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ORIGINAL PAPER

# The Energy Balance Experiment EBEX-2000. Part III: Behaviour and quality of the radiation measurements

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**Abstract** An important part of the Energy Balance Experiment (EBEX-2000) was the measurement of the net radiation and its components. Since the terrain, an irrigated cotton field, could not be considered homogeneous, radiation measurements were made at nine sites using a variety of radiation instruments, including pyranometers, pyrgeometers and net radiometers. At several of these sites multiple instruments were employed, which enabled us to compare instruments and assess accuracies. At all sites the outgoing longwave and shortwave radiation and the net radiation were measured, while the incoming radiation was supposed to be uniformly distributed over the field and was therefore measured at three sites only. Net radiation was calculated for all sites from the sum of its four components, and compared with the direct measurement of net radiometers. The main conclusions were: (a) the outgoing shortwave radiation showed differences of up to 30 W m$^{-2}$ over the field; the differences

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were not clearly related to the irrigation events; (b) the outgoing longwave radiation showed differences of up to 50 W m$^{-2}$; the differences increased during the periods of irrigation; (c) the net radiation showed differences of several tens of W m$^{-2}$ across the field, rising to 50 W m$^{-2}$ or more during the periods of irrigation; (d) the net radiation is preferably to be inferred from its four components, rather than measured directly, and (e) attention should be paid to the characteristics of pyranometers that measure the outgoing radiation, and thus are mounted upside down, while they are commonly calibrated in the upward position. The error in the net radiation at EBEX-2000 is estimated at max (25 W m$^{-2}$, 5%) per site during the day and 10 W m$^{-2}$ at night.

**Keywords** Albedo · EBEX-2000 · Net radiometer · Pyranometer · Pyrgeometer · Radiation

## 1 Introduction

Energy Balance Experiment (EBEX-2000) was an experiment that concentrated on the closure of the energy balance, since in the 1990s it was realised that measurements of the energy balance at the Earth's surface were often not closed. In the literature of that time various explanations were offered, varying from instrumental shortcomings, including those of radiation instruments, to failure of the understanding of all transport processes. EBEX-2000 was designed to assess these difficulties, including an assessment of instrumental accuracies (Oncley et al. 2002).

Being of prime importance to the energy balance, net radiation can be measured in a variety of ways: ranging from a single instrument (often referred to as a net radiometer) to four instruments for the four components, namely outgoing and incoming shortwave radiation and outgoing and incoming longwave radiation, here denoted by $R_{so}$, $R_{si}$, $R_{lo}$ and $R_{li}$, respectively. Because of their simplicity and relative low cost, net radiometers found a wide use in micrometeorological practice. But for several reasons, the most important being traceable calibration, separate measurement of the four components offers advantages (Halldin 2004; see also this publication for an overview of radiometry in the last two decades). Since net radiation is commonly considered to be the most precise term in the energy balance equation, it can be used as a quality check on the measurement of the other terms in field studies of e.g. evapotranspiration, but also of the vertical flux of carbon dioxide since evaporation and carbon dioxide flux measuring methods often partially share common sensors.

In most micrometeorological applications an accuracy of 5% in the measurement of net radiation is acceptable, which amounts to 20 W m$^{-2}$ or more on a sunny day. Much more stringent demands are set by the climate research community since climate models are sensitive to relatively small biases in radiation. For this reason the Baseline Surface Radiation Network (BSRN) was established, with the goal of providing the most accurate possible measurement of the radiation received by the Earth's surface (De Luisi et al. 1992; Gilgen et al. 1995; Ohmura et al. 1998).

Our study concerns the radiation measurements at EBEX-2000, using a strategy of making measurements in such a way that the radiation distribution over the field was obtained, and that different types of radiation instruments could be compared. For this purpose the outgoing components were measured at every site, partly with multiple instruments, and the net radiation was also directly measured at every site. Net radiation was then calculated from the components and compared with the net radiometers. The incoming radiation was not measured at every site since it was considered to be the same at all sites. The quality of instruments was studied by having co-located instruments of different manufacturers. Regarding the incoming radiation, instruments located at different sites were compared. It is important to realise that in EBEX-2000 we used radiation instruments that had "standard" calibrations provided by manufacturers, relevant institutes or the World Radiation Centre (WRC), and that these instruments could not always be operated in the most ideal way; for instance, during irrigation part of the field was inaccessible and cleaning of the instruments not always possible. Conditions and practices were such as are often found in experiments in the field, and not comparable to special calibration set-ups and operation on dedicated platforms. There was no need to aim for accuracies as required by e.g. the BSRN since an accuracy in the order of $10\,\mathrm{W\,m^{-2}}$ would be sufficient for our purpose.

The structure of this report is as follows: an introduction is given for each type of instrument (shortwave, longwave, net radiation), followed by a comparison of instruments of the same type and concluded with the radiation distribution over the field. In the case of net radiation, net radiometers as well as the sum of the four components are considered.

## 2 Experiment description

The field selected for EBEX-2000 was intended to have 'ideal' terrain—nearly flat and with few inhomogeneities—covered with vegetation with high evapotranspiration. The actual site was a cotton field of $800\,\mathrm{m} \times 1600\,\mathrm{m}$ at coordinates 36°06' N, 119°56' W, approximately 20 km south-south-west of the town of Lemoore CA, USA; however, it was not ideal. Gradients in soil water due to the irrigation scheme, a flooding every two weeks starting at the northern end of the field, may have caused horizontal gradients in the evapotranspiration. Such limitations were partly counteracted by the installation of many micrometeorological stations over the field. More information can be found in Oncley et al. (2006).

The radiation instruments were mounted on a stand ('dark horse') at each of nine sites (Fig. 1), with the exception of a Schulze–Däke net radiometer, that was mounted on a pole. The stands were oriented east–west and were 2 m high. At sites 1–3 and 6–9 the centre of the dark horses was located over the line of cotton plants, and at sites 4–5 the centre was located over the furrow between these plants. The instruments they carried varied, with the majority mounted downwards looking since uniform incoming radiation was expected. In Table 1 some of their characteristics and their position in the field are noted. Some of the stands also carried an infrared thermometer, but this measurement has a very local footprint and has been left out of this analysis. The weather conditions during EBEX were remarkable in that almost all days were cloudless, resulting in very smooth radiation curves. This facilitated the comparison between instruments considerably. Fig. 2 gives an example of the diurnal behaviour of the components of the net radiation.

