Comparison of Diffuse Shortwave Irradiance Measurements

J. J. Michalsky and J. Schlemmer
Atmospheric Sciences Research Center
State University of New York
Albany, New York

B. C. Bush, S. Leitner, D. Marsden, and F. P. J. Valero
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, California

R. Dolce and A. Los
Kipp & Zonen, Inc.
Bohemia, New York and Delft
The Netherlands

E. G. Dutton
Climate Monitoring and Diagnostics Laboratory
National Oceanic and Atmospheric Administration
Boulder, Colorado

M. P. Haeffelin
Virginia Polytechnic Institute and State University
Blackburg, Virginia

G. Major
Budapest University of Economic Sciences and Public Administration
Budapest, Hungry

J. Hickey
The Eppley Laboratory, Inc.
Newport, Rhode Island

W. Jeffries
Yankee Environmental Systems, Inc.
Turners Falls, Massachusetts

D. Mathias
Carter-Scott Design
Brunswick, Victoria, Australia

B. McArthur
Meteorological Service of Canada
Downsview, Ontario

R. Philipona
Physikalisch-Meteorologisches Observatorium and World Radiation Center
Davos, Switzerland

I. Reda and T. L. Stoffel
National Renewable Energy Laboratory
Golden, Colorado

Introduction

Shortwave irradiance measurements have improved significantly in the past few years with a major contribution from the Atmospheric Radiation Measurement (ARM) Program as ARM scientists and collaborators have pushed for improved ARM measurements to rigorously test models of radiative transfer. Models and measurements of the direct normal irradiance have been shown to agree to within measurement and modeling errors (Kato et al. 1997; Halthore et al. 1997). Since the direct is measured with a small uncertainty using an absolute reference instrument (the self-calibrating cavity radiometer), the model and measurement agreement gives us some assurance that the model inputs are correct. A significant problem arises when we use these same model inputs to calculate the diffuse horizontal irradiance. Model irradiances persistently exceed measured irradiance for the cleanest sky conditions, e.g., Kato et al. (1997) and Halthore and Schwartz (2000).

In ARM the diffuse horizontal irradiance sensors are pyranometers that are mounted on solar trackers and have direct normal solar irradiance blocked using a tracking ball. In ARM these pyranometers are calibrated in full sun by comparing to a reference system that measures direct and diffuse horizontal components separately and adds to obtain a reference measurement. The pyranometer signal under test is ratioed to the summed components on clear days when the sun is within 5° of a solar elevation of 40°.

Large negative offsets using single-black detector pyranometers can amount to 20% to 30% of the diffuse irradiance in clean, clear-sky situations (Bush et al. 2000). A black and white pyranometer that mostly eliminates this offset has replaced the single black detectors in ARM, but the ultimate solution for measuring diffuse irradiance remains elusive. The main difficulty is that there is not an absolute standard for the diffuse horizontal irradiance measurement as exists for the direct normal irradiance.

As an initial step in establishing some reference, we conducted an intensive operational period (IOP) in September and October 2001 to compare pyranometer measurements of diffuse using most of the commercial pyranometers plus four prototypes. The goal was to determine whether there is a consensus using different instruments calibrated independently.

Some Experimental Details

The invitees included members of the ARM science community, the Baseline Surface Radiation Network (BSRN) (Ohmura et al. 1998), and pyranometer manufacturers. Table 1 is a list of the instruments, denoting whether they were ventilated, and the calibration method used. All pyranometers were mounted on Sci-Tec 2AP two-axis trackers. The tracking during the experiment was flawless with no outages because of tracker failure. The instruments were all mounted with the surface of the detector horizontal and about 20 cm above the trackers' pyranometer shelves according to directions in the 2AP manual. All were shaded by spheres at the same distance from the center of the detector. While the shading was sufficient to block the direct beam for every instrument the detectors vary in size, leading to some differences in measured diffuse of 1-2 W/m^2 caused by geometry.

On one of the trackers we also measured downwelling infrared radiation using an Eppley precision infrared radiometer (PIR) pyrgeometer that was shaded from direct beam irradiance. These measurements are used to correct some of the offsets using the algorithm proposed in Dutton et al. (2001).

We expected to compare measurements on both clear and cloudy days; however, during the four weeks of the experiment the sun shone about 92% of the daylight hours, and during much of this time the skies were cloudless. There were enough totally overcast hours, fortunately, to assess the pyranometers' performance relative to clear skies. The preponderance of clear skies meant that there were many occasions to model the diffuse and compare to measurements. Direct beam absolute cavity radiometer measurements were obtained using the Pacific Northwest National Laboratory's (PNNL) TMI

Table 1. Instruments list for the diffuse IOP, ventilation, and calibration methods.

Instrument – Symbol	Ventilated	Calibration
Carter-Scott Design EQ08-A (prototype) – eq08	No	Australian BoM method[(a)]
Eppley precision spectral pyranometer (PSP) with inner dome and case temperatures – psp-mh	Yes	Forgan method[(b)]
CIMEL black & white – cimel	No	Forgan method[(b)]
EKO MS-801 – eko	No	CMDL method[(c)]
Kipp & Zonen CM11 – cm11	Yes	K & Z method[(d)]
Kipp & Zonen CM22 – cm22	Yes	K & Z method[(d)]
CM22 modified – cm22-rp	Yes and heated	WRC method[(e)]
Eppley 8-48 – 8-48	Yes	Dome[(f)]
Eppley (prototype black&white) – new_epp_bw	Yes	Dome[(g)]
Kipp & Zonen CM21 – cm21	Yes	Dome[(h)]
Schenk Star – schenk	No	Dome[(h)]
Eppley PSP – psp	Yes	Dome[(f)]
Yankee isothermal pyranometer (prototype) – yes	Yes	YES[(i)]
Scripps (prototype) – total solar broadband radiometer (TSBR)	No	Scripps method[(j)]

(a) Compare direct component from Eppley HF plus diffuse component from shaded Kipp&Zonen CM11 at 45° solar-zenith-angle (sza) to pyranometer under test, aka, component sum technique.
(b) Forgan, B., 1996: A new method for calibrating reference and field pyranometers. *J. Atmos. Ocean. Tech*., 13, 638-645.
(c) Component sum using Eppley HF cavity and average of offset-corrected PSP/Eppley 8-48 diffuse.
(d) Kipp & Zonen uses a 1000W tungsten-halogen lamp mounted vertically over horizontally mounted pyranometers; the reference and test pyranometers are read and positions; reference pyranometer (of same type) is calibrated using the WRC method.
(e) Component sum using World Standard Group (WSG) for direct and Eppley PSP for diffuse is standard WRC method; cm22-rp calibration for IOP used shade/unshade method compared to WSG.
(f) The dome methods use diffuse reflection from a painted inner dome illuminated by incandescent light. The test pyranometer output is compared with a reference pyranometer output in or near the same position under the dome the reference is calibrated by summation or shade-unshade methods. The reference pyranometer is the same type that is under calibration.
(g) Shade/unshade comparison to an Eppley HF cavity and component sum technique.
(h) Same as (f).
(i) Outdoor side-by-side comparison using a PSP under overcast skies.
(j) Radiometer is fitted with 5.7° field-limiting aperture and compared to absolute cavity.

radiometer that had been calibrated to the World Radiometric Reference the previous year at the World Radiation Center in Davos, Switzerland. Some model comparisons of direct and diffuse will be made in another paper in this conference (Powell et al. 2002).

Some Results

After examining the data collectively we found the most consistent results among five of the pyranometers, moderate consistency among five others, and less consistency among the prototypes. Our focus was initially on clear-day measurements since those are expected to be the most likely to be in error because of offsets and asymmetric skylight distributions convolved with imperfect cosine responses. We have included discussion of cloudy sky data; also Figure 1 contains data from the clear day on September 28, 2001 (day of year 271). The data plotted are for solar elevations greater than -10°. Time is local standard time; for the Southern Great Plains (SGP) site this means that solar noon occurs after local noon (271.5). The psp-mh data are corrected according to the procedures outlined in Haeffelin et al. (2001). The four others have no corrections. The three Kipp & Zonen (cmxx) pyranometers have very high volume ventilation relative to the other pyranometers in this experiment; the cm22-rp has the only vented air that is heated. The psp-mh and the 8-48 have modest ventilation to keep dew from forming on the outer window. The one-minute difference of each measurement from the mean of the five is plotted in the bottom of Figure 1 (use the left-hand ordinate). The standard deviations among the five are plotted as a function of time according to the right-side ordinate. The range in standard deviation for this day was 0.24 -1.46 W/m^2 with an average deviation of 0.63 W/m^2.

In Figure 2 the PSP has been corrected using the method outlined in Dutton et al. (2001) where the offset is determined using nighttime pyranometer data (sun lower than -10°) regressed against the net PIR signal with the intercept forced through zero. This was also used for the cm21. The Meteorological Services of Canada (MSC) algorithm produces a correction that did not do as well; it is based on an average night correction using the data just before sunrise and just after sunset on each day. The MSC network does not include pyrgeometers at most of its sites, which precludes the routine use of the Dutton et al. (2001) method. The cimel, eko, and schenk were not corrected. The PSP and cm21 were ventilated to prevent dew formation, but the cimel, eko, and schenk were not. These five measurements are plotted in the top of Figure 2. The mean of the five measurements in Figure 1 is included for comparison. The bottom of Figure 2 is a plot of the differences between the mean in Figure 1 and each of the pyranometers of Figure 2.

For each of the four days of data presented in the first 12 figures we assume that the average of the five pyranometers listed in the first of each of the three figures for the day in question is our standard for comparison based on their consistent pattern of agreement. In fact, since there is no absolute standard for diffuse measurements, we cannot be certain of the absolute accuracy of this average.

The four prototypes included in the experiment (eq08, new_ep_bw, yes, and TSBR) are plotted in the top of Figure 3 along with the mean from Figure 1, and the difference from this mean is plotted in the bottom of Figure 3. It appears that some improvement could be achieved with a better calibration and/or offset correction although it is not clear that this would work for every prototype.

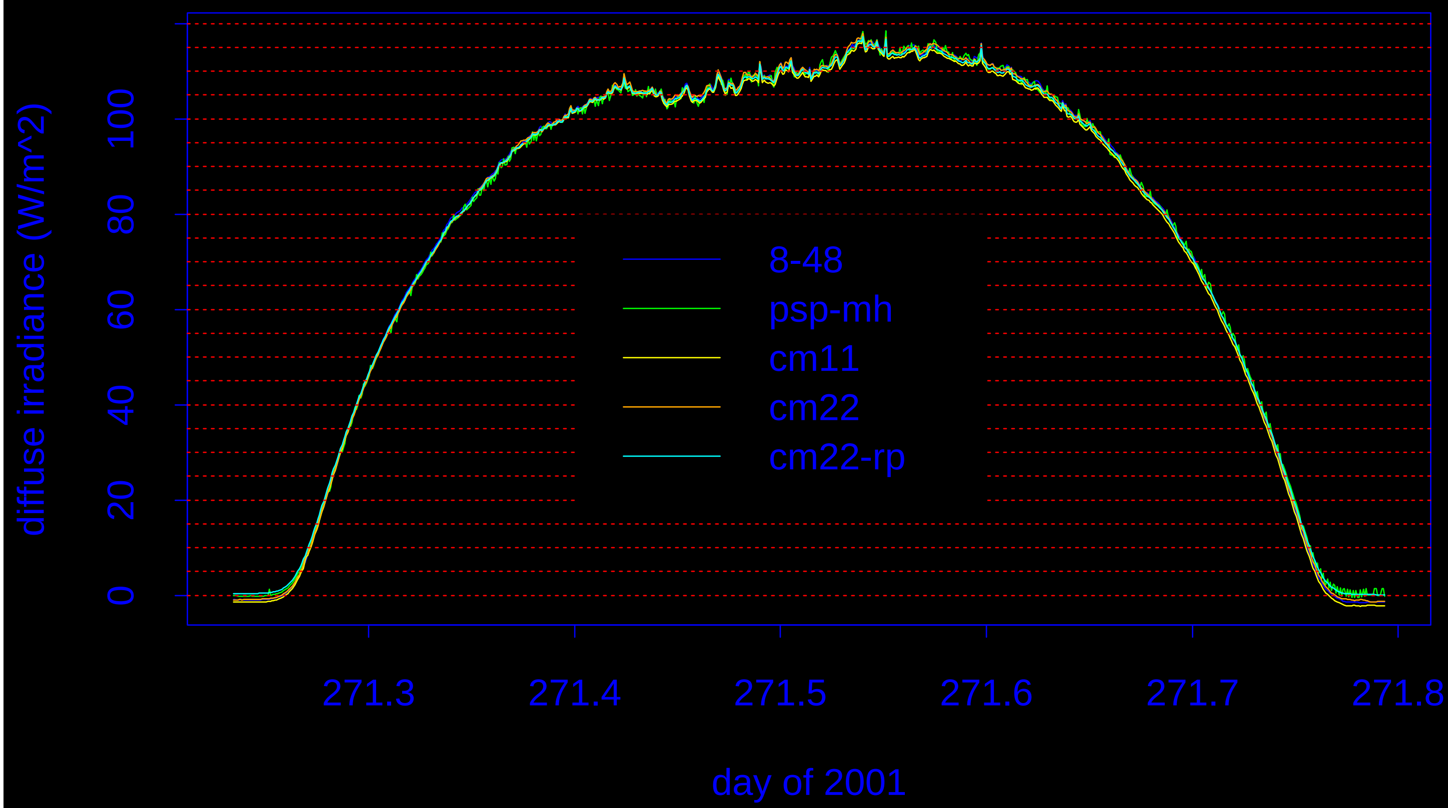
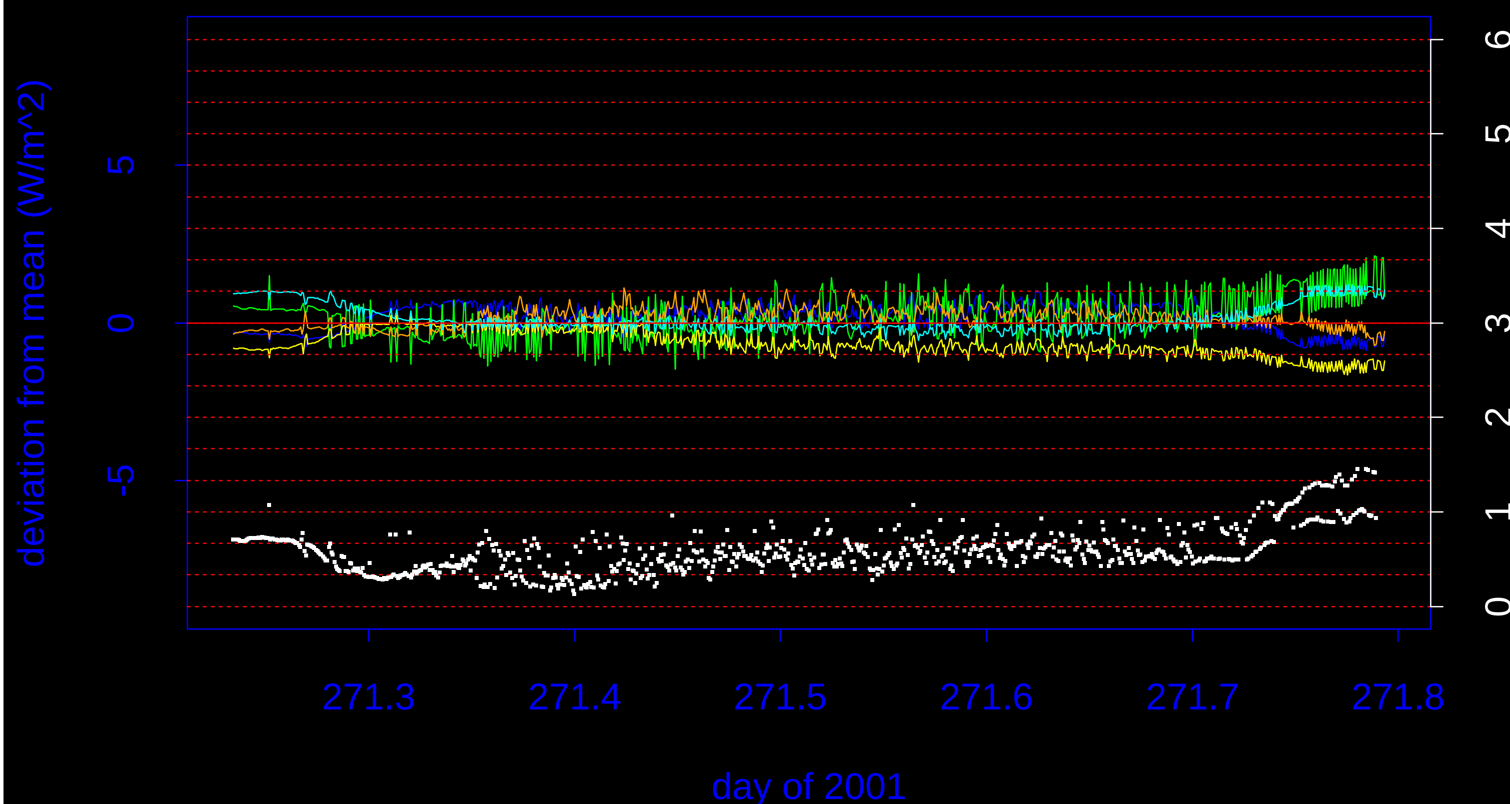


Figure 1. Diffuse horizontal irradiance versus time for September 28, 2001 (top). This plot includes five measurements that were the most consistent group for both clear and overcast conditions throughout the IOP. The bottom plot contains deviations from the mean of the group (left-hand ordinate) and the standard deviation among the group of five (right-hand ordinate). The standard deviations are generally less than 1 W/m^2.



