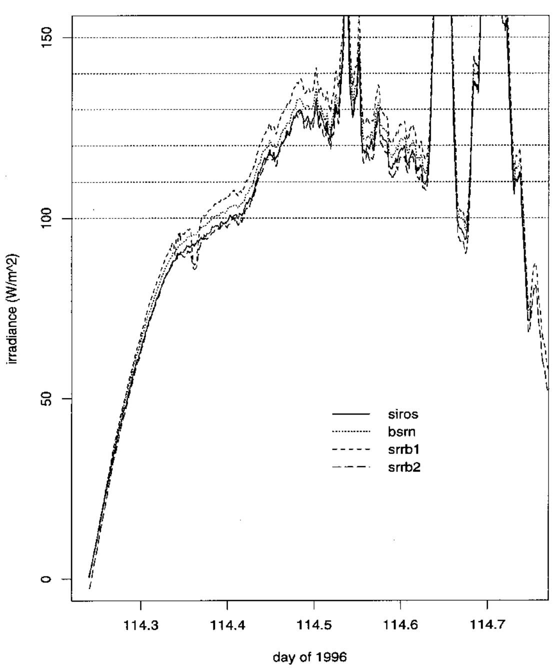

Figure 2. Downwelling diffuse shortwave irradiance for same day as in Figure 1. The spread is 10 W/m^2, and peak irradiance is less.

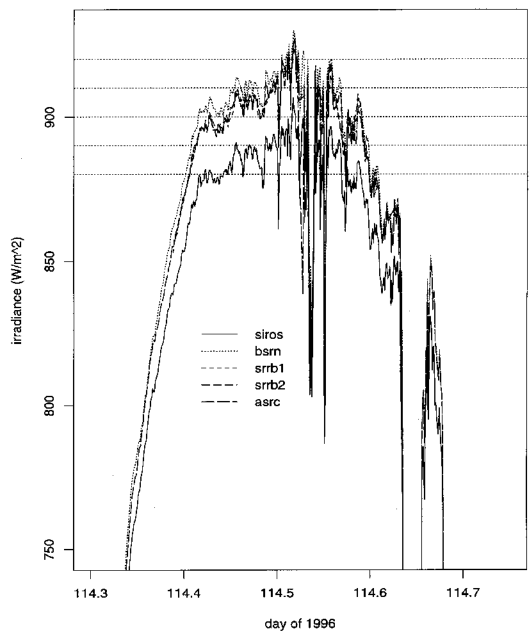

Figure 3a. Direct-normal shortwave irradiance for the same day as in Figure 1. Two cavities and a recently calibrated pyheliometer agree, but two pyheliometers without recent calibration do not.

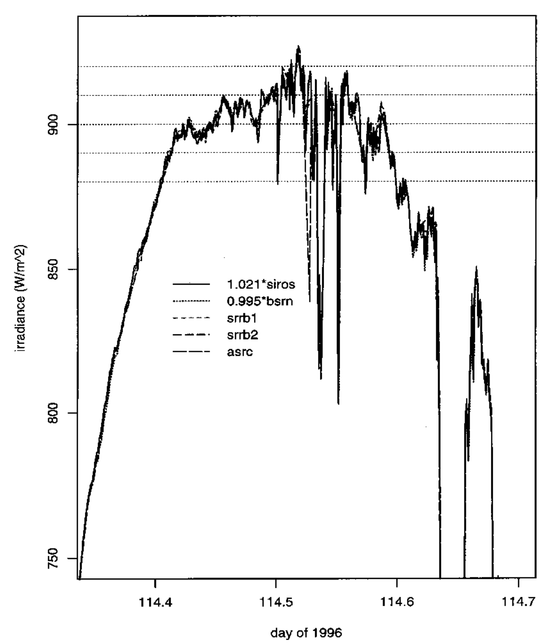

Figure 3b. After calibration using cavity data in the morning of this day, all pyheliometers agree with 4 W/m^2.