**Table 1** Instrument characteristics and site location

| Instrument | Owner | Accuracy | Calibration | Site | Ventilation | Cleaning |
|---|---|---|---|---|---|---|
| Eppley PSP | NCAR | 2% | NOAA 28.6.2000 | 1o,2o,3o,4o,5o,6o, 7o,8o,9o,7i,8i,9i | Y(site 8 only) | Occasional |
| Kipp CM11 | Basel | 1% | K&Z | 9o | | Daily |
| Kipp CM14 | Bayreuth | 1% | K&Z 9.6.1997 | 7o,7i | Y | Daily |
| Kipp CM21 | NCAR | 1% | K&Z 1994,1997 | 1o,2o,3o,4o,5o,6o, 7i | Y | Occasional |
| Kipp CM21 #239 | Basel | 1% | WRC 3.12.1996 | 9i | | Daily |
| Kipp CM21 #009 | Basel | 1% | K&Z 8.4.1997 | 9i | | Daily |
| Eppley PIR | NCAR | $5\,W\,m^{-2}$ | NOAA 4.2.1999 | 1o,2o,3o,4o,5o, 6o, 8o, 8i | Y | Occasional |
| Eppley PIR | Basel | $5\,W\,m^{-2}$ | WRC | 9o,9i | | Daily |
| Eppley PIR | Bayreuth | $5\,W\,m^{-2}$ | WRC 24.9.1997 | 7o,7i | Y | Daily |
| Kipp CNR1 | Basel | $20\,W\,m^{-2}$ | K&Z 1999 | 9 | | Daily |
| Kipp CNR1 | Bayreuth | $20\,W\,m^{-2}$ | K&Z 20.11.1997 | 7 | | Daily |
| REBS Q*7 | NCAR | $20\,W\,m^{-2}$ | REBS | 1,2,3,4,5,6,7,8,9 | | Occasional, but 9 Daily |
| Schulze–Däke | KNMI | $10\,W\,m^{-2}$ | Käseberg 19.12.2000 | 7 | Y | Daily |

*Notes*: Suffix o: outgoing radiation; i: incoming radiation; no suffix: net radiation. Stated accuracies are partly from manufacturers' specifications, partly from the authors' experience. The PIR instrument for outgoing radiation at site 3 was moved to the bare soil location on 14 August

**Fig. 1** The radiation instrumentation ("dark horse") at site 7. In the background, in the middle can be seen the Schulze–Däke net radiometer

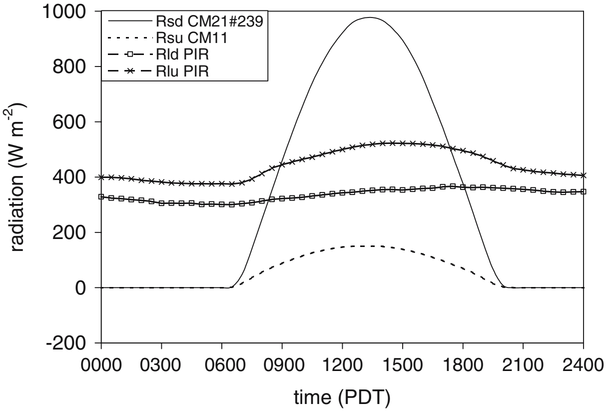


**Fig. 2** Daily course of the four radiation components on 14 August 2000 at site 9 (Basel data)

## 3 Shortwave radiation

### 3.1 Sensor description

Three types of shortwave radiometers were used:

- Eppley Precision Spectral Pyranometer (PSP)
- Kipp & Zonen pyranometer type CM11, CM14 and CM21
- Kipp & Zonen net radiometer CNR1, shortwave component (CM3).

The first two instruments have double domes, with the CM14 being usually applied as a pair for the measurement of the albedo. The physical difference between the CM11 and CM14 lies in the shape of the radiation screen: that of the downlooking instrument is flat, whereas the uplooking instrument has a conically shaped screen. Furthermore, the CM14's two sensors have matched sensitivities. The CM21 is an upgraded version of the CM11. All these Kipp & Zonen instruments match the WMO secondary standard classification for a pyranometer (see Brock and Richardson 2001). Eppley classifies their PSP as a WMO first class radiometer, which is one rank lower than the secondary standard. However, the specifications are much closer to that of the secondary standard than to first class. The CNR1 is a net radiometer, with separate measurements of the four components. The shortwave sensor (CM3) has a single spherical dome and meets the WMO requirements for a second class pyranometer.

A pyranometer often is ventilated to prevent dew formation on the dome. In EBEX some instruments were ventilated, others not (Table 1). Next to the advantage of dew suppression, ventilation may also force the dome temperature closer to the temperature of the instrument housing, which reduces errors due to convective or radiative heat transport between dome and sensor.

One of the main concerns in the measurement of $R_{\mathrm{si}}$ is the offset due to differences in dome and sensor temperatures. It is well known that pyranometers provide a negative reading of several W m$^{-2}$ during clear nights, and this is commonly ascribed to the colder dome. It is debatable whether this nighttime offset can be used for correction during the day (Chess et al. 2000). It also is likely that this effect is at least partially included in the calibration of the instrument, depending on the method of calibration (Reda et al. 2005).

