JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. D22, PAGES 28,129–28,141, NOVEMBER 27, 2001

Atmospheric longwave irradiance uncertainty: Pyrgeometers compared to an absolute sky-scanning radiometer, atmospheric emitted radiance interferometer, and radiative transfer model calculations

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Abstract. Because atmospheric longwave radiation is one of the most fundamental elements of an expected climate change, there has been a strong interest in improving measurements and model calculations in recent years. Important questions are how reliable and consistent are atmospheric longwave radiation measurements and calculations and what are the uncertainties? The First International Pyrgeometer and Absolute Sky-scanning Radiometer Comparison, which was held at the Atmospheric Radiation Measurement program's Southern Great Plains site in Oklahoma, answers these questions at least for midlatitude summer conditions and reflects the state of the art for atmospheric longwave radiation measurements and calculations. The 15 participating pyrgeometers were all calibration-traced standard instruments chosen from a broad international community. Two new chopped pyrgeometers also took part in the comparison. An absolute sky-scanning radiometer (ASR), which includes a pyroelectric detector and a reference blackbody source, was used for the first time as a reference standard instrument to field calibrate pyrgeometers during clear-sky nighttime measurements. Owner-provided and uniformly determined blackbody calibration factors were compared. Remarkable improvements and higher pyrgeometer precision were achieved with field calibration factors. Results of nighttime and daytime pyrgeometer precision and absolute uncertainty are presented for eight consecutive days of measurements, during which period downward longwave irradiance varied between 260 and 420 W m^{-2}. Comparisons between pyrgeometers and the absolute ASR, the atmospheric emitted radiance interferometer, and radiative transfer models LBLRTM and MODTRAN show a surprisingly good agreement of <2 W m^{-2} for nighttime atmospheric longwave irradiance measurements and calculations.

1. Introduction

Atmospheric longwave downward radiation is directly related to the greenhouse effect. This dependence and its small year to year variation makes longwave downward radiation at the Earth's surface a very promising element for monitoring climate change with respect to global warming. Uncertainty levels of atmospheric longwave radiation measurements have been considerably reduced in recent years which makes this element even more attractive in climate change research [*Philipona et al.*, 1996; *Ohmura et al.*, 1998; *Marty*, 2000]. Accurate longwave radiation measurements also allow cloud detection and are used to separate clear-sky from cloudy-sky situations [*Marty and Philipona*, 2000a] especially during dark hours. Cloud effects on the radiation budget, referred to as "cloud forcing" [*Marty and Philipona*, 2000b], are determined by subtracting clear-sky from all-sky net radiation, and the distinction between clear-sky and all-sky greenhouse effects reveals the impact of clouds on the greenhouse effect. In fact, long-term changes in cloud amount, and the resulting effect on the radiative energy balance, is one of the largest uncertainties in global climate change research [*Ramanathan et al.*, 1989].

Pyrgeometers are the most widely used instruments for measuring atmospheric longwave irradiance. In meteorological and climatological networks, pyrgeometers are preferred over pyrradiometers primarily because of their long-term stability due to their very stable silicon domes compared to polyethylene domes of pyrradiometers. Compared to pyrradiometers, which measure the shortwave and the longwave flux, pyrgeometers have the additional advantage of reflecting the shortwave radiation and directly measuring the longwave component. One of the oldest pyrgeometers, the Eppley Precision Infrared Ra-

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Paper number 2000JD000196.
0148-0227/01/2000JD000196$09.00

diometer (PIR) [*Drummond et al*., 1970; *Albrecht et al*., 1974] was equipped with a silicon dome in 1976, which made the instrument suitable for long-term measurements, and it was further improved over the years [*Philipona et al*., 1995], to finally become the most reliable and most used longwave instrument by the end of the 1990s. Kipp & Zonen introduced a new pyrgeometer, CG4, in 1999 with a meniscus-shaped silicon dome that provides a 180° field of view and makes depositing of the 4-μm low-pass interference filter on the inside wall more manageable, providing a more uniform and reproducible dome spectral transmission [*Miskolczi and Guzzi*, 1993]. A new type of pyrgeometer was introduced by *Lorenz et al*. [1996] that uses a target and a reference pyroelectric detector and modulation of the atmospheric irradiance by a mechanical chopper.

Calibration of pyrgeometers has always been performed using blackbody radiation sources. Uncertainties of longwave irradiance measurements were still up to 10% in the early 1990s [*Dehne et al*., 1993]. A major impetus to the investigation of pyrgeometer field measurements and calibration methods was given by the World Climate Research Program's Baseline Surface Radiation Network (WRCP/BSRN) [*World Meteorogical Organisation* (WMO), 1991; *DeLuisi et al*., 1992; *Dutton*, 1993]. The international pyrgeometer calibration round-robin experiment [*Philipona et al*., 1998], comparing 11 different laboratory blackbody calibration sources, has shown calibration factors, determined with six well-operated blackbody calibration sources, to agree within 1–2% of the median value. In fact, relative measurement uncertainty between state-of-the-art pyrgeometers, with uniform blackbody calibration and proper ventilation and shading, is now reaching levels of 2–3 W m^{-2}. However, pyrgeometer measurements and blackbody calibration standards provide no information about uncertainty of the absolute value of atmospheric longwave radiation measurements. To overcome this deficiency an absolute sky-scanning radiometer (ASR) [*Philipona*, 2001] was developed at the Physikalisch-Meteorologisches Observatorium Davos and World Radiation Center (PMOD/WRC) as a reference standard instrument that allows us for the first time to relate longwave radiation measurements to absolute standards of internationally accepted metrological units.

This paper presents results of the first International Pyrgeometer and Absolute Sky-scanning Radiometer Comparison (IPASRC-I), which was held in September 1999 at the Atmospheric Radiation Measurement (ARM) program's Southern Great Plains (SGP) site in Oklahoma. IPASRC is an initiative of the Baseline Surface Radiation Network (BSRN) community, with the aim of improving the precision and uncertainty of pyrgeometer field measurements and the ultimate goal of introducing a world radiometric reference for longwave irradiance measurements [*Philipona and Ohmura*, 2000]. The first goal of the comparison was to learn about uncertainties of pyrgeometer field measurements relative to each other and in relation to absolute values measured with the absolute sky-scanning radiometer. Remarkable improvements of pyrgeometer precision were observed with the new field calibration factors compared to blackbody calibration factors. The second goal was to determine how well state-of-the-art longwave radiation measurements compare with state-of-the-art radiation transfer model calculations. Although all pyrgeometers were properly ventilated and shaded, shortwave radiation still seemed to interfere with longwave measurements, showing larger daytime differences between pyrgeometers. Also, with the windowless ASR, sky-scanning is not possible during daytime. Hence only nighttime clear-sky pyrgeometer measurements were compared with ASR measurements, with atmospheric emitted radiance interferometer (AERI) measurements [*Revercomb et al*., 1988] and with radiative transfer model calculations performed with LBLRTM [*Clough et al*., 1992] and MODTRAN [*Acharya et al*., 1998].

The instruments used at IPASRC-I are described in section 2, and pyrgeometer evaluation formulas and calibration factors are presented in section 3. Section 4 describes the IPASRC-I measurements used for the analysis. Results from relative comparisons among pyrgeometers are given in section 5, and section 6 presents pyrgeometer measurements compared to absolute measurements. Comparisons among pyrgeometer measurements, ASR, and AERI and values determined by transfer model calculations are given in section 7. In section 8 the results are discussed, and conclusions and future plans are presented in section 9.

2. Instruments

A total of 15 calibration traced standard pyrgeometers, chosen from a broad international community, were compared at IPASRC-I (see Table 1). There were 14 Eppley manufactured PIR pyrgeometers and 1 Kipp & Zonen CG4 pyrgeometer, and they were subdivided into two groups. The first group consisted of eight original Eppley PIR pyrgeometers. Original PIRs are instruments as available from the manufacturer but which are used in the "nonbattery" mode, which means that the body temperature is separately measured and not compensated by the battery circuitry. The second group comprised six Eppley manufactured PIR pyrgeometers, which were modified at PMOD/WRC, and one new CG4 pyrgeometer from Kipp & Zonen. The separation was primarily made to investigate possible improvements due to new dome- and dome-temperature-measurement designs. Original Eppley PIRs have one thermistor at the rim of the dome for the dome temperature measurement T_D. For a more uniform temperature measurement and to account for temperature gradients, which can build up within a PIR dome, a three-thermistor dome temperature measurement positioned at 45° elevation in three equally spaced azimuthal directions is installed in PMOD/WRC modified pyrgeometers [*Philipona et al*., 1995]. The new CG4 is designed so that temperature effects are minimized by optimizing thermal contact between the pyrgeometer body and the silicon dome. All pyrgeometers were identically mounted in ventilation housings and distributed on five Sun trackers providing shading balls to shade the instrument domes from direct sunlight. The instruments were ventilated to prevent dew as silicon domes cool during clear-sky nights, and the shading prevented direct solar radiation from interfering with longwave measurements.