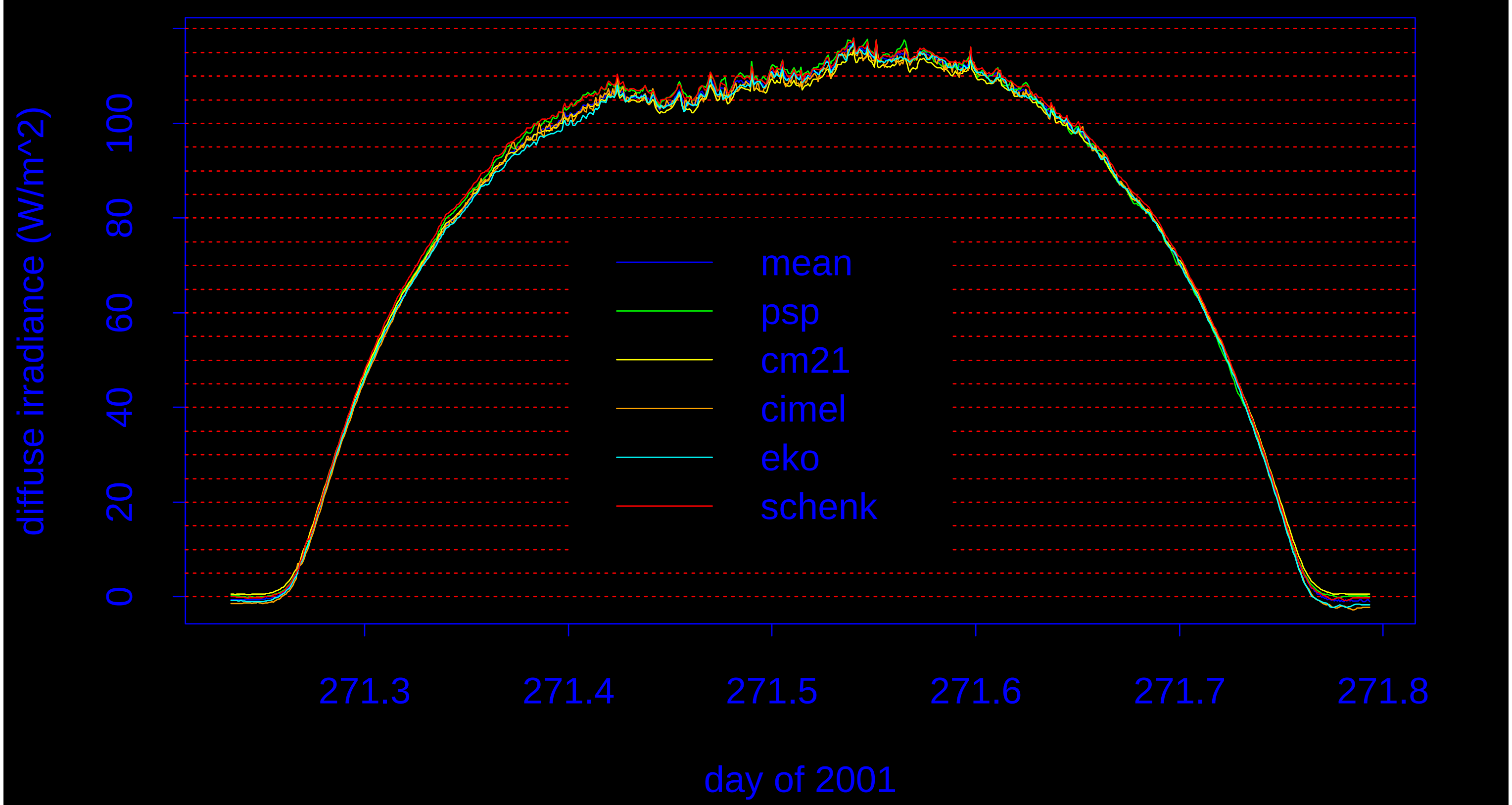
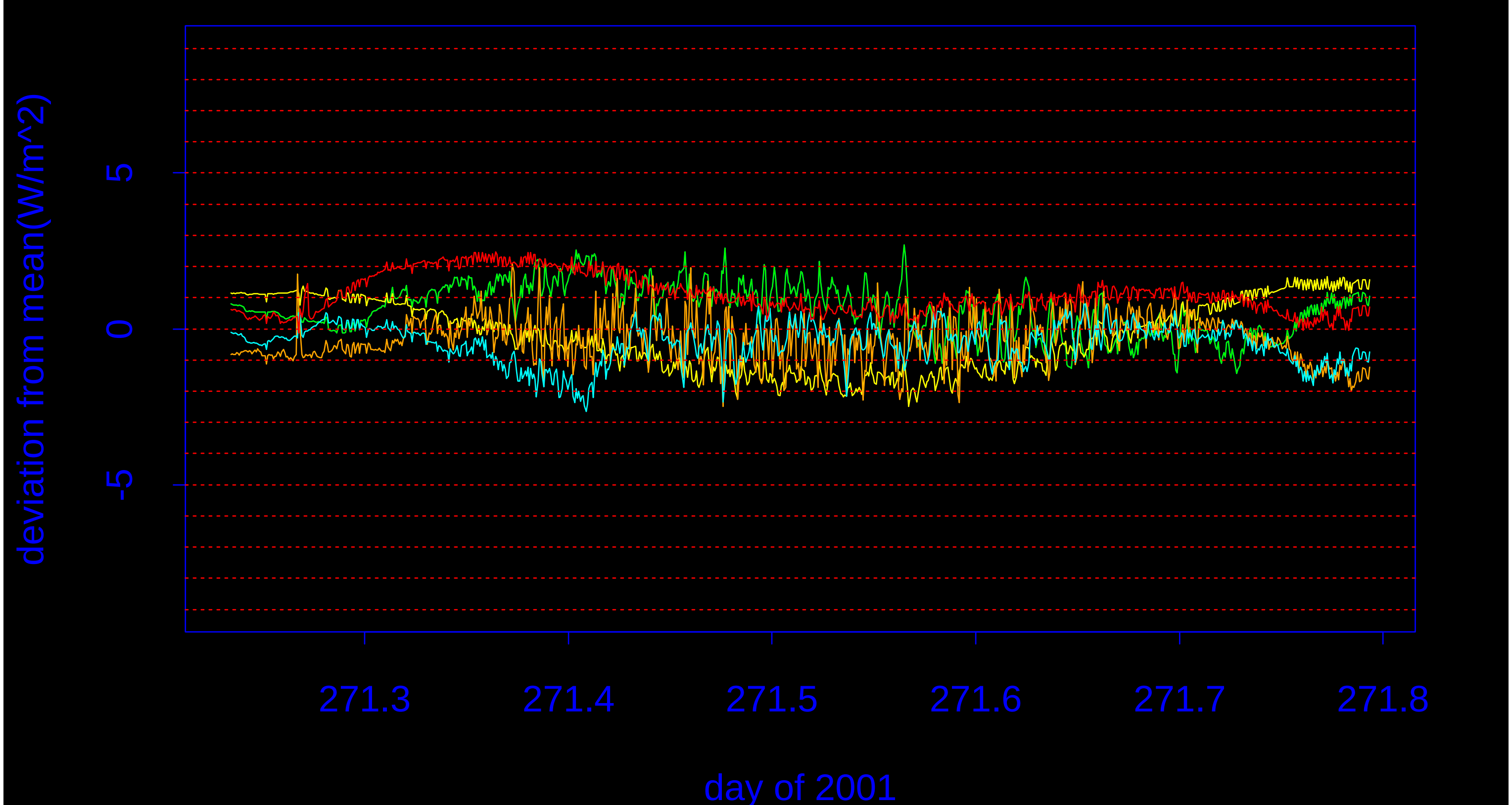


Figure 2. A plot similar to Figure 1 for the second most consistent group of diffuse radiometers along with the mean from Figure 1. The deviations plotted on the bottom of this figure are those from the mean of Figure 1. The deviations are about twice that of Figure 1.



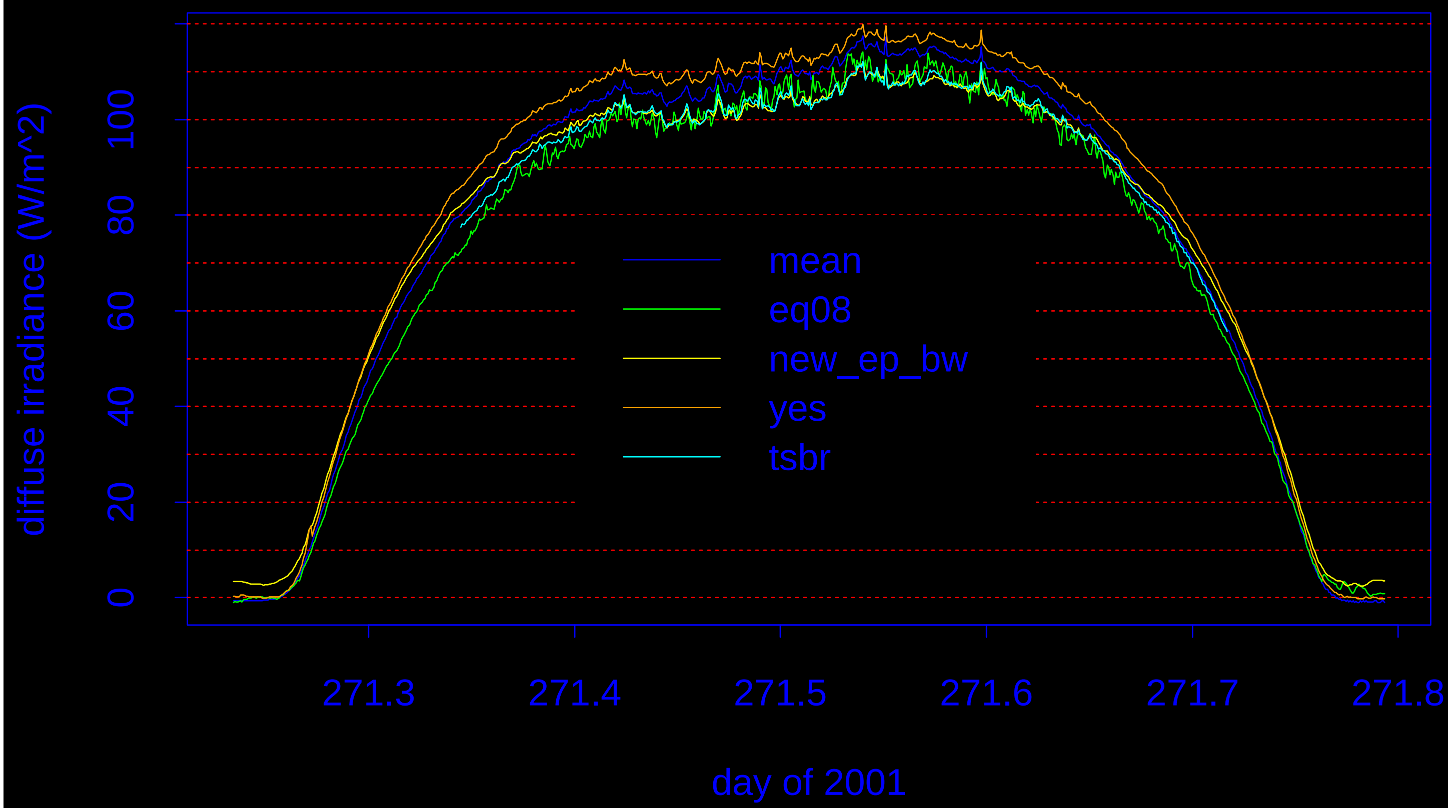
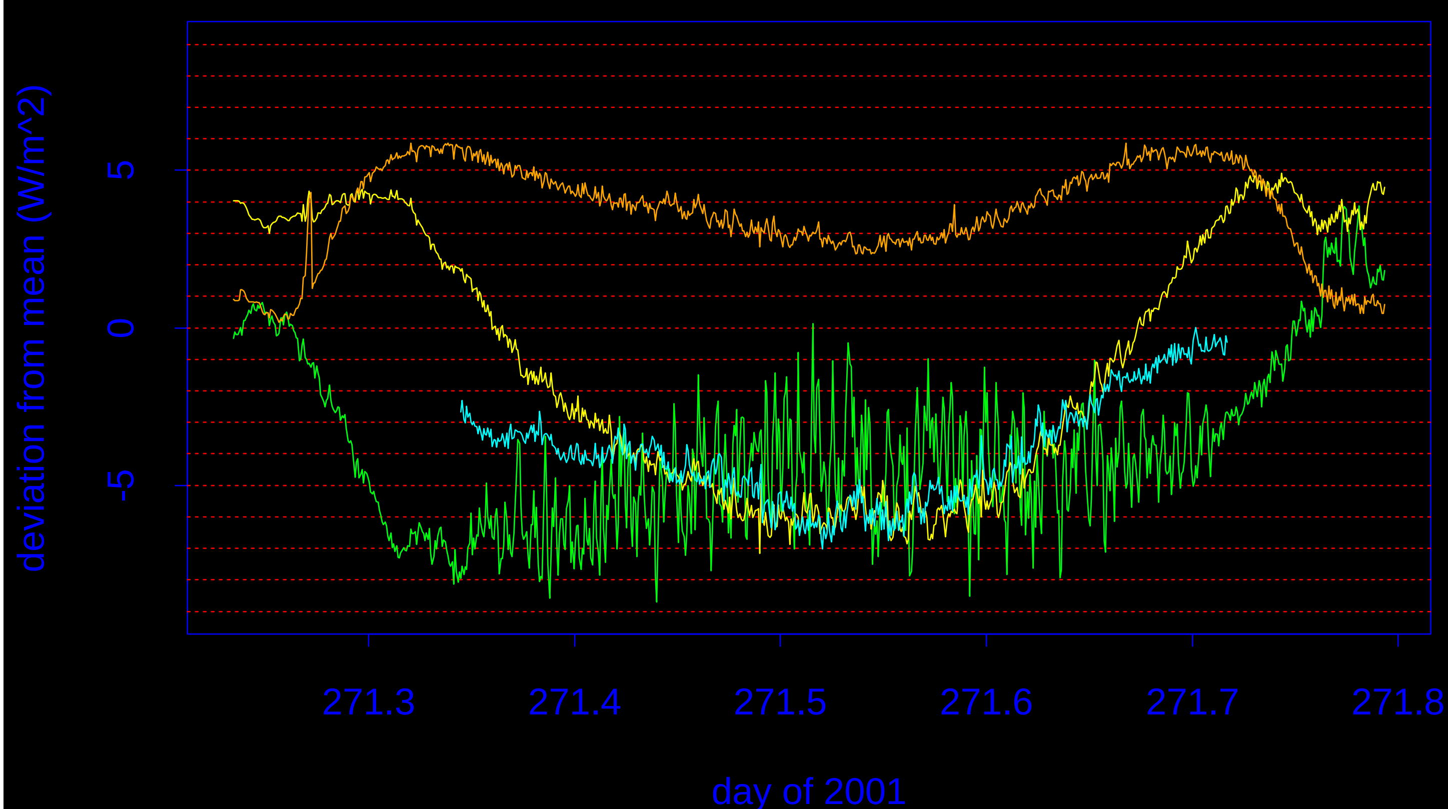


Figure 3. A plot similar to Figure 2 for the four prototypes included in the study. Not that the deviations in the bottom of the figure are considerably larger than for Figures 1 and 2.