### 3.2 Incoming shortwave radiation comparison

Since almost all days were cloudless, it is reasonable to assume that $R_{\mathrm{si}}$ was the same at all sites, so all instruments can be compared. The Kipp & Zonen CM21 pyranometer #239 of the Basel University at site 9 was used as the reference for this study, a choice that was based on (1) the higher WMO class of the Kipp & Zonen CM21 as compared to that of the Eppley PSP, (2) better specifications of the CM21 as compared to the CM11 or CM14, and (3) consistent cleaning of this instrument. The comparison revealed the following:

- Regarding the diurnal behaviour, averaged over all days, the CM21 #009 and the PSP (both at site 9) agreed within 10 W m$^{-2}$ with the reference (Fig. 3). Since the global radiation reached a maximum value of about 900 W m$^{-2}$, the agreement was within 1% or 10 W m$^{-2}$, whichever is greater.
- The CM14 showed a noticeable amplitude with approximately 15 W m$^{-2}$ larger values in the afternoon. Regarding individual half-hour averages, a few outlying values of 40 W m$^{-2}$ were noticed (no figure). After EBEX-2000 was completed, it was found that the CM14 probably had a levelling problem, which may explain the deviations.
- the PSPs at sites 7 and 8, and the CM21 at site 7, showed deviations of up to several tens of W m$^{-2}$, likely related to cleaning procedures. Notable were the effects of cleaning on 16 August, leading to an increase of 50 W m$^{-2}$ in the CM21 (site 7) values, and on 21 August, an increase of approximately 80 W m$^{-2}$ in the PSP values at site 8 (no figure). However, not all deviations could be explained in this way. In particular the PSP at site 7 gave about 4% larger values than the reference, which points to an instrumental problem. Measurements using this instrument up to 8 August were omitted because of unrealistic values.

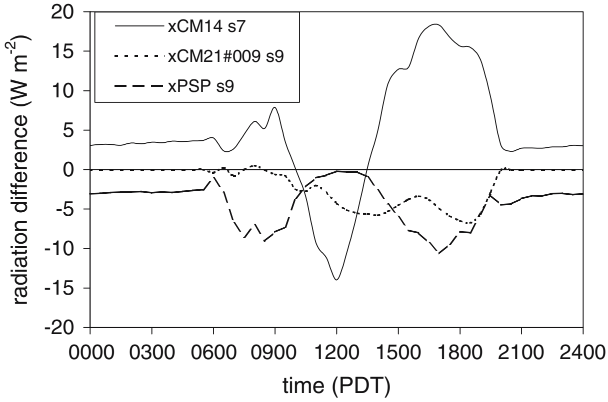


**Fig. 3** Daily course of incoming shortwave radiation differences. The CM14 (site 7), the CM21 #009 (site 9), and the PSP (site 9) with respect to the CM21 #239 (site 9). Average of all days from 28 July to 25 August 2000

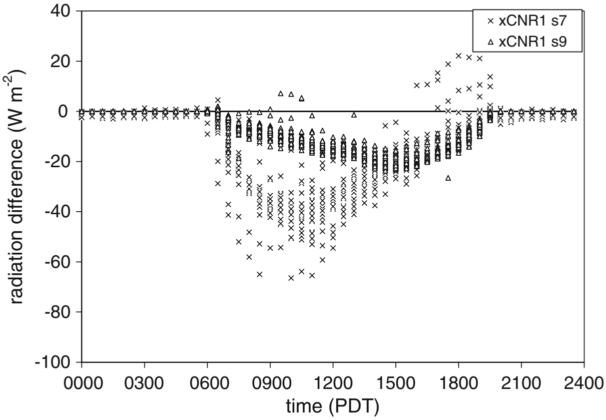


**Fig. 4** Daily course of incoming shortwave radiation differences. The CNR1 at sites 7 and 9 relative to the CM21 #239. All half-hour averages are shown

- The two CNR1 instruments showed lower $R_{si}$ values (Fig. 4); that at site 9 had differences of about –20 W m$^{-2}$ in the afternoon, and that at site 7 had differences of about –40 W m$^{-2}$ in the morning with some outliers of –60 W m$^{-2}$.
- Nighttime values of the two CM21 pyranometers at site 9 were exactly zero, reflecting a software cut-off. Other instruments showed nighttime values of –2 to –4 W m$^{-2}$, with the exception of the CM14 which was about 3 W m$^{-2}$ (positive) at night.

*Conclusion*: The regularly cleaned instruments at site 9 (two CM21, one PSP) agreed within their specifications (1%). Other PSP instruments showed larger deviations which may partly be due to dirty domes. The PSP at site 7 gave values that are about 4% larger than the reference (the CM21 #239 at site 9), which cannot be explained by dirt. The CM14 agreed within 2% for most of the time, with some isolated outliers, thereby marginally matching its specifications. Nighttime values of

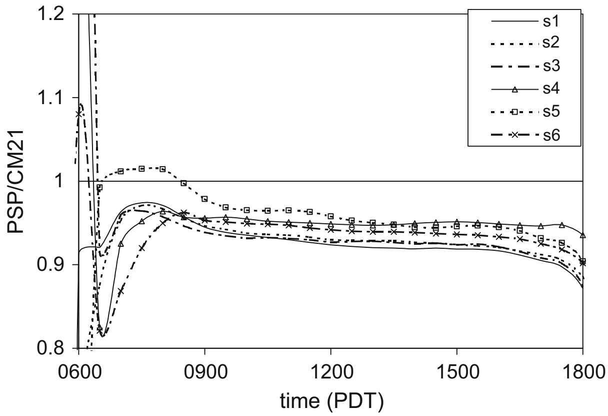


**Fig. 5** Daily course of the outgoing shortwave radiation. Ratio of the PSP and the CM21 at sites 1 to 6. All NCAR instruments. Average of all days from 28 July to 25 August 2000

this instrument were about $3\,\mathrm{W\,m^{-2}}$ and daytime values may have been affected by a levelling error. The CNR1s performed within their specification.

## 3.3 Outgoing shortwave radiation comparison

This section is divided into three parts: comparison of instruments at a common site, a discussion of the distribution of $R_{\mathrm{so}}$ over the field, and the albedo. Instruments were installed at all sites in order to investigate the distribution of the outgoing radiation over the field, with multiple measurements made at all sites for quality control, except at site 8.

At stations 1–6 PSP and CM21 downward looking pyranometers were installed; the ratio PSP/CM21 as a function of time showed a broad plateau between 0.90 and 0.97, which corresponds to a difference of about 17 to $5\,\mathrm{W\,m^{-2}}$ at midday (Fig. 5). These differences exceeded the specifications of the instruments. The CM21 instruments were ventilated, the PSP were not, but this does not explain the differences since the domes were shaded most of the time and the dome-case temperature differences consequently small.