Two new chopped pyrgeometers, which were developed by the Deutsches Forschungszentrum für Luft- und Raumfahrt, Oberpfaffenhofen and built for ground-based and airborne measurements, also participated at the comparison. The chopped pyrgeometer uses two pyroelectric detectors and a chopper wheel to which the measurement is referred. Thermal effects of the silicon dome are prevented since the target detector just measures the difference between the chopper wheel and the target irradiance. The irradiance of the chopper wheel is determined with the reference detector and an internal blackbody which is referred to a blackbody calibration source. For the evaluation of the IPASRC-I data the original calibra-

Table 1. Pyrgeometer Inventory and Calibration and Correction Factors

			FACT	User		CMDL		PMOD					FIELD				
Serial	Owner[a]	T_D	C	C	K	C	K	C	k_1	k_2	k_3	K	C	k_1	k_2	k_3	K
PIR13678F3	BoM Australia	1	4.13	4.29	4.0	3.97	4.0						4.27		0.997		4.0
PIR28492F3	SUNYA USA	1	3.74	3.74	4.0	3.49	4.0						3.43		0.994		4.0
PIR28898F3	University of Maryland USA	1	4.00	4.00	4.0	3.91	3.0						3.90		1.003		3.0
PIR29255F3	NOAA/SRRB USA	1	3.82	4.00	4.0	4.01	3.0						3.97		1.002		3.0
PIR30555F3	NOVA/CMDL USA	1	3.57	3.57	4.0	3.52	3.5						3.69		1.000		3.5
PIR31195F3	NREL USA	1	3.56	3.56	4.0	3.49	3.5						3.41		1.003		3.5
PIR32227F3	Eppley USA	1	3.90	3.90	4.0	3.93	3.5						3.83		1.003		3.5
PIR32690F3	Saudi Arabia	1	4.00	4.00	4.0	4.19	3.5						4.10		1.002		3.5
PIR26036mod	NASA USA	3	(4.14)	3.84	3.48	3.78	4.0	4.36	0.1218	1.0038	3.58		4.42	0.1218	1.0000	3.58	
PIR28146mod	AES Canada	3	(3.88)	3.69	3.42	3.67	4.0	4.34	0.1510	1.0024	3.61		4.32	0.1510	1.0024	3.61	
PIR29143mod	DOE/ARM USA	3	(3.30)	3.38	3.51	3.33	4.0	4.28	0.2360	1.0050	3.64		4.37	0.2360	1.0020	3.64	
PIR30475mod	DWD Germany	3	(3.93)	3.63	3.13	3.63	3.5	3.95	0.0733	1.0014	3.11		4.05	0.0733	1.0000	3.11	
PIR31463mod	PMOD Switzerland	3	(3.63)	3.32	3.53	3.34	4.0	3.71	0.0766	0.9974	3.39		3.80	0.0766	0.9974	3.39	
PIR32205mod	JMA Japan	3	(4.04)	3.92	2.66	3.80	3.5	4.25	0.1112	1.0031	2.75		4.26	0.1112	1.0031	2.75	
CG4-4	K&Z Netherlands	1	—	12.29	0.3	12.2	1.4	12.29				0.3	12.50		1.004		0.3

[a] BoM, Bureau of Meteorology; SUNYA, State University of New York at Albany; SRRB, Surrace Radiation Branch; NREL, National Renewable Energy Laboratory; AES, Atmospheric Environmental Service; DOE/ARM, Department of Energy Atmospheric Radiation Measurement Program; DWD, Deutsche Wetter Dienst; PMOD, Physikalisch-Meteorologisches Observatorium Davos; JMA, Japanese Meteorological Agency; K&Z, Kipp & Zonen.

tion of a chopped pyrgeometer [*Lorenz et al.*, 1996] was slightly modified.

The absolute sky-scanning radiometer [*Philipona*, 2001], which measures longwave radiation in a completely different way compared to pyrgeometer measurements, was used as a reference standard instrument. The ASR measures radiance in a narrow viewing angle of 6° and scans the sky at four elevation angles and eight azimuthal directions. Hemispherical longwave irradiance is computed by using Gaussian quadrature to integrate over the 32 measuring points. The ASR uses no window and optical components except of a 90° reflecting gold mirror which directs the narrow field of view to the sky or to the reference blackbody source for calibration. Hence the ASR is still blackbody calibrated, and via absolute temperature measurements, it is related to absolute standards of internationally accepted metrological units. However, unlike pyrgeometers, it is not subject to spectral and directional dome transmission problems, which produce uncertainties in pyrgeometer measurements particularly with respect to absolute measurements. Figure 1 shows the absolute sky-scanning radiometer in front of the 15 pyrgeometers distributed on the five Sun trackers on the roof platform of the SGP radiation trailer. The two chopped pyrgeometers (not shown in the picture) were positioned close by on the same platform.

The atmospheric emitted radiance interferometer (AERI) is located ~100 m away in a separate trailer at the SGP site and measures absolute infrared radiance spectra from 3.3 to 19 μm in the zenith direction every 10 mins. AERI measures with a resolution of ~0.5 cm^{-1}, and for comparison with LBLRTM models a 10 cm^{-1} grid is used to derive fluxes for AERI and LBLRTM radiance measurements and calculations, respectively assuming horizontal homogeneity of the atmosphere. Quality measurement experiments focused on longwave measurements, and calculations comparing AERI and LBLRTM were conducted previously [*Brown et al.*, 1997] and a new assessment has been initiated. The Balloon-Borne Sounding

Figure 1. Absolute sky-scanning radiometer and 15 pyrgeometers distributed on five Sun trackers on the roof platform of the SGP radiation trailer.

System (BBSS) which provides in situ measurements (vertical profiles) of the thermodynamic state of the atmosphere, and the Microwave Water Radiometer (MWR), which provides time series measurements of column-integrated amounts of water vapor and liquid water, were routinely operating during the comparison. BBSS and MWR information was used as input for radiative transfer model calculations.

3. Evaluation Formulas and Calibration Factors

Two pyrgeometer formulas were used for the evaluation of the measured longwave irradiance. The Albrecht et al. formula [*Albrecht et al.*, 1974] was primarily used to evaluate original Eppley PIRs, but for comparisons it was also used for the modified instruments. The Philipona et al. formula [*Philipona et al.*, 1995] was applied for modified pyrgeometers only. The Albrecht et al. formula calculates downward irradiance E_L as follows:

$$E_L = \frac{U_{\mathrm{emf}}}{C} + (k_2)\sigma T_B^4 - K\sigma(T_D^4 - T_B^4), \tag{1}$$

with U_{emf} the thermopile signal, T_B and T_D the absolute temperature of the pyrgeometer body and dome, σ the Stefan-Boltzmann constant, and C and K the pyrgeometer calibration and dome correction factors, respectively. The correction factor k_2 has been introduced for the field calibration only and has the same purpose as k_2 in the Philipona et al. formula. In the original Albrecht et al. formula this value is set to unity. The Philipona et al. formula is similar but uses three correction factors k_1, k_2, k_3 and is defined as

$$E_L = \frac{U_{\mathrm{emf}}}{C}(1 + k_1\sigma T_B^3) + k_2\sigma T_B^4 - k_3\sigma(T_D^4 - T_B^4) \tag{2}$$

with k_1 a small number taking care of possible thermal nonlinearity of the detector, k_2 close to one and provides corrections on the body temperature measurement, and k_3 the dome correction factor and equal to K.