We observed that the cimel and eq08 were more sensitive to wind gusts than other instruments. Compare the fluctuations in the bottoms of Figures 2 and 3 with the other pyranometers' fluctuations in those figures. When the wind was calm or laminar we were less likely to notice these amplitude fluctuations in the data.

Figures 4, 5, and 6 are for another clear day (October 2, 2001, day of year 275) presented in the same way as Figures 1, 2, and 3. This is a lower aerosol day with smaller diffuse. The average standard deviation among the five pyranometers in Figure 4 for the day was 0.73 with a range of 0.20 W/m^2 to 1.26 W/m^2. The spread among the pyranometers in Figure 5 is slightly greater than it was for day 271 in Figure 2, especially for the schenk. The same pattern of disagreement among the prototypes appears in Figure 6 as we saw for day 271 in Figure 3 with the exception of the TSBR, which is closer to agreement with our comparison standard than it was in Figure 3.

On October 5, 2001 (day of year 278), we had our first opaque clouds of the IOP. Figures 7, 8, and 9 are plots for the same sets of instruments as presented in the previous two sets of figures for the part of the day (2.4 hours in length) known to be overcast based on direct beam data. There is a fairly tight grouping in Figure 7 of the five that had the best consistency in earlier figures. The standard deviations are only slightly higher than we had for clear days in Figures 1 and 4 (see right-hand-side ordinate) with the differences fairly constant in time. The next most consistent group in Figure 8 shows a larger spread than they did for clear skies. In the bottom of Figure 8 the deviations from the mean in Figure 7 are plotted. In the bottom of Figure 9 the prototype differences from the mean in Figure 7 show about the same consistency as shown for the clear days in Figures 3 and 6.

Figures 10, 11, and 12 contain data for the cloudy afternoon of October 9, 2001 (day of year 282). The instruments were cleaned this day even though it was after the official close of the IOP. The behavior is consistent with October 5, 2001. The TSBR instrument was removed on October 6, 2001, so TSBR data do not appear in Figure 12.

Figure 13 contains plots of the pyranometer readings with the sun below -10° versus the net PIR signal for 13 of the 14 radiometers. The solid line is the least squares fit to the data with the intercept forced through zero; the dashed line is the least squares fit to the data with the intercept unrestricted. The uncorrected PSP, psp-mh, and cm21 have the largest offsets; the PSP and cm21 were corrected with the Dutton et al. (2001) method; and the psp-mh was corrected using the measured temperature difference between the inner glass dome and the case temperature according to the procedure in Haeffelin et al. (2001). The 8-48, cm11, cm22, cimel, and eko have smaller dependencies on the net PIR signal and were not corrected for offset. The cm22-rp, eq08, new_ep_bw, schenk, and yes offsets are practically independent of net PIR, and are almost zero with the exception of the new_epp_bw; which has about a 4 W/m^2 positive offset.

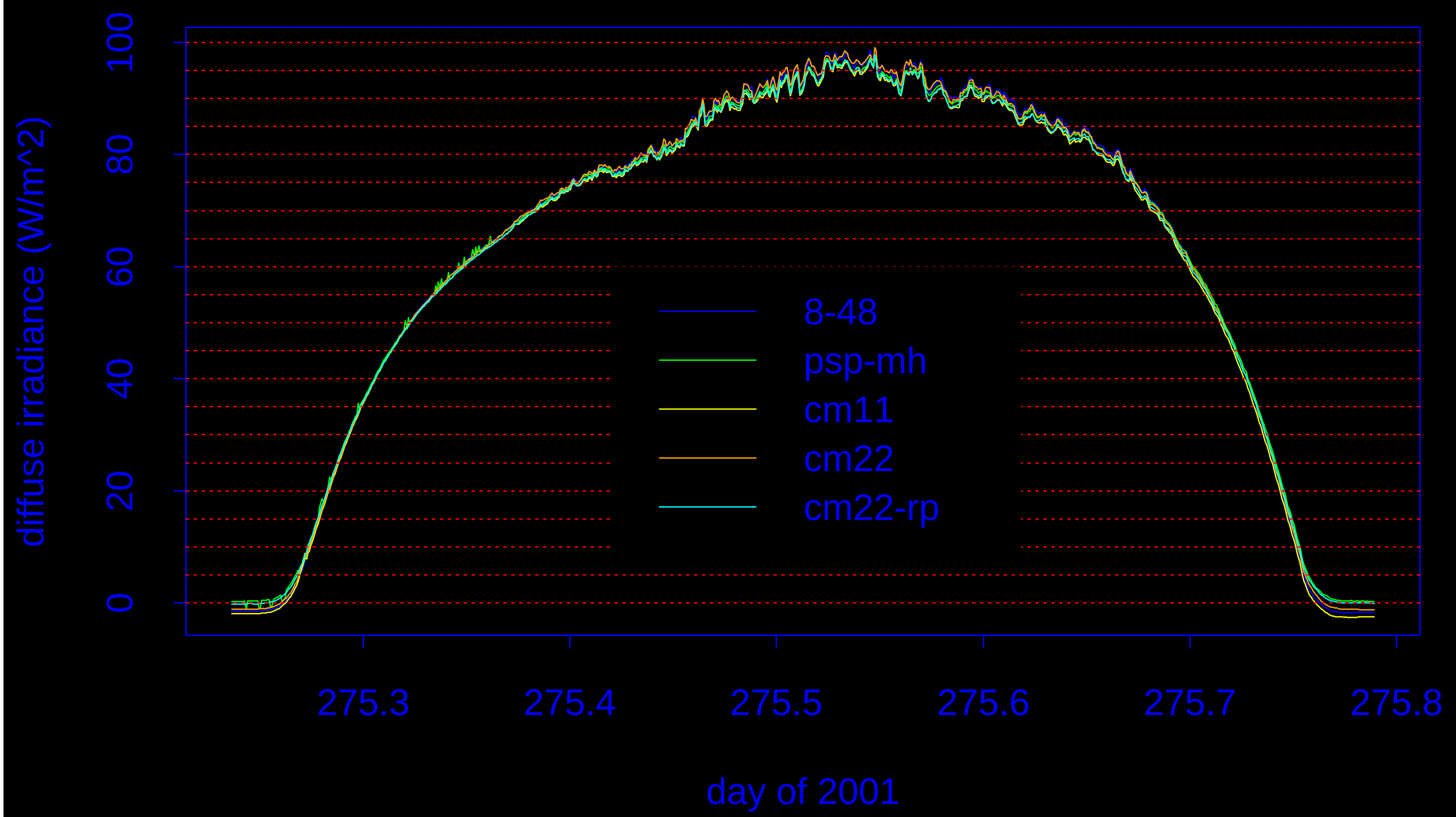
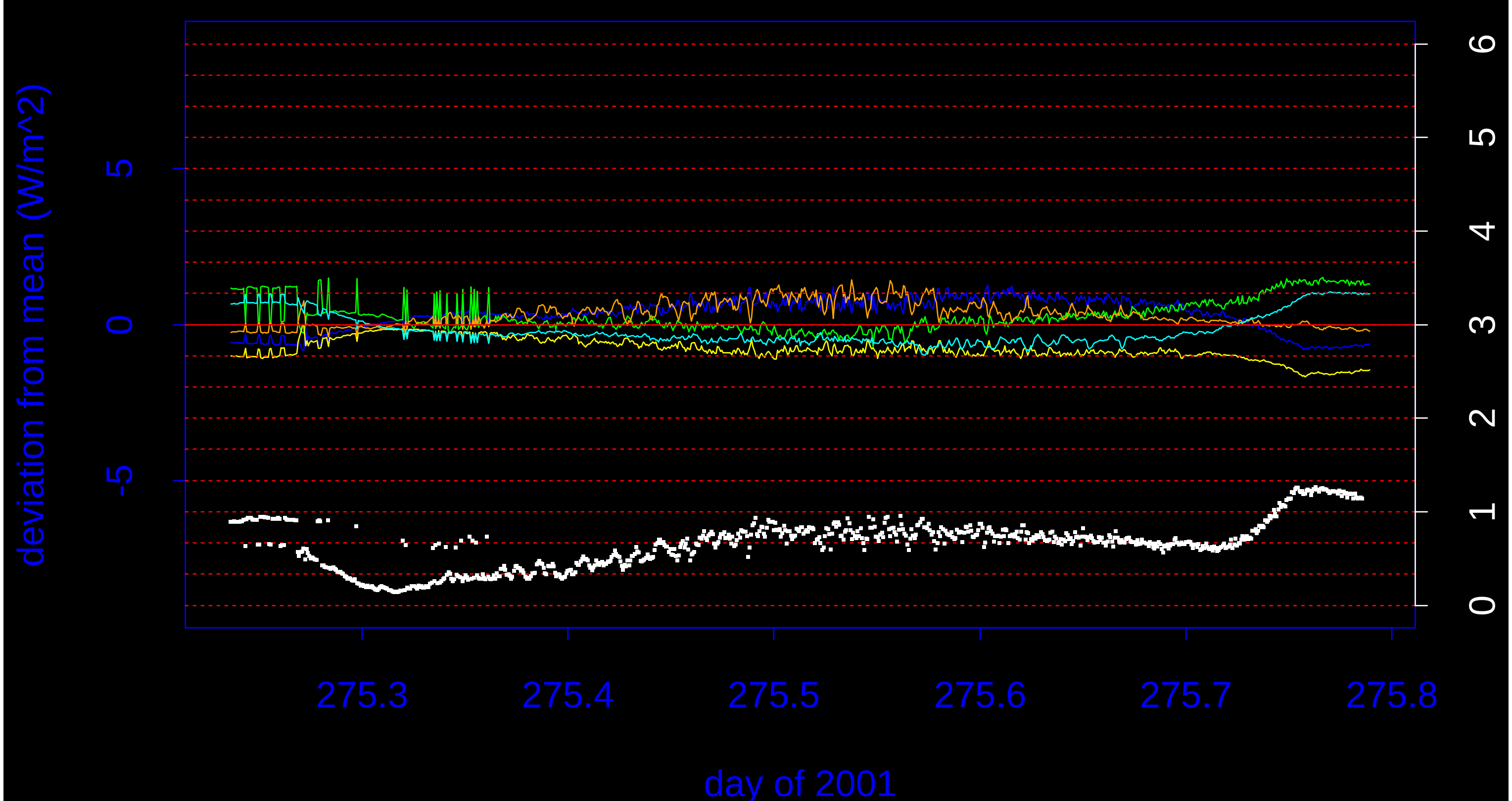


Figure 4. A plot similar to Figure 1 for October 2, 2001. This day had a smaller aerosol burden and therefore lower diffuse. The results are similar to those in Figure 1.



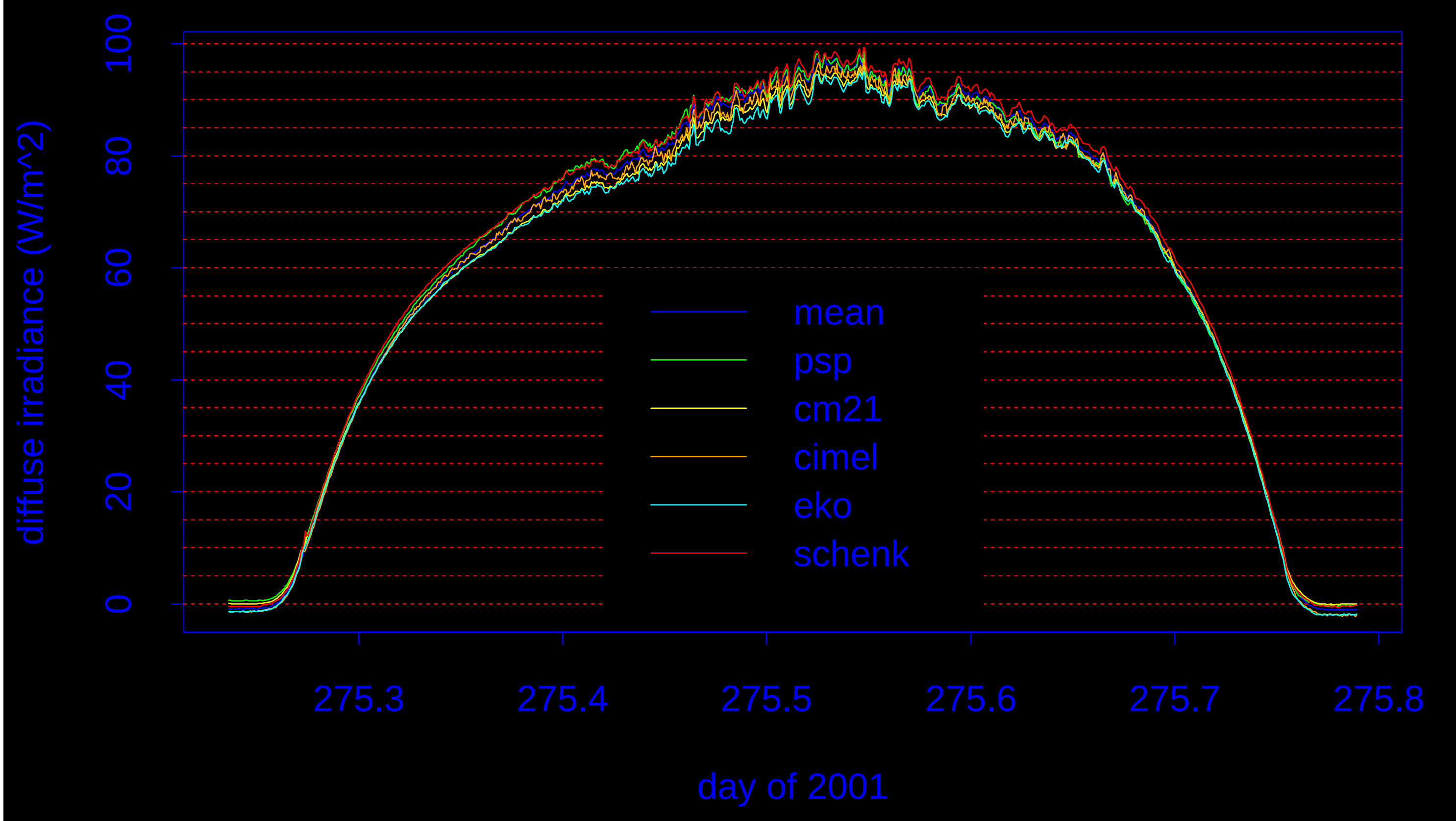
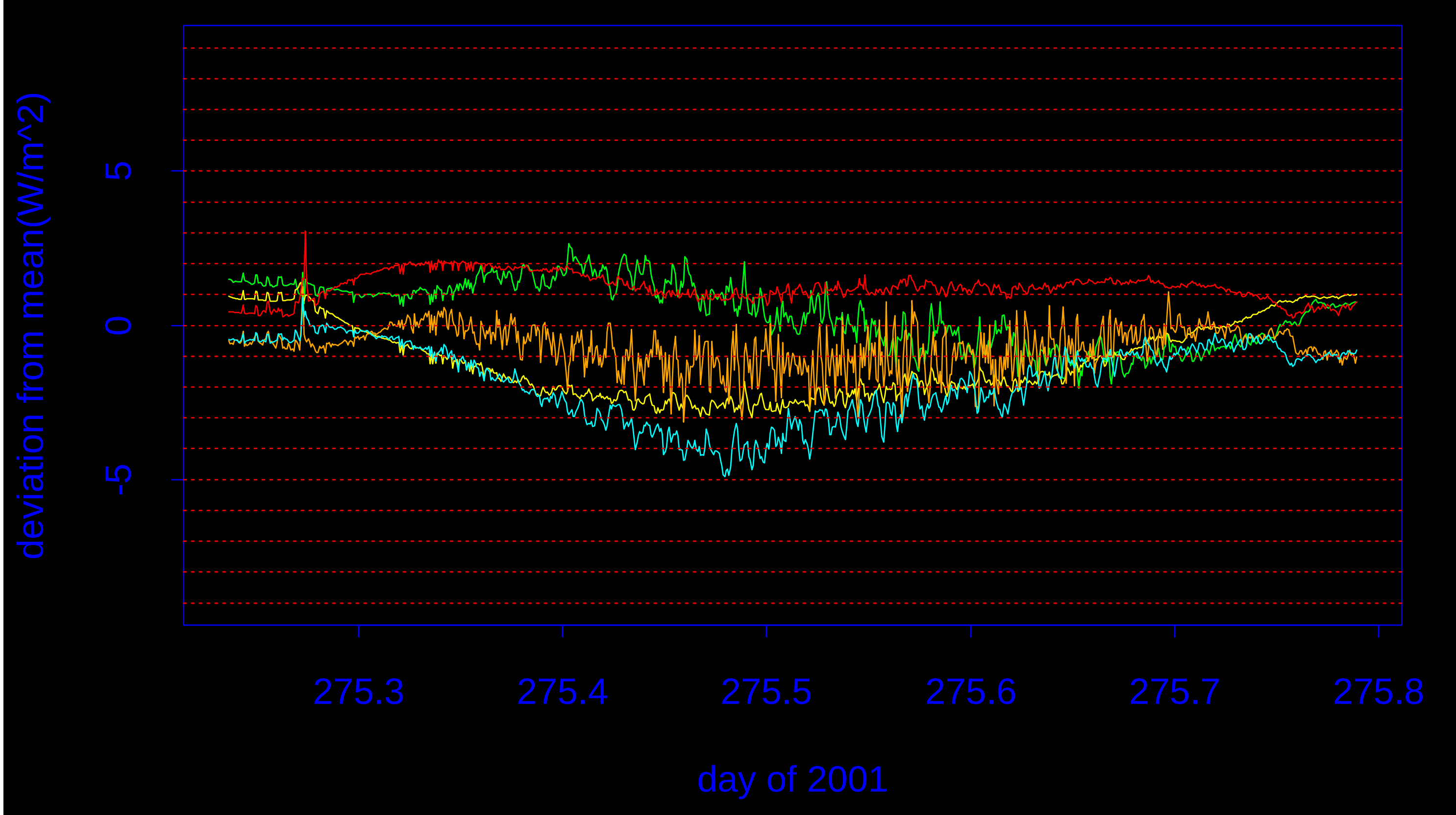


Figure 5. Same day as Figure 4 for the second group of instruments as in Figure 2. The deviations are somewhat larger than in Figure 2.