We continue with $R_{\mathrm{so}}$ at sites 7 and 9. At site 7 we had the CNR1 instrument of Bayreuth, the PSP of NCAR and the CM14 also of Bayreuth, and as a reference we took the CM14. At midday the PSP had on the average about $8\,\mathrm{W\,m^{-2}}$ lower values than the CM14, whereas the CNR1 was about $15\,\mathrm{W\,m^{-2}}$ lower than the PSP in the morning and afternoon (Fig. 6). Given the fact that the value of $R_{\mathrm{so}}$ at midday was about $170\,\mathrm{W\,m^{-2}}$, the discrepancies amounted to several per cent for the PSP-CM14 difference and about 9% for the CNR1-CM14 difference, thereby exceeding the specifications of these instruments. The maximum deviations of the CNR1 in the morning and afternoon suggest a contribution of internally reflected radiation at lower sun angles. At site 9 the same features were observed regarding the CNR1 (Fig. 6), the reference being the CM11 of Basel. However, the differences were shifted to more positive values as compared to site 7. At midday, the PSP was about $10\,\mathrm{W\,m^{-2}}$ larger than the CM11. Note that at all other sites the PSP had smaller values than the Kipp & Zonen CM21. It is tempting to lower the values of the CM14 reference by a

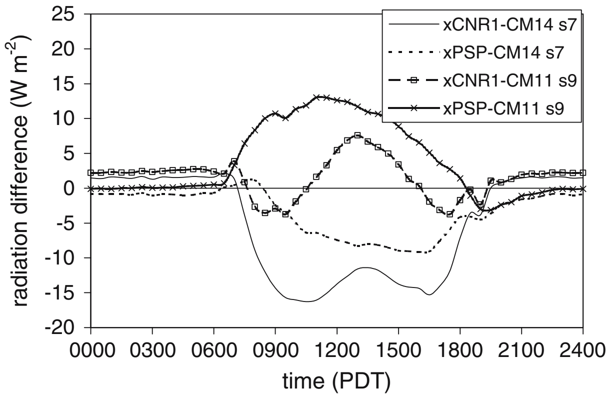


**Fig. 6** Daily course of outgoing shortwave radiation differences at sites 7 and 9. The CNR1 and the PSP relative to the CM14 and CM11, respectively. Average of all days from 28 July to 25 August 2000

certain fraction, since this would increase the differences and there would be a better agreement between sites 7 and 9, but to the same effect one may equally well have increased the CM11 reference. Since we have no reason to prefer one reference over the other, Fig. 6 gives an example of measurement inaccuracy of $R_{so}$ we experienced at EBEX-2000

Next the distribution of $R_{so}$ over the field is discussed by considering the PSP data. Appreciable differences were found that are believed to reflect true spatial differences since all PSPs were calibrated in the same way. All PSP data appeared to be positively biased with respect to the reference, the CM11 at site 9, and the spread of the data at sites 1–9 was about 30 W m$^{-2}$, or 20% of the absolute value at midday (Fig. 7). The bias might be ascribed to the vegetation cover at site 9, which was less dense than at the other sites. Presumably, the soil had a lower reflectivity than the plants. The most positive PSP data were those of sites 4 and 5, where the dark horse was located over the furrows, and of site 1, where the dark horse was located between the furrows. The vegetation was closed at these sites; it thus appears that the high $R_{so}$ value is not related to the position of the radiation instruments relative to the furrows. As a fraction of the net radiation, the spread of $R_{so}$ was about 5%, and no clear relation with the irrigation scheme was found.

Finally we discuss the albedo. Site 7 was the only site that was equipped with an albedometer (Kipp & Zonen CM14), while at sites 8 and 9 we had upward and downward facing pyranometers. A downward facing "regular" pyranometer can be influenced by internal reflections at low sun angles, while the radiation shield of an albedometer prevents this effect. From Fig. 8, which shows the albedo of site 7 for different instruments on successive days at the same time (half-hour average around 1215 local time, PDT), a value between 0.16 and 0.18 is noted. As is usually the case, much larger values were found near sunrise and sunset (no figure). The albedo decreased around the times of irrigation (2 and 16 August), but decreases were also found at other times, and albedos calculated from the downward looking PSP instruments and one common upward looking pyranometer showed decreases that were not related to irrigation (no figure). At site 9 an albedo between 0.15 and 0.16 at 1215 PDT was observed. As noted above, the vegetation at site 9 was less dense than at the other sites. Remarkably, the order by which the measurements ranked at site 9 was

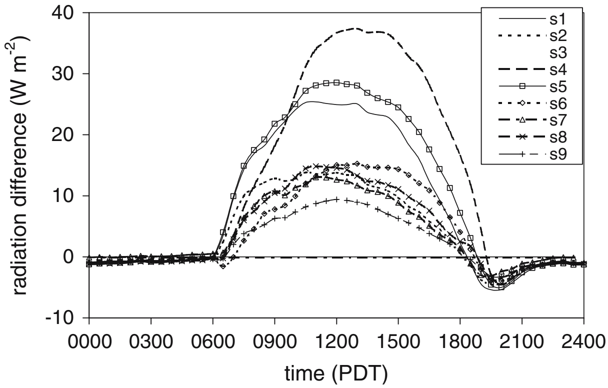


**Fig. 7** Distribution of the outgoing shortwave radiation. All PSP instruments relative to the CM11 at site 9. Average diurnal course, 28 July to 25 August 2000

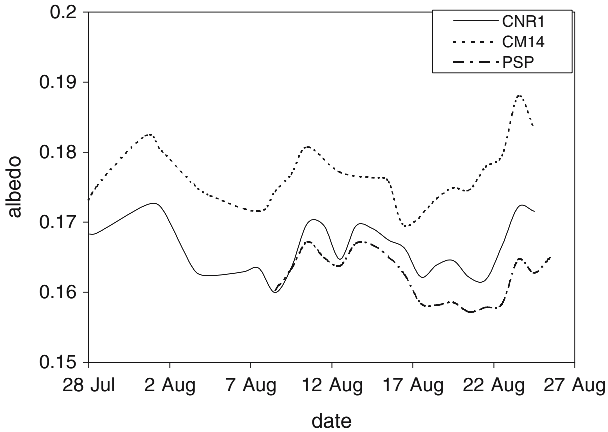


**Fig. 8** The albedo at site 7 at 1215 PDT from 28 July to 25 August 2000. Instruments: CNR1(up and down), CM14 (up and down) and PSP (up and down). Data of the PSP before 8 August were suspect and not shown

different from that at site 7: at site 9, the PSP gave the highest albedo, followed by the CNR1 and the CM11/CM21, whereas at site 7 the order was CM14, CNR1, PSP. This is an indication of the instrumental accuracy.