Table 1 shows several sets of calibration factors which were used for the analysis of the IPASRC-I pyrgeometer measurements. Original Eppley PIR pyrgeometers come with a calibration factor stamped on the label of the instrument. These factors C are named FACT calibration factors, and it is assumed that a dome correction factor $K = 4$ is used in the Albrecht et al. formula. Modified PIRs also have a FACT calibration factor, but with the modification of the instrument this value is no longer applicable. The CG4-4 is a prototype instrument and had no factory calibration. Since some of the FACT calibration factors are missing or not applicable, we did not use them at all in the analysis. From the owners of the instruments we received calibration factors C which they use in their measurements, and we called these the USER calibration factors, which for all original PIRs also use $K = 4$ as dome correction factor. The seven modified pyrgeometers have USER calibration and correction factors C and K, which were determined at PMOD/WRC after modification. In addition, prior to the comparison all 15 pyrgeometers were calibrated in the blackbody source supplied by S. Cox of Colorado State University (Cox/CSU) at National Oceanic and Atmospheric Administration Climate Monitoring and Diagnostics Laboratory (NOAA/CMDL), and these C and K calibration and correction factors are called the CMDL factors. In the following analysis, USER and CMDL calibration factors will be used for all 15 instruments with the Albrecht et al. formula. However, modified pyrgeometers are normally used with the Philipona et al. formula and therefore come with PMOD calibration factors C, k_1, k_2, and k_3, which are determined at PMOD/WRC. For the CG4 only, C and K were determined and were always used with the Albrecht et al. formula.

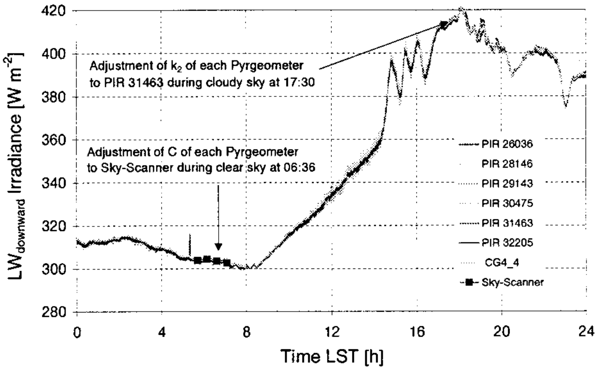

Figure 2. Longwave downward irradiance measured with seven modified pyrgeometers and the ASR on September 24, 1999, at SGP. The absolute sky-scanner measurement taken at 0636 LT (local standard time) was used to Field calibrate all pyrgeometers during the IPASRC-I comparison.

FACT, USER, CMDL, and PMOD calibration factors are all determined with blackbody calibration sources. At IPASRC-I we tried for the first time to field calibrate pyrgeometers by comparing pyrgeometer measurements to the ASR reference instrument. The field calibration was made with ASR measurements on a day with extreme irradiance situations available: a clear-sky situation with very high net irradiance and an overcast situation with almost zero net irradiance. At very low or zero net irradiance, pyrgeometers come to quasi-thermal equilibrium showing no signal at the thermopile, and the irradiance measurement becomes a pure temperature measurement and is reduced to the σT_B^4 Planck radiation term. Pyrgeometers showing different irradiance values can now be corrected by changing their k_2 correction factor or, as mentioned above, by introducing a k_2 value different from unity with the Albrecht et al. formula. Once the zero point is corrected, with the new k_2, the pyrgeometer can now be compared to the clear-sky ASR absolute irradiance value and the Field calibration can be completed by varying the calibration factor C, such that the pyrgeometer irradiance value matches the ASR irradiance measurement. K as well as k_1 and k_3 can not be field calibrated and were taken from the CMDL and PMOD blackbody calibration, respectively.

Figure 2 shows longwave downward measurements of September 24 which were used to determine the FIELD calibration factors of all pyrgeometers. The zero point adjustment was made at 1730 LT (local standard time), where k_2 correction factors of 14 pyrgeometers were adjusted to match the irradiance measured by PIR 31463. Afterward, using the new k_2 values, the calibration factors of all 15 pyrgeometers were determined by varying C to match the irradiance readings to the sky-scanner reading at 0636 LT. Hence FIELD calibration factors C and correction factors k_2 were determined only with these two time sequences and subsequently used for the 8 days of measurements.

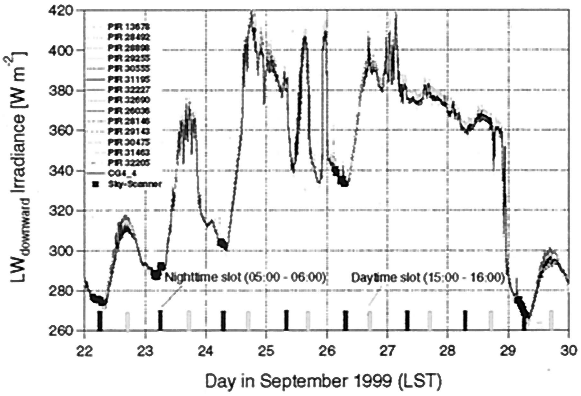

Figure 3. Longwave downward irradiance measured with all pyrgeometers and the absolute sky-scanning radiometer from September 22 to 29, 1999, at SGP. Field calibration and Albrecht et al. formula with C, k_2, and K is used for all pyrgeometers. Nighttime and daytime slots are used for the analysis of nighttime and daytime measurements.

4. IPASRC-I Measurements

The comparison lasted from September 21 to 30, 1999. The 15 standard pyrgeometers were continuously logged with data logger systems taking measurements every second and storing average values every minute. Throughout the paper the data are presented in local standard time (LT) and a 24-hour clock. Eight complete days of consecutive measurements are available from all pyrgeometers and are shown in Figure 3, together with nighttime measurements taken with the ASR. The comparison started out with very clear skies, then broken clouds on September 24, and then mostly overcast for the next 3 days before clearing up again on September 29 and 30. These ideal weather conditions allowed us to compare longwave downward irradiance levels from 260 to ~400 W m^{-2}, which covers the range of midlatitude summer conditions. Nighttime (0500–0600 LT) and daytime (1500–1600 LT) average values from all the 8 days are used for relative comparisons between the 15 pyrgeometers. The two chopped pyrgeometers also measured continuously in the same time period, but their domes were only shaded part of the time.

As previously mentioned, the absolute sky-scanning radiometer does not have any window, and therefore, in order to stay away from interfering shortwave radiation, it can only be used during nighttime. Also, since a sky scan with 32 measurements lasts for 24 min, the sky should be more or less homogeneous during the scan. Absolute measurements are therefore only taken during the night and comparisons between ASR, pyrgeometers, chopped pyrgeometers, AERI, and model calculations are only shown for clear-sky nighttime sequences, for which radiosonde data and MWR information are also available. A total of 48 scans were performed during six more or less clear-sky nights with longwave irradiance levels between 265 and 340 W m^{-2}, but only four cases with all the measurements, including radiosonde data, are available for absolute comparison.

5. Pyrgeometer Precision or Comparability

Because there is no interfering shortwave radiation, nighttime longwave measurements are easier, and pyrgeometer-measured irradiances are more congruent than daytime measurements. Nighttime and daytime pyrgeometer measurements are therefore separated in our analysis. Since longwave irradiance during clear-sky nights steadily decreases, showing a minimum toward the morning, the hour before dawn, from 0500 to 0600 LT, was chosen for the analysis of nighttime measurements. Daytime longwave measurements reach a maximum 2–3 hours after solar noon and the hour from 1500 to 1600 LT is therefore chosen for daytime investigations. Figures 4–6 (left) show pyrgeometer-measured irradiances, calculated with one particular set of calibration factors, for night or day and for the eight consecutive days of measurements. Hourly averages of each individual pyrgeometer were calculated, and the difference between maxima and minima value (Max − Min) is given as an indicator of the measurement uncertainties. An average value ⟨Max − Min⟩ of the 8 days (Max − Min) values is then calculated to evaluate a given group of pyrgeometers and a certain set of calibration factors. Figures 4–6 (right) show the difference between hourly average irradiances of individual pyrgeometers and the mean value measured by all pyrgeometers of this group during this same hour. Hence Figures 4–6 allow one to trace the behavior of individual instruments.

5.1. Nighttime Precision

Figure 4 shows nighttime longwave downward irradiance measured with eight original PIRs during eight consecutive days of the comparison. Three sets of calibration factors were used, and the calculations were performed with the Albrecht et al. formula. With USER8 calibration factors the differences between individual measurements can be above 13 W m^{-2}, and an average of 11.1 W m^{-2} has been determined. We observe, however, that PIR28492 shows considerably higher values than all others, and that the USER calibration factor used is still the old original FACT calibration factor. CMDL8 calibration factors show better result with an average of 8.4 W m^{-2} (Max − Min) difference over the 8 days of measurements. A much better result, however, is shown, on the lowest graph with the FIELD8 calibration factors used. Eight original PIR pyrgeometers showing nighttime measurements agreeing to within better than 4 W m^{-2} over 8 days of measurements and an irradiance variability of more than 100 W m^{-2} is considered a good result.