The total-horizontal irradiance is commonly measured using a single unshaded pyranometer for convenience. However, the World Climate Research Program's (WCRP) BSRN recommends that it be calculated by summing the horizontal component of the direct-normal irradiance (measured by a normal-incidence pyranometer or cavity) and the diffuse-horizontal irradiance (measured by a pyranometer with a shading disk). Figure 4 is a plot of the total-horizontal irradiance obtained through this summation for the four systems operating on April 23, 1996. The spread is Å 10 W/m^2 with a maximum value near solar noon of 970 W/m^2. Contrast this with Figure 1, which shows an apparent spread among pyranometer measurements of 60 W/m^2.

In Figure 1, the three highest-reading unshaded pyranometers were all calibrated using the same technique soon after April 1996, and the measurements of these three cluster within 10 W/m^2. The two outliers, the SIROS and BSRN pyranometers, are lower by 10 and 40 W/m^2, respectively. However, we assume that if they had been post-calibrated along with the other three, then all would have agreed to Å 10 W/m^2. However, these data from unshaded pyranometers are about 30 W/m^2 higher than the values reported by the summation method shown in Figure 4.

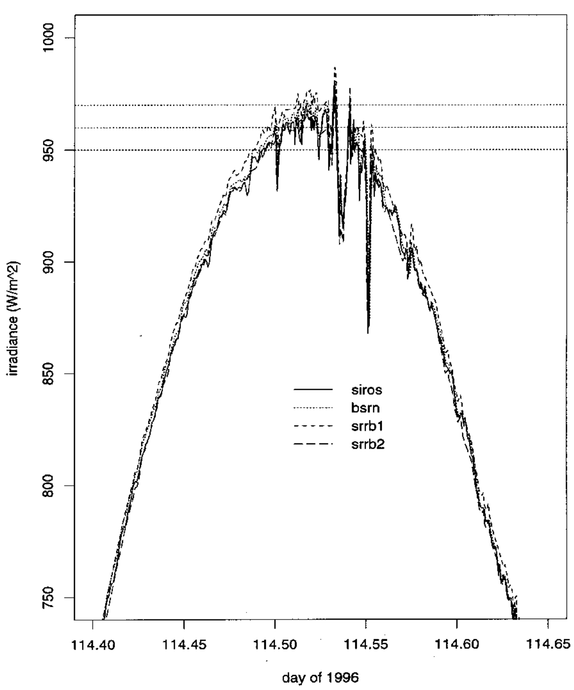

Figure 4. Total Downwelling shortwave irradiance by summing direct-horizontal and diffuse-horizontal shortwave irradiance show a spread of 10 W/m^2. Compare with Figure 1.

Which measurement is correct: that from an unshaded pyranometer or the sum based on pyheliometer and shaded pyranometer measurements? We agree with the WCRP/BSRN recommendation that the latter is the better estimator of total-horizontal irradiance. Our reason is that it reduces the impact of angular response errors on the part of the pyranometer. Typically the angular response of an Eppley PSP decreases more rapidly as the zenith angle increases than does the ideal (cosine) angular response.

ARM uses the broadband outdoor radiometer calibration (BORCEAL) method to calibrate pyranometers; the pyranometer is intermittently shaded with a disk that occults the sun so that the direct solar radiation at 45-55° solar zenith angle (SZA) can be estimated by subtraction. This result is then calibrated against a cavity or pyrheliometer. An Eppley PSP is less sensitive at these angles than at 25° SZA: the solar position at solar noon on April 23 at SGP. Consequently, an unshaded Eppley PSP will overestimate the total-horizontal irradiance for the lower SZA, a conclusion consistent with the difference between Figures 1 and 4.

The angular response errors of the device make much smaller error contributions (measured in W/m^2) to the diffuse-horizontal. The diffuse component is a small contribution to the total irradiance under clear-sky conditions. Further, the diffuse-sky radiance distribution is integrated over angles both smaller and larger than the calibration angle, so errors partially compensate. If the sky radiance is Lambertian, the maximum contribution comes from 45° SZA and decreases to zero at both 0 and 90° SZA. Even though skylight is not ideally Lambertian, the compensation of errors associated with calibration at 45° makes the resulting error in the diffuse component a small contributor to error in the total-horizontal irradiance for clear-sky conditions. Further, it implies that overcast sky measurements are better than clear-sky ones.