*Conclusion:* The outgoing shortwave radiation appeared unevenly distributed over the field, with differences of up to 30 W m$^{-2}$. Instrumental or observational shortcomings were observed that exceed the specifications of the instruments. At this point we mention that pyranometers are commonly calibrated in an upward position, and the authors are not aware of reports on calibration of instruments in an inverted position. The albedo of the cotton field was about 0.17 at midday and had maximum values near sunrise and sunset; difference in albedo of 10% were observed between co-located instrument combinations. Although the albedo seemingly decreased at times of irrigation, a distinct relation could not be proven.

## 4 Longwave radiation

### 4.1 Sensor description

Two types of longwave radiometers were used:

- Eppley Precision Infrared Radiometer (PIR)
- Kipp & Zonen net radiometer CNR1, longwave component (CG3).

Longwave radiometers, or pyrgeometers, have an optical filter that rejects the shortwave radiation and transmits the longwave radiation. Since the filter is only partly transmittant, it also emits infrared radiation. Thus, the radiation received by the thermopile is a balance of its own emission, the emission by the filter and the transmitted atmospheric radiation. It should be noted here that the filter and thermopile not only exchange energy by radiation, but also by convection, leading to an overestimate of 10 – 20 $\mathrm{W\,m^{-2}}$ in bright sunshine. Forced ventilation helps in reducing the effect since it reduces the temperature difference between dome and thermopile ( e.g., Pérez and Alados-Arboledas 1999).

To infer the atmospheric radiation, three quantities have to be known: the thermopile voltage, the thermopile's upper surface temperature and the dome temperature. The PIR has a dome-shaped optical filter and has signal outputs for the thermopile, the case temperature and the dome temperature. The latter is commonly sensed near the base of the dome, but on request sensors can be installed at other positions. The difference between the case temperature and the thermopile's upper surface temperature is incorporated in the sensitivity coefficient of the thermopile, which consequently leads to a temperature dependency. A built-in passive electric circuit compensates for this dependency.

The CNR1 longwave sensor, CG3, has a flat optical filter and lacks measurement of the filter temperature. As a consequence of the design, the cosine response is not as good as that of the Eppley PIR and, more seriously, the contribution of the filter remains uncorrected. In comparison with the PIR, the filter of the CG3 has a better thermal coupling to the instrument housing, thus alleviating some of the disadvantage of not knowing its temperature. Another difference with the PIR is the shortwave cutoff of the filter: it is 5 $\mu$m for the CG3 and 3.5 $\mu$m for the PIR. This is of importance to the shortwave–longwave overlap, which will be discussed below.

Regarding the calibration of the pyrgeometers, it is noted that, unlike the case of shortwave pyranometers, no international agreement exists on a radiation standard and calibration procedure. Moreover, there is no agreement on the mathematical description of the physics of the instrument ("the pyrgeometer formula"). Eppley calibrates its instruments against a black-body radiator (Eppley 1995), and only gives a response coefficient for the thermopile (or the combination of thermopile and the electric equivalent of the case emission). A correction for the dome temperature is left to the user. Besides the Eppley company (Eplab), there are a number of other institutes that perform infrared calibration. Stimulated by the demand for more accurate measurements, several pyranometer inter-comparisions have been made in the last decade, e.g., Dehne et al. (1993) and Philipona et al. (1998). The latter authors report on a comparison experiment involving five PIR instruments and eleven laboratories. Of these institutes, six reported a responsivity that was within 2% of the median, including Eplab, the WRC and the Meteorologisches Observatorium Potsdam (MOP) of the Deutscher Wetterdienst. Kipp & Zonen was not included. These institutes are mentioned here specifically because of their relevance to EBEX. At the WRC not only the response of the thermopile is measured, but also the effect of the dome. Kipp & Zonen calibrate against a constant temperature source; details are not given.

Extensive literature exists on the pyrgeometer formula. Recommended by the WRC is (Philipona et al. 1995):

$$R_{\mathrm{lw}} = \frac{U_{\mathrm{pile}}}{C}(1 + k_1 \sigma T_{\mathrm{case}}{}^3) + k_2 \sigma T_{\mathrm{case}}{}^4 - B\sigma(T_{\mathrm{dome}}{}^4 - T_{\mathrm{case}}{}^4), \tag{1}$$

where $C, k_1, k_2$ and $B$ are constants to be found by calibration, $\sigma$ is the Stefan–Boltzmann constant, $U_{\mathrm{pile}}$ is the voltage output of the thermopile, $C$ is the sensitivity coefficient of the thermopile, $k_1$ corrects for imperfections of the above-mentioned passive electric compensation network and the last term with constant $B$ corrects for the dome emission and convection. The justification of the constant $k_2$ was independently questioned by Kohsiek and van Lammeren (1997), and by Fairall et al. (1998) who both argued that under perfect thermodynamic equilibrium the radiation is that of a blackbody, $U_{\mathrm{pile}} = 0$, $T_{\mathrm{dome}} = T_{\mathrm{case}}$ and consequently $k_2 = 1$. If heat exchange between the dome and case is by radiation only, Kohsiek and van Lammeren (1997) show that $k_2$ is in fact the ratio of the average dome transmission for a black-body radiator at case temperature and the average dome transmission for the atmospheric radiation, and thus depends on the spectral distribution of the atmospheric radiation. Forcing $k_2$ to a constant value as recommended by the WRC, rather than considering it dependent on the spectral signature of the atmospheric radiation, may lead to disagreement of a few $\mathrm{W\,m^{-2}}$ under conditions that approach thermodynamic equilibrium, e.g. a heavy overcast sky.