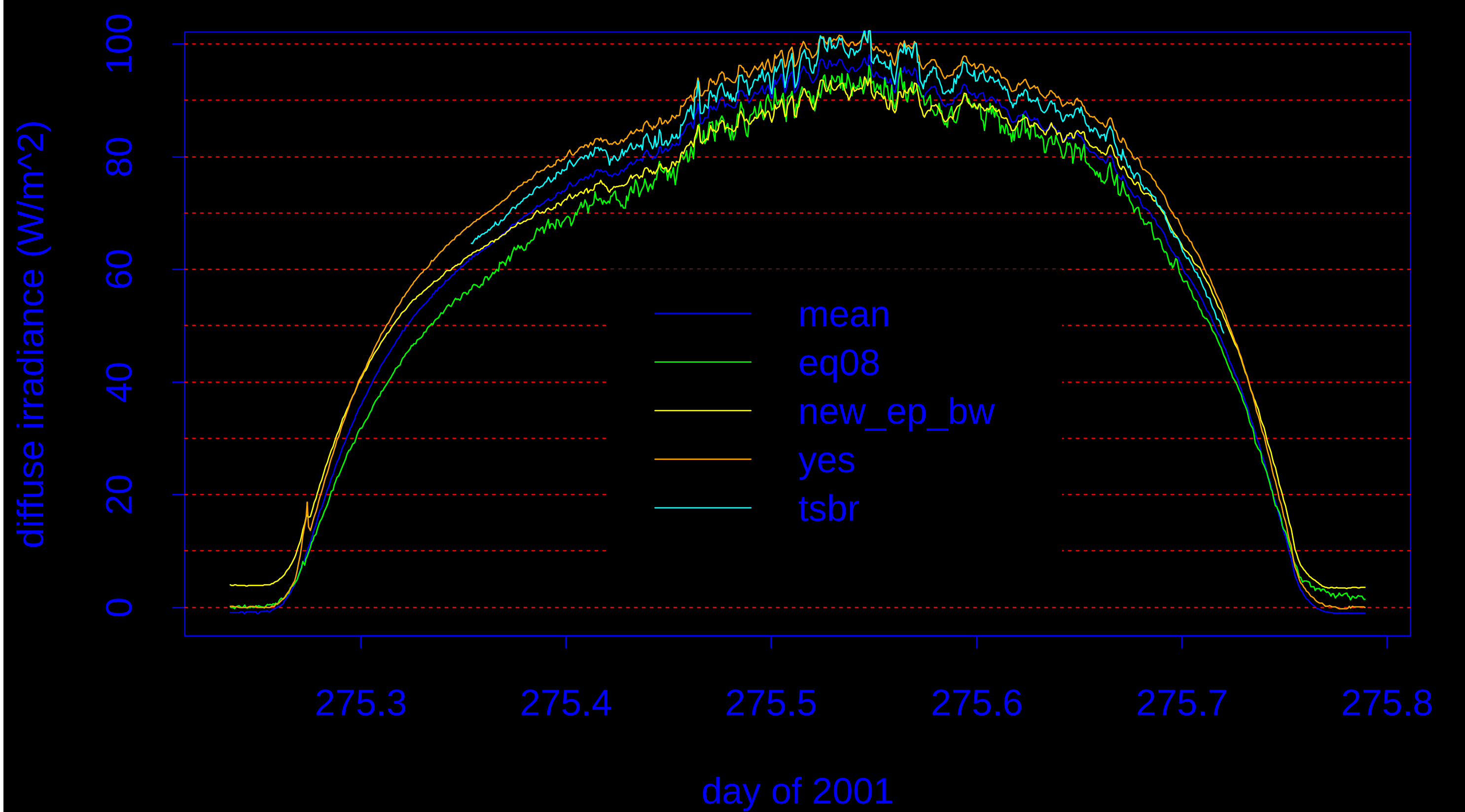
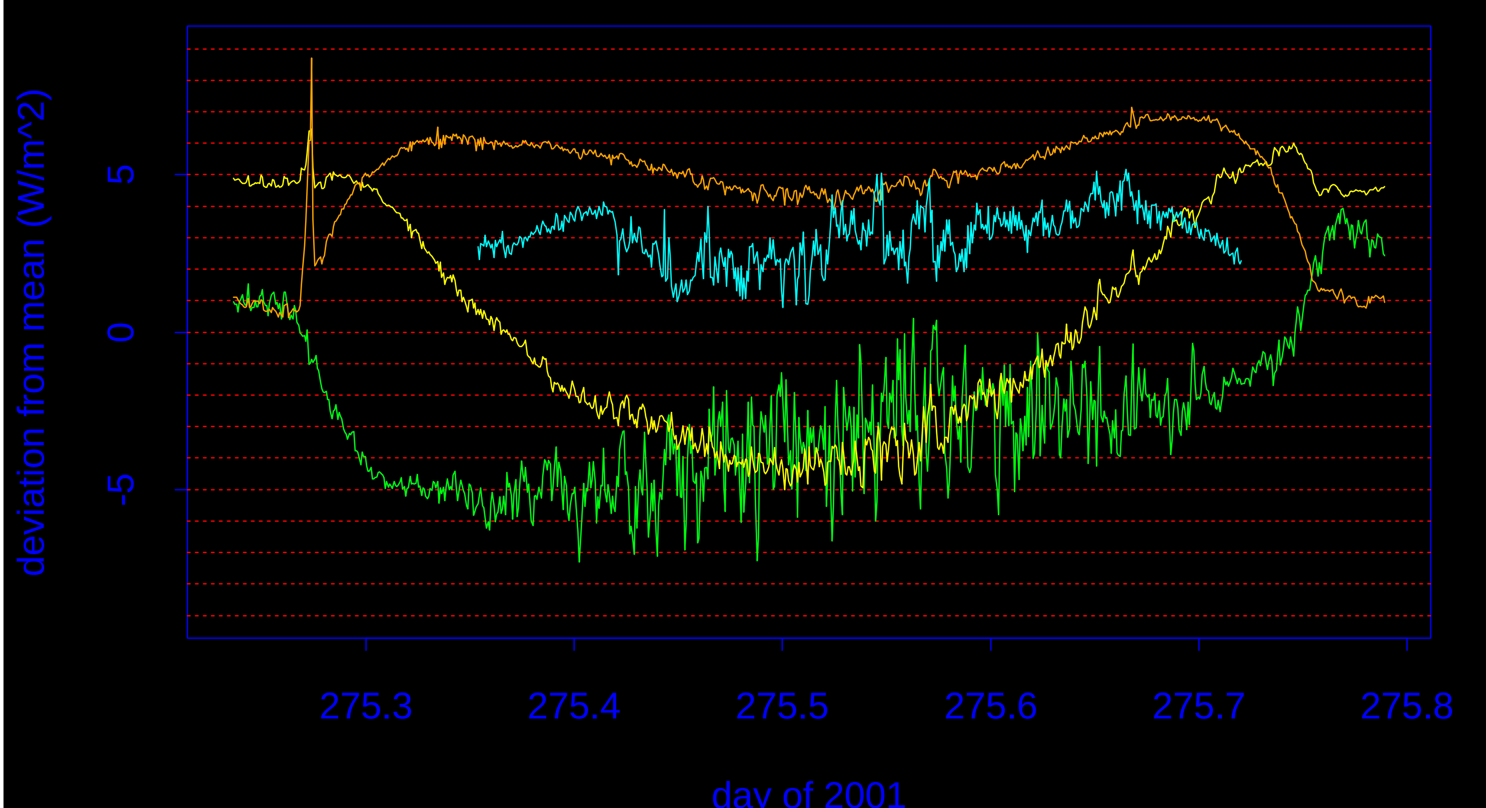


Figure 6. Same day as Figure 5 for the prototypes. The deviations are similar to Figure 3 with the exception of the TSBR, which is now higher than the mean of Figure 4.



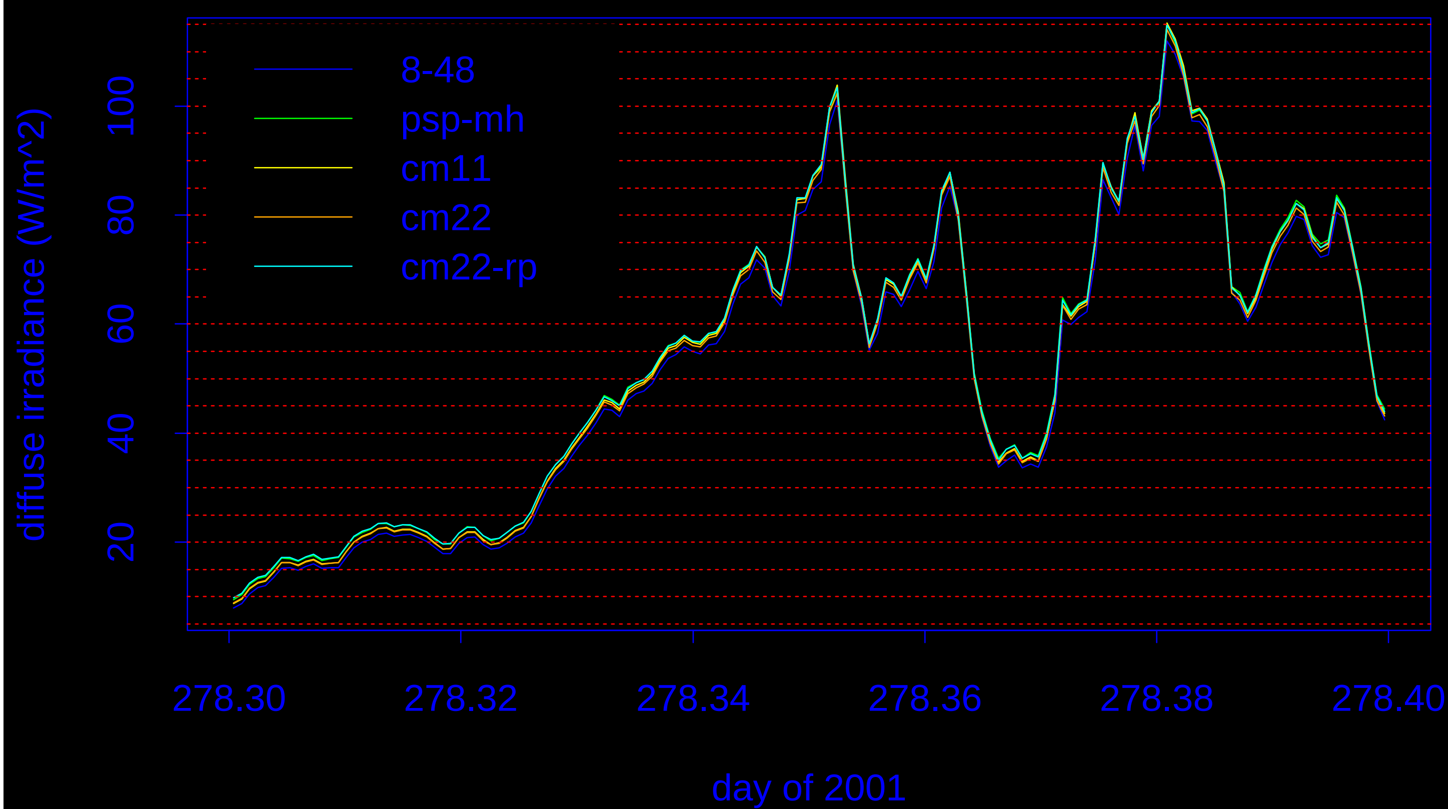
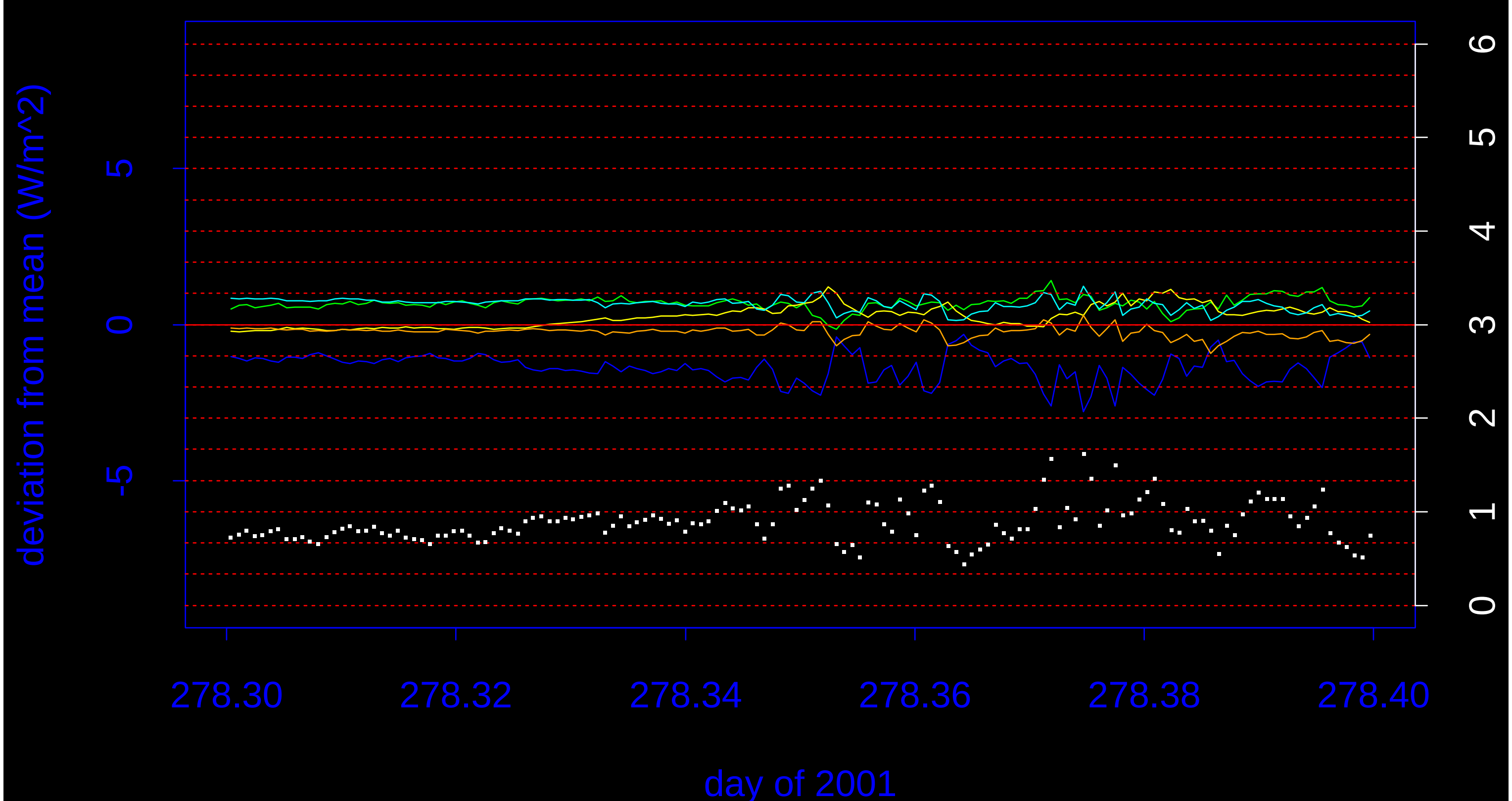


Figure 7. Diffuse horizontal irradiance versus time for the completely overcast portion of October 5, 2001. This plot includes five measurements that were the most consistent group for both clear and overcast conditions throughout the IOP. The bottom plot contains deviations from the mean of the group (left-hand ordinate) and the standard deviation among the group of five (right-hand ordinate). The standard deviations are generally less than 1 W/m^2 except for the 8-48, which has about twice the deviation from the mean as the others.