Cloud Optical Depths and Column Absorption Under Cloudy Skies

In Min and Harrison (1996), we describe a family of inversion methods to infer the cloud optical properties from the surface measurements of the MFRSR in conjunction with the Microwave Radiometer (MWR). We applied these retrievals to data at the ARM SGP site, and compared our inferred cloud optical depth with the Geostationary Operational Environmental Satellite (GOES) results for overcast conditions. The top panel of Figure 5 compares our results

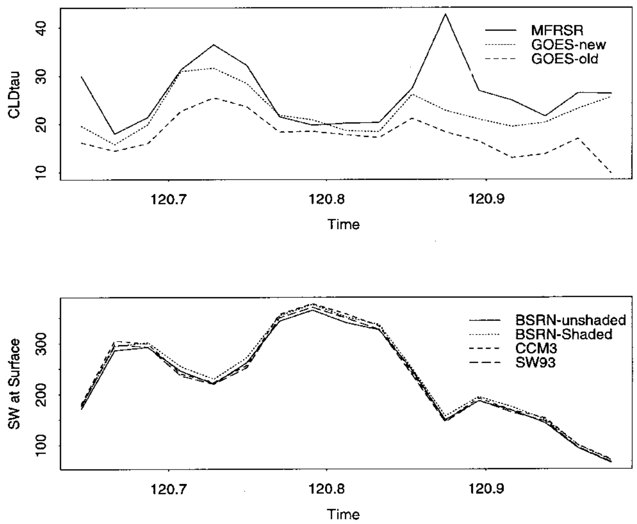

Figure 5. Top Panel: Cloud optical depths measured by GOES (both "old" and "new" corrected values) and by MFRSR at SGP for a fraction of April 30, 1994 around local noon.

to GOES. The GOES retrievals, against which we originally compared (labeled "GOES-old"), are lower by approximately a factor of two compared with ours for cloud optical depths > 10. Subsequently, the GOES retrievals have been revised to significantly increase the cloud optical depths, and are much closer to ours (labeled "GOES-new").

To further validate our inferred cloud optical properties from the MFRSR, we have used two different atmospheric shortwave models: Version 3 of the National Center for Atmosperhic Research's (NCAR) Community Climate Model (CCM3) (Breigleb 1992) and SW93 (Smith and Shi 1994) to compare measured and calculated surface shortwave irradiances at SGP. For this study we chose two overcast days from a 1994 ARM IOP at SGP: April 22 and 30. On those days the GOES measurements indicated only a single cloud layer and cloud amounts of 100% for all adjacent boxes. Consequently, the cases well approximate horizontally homogeneous clouds. The direct irradiances of the MFRSR at the central facility were fully blocked, and all relevant measurements were available.

The bottom panel of Figure 5 displays the measured and calculated surface shortwave irradiances for 30-minute intervals, and indirectly illustrates measurement uncertainties. The unshaded BSRN and SIROS pyranometers show consistent measurements of total-horizontal shortwave irradiance. However, the shaded BSRN pyranometer (intended to measure the diffuse irradiance) should be identical under overcast conditions, but instead had a bias of 8.2 W/m^2 or 4% higher than that of the unshaded instruments. This may be an estimator of the uncertainty for the measurements. Unfortunately, the SIROS diffuse shortwave measurements were not available at the time for comparison.

The modeled irradiances were computed using the H_2O profile taken from balloon sonde data, cloud top and bottom heights from the cloud product dataset, and spectral surface albedos from downward looking sensors at the site. The mean droplet radius was that inferred by our method using the MWR data in conjunction with the optical depth from the MFRSR. To test our shortwave models, we set the input parameters for the SW93 to the same as those set for the CCM3, and used the parameterization scheme of Slingo (1989) for the cloud optical properties for 24 spectral bands. The calculated surface irradiances show only small discrepancies between the models. Figure 6 shows the scattergram of the measured and calculated surface shortwave for the 5-minute cases, which include the results of April 22, and April 30, 1994. The surface irradiances predicted by CCM3 agree well with the pyranometer measurements, given the likely uncertainty of 10 W/m^2 associated therewith. This agreement demonstrates:

- The cloud optical depths derived from the MFRSR measurement at 415 nm must be accurate to better than 5%; larger errors in cloud optical depth would produce discrepancies in the modeled surface irradiance greater than that seen.