Philipona et al. (1995) also considered the effect of shortwave radiation leakage through the longwave optical filter. Since there is no perfect gap between the shortwave and longwave radiation spectrum, shortwave radiation in the region between 3 and 4 $\mu$m may be counted twice: by the pyranometer and by the pyrgeometer. This is of particular concern for the Eppley PIR, and not so much for the Kipp & Zonen CG3, which has a higher shortwave cut-off wavelength. Philipona et al. (1995) introduced a factor $f$ that, multiplied by $R_{\mathrm{si}}$, gives the correction for the longwave measurement, though they do not quantify $f$. Since $f$ depends on the shape of the spectrum of the incoming radiation and the transmission characteristics of the optical filter, it is expected to vary per instrument and per location.

### 4.2 Incoming longwave radiation comparison

We employed two types of instruments: the Eppley PIR (NCAR, Bayreuth, Basel) and the Kipp & Zonen CNR1 (Bayreuth and Basel). The manufacturer calibrated the CNR1 instruments, whilst regarding the PIR, the Basel group instruments were calibrated at the WRC, with an instrument specific dome correction applied; they did not apply a shortwave ($f$) correction. The Bayreuth group's instruments were also calibrated by the WRC, with a dome correction applied for the upward looking instrument, but not for the downward looking one. The group used the observed temperature differences across the dome of the PIR as a characterisation of the shortwave radiation error and determined the correction factor once during EBEX (by shading the pyrgeometer); data were provided with and without the shortwave correction. NCAR's instruments were calibrated by NOAA, with an instrument specific

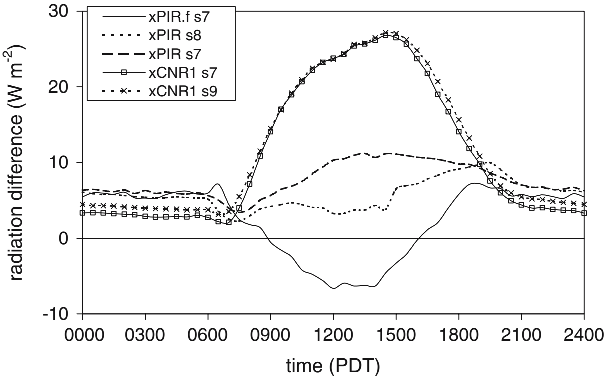


**Fig. 9** Daily course of incoming longwave radiation differences. The PIR at sites 7 and 8, and CNR1 at sites 7 and 9 relative to site 9 PIR. The PIR at site 7 is given with the shortwave (f) correction included, and without this correction. Average of all days from 28 July to 25 August 2000

dome correction ($B$) and a generic shortwave correction $f = 0.02$ applied. There were differences in ventilation policy: Bayreuth and NCAR ventilated, Basel did not. As a reference for comparison, the Basel PIR (site 9) was adopted.

The comparison of the PIR instruments showed a diurnal behaviour where, compared to the Basel values, the Bayreuth values (site 7) were about 5–15 $\mathrm{W\,m^{-2}}$ larger at midday, and the NCAR values (site 8) about 5–10 $\mathrm{W\,m^{-2}}$ larger (Fig. 9). At night, both the Bayreuth and the NCAR values were 6–7 $\mathrm{W\,m^{-2}}$ larger than the Basel values. The Bayreuth values discussed here were those without shortwave correction. Inclusion of this correction would lead to a more pronounced diurnal behaviour of the difference with Basel, with about 6 $\mathrm{W\,m^{-2}}$ smaller values at midday. This points to an over-correction of the transmitted solar radiation. Remarkably, NCAR's $f$ corrected data compared well with Basel's, which had no $f$ correction and suggests that the correction is strongly instrument dependent. In a comparison experiment done after EBEX it was found that, due to inaccuracies in the measurement of the case and dome temperatures, the Basel instrument was biased by –5 $\mathrm{W\,m^{-2}}$ with respect to the Bayreuth instrument, which is in line with the present observations. The NCAR PIR values were also larger than the Basel values, at night as well as by day. It is not likely that an error in the calibration factor of the thermopile can explain such a difference; internal temperature gradients may be a cause, since such would lead to an improper calculation of the radiation emitted by the thermopile. A difference in ventilation policy, as is here the case, may cause different internal temperature gradients.

The CNR1 instruments showed a similar behaviour (Fig. 9). When compared to the Basel PIR a pronounced daily pattern was found, where the CNR1 instrument values were a few $\mathrm{W\,m^{-2}}$ larger than the PIR at night and about 25 $\mathrm{W\,m^{-2}}$ larger at midday. The diurnal pattern points to an effect of solar heating of the dome; Kipp & Zonen specify an effect of 25 $\mathrm{W\,m^{-2}}$ at 1000 $\mathrm{W\,m^{-2}}$ normal solar radiation, thus the present findings agree with their specifications.

*Conclusion:* During the daytime, the PIR instruments showed significant differences from one another, up to 10 $\mathrm{W\,m^{-2}}$. This is ascribed to dome heating and dome shortwave transmission effects, as well as a bias that was particularly apparent at night and is in part related to inaccuracies in the measurement of the

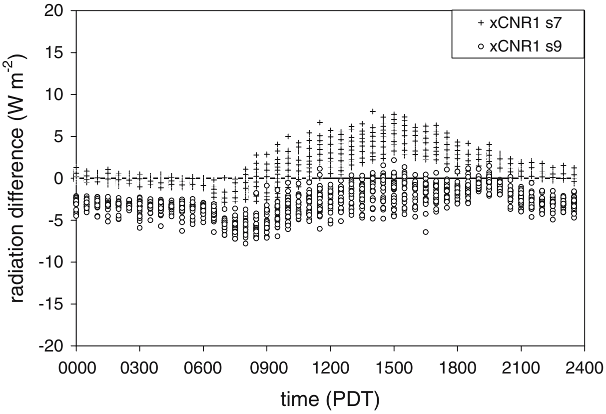


**Fig. 10** Daily course of the outgoing longwave radiation differences CNR1- PIR at site 7 and 9. All half-hour averages are shown

case temperature. The question whether or not the shortwave *f* correction is necessary cannot be answered from our data and may be very instrument dependent. The CNR1 instruments showed a distinct solar heating effect. Application of the manufacturer's filter heating correction would improve the quality of the data significantly.