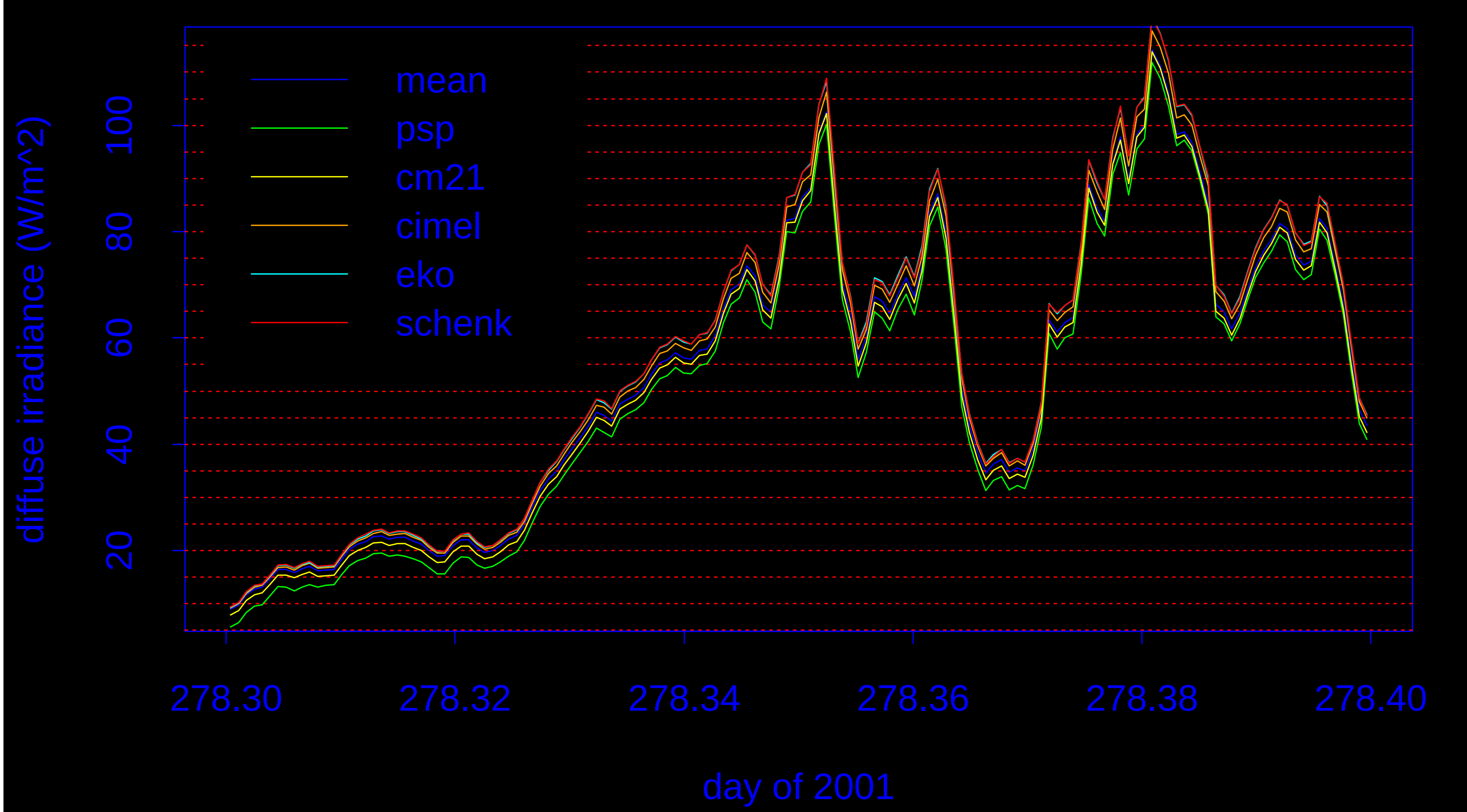
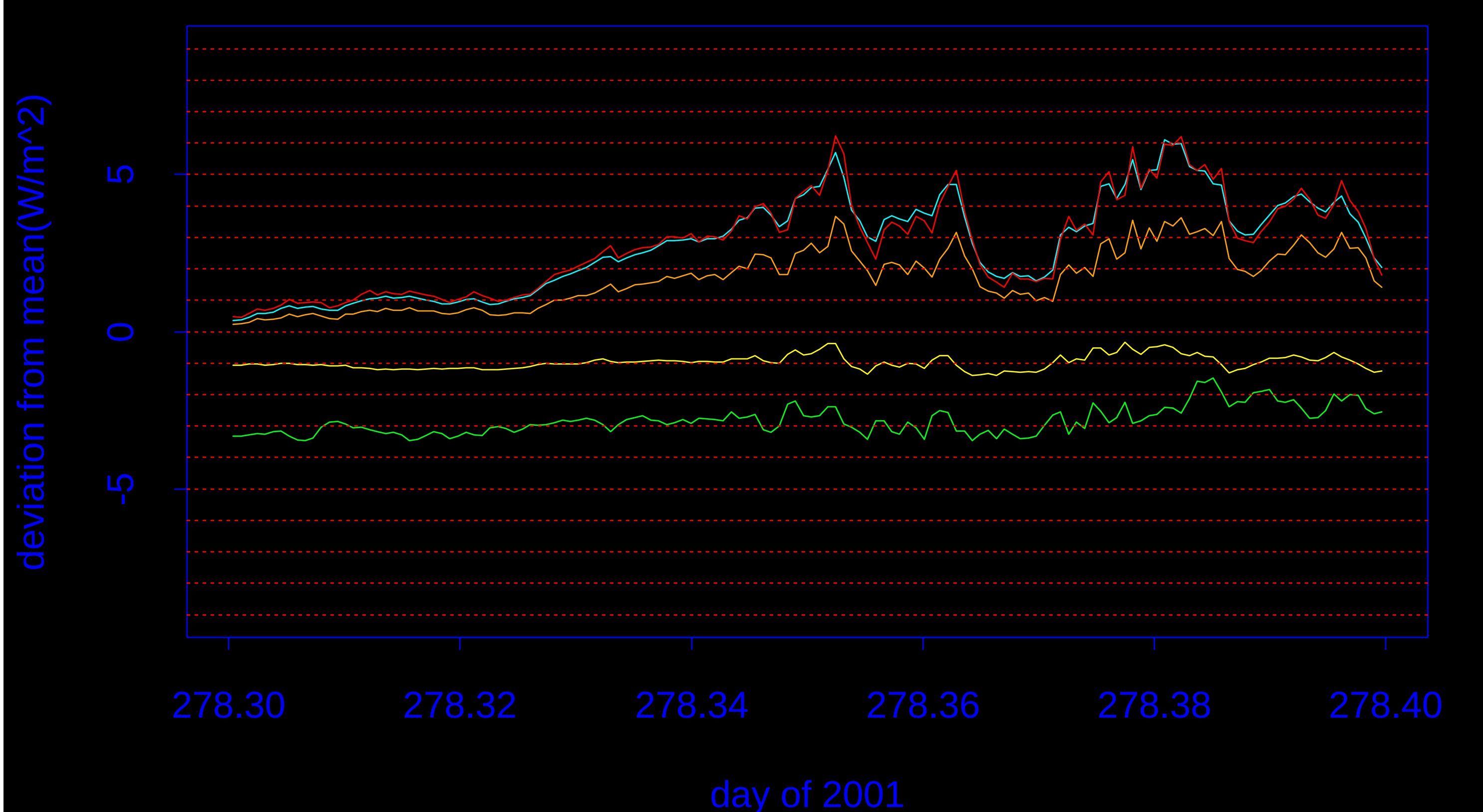


Figure 8. The second most consistent group of the comparison on the cloudy day of October 5, 2001. The deviations are greater than they were for the clear days.



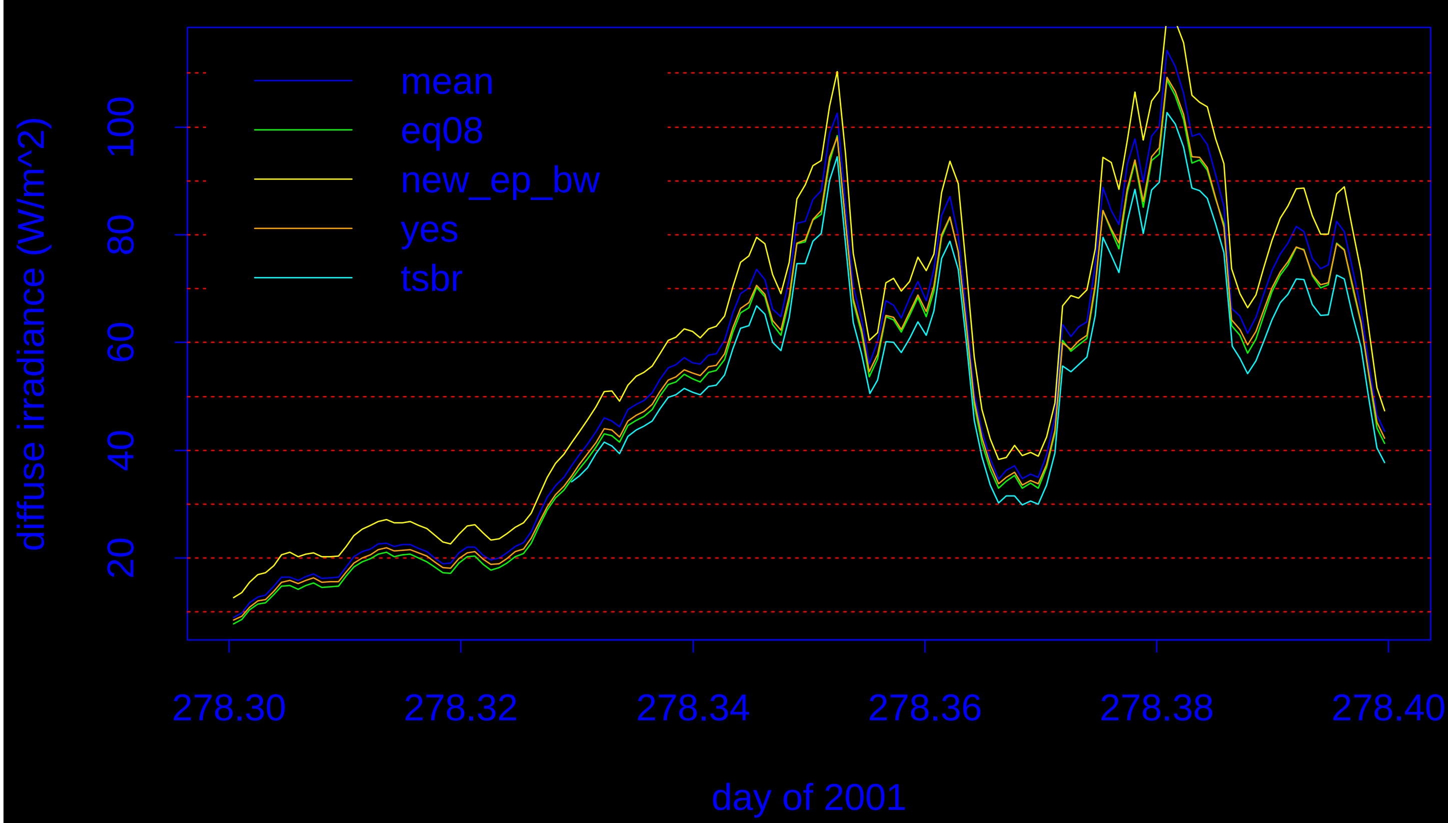
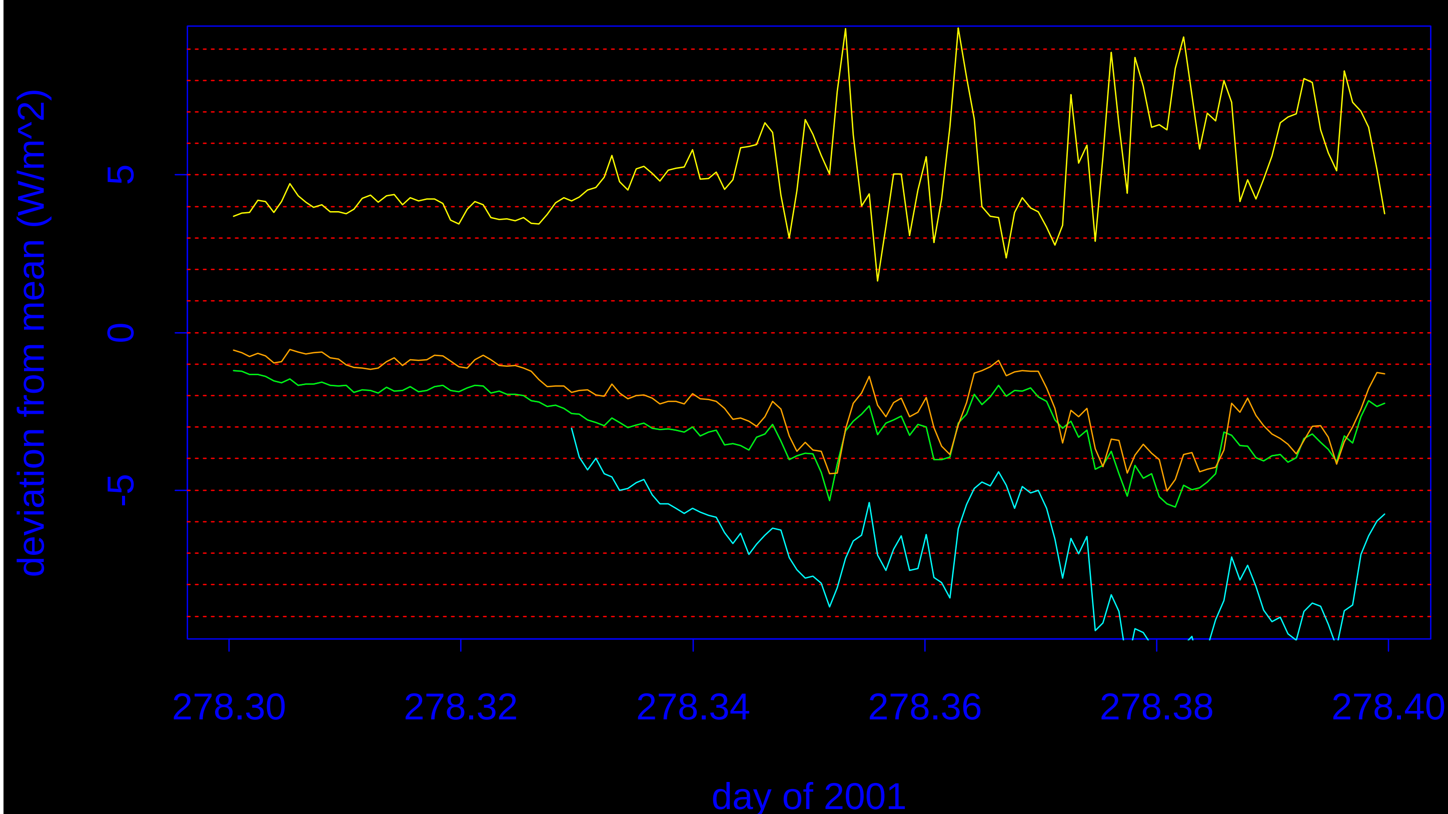


Figure 9. The deviations among the prototypes for October 5, 2001 are about as large or larger than the results in Figure 8.