- The modeled H_2O absorption is not contributing significant error. Note that at time 120.86 the cloud optical depth goes to nearly 45 -- under these conditions the lines are effectively opaque, and the incremental absorption with increasing optical depth is dominated by the continuum. The ability of the model to predict the declining irradiance under these great optical depths is an indirect demonstration that remaining uncertainties in the continuum absorption are not limiting at present.

We conducted an extensive uncertainty analysis of irradiance (both surface and upwelling at the TOA) prediction for this range of conditions. As is intuitive, the greatest sensitivity is to the cloud optical depth. In our paper describing the MFRSR-derived cloud optical depths (Min and Harrison 1996), we conservatively estimated the uncertainty in the optical depth retrieval from all instrumental and calibration contributions to less than 10% in cloud optical depth. Clearly we are doing better than that here.

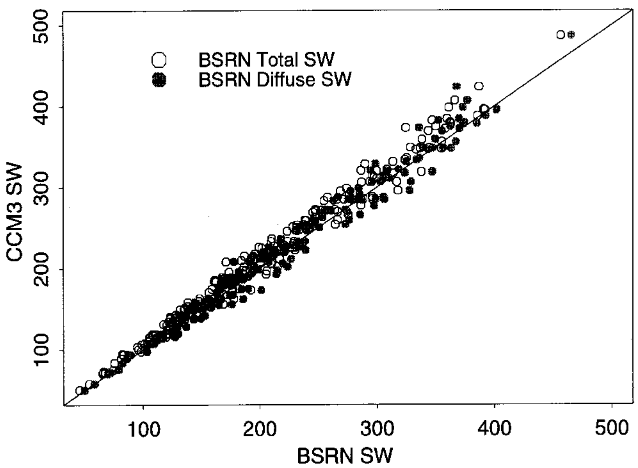

Figure 6. A scattergram comparing the CCM3 model prediction of surface shortwave irradiance vs. the two BSRN pyranometric measurements.

These results also provide two constraints on potential "anomalous absorption." The first is simple and stems from direct energy balance. Given the likely measurement uncertainty, the results are congruent with no anomalous absorption. However if we assume that *all* the discrepancy is the result of anomalous absorption we can compute the column absorption from the surface deficit as follows: we use the model to compute _I/_C, where I is the measured surface irradiance and C is the total atmospheric column absorption as a function of the cloud optical depth (and other parameters) by artificially incrementing the cloud absorption. For the conditions encountered in these cases, _I/_C is approximately 0.5 for a cloud optical depth of 10 and decreases to Å 0.3 at an optical depth of 20. Again, assuming that the discrepancies between the modeled results and observation are caused by "anomalous absorption" then the regression results shown in Figure 6 demonstrate a limit to potential anomalous absorption in the total atmospheric column of Å 11 W/m^2 combining both measurements. This is an "instantaneous" mid-day value at a cloud optical depth of 10 at SGP. Scaled to a global-mean optical depth of Å 5 and a 24-hour average yields a result < 3 W/m^2.

A more stringent test is potentially available from data of these kinds. All plausible mechanisms of column absorption will yield _I_{abs}/_† _ 0 († is the cloud optical depth). This is shown in Figure 7 where the fractional change in the surface irradiance is computed applying various artificial absorption mechanisms to our case data. In principle, we can test for artificial absorption by testing for a statistically significant *slope* with respect to cloud optical depth in this plot. The advantage of this method is that a calibration-scale error

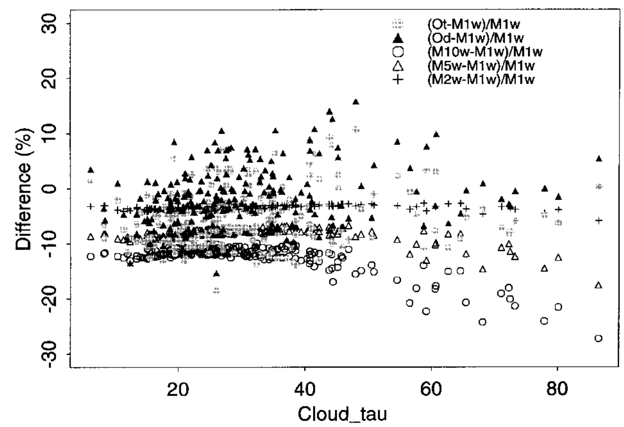

Figure 7. Fractional changes of the surface shortwave irradiance vs. cloud optical depth: Ot and Od represent observed total (unshaded) shortwave and observed diffuse (shaded) shortwave; M1w, M2w, M5w and M10w represent the predicted surface shortwave from the CCM3 where the cloud-specific absorption is multiplied by a factor of 1, 2, 5, and 10, respectively.