## 4.3 Outgoing longwave radiation comparison

We compared instruments at common sites and analysed the distribution of the radiation across the field. First we make a few comments. The Bayreuth group did not correct for the dome temperature, whilst the Basel group did, but since the dome and case temperatures of downward looking instruments are close, the correction would be small. The data of site 3 after 14 August 0715 PDT were omitted since the instrument was moved to a bare soil location on that day. Multiple measurements at a single site with PIR instruments were not made.

At sites 7 and 9 both PIR and CNR1 instruments were installed. Figure 10 shows that the difference between the two instrument types is between –5 and 5 $\mathrm{W\,m^{-2}}$, which is quite satisfactory.

To analyse the radiation distribution over the field, all PIR instruments were compared to that at site 9. The differences showed an average daily course of roughly between 5 and –25 $\mathrm{W\,m^{-2}}$ (Figure 11). Considering individual half-hour values, differences as large as –50 $\mathrm{W\,m^{-2}}$ were encountered, thus site 9 was the location with the highest surface temperature at daytime. It is recalled that this site had less vegetation cover than the others. Figure 11 also shows that the sites 1, 4 and 5 apparently were the coolest. Thus, the thermal differences between site 9 and these sites reflected the difference in outgoing shortwave radiation (Sect. 3.3): sites with a higher albedo were cooler. Similar to the case of $R_{\mathrm{so}}$, the character of the differences was the same before and after irrigation, which indicates that the differences were related to inhomogeneity of the vegetation cover, rather than to irrigation practice. However, irrigation reduced the midday peak values of $R_{\mathrm{lo}}$ by several tens of $\mathrm{W\,m^{-2}}$ at the southern sites 6–9, whereas at the other sites such behaviour was not evident, leading to increased differences across the field.

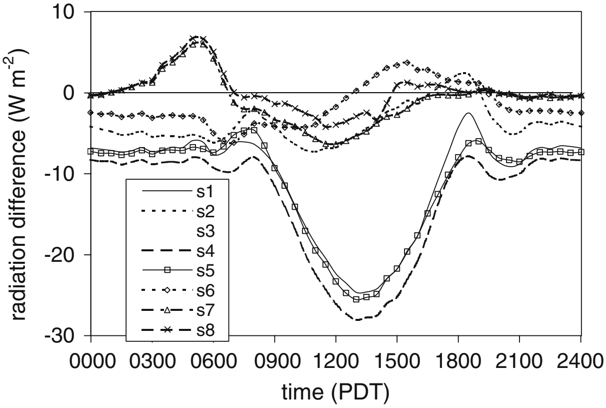


**Fig. 11** Distribution of the outgoing longwave radiation. All PIR instruments compared to the one at site 9. All instruments are from NCAR, except the one at site 7 that is from the Bayreuth group. Average of all days from 28 July to 25 August 2000

*Conclusion:* $R_{\mathrm{lo}}$ was not uniformly distributed over the field. Site 9, where the vegetation was less dense than at the other sites, often showed the largest long-wave outgoing radiation. Differences of up to 50 W m$^{-2}$ (half hour average, daytime) between the sites were observed, where the coolest sites were also the ones with the highest albedo. Irrigation reduced the radiation by several tens of W m$^{-2}$at sites 6–9, but at the other sites the effect was less, The CNR1 instruments compared favourably with their PIR companions.

## 5 Net radiation

### 5.1 Sensor description

Three types of net radiometers were used:

- Kipp & Zonen CNR1
- REBS (Radiation and Energy Balance Systems) Q*7
- Schulze–Däke.

The CNR1 is a 4-component system, and the sensitivities of the four sensors are matched, so they may be added electrically to produce a single output representing the net radiation. The properties of the single sensors have been discussed above.

The Q*7 is a single signal instrument with two polyethylene domes that protect the thermopile from wind and rain. According to the manufacturer, the domes are 0.25 mm thick and require no pressurising to maintain shape. Upon inspection, we found that there is a considerable change of thickness from apex to edge, 0.25 mm being an intermediate value. The domes were ventilated by the natural wind only. The instruments were calibrated by the manufacturer by means of a comparison against a pyranometer or a pyrheliometer regarding its shortwave response and a black-body radiator for the longwave response (Fritschen and Fritschen 1991). One single calibration factor is given. A correction for dome heating as a function of wind speed is also recommended and applied by the NCAR group.

The Schulze–Däke has separate thermopiles for the outgoing and incoming radiation, and the case temperature can also be measured (a Pt100 resistance element); it is therefore a 3-signal instrument. From these signals, the total outgoing radiation and the total incoming radiation can be calculated. The instrument has two 0.1-mm thick self-supporting protection domes of polyethylene (known as Lupolen). These domes have a transmission of over 95% over the entire spectrum, with the exception of isolated absorption bands at 3.5, 6.9 and 14 $\mu$m. The case of the instrument and the two domes are ventilated by a forced air stream that is heated several °C above ambient. According to the manufacturer, the shortwave calibration is made by means of a comparison with another Schulze–Däke radiometer using an artificial light source; the "reference" is in turn calibrated against pyranometers. Longwave calibration is done with a black-body, and the manufacturer gives a calibration factor for each of the four components, which differ by 4% at most for the instrument used in EBEX-2000. Instead of using the four calibration factors, we adopted a single factor that was the average of the shortwave outgoing and incoming factors, weighted with an albedo of 0.16. The error thus introduced is less than 5 W m$^{-2}$.

As a consequence of the difference in measuring principle and calibration procedure, the three types of instruments have different accuracies; it is generally accepted that the best way of inferring the net radiation is by means of its four components. An important reason is that the measurement of the shortwave component can be made with relatively high precision. The CNR1 approaches this ideal only partly because its shortwave sensors are not of the highest class and its longwave sensors are affected by solar heating of the filter. Drawbacks of direct net radiation instruments are (a) imperfect dome transmission, (b) convective and radiative heat transfer between dome and thermopile surface, (c) unequal sensitivity for shortwave and longwave radiation, and (d) not well established calibration procedures. Although specific information on the Q*7 dome transmission is lacking, it can be assumed that the Schulze–Däke's Lupolen domes have higher transmission because they are much thinner. Also, ventilation helps to maintain the dome temperature close to the thermopile temperature, thus reducing the convective and radiative heat exchange. Calibration poses problems that the other radiation instruments do not have. The situation regarding an internationally accepted calibration procedure is even worse than that with the longwave instruments. For example, intercomparisons between laboratories have not yet been done for net radiometers.