Even better consistency is found on nighttime longwave irradiance measurements among the seven modified pyrgeometers shown in Figure 5. USER7 and CMDL7 calibration factors used with the Albrecht et al. formula show very similar results with an average difference between (Max − Min) of ~5 W m^{-2}. PMOD7 calibration factors with the improved evaluation formula of Philipona et al. reduce the average difference to 3.4 W m^{-2}. If the FIELD7 calibration factors are used with the Philipona et al. formula, nighttime measurements of seven pyrgeometers agree within better than 2 W m^{-2} for all 8 days of consecutive measurements, and the average (Max − Min) difference is down as low as 1.2 W m^{-2} with a standard deviation of 0.4 W m^{-2}.

Nighttime longwave irradiance precision and comparability between individual pyrgeometer measurements is summarized in Table 2, showing maximum, minimum, average, and SD values of (Max − Min) differences over the 8 days of measurements, of original and modified pyrgeometers for all sets of calibration values used. Modified instruments show better agreement between individual measurements than original PIR pyrgeometers, and FIELD calibration values improve nighttime measurements by a factor of 3 over blackbody calibrated instruments.

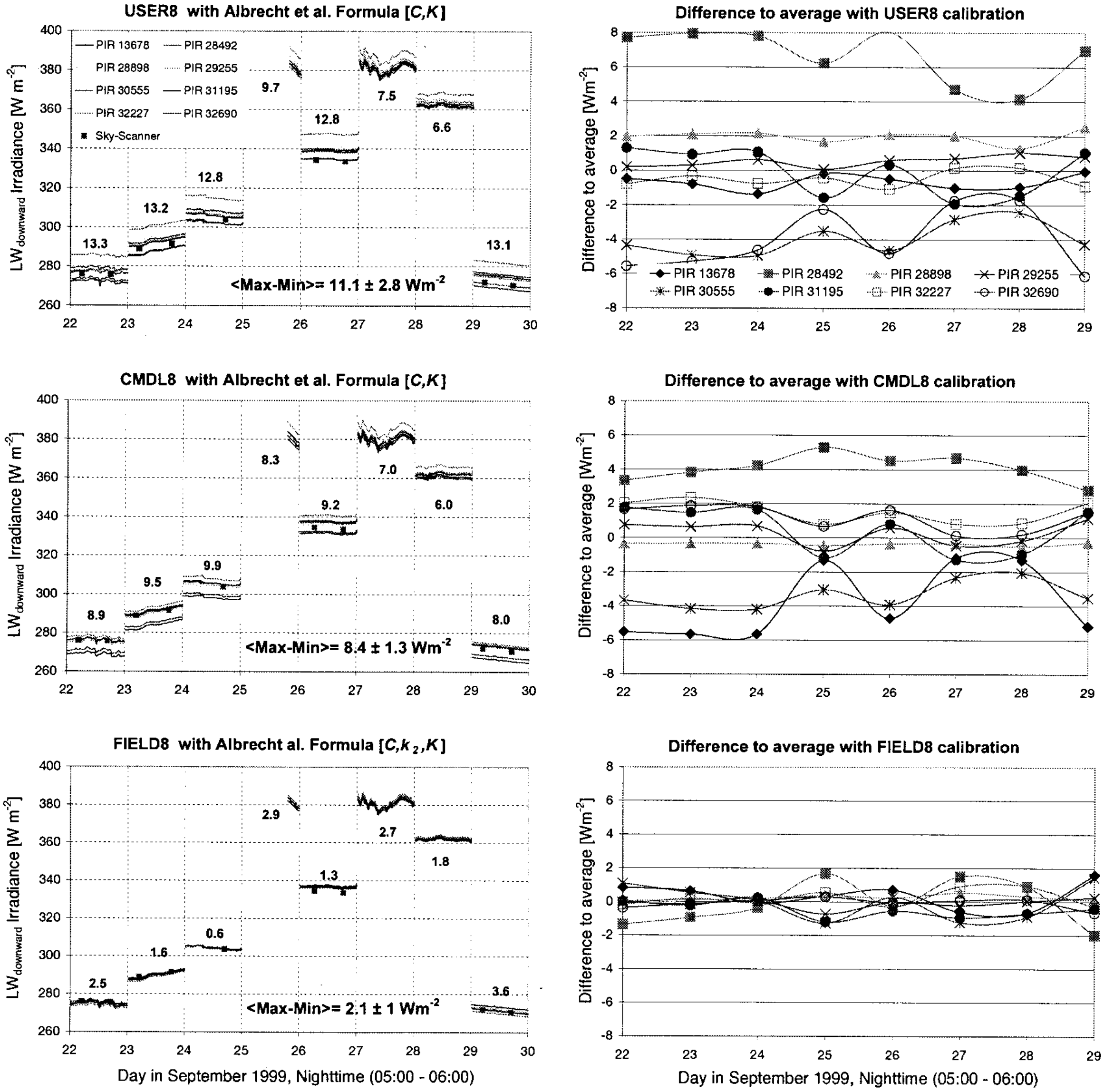

Figure 4. Night hour (0500–0600 LT) longwave downward irradiance, measured with eight original Eppley PIRs and the ASR from September 22 to 29. USER8, CMDL8, and FIELD8 calibration factors are used with the Albrecht et al. formula. (left) Irradiances plotted for this hour annotated by the (Max − Min) difference between eight PIRs. (right) Differences compared to hourly mean values of the eight PIRs for each individual pyrgeometer.

5.2. Daytime Precision

Figure 6 (top) shows daytime longwave measurements of eight original PIRs calculated with USER8 calibration factors. Maximum differences of 20 W m^{-2} are measured, and the (Max − Min) average is ~3 W m^{-2} higher than nighttime measurements. Figure 6 (middle) shows measurements of seven modified instruments with USER7 calibration factors. Maximum differences are about half compared to original pyrgeometers above, and the (Max − Min) average is again ~3 W m^{-2} higher than nighttime measurements of the same group. Figure 6 (bottom) presents measurements of the seven modified instruments with FIELD7 calibration factors showing average differences more than twice as high as nighttime measurements. A more complete picture of daytime measurements is given in Table 3 showing results of the two instrument groups and all calibration sets.

6. Pyrgeometer Uncertainty

In section 5, pyrgeometer precision or comparability of individual pyrgeometer measurements within a group of pyrgeometers was investigated. Hence mean irradiance values of groups of pyrgeometers and calibration factor sets are investigated and compared to absolute measurements. Absolute ASR measurements are only available for clear-sky nighttime situations. However, as indicated above, the FIELD calibration factors have been determined with respect to one well-chosen absolute sky scan and the good agreement of irradiances with FIELD calibration factors with several ASR sky scans is shown in section 7. Moreover, results from section 5 showed highest precision among the seven modified pyrgeometers with the FIELD7 calibration factors. We therefore take the mean value of this group as the reference measurement for the 8 days of