affecting the pyranometry no longer matters; we need only a detector that is stable and linear. However, errors in spectral surface albedo will also introduce a slope. We have not yet completed sensitivity analysis studies for this latter interference for a full range of cases, and so are not ready to draw conclusions from this analysis. But in principle, this method applied to large data sets from a site with well-known spectral surface albedo can yield a very stringent test of radiative transfer models and unaccounted-for absorption mechanisms.

Rotating Shadowband Spectroradiometry

We have developed a new instrument called the Rotating Shadowband Spectroradiometer (RSS).[a] It couples the MFRSR fore-optic and shadowbanding method to a charged-coupled device (CCD) spectrograph to provide spectral direct, diffuse, and total horizontal irradiances over the wavelength range from 350 to 1075 nm. We operated the two prototype

(a) A much more extensive report is available as "RSS_report.ps" or "RSS_report.pdf" by anonymous ftp from the /pub directory of solsun1.asrc.albany.edu. ARM Scientists can obtain our data both for the IOP and that subsequently taken by ASRC: contact mark@uvb.asrc.albany.edu.

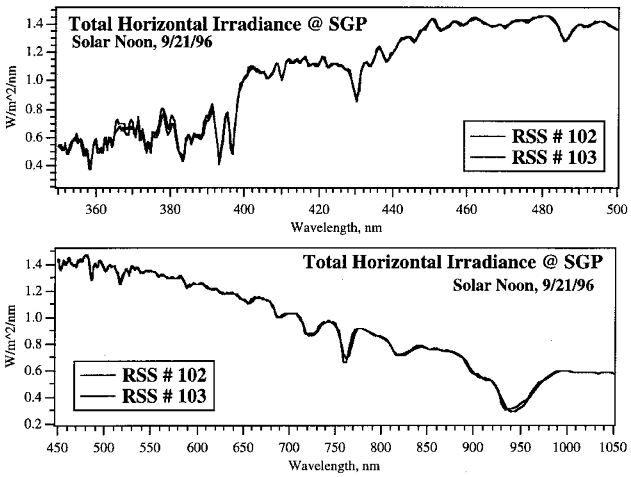

Figure 8. Comparison of spectra from both RSS instruments at SGP
Top: from 350 to 500 nm
Bottom: from 450 to 1050 nm.

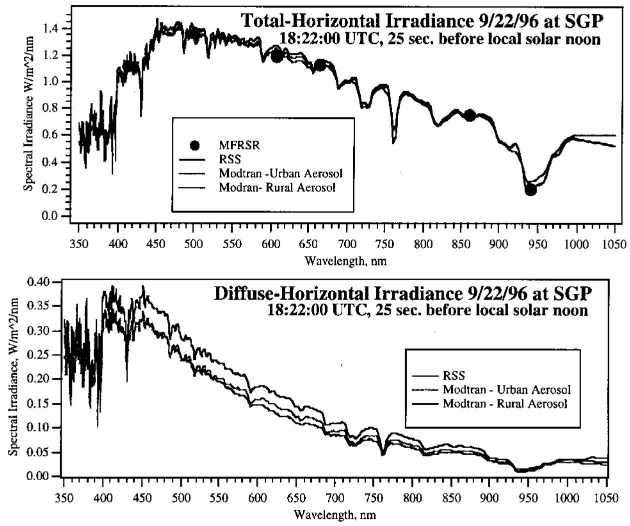

Figure 9. Top: RSS Total-Horizontal and two MODTRAN-3.5 cases
Bottom: RSS Diffuse-Horizontal, ditto.

RSS instruments at the H_2O IOP held at SGP during September 1996. Figure 8 shows representative spectra at solar noon.