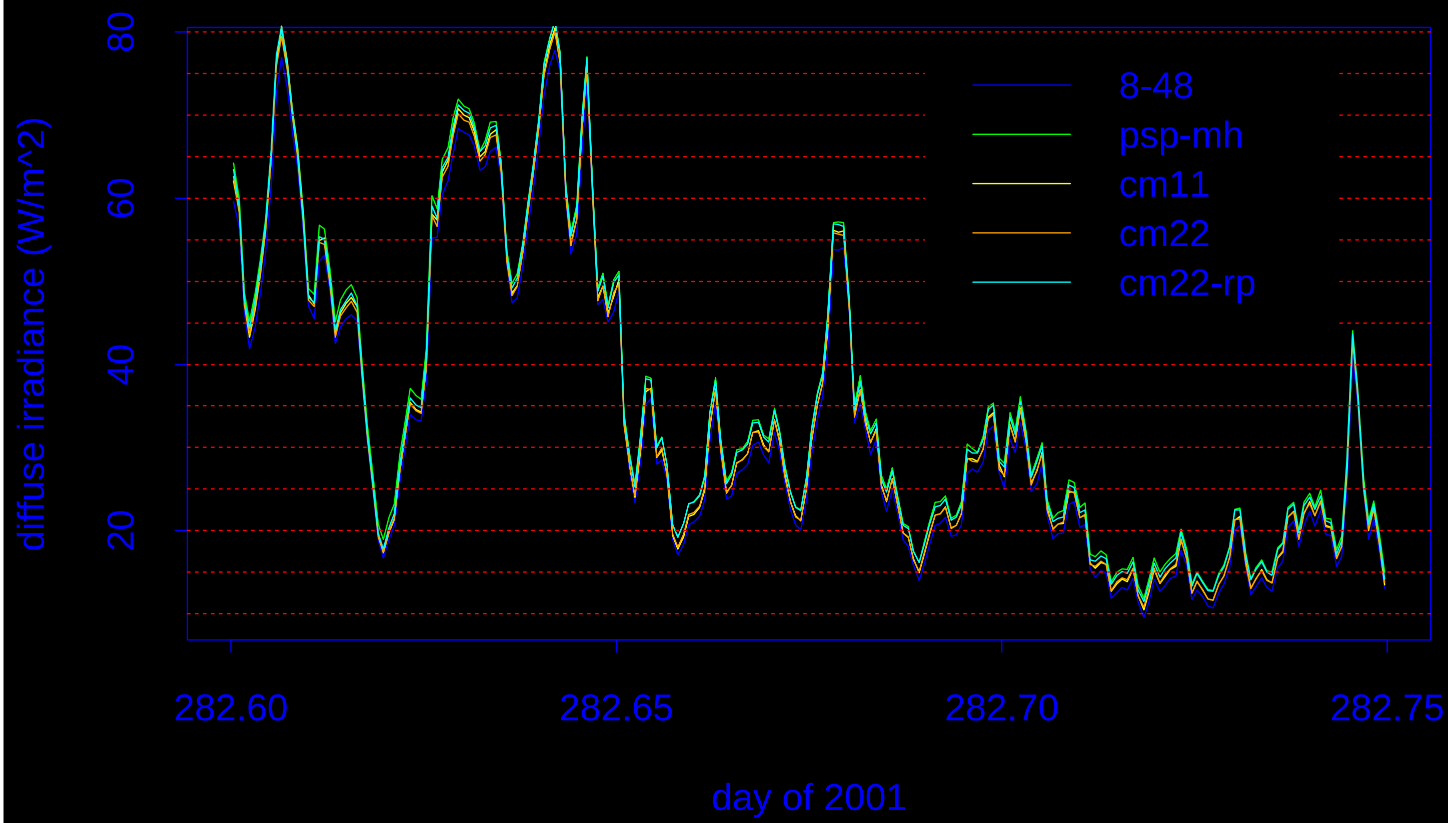
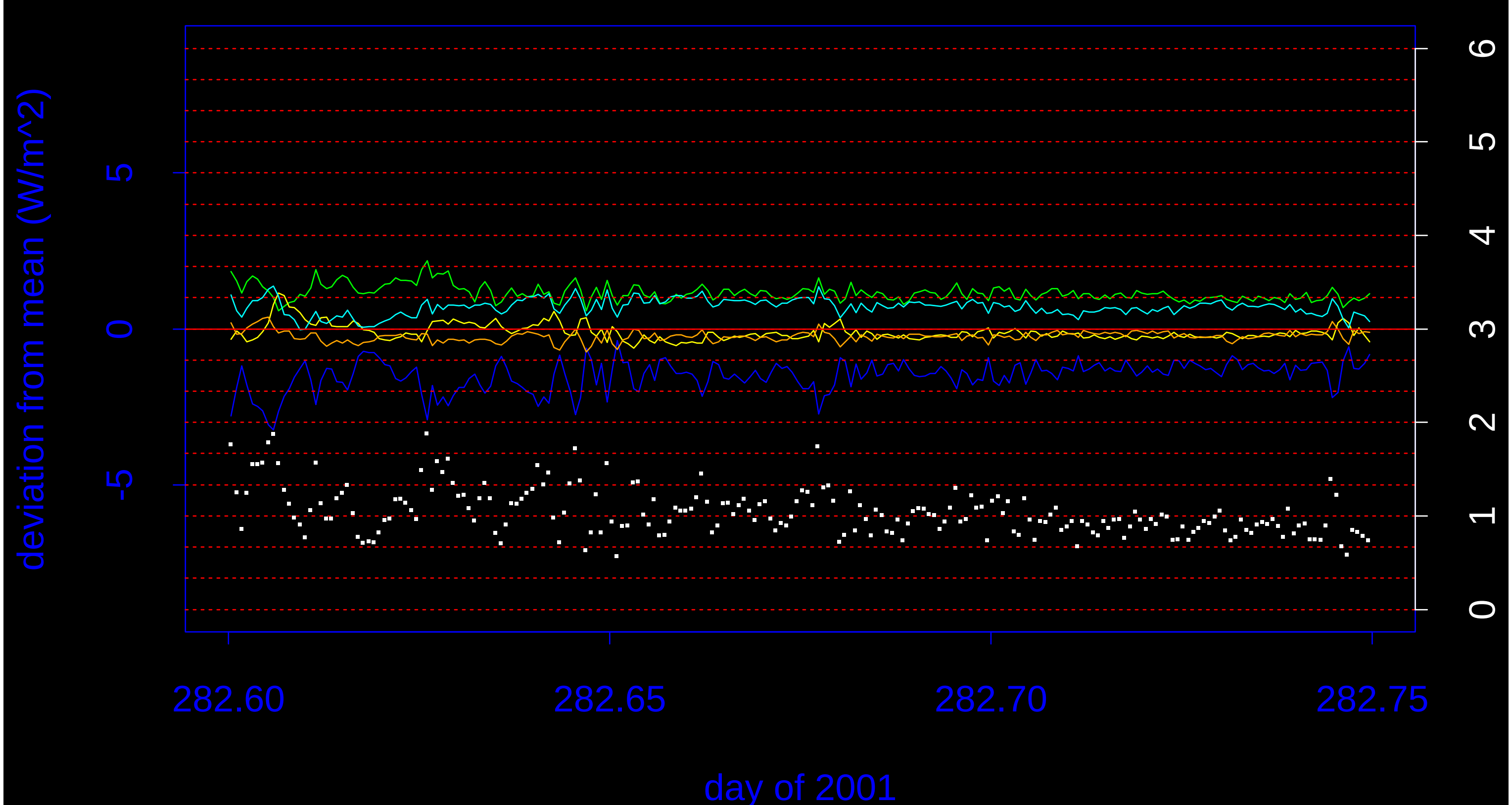


Figure 10. Same as Figure 7 for an overcast portion of October 9, 2001.



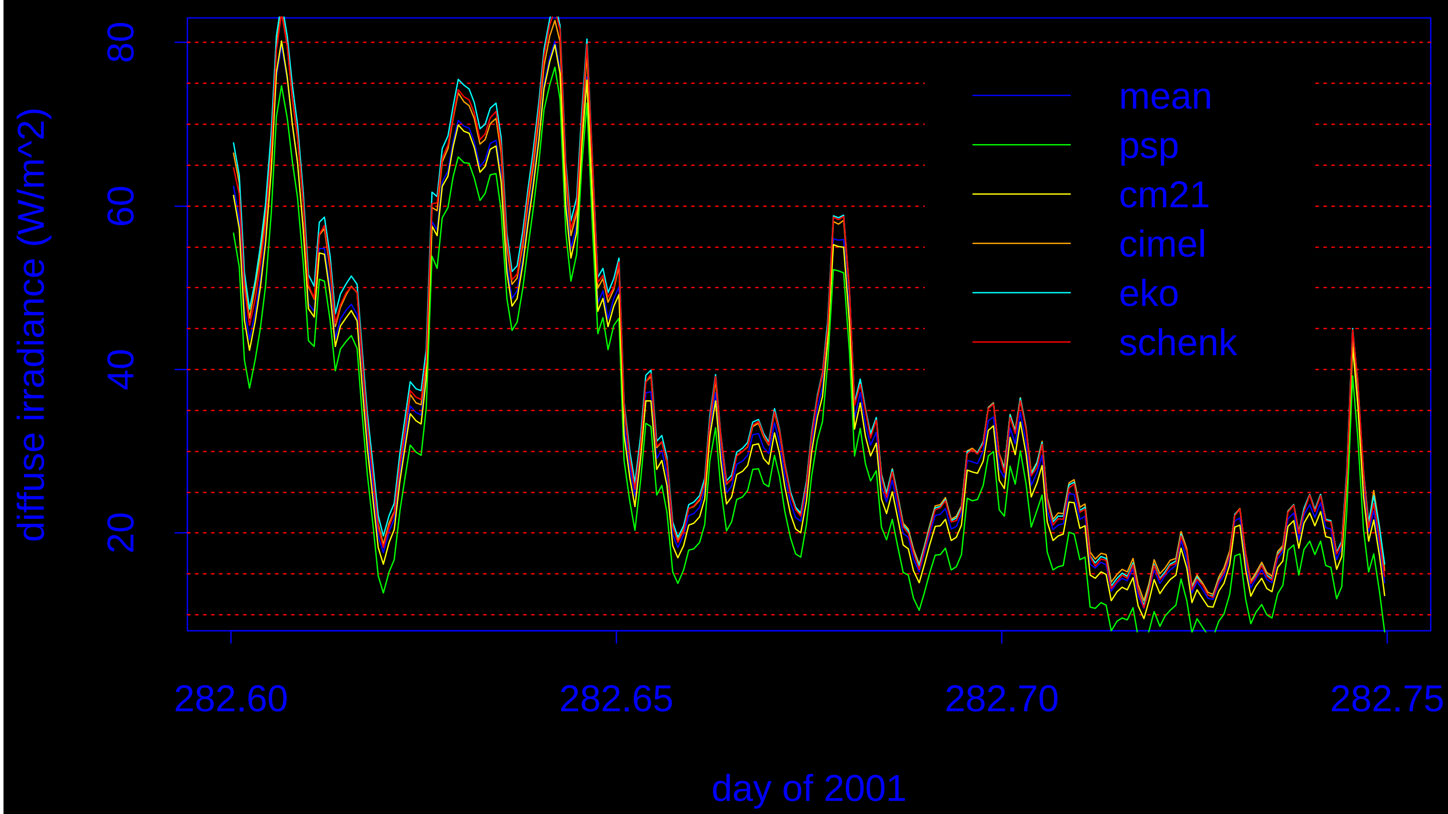
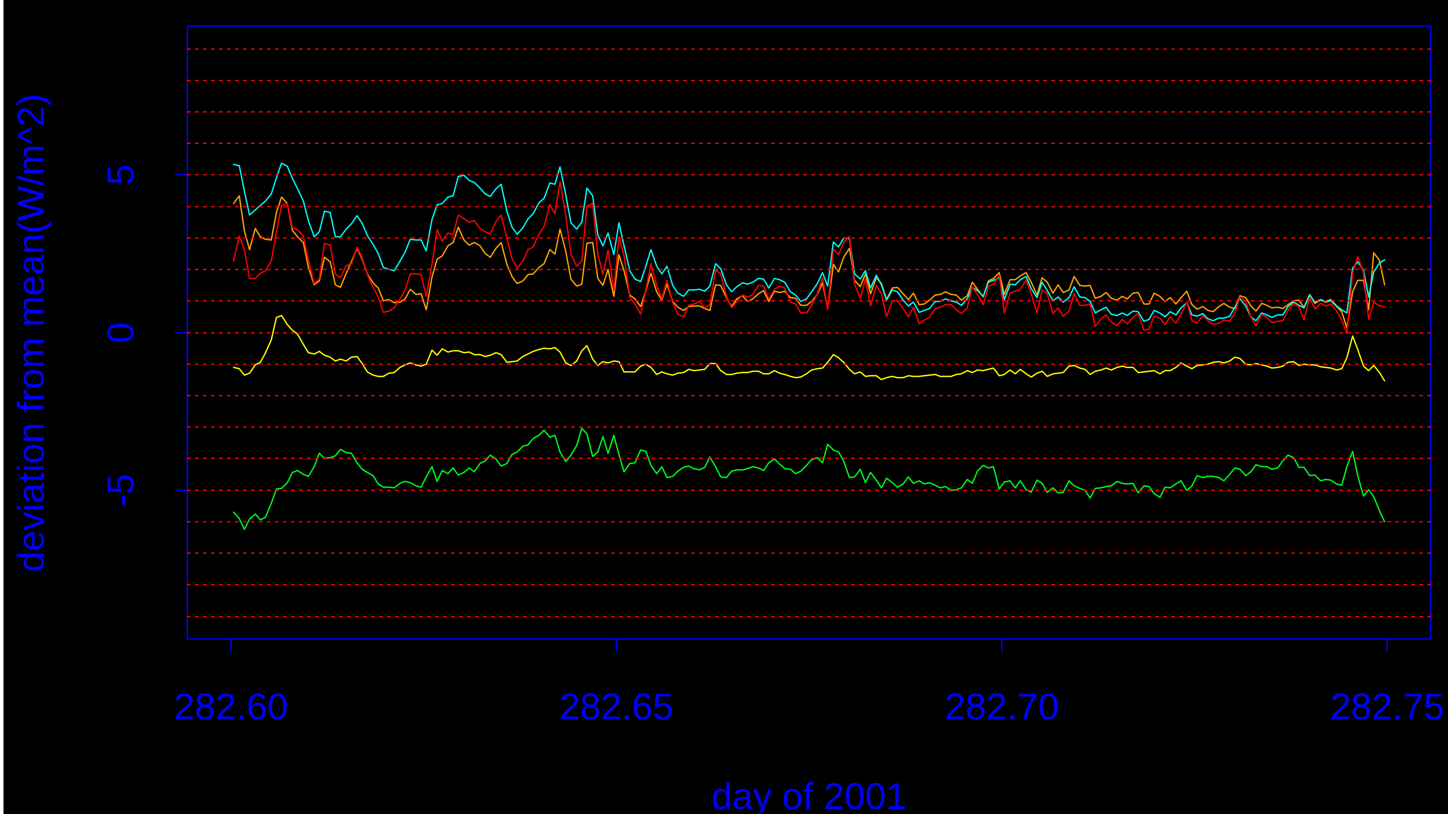


Figure 11. Same as Figure 8 for an overcast portion of October 9, 2001.