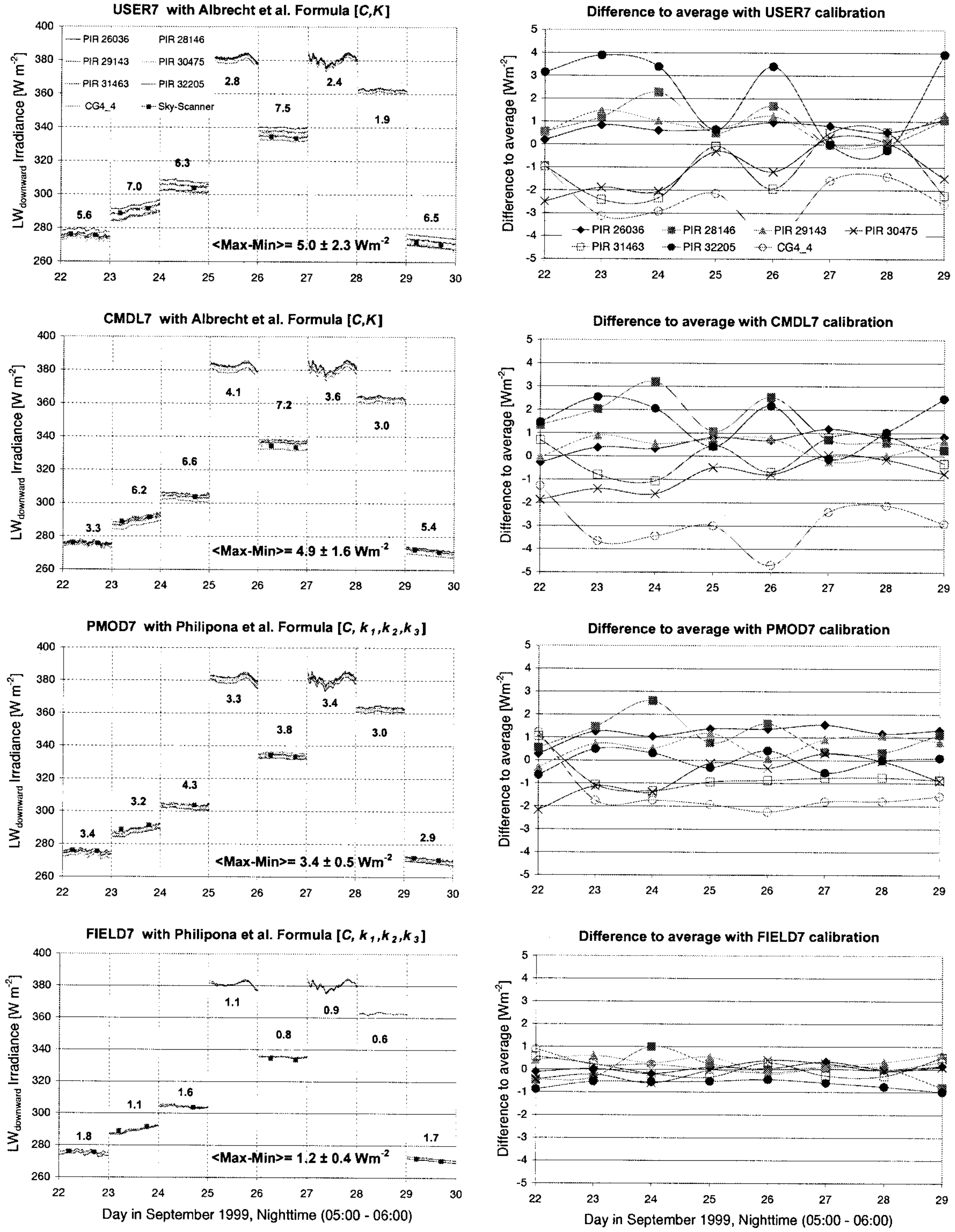

Figure 5. Nighttime (0500–0600 LT) longwave downward irradiance, measured with seven modified pyrgeometers and the ASR from September 22 to 29. USER7 and CMDL7 calibration factors are used with the Albrecht et al. formula, and PMOD7 and FIELD7 are used with the Philipona et al. formula. (left) Irradiances plotted for this hour annotated by the (Max − Min) difference between the seven pyrgeometers. (right) Differences compared to hourly mean values of the seven instruments for each individual pyrgeometer.

measurements and compare mean hourly values of the other groups to this FIELD7 reference measurement.

6.1. Nighttime Uncertainty

Table 4 shows nighttime hourly mean irradiance values of all seven calibration sets for the 8 days of measurements. It further shows the differences between hourly mean values of individual groups and the FIELD7 reference group, and an average of the differences is also given. The differences of the six first groups to the reference group are also presented in Figure 7. The graph clearly shows that the USER8 group

Table 2. Nighttime Longwave Irradiance Precision and Comparability of Pyrgeometer Measurements With Different Calibration Factor Sets

Group	Formula and Calibration Factors	Maximum, W m^{-2}	Minimum, W m^{-2}	Average, W m^{-2}	SD
USER8	Albrecht et al. [C, K]	13.3	6.6	11.1	2.8
CMDL8	Albrecht et al. [C, K]	9.9	6.0	8.4	1.3
FIELD8	Albrecht et al. [C, k_2, K]	3.6	0.6	2.1	1.0
USER7	Albrecht et al. [C, K]	7.5	1.9	5.0	2.3
CMDL7	Albrecht et al. [C, K]	7.2	3.0	4.9	1.6
PMOD7	Philipona et al. [C, k_1, k_2, k_3]	4.3	2.9	3.4	0.5
FIELD7	Philipona et al. [C, k_1, k_2, k_3]	1.8	0.6	1.2	0.4

measures too high, and this is due to one instrument which measures higher than the others. The other groups show mean values of nighttime measurements to be within ±1 W m^{-2} to the reference group which by the field calibration is related to the absolute measurement.

6.2. Daytime Uncertainty

Daytime comparisons of irradiance mean values of individual groups are shown in Table 5. Differences to the FIELD7 reference group are given in the same table and are also shown

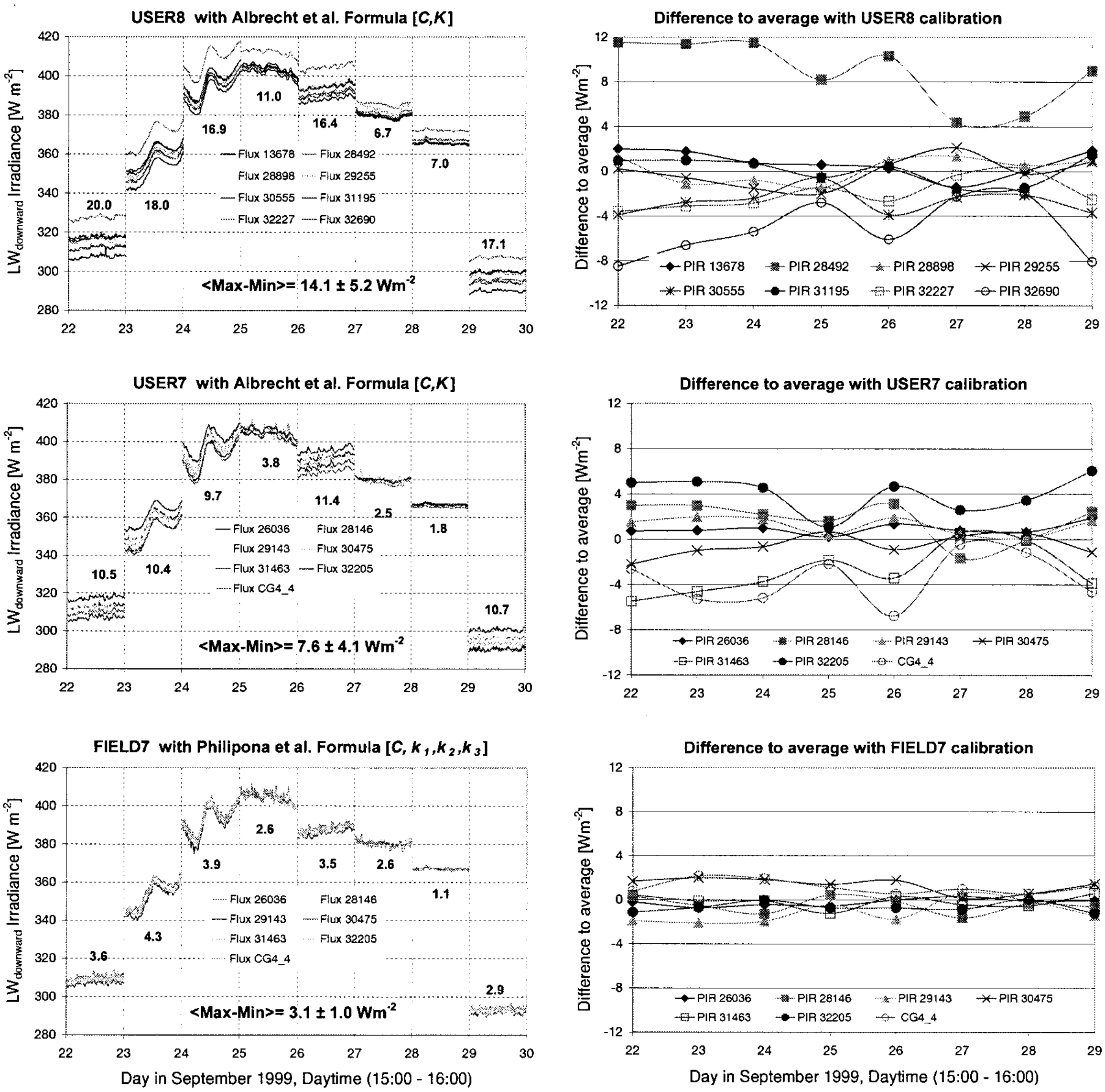

Figure 6. Daytime (1500–1600 LT) longwave downward irradiance, measured with original and modified pyrgeometers from September 22 to 29. USER8 and USER7 calibration factors are used with the Albrecht et al. formula, and FIELD7 is used with the Philipona et al. formula. (left) Irradiances plotted for this hour annotated by the (Max − Min) difference. (right) Differences compared to hourly mean values for each individual pyrgeometer.