Both instruments operated continuously without failure for the campaign. Each instrument was calibrated at least once per day to assess instrument stability under field conditions. The instruments were stable and reproducible to Å 0.3% in irradiance (the limit of stability of our calibrating standard) over the experiment period, with no statistically significant trend. However, a variable but systematic error of wavelength registration associated with differential external thermal loads was observed that had not demonstrated itself in our laboratory and rooftop testing (where large temperature ranges were tested, but ambient conditions were much closer to isothermal). This error has been corrected by post-processing of the data taken at the SGP, and subsequent simple modifications to the instruments have eliminated the problem.

In Figure 9, we compare SGP clear-sky data to that taken by a collocated MFRSR and model calculations using MODTRAN-3.5 (the recent release that includes a discrete-ordinates code so that scattering atmospheres can be treated). Agreement is generally excellent (better than ±2%, an optimistic assessment of our calibrator's absolute uncertainty), with two caveats:

- The modeled diffuse irradiance is substantially too large for the two clear days of the IOP in comparison to the observed results unless MODTRAN's "urban aerosol" properties for the single-scattering albedo and phase function are used. If the "rural aerosol model" is used then the diffuse horizontal irradiance predicted by the model is about 8% too large. The broad spectral behavior of this potential discrepancy, and its presence only in the diffuse component, clearly identifies it as associated with scattering processes, not trace gas absorption. In the absence of more data, and hopefully in-situ measurements of single-scattering albedo and asymmetry parameter, the question of whether there is a "clear sky anomaly" remains moot.

- Both RSS instruments yielded excess irradiance at wavelengths > 900 nm, compared to both MODTRAN-3.5 and the collocated MFRSR. This problem was a result of inadequate out-of-band (OOB) rejection, with the effect being manifest only in this long-wavelength limit due to both declining spectral irradiance and sharply declining CCD responsivity. The OOB performance was being limited by scattering from a window on the CCD itself. After the field trial we corrected this problem by substitution of a windowless array.

RSS #102 is now operating continuously at our observing facility at ASRC, and unit #103 is being prepared for long-term deployment at the SGP site. In Figure 10, we show clear-sky data taken at ASRC (Albany, New York) after the substitution of a windowless CCD array, and other minor modifications made after our return. MODTRAN-3.5 was run with the default standard seasonal atmosphere (for H_2O) and the urban aerosol model. The fractional errors are shown in the bottom panel. In this case, the atmosphere clearly had a greater water column than the model's default, but otherwise agreement is excellent throughout the spectrum, except for the A-band of O_2. The likely cause of this discrepancy is a mild underestimate of the width of the instrument-function used to convolve the modeled spectrum.

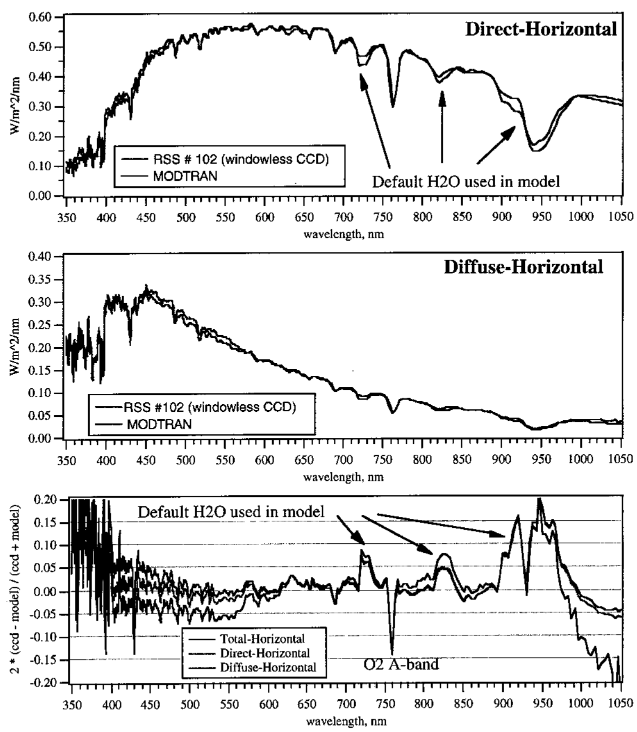

Figure 10. Data taken at ASRC:
Top: RSS Direct-Horizontal and MODTRAN-3.5 (urban aerosol)
Middle: RSS Diffuse-Horizontal and MODTRAN-3.5 (urban aerosol)
Bottom: Fractional differences between model and data.

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