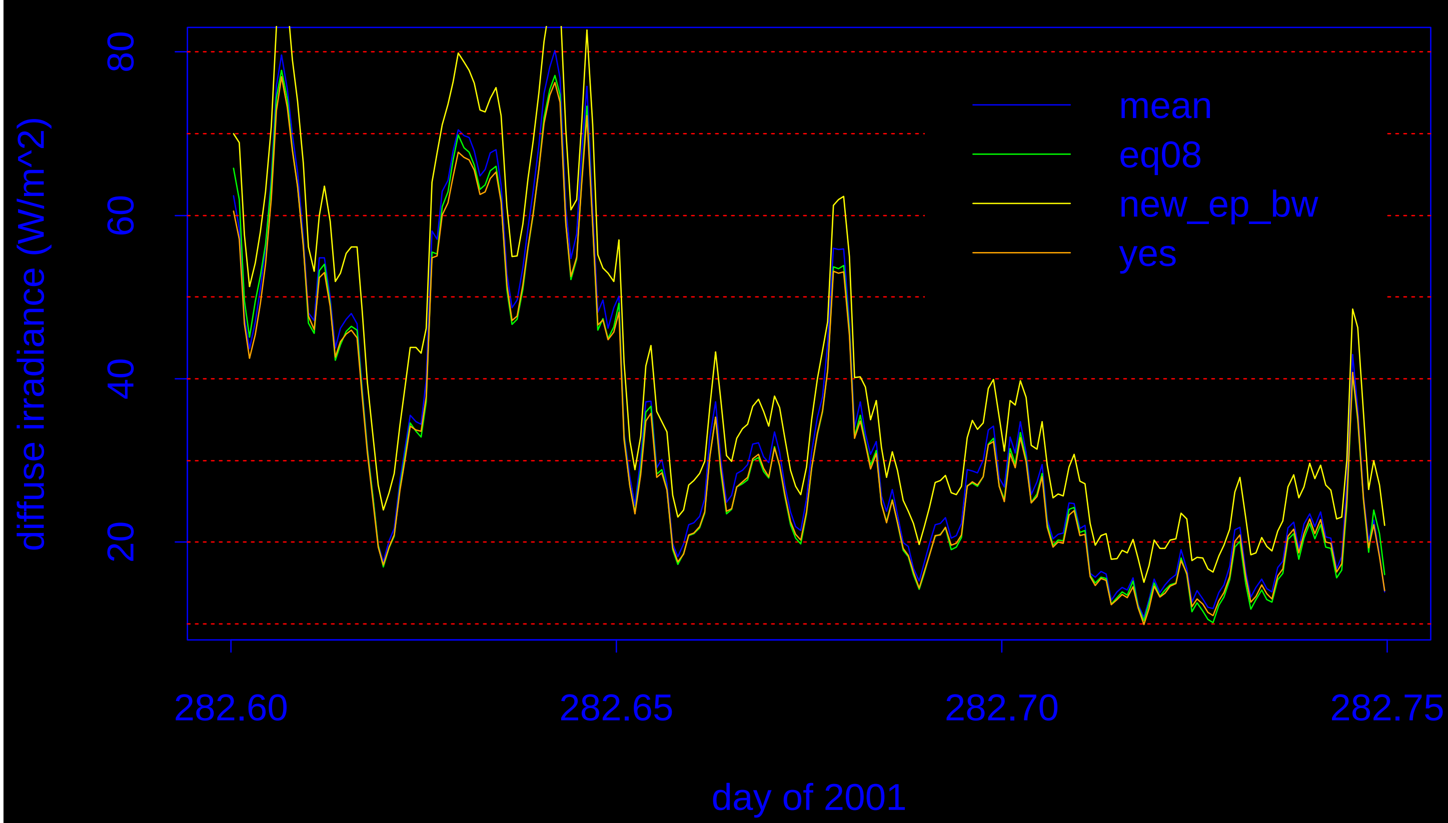
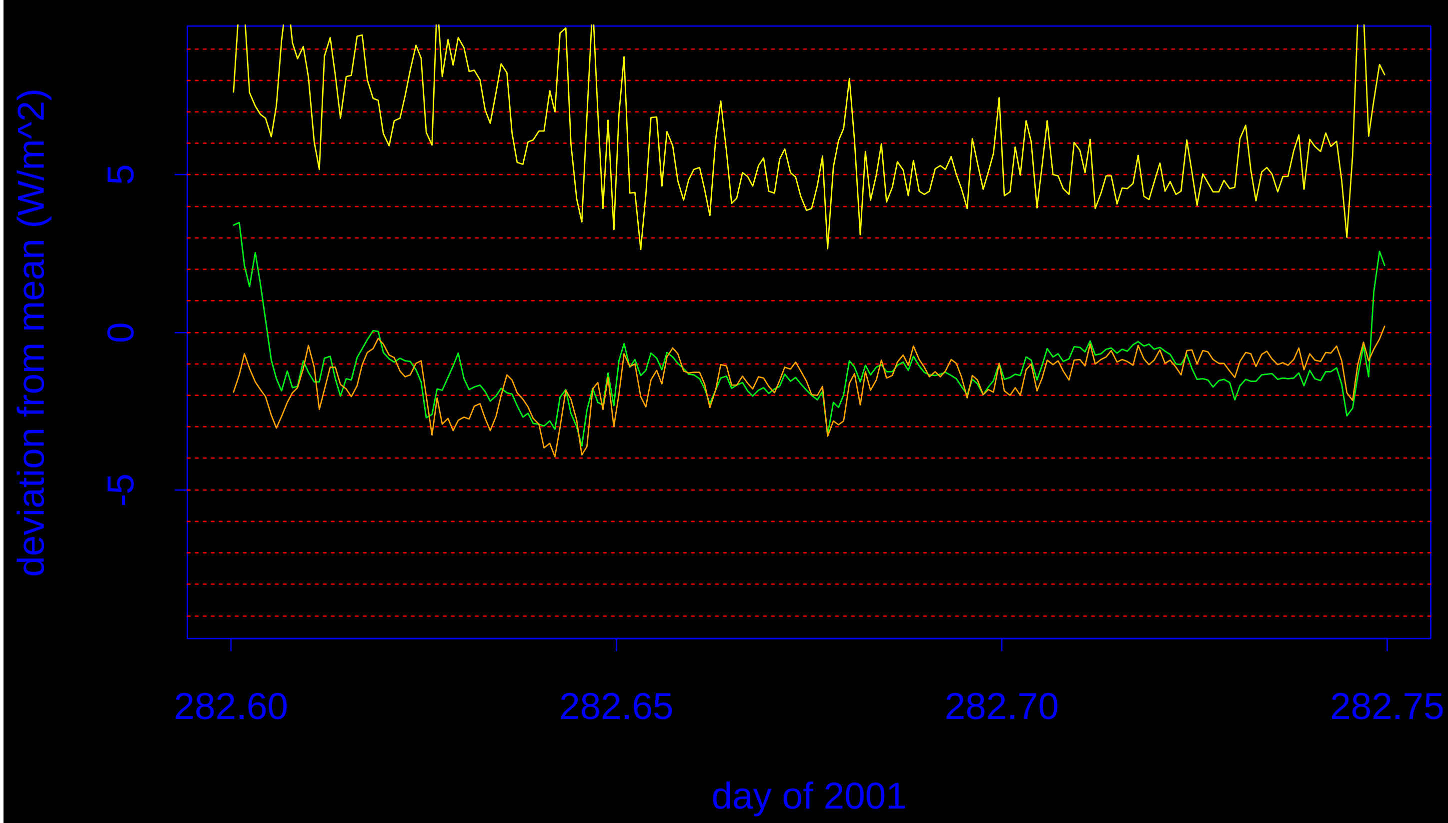


Figure 12. Same as Figure 9 for an overcast portion of October 9, 2001. The TSBR does not appear here because it was removed on October 6, 2001.



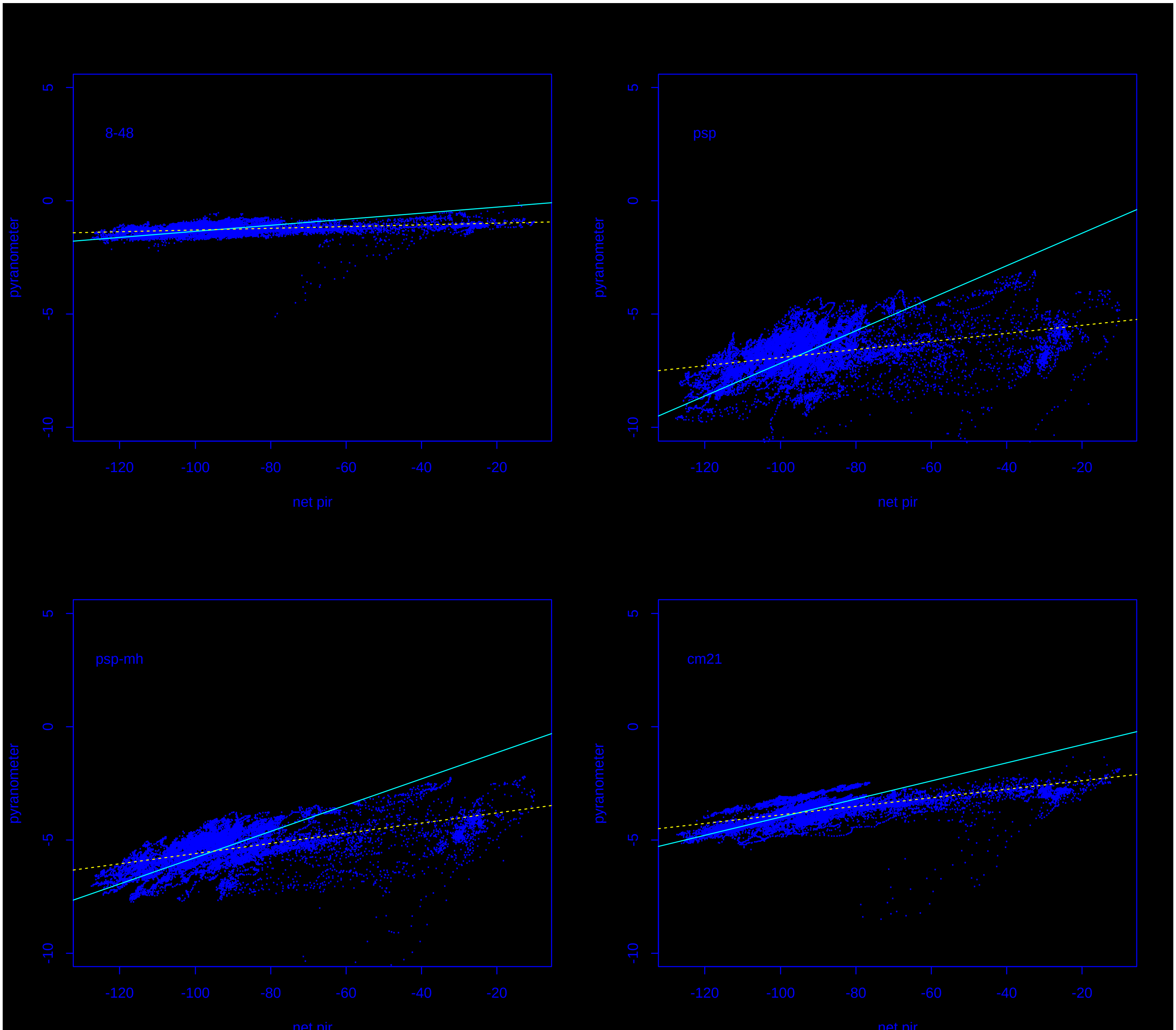
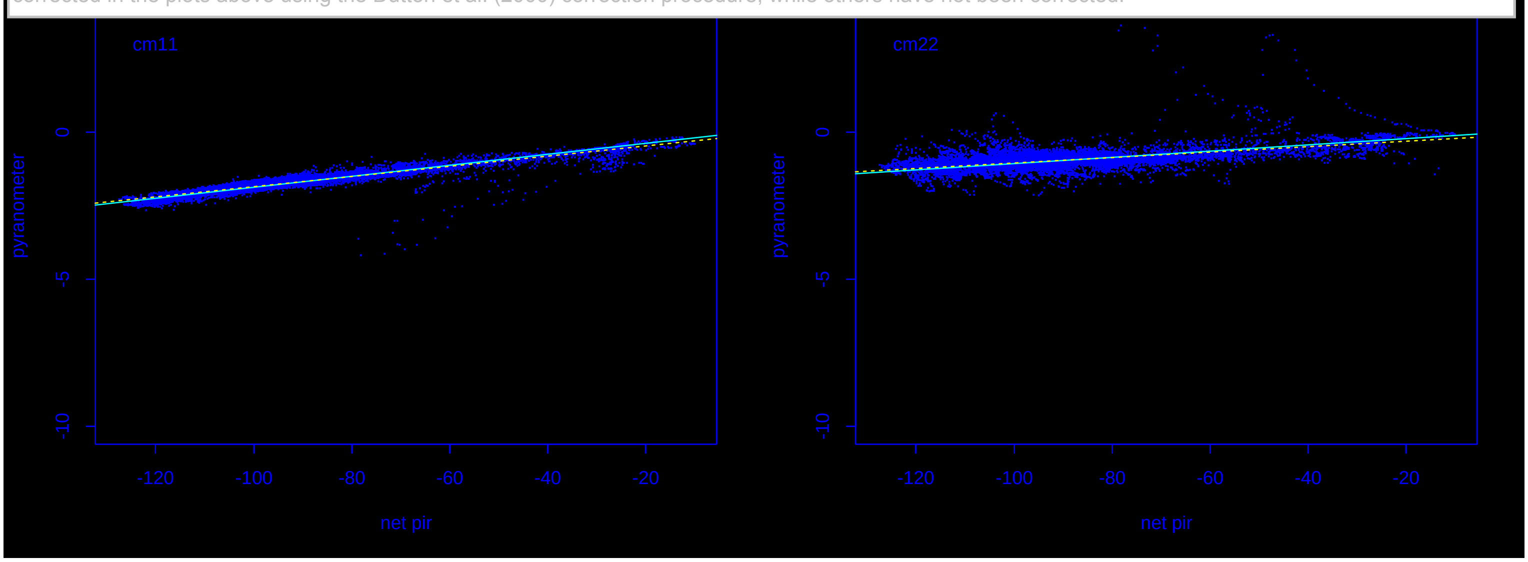


Figure 13. These plots include only data with the sun at least 10° below the horizon. The plots are the offsets of the diffuse irradiance as a function of the net infrared measurements made by the Eppley PIR pyrgeometer. These plots are explained in Dutton et al. (2001). The dashed lines are linear fits through the points and the solid lines are fits through the points forced to zero diffuse at zero net infrared irradiance. Ideally, these plots would show no dependence on net infrared as seen for the schenk and the yes. The PSP and psp-mh have the largest offsets, and the others are in between. Some of these offsets are corrected in the plots above using the Dutton et al. (2000) correction procedure, while others have not been corrected.