Table 3. Daytime Longwave Irradiance Precision and Comparability of Pyrgeometer Measurements With Different Calibration Factor Sets

Group	Formula and Calibration Factors	Maximum, W m^{-2}	Minimum, W m^{-2}	Average, W m^{-2}	SD
USER8	Albrecht et al. [C, K]	20.0	6.7	14.1	5.2
CMDLS	Albrecht et al. [C, K]	11.0	5.7	8.8	2.0
FIELD8	Albrecht et al. [C, k_2, K]	6.8	1.6	4.3	2.1
USER7	Albrecht et al. [C, K]	11.4	1.8	7.6	4.1
CMDL7	Albrecht et al. [C, K]	11.5	2.1	6.9	3.5
PMOD7	Philipona et al. [C, k_1, k_2, k_3]	5.1	2.5	3.4	0.8
FIELD7	Philipona et al. [C, k_1, k_2, k_3]	4.3	1.1	3.1	1.0

in Figure 8. On the daytime measurements a remarkable difference is observed between the PMOD7 group which uses the Philipona et al. formula, as the FIELD7 reference group does, and the other five groups which use the Albrecht et al. formula. Also, there is a clear difference between clear-sky and cloudy-sky (September 25, 27, and 28) measurements. During cloudy-sky situations all groups agree within more or less ±1 W m^{-2} to the reference group, while during clear-sky the groups which use the Albrecht et al. formula show 2–3 W m^{-2} higher irradiance. This observation suggests that either the first or the third term of the pyrgeometer formula is responsible for this daytime offset. Since the third term is treated equally in both equations, it rather seems that the difference between the first terms of the two formulas is responsible. The Philipona et al. formula contains a temperature dependence in its first term and, in fact, temperatures from 16°C up to 33°C were measured during these daytime measurements, whereas nighttime temperatures varied only in the range of 12°C to 20°C. The problem, however, is that no absolute sky-scanner daytime measurements are available, and it is therefore at this stage not possible to determine which of the two formulas is showing the correct irradiance.

7. Longwave Measurements Compared to Model Calculations

From section 6 we learned that individual groups of pyrgeometers and calibration factors show consistent mean irradiance values and that they are interestingly close to reference values which are related to absolute measurements of the sky-scanning radiometer. These measurements have then been further compared to measurements from the chopped pyrgeometers and to atmospheric emitted radiance interferometer (AERI) measurements. Furthermore, to compare absolute sky-scanner measurements to model calculations, nighttime clear-sky time sequences were chosen for which radiosonde and sky-scanner measurements are available. Four early morning cases were chosen with the balloon radiosonde starting at 0630 LT just before dawn. During its ascent the radiosonde takes about half an hour to go through the tropospheric layers, which contain most of the water content in the atmosphere. We therefore averaged pyrgeometer measurements over this half hour and chose sky scans which were taken during the same time.

All these longwave irradiance measurements were then compared to line by line radiative transfer model LBLRTM calculations and also to MODTRAN radiative transfer model calculations. The results are all fluxes given in W m^{-2} at an elevation of 320 m above sea level (asl). The spectral range is 10–3000 cm^{-1}. Both models used the same temperature and moisture profiles. Water vapor profiles were derived from ARM radiosonde data which were scaled to obtain agreement between their column amount and the concurrent MWR measurements. The scaling is made by an iterative process which modifies each level by a percentile amount. The ozone profiles used for the calculations were scaled so that their column amount agreed with the corresponding Total Ozone Mapping Spectrometer (TOMS) measurement and the effects of the CFCs were included in the calculations. The CO_2 mixing rate was assumed to be 360 ppmv, and those of other trace gases were used according to the U.S. Standard Atmosphere. To compare MODTRAN calculations with LBLRTM, the calculations were performed without aerosols. In a second run,

Table 4. Accuracy Evaluation of Nighttime Pyrgeometer Measurements[a]

Group	Sept. 22	Sept. 23	Sept. 24	Sept. 25	Sept. 26	Sept. 27	Sept. 28	Sept. 29	Average Difference
USER8	277.79	292.97	307.12	382.48	339.53	382.73	363.81	276.10	
Difference to FIELD7	2.53	3.49	2.7	1.22	3.88	2.10	1.05	3.25	2.54 ± 1.04
CMDL8	274.42	289.45	303.82	380.22	336.18	380.75	361.98	271.37	
Difference to FIELD7	−0.84	−0.03	−0.60	−1.04	0.53	0.12	−0.78	−0.38	−0.38 ± 0.54
FIELD8	274.86	289.90	304.25	380.53	336.62	381.00	362.23	271.83	
Difference to FIELD7	−0.40	0.42	−0.17	−0.73	0.97	0.37	−0.53	0.08	0.00 ± 0.57
USER7	275.49	289.57	304.49	381.17	336.44	380.30	362.25	271.44	
Difference to FIELD7	0.23	0.09	0.07	−0.09	0.79	−0.33	−0.51	−0.31	0.01 ± 0.41
CMDL7	275.79	290.11	305.00	382.03	337.01	381.12	362.97	271.73	
Difference to FIELD7	0.53	0.63	0.58	0.77	1.36	0.49	0.21	−0.02	0.57 ± 0.41
PMOD7	274.78	288.20	303.31	380.96	334.56	380.52	362.63	270.4	
Difference to FIELD7	−0.48	−1.28	−1.11	−0.30	−1.09	−0.11	−0.13	−1.35	−0.73 ± 0.53
FIELD7	275.26	289.48	304.42	381.26	335.65	380.63	362.76	271.75	

[a] Mean irradiances of six pyrgeometer groups are compared to the FIELD7 group which is traced to the ASR measurement. Units are W m^{-2}.

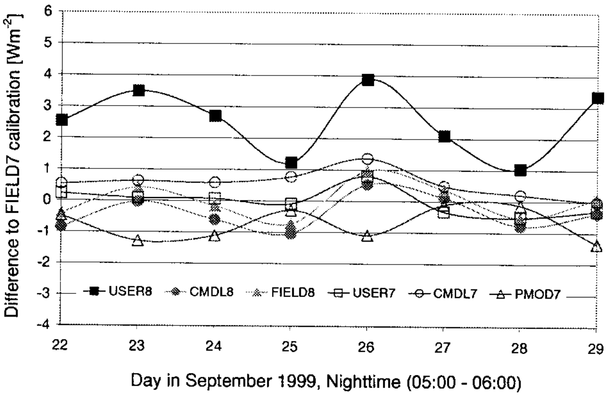

Figure 7. Nighttime (0500–0600 LT) differences between hourly mean values of individual groups and the FIELD7 reference group. Mean values of all groups are relatively close except for the USER8 group, which has one instrument which measures too high.

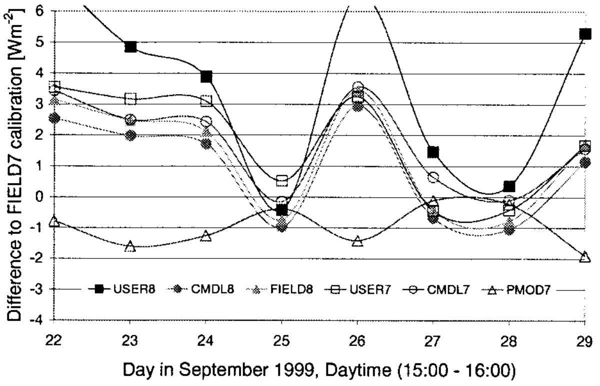

Figure 8. Daytime (1500–1600 LT) differences between hourly mean values of individual groups to the FIELD7 reference group. There is a notizable difference between the groups using Albrecht et al. formula evaluation and the one using the Philipona et al. formula evaluation for clear-sky daytime measurements.

MODTRAN calculated with aerosols using MODTRAN's standard rural extinction with 23 km visibility.

Table 6 summarizes the comparison results of atmospheric longwave irradiance measurements and calculations for the four nighttime cases of the September 22, 24, 29, and 30, 1999, at SGP. Irradiances are first shown for the seven pyrgeometer and calibration factor groups, followed by the irradiances measured by the chopped pyrgeometer. AERI, LBLRTM, and MODTRAN irradiances follow next before the absolute sky-scanner measurements to which all irradiances are compared. For each measurement or calculation the difference between the irradiance value and the sky-scanner irradiance is given and an average value and standard deviation of the difference to the sky scanner is shown. A graphical presentation of the results is given in Figure 9.

Average differences of the pyrgeometer groups to the sky scanner are very similar to the ones shown earlier for nighttime measurements showing very good agreement except for the first group which has one instrument measuring too high. Standard deviations are of the same magnitude or slightly smaller for all groups. Substantially lower irradiances are measured by the chopped pyrgeometer of which just one instrument is shown. This same instrument was then field calibrated in a way similar to the other pyrgeometers by changing the sensitivity of the target detector r_1 given in formula (1a) of [*Lorenz et al.*, 1996]. The CHOPP-FIELD values show results which nicely follow the sky-scanner irradiances with a slightly higher standard deviation than the pyrgeometers show. AERI measurements are on the average within 2 W m^{-2} to the sky scanner, however, with values above and below, it shows a high standard deviation.

LBLRTM and MODTRAN model calculations without aerosols are 2.30 and 0.75 W m^{-2} below the sky scanner, respectively, and show also rather high standard deviations. LBLRTM being the model which best represents the modeled flux will get close to 1 W m^{-2} to the ASR measurement if an expected aerosol influx of 1 to 1.5 W m^{-2} is added to the calculation. MODTRAN calculates 1.7 W m^{-2} higher values with aerosols, and the average value is then 0.98 W m^{-2} above the absolute sky-scanner measurements. This rather large difference is probably due to MODTRAN's standard rural extinction of 23 km which is at the low side for the visibility at SGP.

8. Discussion

8.1. Longwave Irradiance Precision

Precision or comparability of individual measurements of atmospheric longwave irradiance largely improves going from

Table 5. Accuracy Evaluation of Daytime Pyrgeometer Measurements[a]

Group	Sept. 22	Sept. 23	Sept. 24	Sept. 25	Sept. 26	Sept. 27	Sept. 28	Sept. 29	Average Difference
USER8	315.94	357.96	396.62	403.72	394.16	381.31	367.33	298.19	
Difference to FIELD7	7.08	4.85	3.88	−0.42	6.55	1.46	0.36	5.30	3.63 ± 2.84
CMDL8	311.40	355.09	394.45	403.17	390.55	379.18	365.93	294.03	
Difference to FIELD7	2.54	1.98	1.71	−0.97	2.94	−0.67	−1.04	1.14	0.95 ± 1.62
FIELD8	312.01	355.59	394.87	403.41	391.05	379.43	366.19	294.61	
Difference to FIELD7	3.15	2.48	2.13	−0.73	3.44	−0.42	−0.78	1.72	1.37 ± 1.76
USER7	312.41	356.28	395.83	404.66	390.86	379.41	366.55	294.57	
Difference to FIELD7	3.55	3.17	3.09	0.52	3.25	−0.44	−0.42	1.68	1.80 ± 1.70
CMDL7	312.29	355.61	395.17	403.99	391.17	380.50	366.87	294.46	
Difference to FIELD7	3.43	2.50	2.43	−0.15	3.56	0.65	−0.10	1.57	1.74 ± 1.48
PMOD7	308.08	351.51	391.48	403.76	386.20	379.74	366.74	291.00	
Difference to FIELD7	−0.78	−1.60	−1.26	−0.38	−1.41	−0.11	−0.23	−1.89	−0.96 ± 0.68
FIELD7	308.86	353.11	392.74	404.14	387.61	379.85	366.97	292.89	

[a] Mean irradiances of six pyrgeometer groups are compared to the FIELD7 group which is traced to the ASR measurement. Units are W m^{-2}.

Table 6. Pyrgeometer Measurements, AERI, and Model Calculations Compared to Absolute Sky-Scanner Measurements

Group	Sept. 22 0630–0700 LT	Sept. 24 0630–0700 LT	Sept. 29 0630–0700 LT	Sept. 30 0630–0700 LT	Average Difference W m^{-2}
USER8	276.55	306.07	271.45	275.39	
Difference to SKY	2.48	2.58	3.53	2.53	278 ± 0.50
CMDL8	273.12	302.92	267.78	272.62	
Difference to SKY	−0.95	−0.57	−0.14	−0.24	−0.48 ± 0.37
FIELD8	273.45	303.23	268.14	272.94	
Difference to SKY	−0.62	−0.26	0.22	0.08	−0.15 ± 0.38
USER7	274.10	303.34	268.11	273.21	
Difference to SKY	0.03	−0.15	0.19	0.35	0.10 ± 0.21
CMDL7	274.51	303.72	268.35	273.29	
Difference to SKY	0.44	0.23	0.43	0.43	0.38 ± 0.10
PMOD7	273.47	302.18	267.35	272.59	
Difference to SKY	−0.60	−1.31	−0.57	−0.27	−0.69 ± 0.44
FIELD7	273.95	303.28	268.71	272.79	
Difference to SKY	−0.12	−0.21	0.79	−0.07	0.10 ± 0.47
CHOPPED	267.89	298.98	262.59	268.46	
Difference to SKY	−6.18	−4.51	−5.33	−4.40	−5.11 ± 0.83
CHOPP-FIELD	273.32	303.47	268.66	273.61	
Difference to SKY	−0.75	−0.02	0.74	0.75	0.18 ± 0.72
AERI	275.93	305.39	271.38	272.97	
Difference to SKY	1.86	1.90	3.46	0.11	1.83 ± 1.37
LBLRTM no aerosols	272.10	301.72	267.48	267.83	
Difference to SKY	−1.97	−1.77	−0.40	−5.03	−2.30 ± 1.94
MODTRAN no aerosols	273.56	303.29	268.96	269.53	
Difference to SKY	−0.51	−0.20	1.04	−3.33	−0.75 ± 1.85
MODTRAN with aerosols	275.32	305.06	270.63	271.27	
Difference to SKY	1.25	1.57	2.71	−1.59	0.98 ± 1.83
Sky scan	274.07	303.49	267.92	272.86	

USER to FIELD calibration factors. Measurements of the eight original PIRs show larger (Max − Min) differences with the USER blackbody calibrations than with uniform blackbody calibration factors from CMDL, but this is mainly due to PIR28492 which has to be considered an outlier. In the case of the seven modified pyrgeometers, USER calibration factors are also uniformly determined with the calibration facility at PMOD/WRC, and (Max − Min) differences found with USER and CMDL calibration factors are almost identical. The CMDL calibration factors were identically determined for all 15 pyrgeometers and are always used with the Albrecht et al. formula, yet the seven modified instruments show an average ⟨Max − Min⟩ difference which is just about half as large as the average difference of the original PIRs. This fact demonstrates the advantages of the new dome temperature measurement on the modified pyrgeometers. If the Philipona et al. formula and the PMOD calibration factors are used on the modified pyrgeometers, the average ⟨Max − Min⟩ difference is again reduced by 30% compared to the CMDL average difference. Hence the new formula also improves the results.

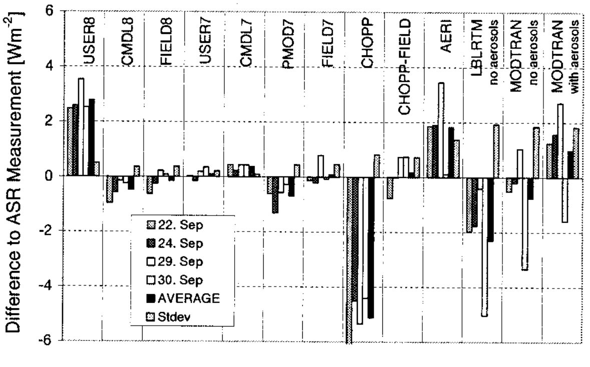

Figure 9. Differences between nighttime longwave downward irradiance measurements and calculations and ASR measurements.