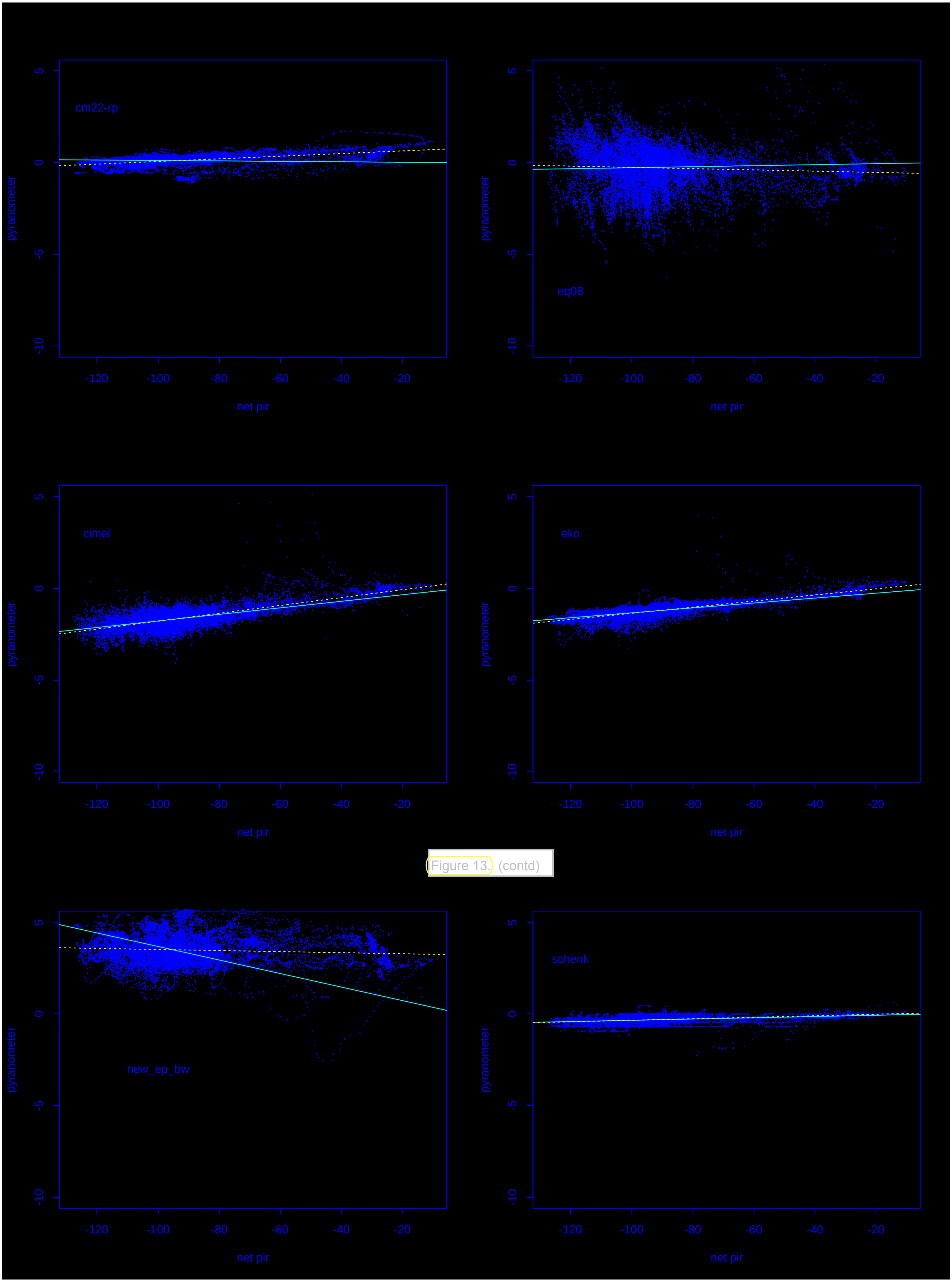


Figure 13. (contd)

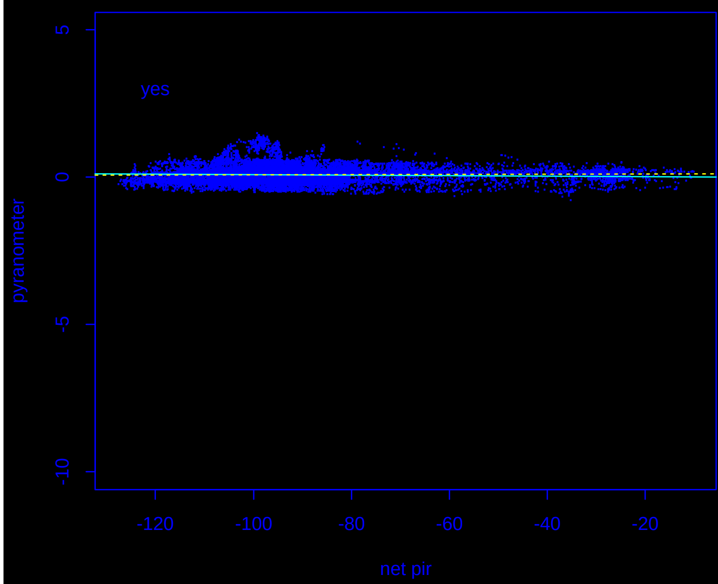


Figure 13. (contd)

Figure 14 shows the results of the capping experiment done when the instruments, measuring diffuse, were shaded in the early afternoon of a clear day (September 29, 2001, day of year 272). Samples were written to the file every two seconds. The capping was repeated four times. The net infrared signal measured by the PIR was near –146 W/m^2 during this time. If we assume that the Dutton et al. (2001) method (hereafter, net-PIR method) applies to the instruments that show some dependence on net PIR signal as discussed earlier, we can estimate the expected offset at time of capping. However, it should not be assumed that the net-PIR method should be applied to all of these cases.

The eq08 and cimel were sensitive to gusty winds and both show this behavior if we compare the stability of the other instruments in the capping experiment at full diffuse signal. The eq08, according to Figure 13, does not depend on net pir, and the amplitude of the offsets in Figure 13 and the amplitude of the noise in the uncapped signal are plausibly consistent with the offset behavior in Figure 14. For the net-PIR signal measured during this time we might expect a cimel offset of -2.6 W/m^2, which again is plausible given the noise in the uncapped signal. The wind effects on the signal make this a difficult confirmation without more tests.

The eko expected offset was about -2 W/m^2, but the offset, as judged by the lowest dip is 2 to 3 times this measurement. The new_ep_bw was expected to have a positive offset judging from the data at night in Figure 13, but goes negative by a few W/m^2. The schenk is barely negative, which is consistent with Figure 13, and the yes is zero, consistent with Figure 13 results.

The 8-48 goes slightly negative upon capping, which is consistent with an expected -1 W/m^2 or -2 W/m^2 offset from the net-PIR estimate and the very slow time response of this instrument. Both PSP and uncorrected psp-mh show the expected offset from the net-PIR estimate. The cm21 estimated offset based on the net pir is about 6 W/m^2, which is close to the 7 W/m^2 - 8 W/m^2 offset from capping. The cm11, cm22, and cm22-rp capped offsets are small and consistent with the net-PIR estimates.

Discussion and Summary

Fourteen measurements of diffuse horizontal irradiance were made simultaneously over a four-week period in September and October 2001. Tracking to keep the instruments shaded was excellent, and there was a preponderance of clear, cloud-free weather. Five of the measurements were consistently within 1 W/m^2 to 2 W/m^2 of their mean for both clear and cloudy conditions. Five other measurements were only slightly less stable with most measurements within 2 W/m^2 to 3 W/m^2 of this mean. The four prototype instruments showed less agreement with our most consistent group than the commercial instruments.

There are still some issues regarding calibration that need to be resolved. The current procedure in ARM produces calibrations that result in higher diffuse irradiances than are measured by the most consistent group of five. The 8-48 and PSP that showed consistency with the best group used factory calibrations, rather than the ARM calibrations. ARM calibrations would give readings about 3 W/m^2 to 4 W/m^2 higher in the examples shown. The benefits of high-volume ventilation to minimize the temperature difference between case and dome has been demonstrated as three of the single-black detectors, which otherwise would be expected to have high offsets, are among the consistent group showing little nighttime offset and capping results that are consistent with their small nighttime offsets.

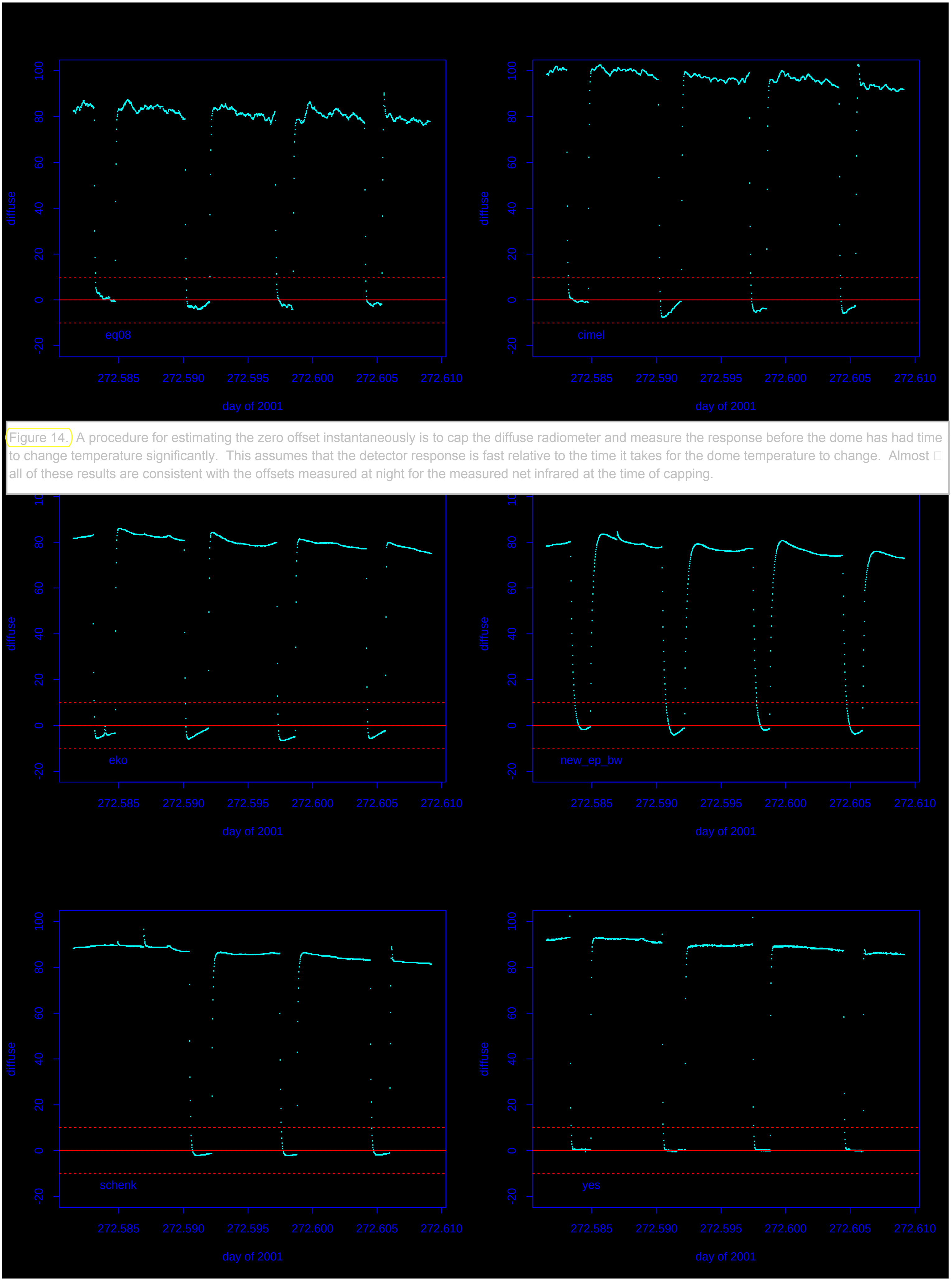


Figure 14. A procedure for estimating the zero offset instantaneously is to cap the diffuse radiometer and measure the response before the dome has had time to change temperature significantly. This assumes that the detector response is fast relative to the time it takes for the dome temperature to change. Almost all of these results are consistent with the offsets measured at night for the measured net infrared at the time of capping.

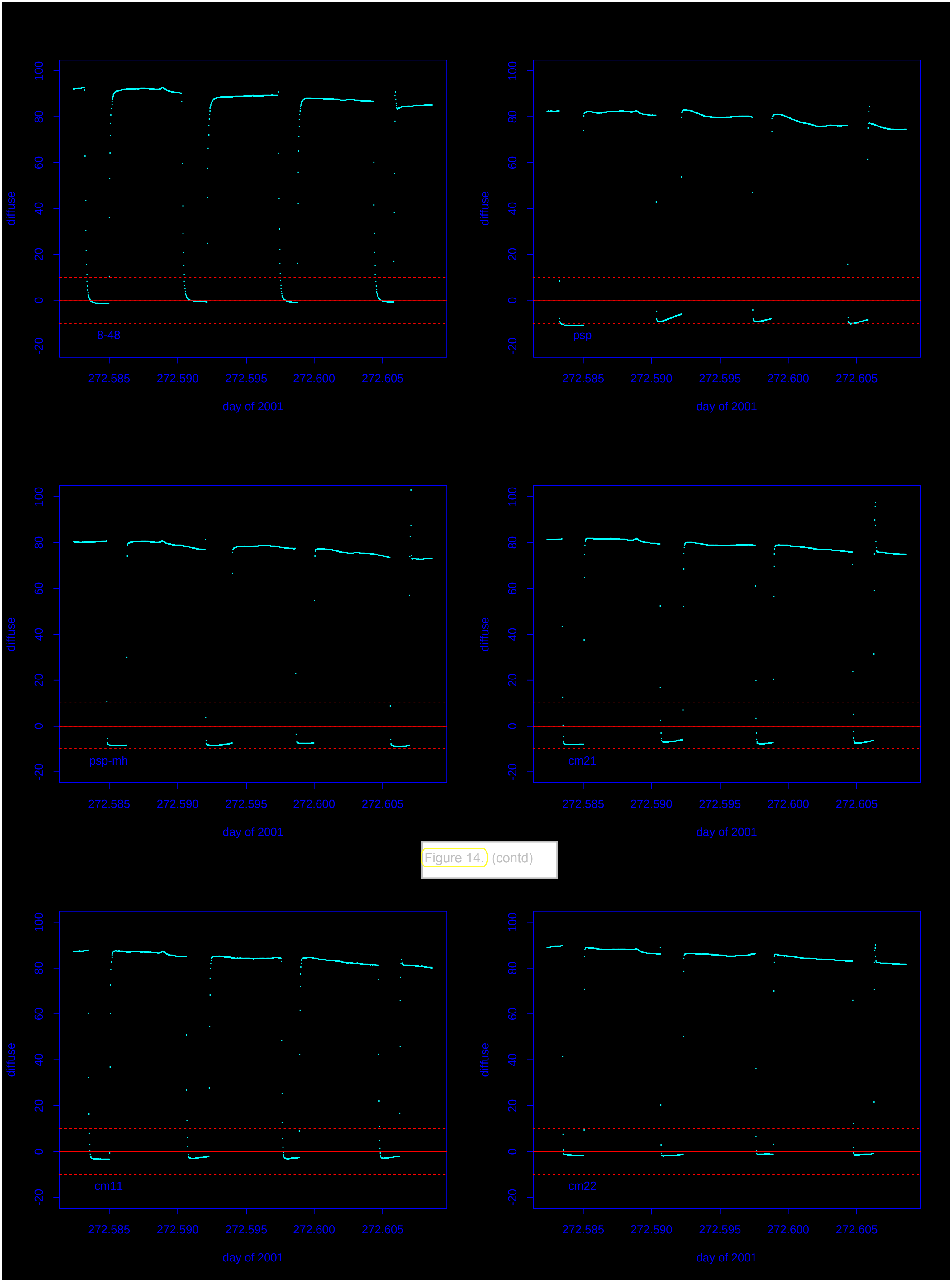


Figure 14. (contd)

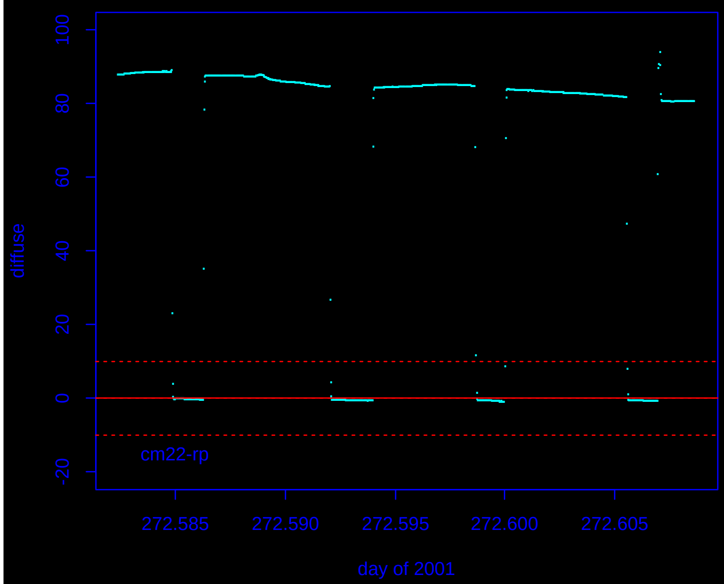


Figure 14. (contd)

There are geometry differences in the radiometer detectors. Since all were shaded similarly with the same size blocker at a fixed distance, the larger detectors receive more diffuse radiation from the penumbra than the smaller detectors. The largest differences from this effect will occur in clear, hazy conditions. Calculations suggest that the differences between the largest and smallest detectors will be less than 2 W/m^2 for the data shown in this paper.

Based on this study and work to follow, it appears that we should be able to establish a group of instruments that we can maintain as a working diffuse standard group for ARM. However, the question of how close this standard is to the true absolute value will remain elusive until an absolute diffuse radiometer is developed.

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