However, by far the largest improvements are due to the field calibration. Field calibration factors improved precision of nighttime pyrgeometer measurements by a factor of 3 over the best blackbody calibration. Again, modified instruments show a (Max − Min) difference only about half as large as the original PIRs during nighttime measurements. Hence a group of modified and field-calibrated pyrgeometers is capable of measuring hourly averages of nighttime longwave irradiance with ⟨Max − Min⟩ differences of <2 W m^{-2}, which corresponds to a precision of ±1 W m^{-2} compared to the mean irradiance value of the group. Daytime measurements show average ⟨Max − Min⟩ differences of ~2 W m^{-2} larger than nighttime measurements, even though instruments were properly shaded from direct solar shortwave radiation. This increased daytime uncertainty is not fully understood, but part of it can be due to nonuniform radiation from the shading balls which are used to shade pyrgeometers from direct solar radiation or due to minor diffuse shortwave leaking.

8.2. Longwave Irradiance Uncertainty

Mean values of hourly averaged nighttime longwave irradiance of all seven pyrgeometer groups show average differences over the 8 days of <1 W m^{-2} except for the USER8 group that has the one instrument that was measuring far too high. All groups were compared to the FIELD7 group with field calibration factors that were determined with the absolute measurement of the sky-scanning radiometer. Hence this result shows that with blackbody calibration factors determined at NOAA/CMDL and PMOD/WRC the mean irradiance measured by a group of seven or eight pyrgeometers is within ±1 W m^{-2} to the measurement of the absolute sky-scanning radiometer. In consideration of the hemispherical measurement on a flat pyrgeometer receiver being completely different from the Gaussian quadrature integration of 32 radiance measurements made by the ASR instrument, this is certainly a very satisfactory result that shows that directional or spectral effects of pyrgeometer domes in connection with blackbody calibration do not lead to offsets in relation to absolute longwave irradiance measurements.

Daytime measurements show average differences of ~2 W m^{-2} (without USER8 group) which seem to be strongly connected to the pyrgeometer formula used. Since for the time being no daytime absolute sky-scanner measurements are available, it is difficult to argue about absolute daytime measurements. However, with the daytime precision given above and the results shown in Table 5, the uncertainty on daytime longwave irradiance measurements is considered to be less than ±3 W m^{-2}.

The four balloon sounding cases shown in Table 6 confirm the good nighttime agreement between the seven pyrgeometer groups. The chopped pyrgeometer shows irradiances lower than the pyrgeometer groups and the ASR measurements. However, with AERI and the models showing results which agree well with the ASR and the seven pyrgeometer groups, we conclude that the chopped pyrgeometer, which shows a low standard deviation compared to the ASR measurement, has an offset of about −5 W m^{-2}. AERI, LBLRTM, and MODTRAN are close to the absolute ASR measurement. However, they show substantially larger standard deviations in comparisons to the absolute measurement than pyrgeometer measurements. Since LBLRTM and MODTRAN show similar large differences, for example, the September 30 case, this problem seems connected with atmospheric profile data used in model calculations rather than with the measurements. In fact, a more widespread investigation, which will be published separately, will show that our four early morning cases show larger residuals between AERI and LBLRTM than what was found for other time periods during the day. The specification of the atmospheric state is not perfect, and nightly inversions are likely in transition at this time. Nevertheless, on average, over the four investigated cases, IPASRC-I shows that atmospheric longwave irradiance measurements and calculations agree very well, which indicates that state-of-the-art longwave radiometers and radiative transfer models are able to determine nighttime atmospheric longwave irradiance with an absolute uncertainty of ±1.5 W m^{-2}.

9. Conclusions

The results of the IPASRC-I campaign reflect the state of the art of experimental and theoretical methods to determine atmospheric longwave irradiance at the Earth's surface. In the early 1990s, precision and uncertainties of longwave measurements were of the order of 10%, but instruments and calibration methods have dramatically improved since. With respect to pyrgeometer measurement precision the IPASRC-I comparison shows comparable results among instruments, whether nonuniform (USER) or uniform (CMDL) blackbody calibration factors are used. Precision is improved with modified pyrgeometers compared to original Eppley PIRs. The enhanced Philipona et al. pyrgeometer formula provides a better interpretation of pyrgeometer measurement and hence further improves estimates of the irradiance. By far the largest improvement in precision is achieved with field, as opposed to blackbody, calibrated pyrgeometers. The results demonstrate that blackbody pyrgeometer calibration is a first step and that fine tuning of k_2 and C should be done in the field, comparing pyrgeometer measurements to an absolute reference standard instrument. IPASRC-I showed that for midlatitude summer, nighttime precision of optimized pyrgeometer measurements reaches levels of ±1 W m^{-2} or 0.4% for longwave irradiance values in the range of ~250–350 W m^{-2}. Daytime pyrgeometer precision is twice as high and shows levels of about ±2 W m^{-2} which is still within 1%.

By comparing nighttime mean irradiance values measured by groups of seven or eight pyrgeometers we observe that with uniformly determined CMDL or PMOD calibration factors the results are within 1 W m^{-2} of the FIELD7 group, which by field calibration is traced to the absolute measurements of the sky-scanning radiometer. Hence two completely different methods for measuring longwave radiation produce statistically similar results. This is very satisfactory since it demonstrates that blackbody calibration does not produce offsets in one or another direction, even though pyrgeometer domes are not at all ideal optical components with respect to directional and spectral longwave transmissions and the spectral curve of atmospheric radiation is very different from a Planck curve. The same comparisons also show rather small standard deviations of the differences to the absolute measurement which demonstrates that all instruments, the field-calibrated chopped pyrgeometer included, track each other over all nighttime measurements between 270 and 380 W m^{-2}. Daytime measurements show 2 to 3 W m^{-2} higher irradiances with the Albrecht et al. formula than the FIELD7 group that uses the Philipona et al. formula.

Radiative transfer model calculations of clear-sky nighttime situations that did not include aerosols are slightly below absolute measurements. With aerosols included, MODTRAN shows values slightly above the ASR measurements. A 1 to 1.5 W m^{-2} flux increase which is expected from aerosols would bring the LBLRTM calculations, which best represents the modeled flux, close to ~1 W m^{-2} to the absolute sky-scanning radiometer measurements. The larger standard deviations on model calculations compared to measurements are most probably related to uncertainties on the specifications of the atmospheric state which go into the model calculations. However, the very small average difference between pyrgeometer measurements, absolute measurements, and model calculations boosts confidence in the correctness of present-day clear-sky nighttime atmospheric longwave irradiance measurements and calculations and indicates that absolute uncertainty as low as ±1.5 W m^{-2} or 0.5% are practicable and realistic at least for midlatitude summer conditions.

To compare highest-quality longwave irradiance measurements and model calculations, absolute comparisons were made for nighttime clear-sky situations only. The ASR is not used during cloudy situations, and AERI measurements and model calculations would also not do quite so well during broken cloud situations, mainly due to the radiance to flux conversion. However, there is no reason to assume that pyrgeometers measure less accurately during all-sky nighttime situations. Daytime pyrgeometer measurements still show minor problems, as indicated above, which need to be addressed, and arctic winter longwave uncertainty was investigated during IPASRC-II in March 2001 at the ARM site in Barrow, Alaska. IPASRC-I has also demonstrated the need for a future world radiometric reference for longwave irradiance measurements, which serves as a world reference standard and which guarantees long-term stability for the measurements. The demonstrated low uncertainties on atmospheric longwave irradiance measurements are very encouraging and may allow the observation of possible changes in the greenhouse radiative forcing, induced by greenhouse gas increases, in the future.

Acknowledgments. The authors would like to thank Atsumu Ohmura of the Institute for Atmospheric and Climate Science of ETH-Zürich for his continuous encouragement and support of this work. We would further like to thank for the great support received from Jim Teske's staff at the ARM SGP site, particularly to Dan Nelson, Craig Webb, Cindy Kugel, Rod Soper, and Tim Grove. Special thanks go further to Jim Treadwell and Don Nelson. The authors would like to acknowledge the BSRN community, as it was under its auspices that the IPASRC-I was carried out, and particularly thank all the members who provided pyrgeometers to the comparison. NREL at Golden was supported by the U.S. DOE ARM program through interoffice work order 353925-A-WO. SUNY Albany support was from the U.S. DOE ARM program through grant DE-FG02-90ER61072.

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(Received November 28, 2000; revised May 29, 2001;
accepted June 4, 2001.)