Net radiometry has been the subject of recent debate. Halldin and Lindroth (1992) made a study of six different instruments including a Schulze–Däke and a Q*4 of REBS, which is an earlier version of the Q*7. They judged the performance of their Schulze–Däke superior over that of the other instruments. Brotzge and Duchon (2000) reported on a field comparison of a domeless net radiometer, a Q*7 and a CNR1; their reference was an Eppley PSP/PIR combination. The Q*7 showed an underestimate of about –50 W m$^{-2}$ at midday and an overestimate of several tens of W m$^{-2}$ at night, while the CNR1 performed somewhat better, especially at night. The authors stress that their results are unique to their location (Oklahoma) and different results may be obtained at other locations. Vogt (2000) reports on a similar study of the Schenk net radiometer (not used in EBEX), Schulze–Däke, REBS Q*7 and CNR1 net radiometers in a series of field experiments in Europe, using a Kipp & Zonen CM11/Eppley PIR combination as reference. After in-field calibration of the instruments they found that the performance of the instruments was not significantly different from

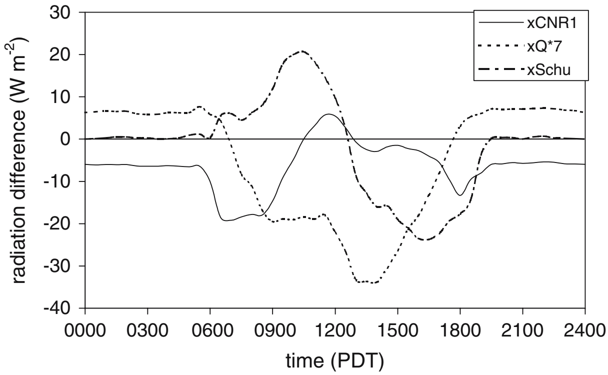


**Fig. 12** Daily course of net radiation differences at site 7. The CNR1, Q*7 and the Schulze–Däke relative to the sum of the four components (CM14 and PIR). Average of all days from 28 July to 25 August 2000

one another. The differences between the seven Schulze–Däke instruments of this study appeared to be larger than suggested by Halldin and Lindroth (1992).

### 5.2 Net radiation comparison

Net radiation differs from site to site according to the behaviour of the outgoing shortwave and longwave radiation fluxes. The performance of the net radiometers was checked in two ways. First, at sites 7 and 9, net radiometers of different types were used, and these instruments were compared to the sum of the components at their relevant sites. Second, at all sites Q*7 net radiometers were installed and they, too, were compared to the sum of the four components, but in this case only $R_{so}$ and $R_{lo}$ were obtained from the specific sites and $R_{si}$ and $R_{li}$ from a common reference site. The section is concluded with a discussion of the distribution of the net radiation over the field.

At site 7 we had available the REBS Q*7, the Kipp & Zonen CNR1, the Schulze–Däke and the four individual components: the CM14 (up and down) and the two PIR instruments. At site 9 we had the same suite of instruments except for the Schulze–Däke. The deviations of both the CNR1 and the Schulze–Däke were found to be within 20 W m$^{-2}$, whereas the Q*7 showed differences below –30 W m$^{-2}$ (Fig. 12). In particular the Schulze–Däke instrument had a positive peak in the morning and a negative one in the afternoon, indicating a levelling problem. When comparing the Schulze–Däke to the 4-component net radiation of site 9, no such behaviour was seen. Thus, the presumed levelling error is not necessarily a problem with the Schulze–Däke. We recall that the CM14 may have been plagued by a levelling error (Sect. 3.2). At night the differences were within $\pm$10 W m$^{-2}$. The comparison at site 9 gave a similar outcome (no figure). In Sects. 3.2 and 4.2 it was noted that the shortwave sensor of the CNR1 underestimates during the day, while the longwave sensor overestimates. Thus, the errors partly compensate.

The second comparison, involving the Q*7 instruments, was done as follows. At each site a reference was constructed from the four components: $R_{si}$ was taken equal to the CM21 #239 of site 9, and $R_{li}$ equal to the PIR of site 9; $R_{so}$ was that of the local PSP instruments, except for site 7 where the CM14 was chosen, and $R_{lo}$ was taken

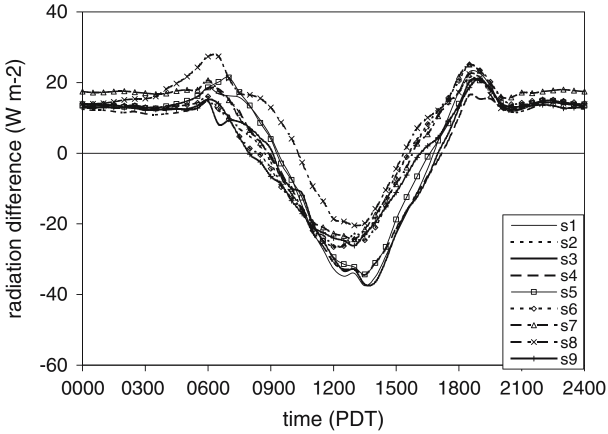


**Fig. 13** Daily course of the differences between the Q*7 net radiometer and the sum of the four components. All sites. Average of all days from 28 July to 25 August 2000

from the local PIR instruments. It was found that the pattern of the deviations was the same for all sites: a weak maximum in the early morning and late afternoon, and a pronounced minimum at noon (Fig. 13). The differences were typically between 20 and –20 W m$^{-2}$ for the southern sites and between 20 and –40 W m$^{-2}$ for the northern ones. At night the Q*7 instruments gave typically 15 W m$^{-2}$ higher values than the references, findings that are in line with Broztge and Duchon (2000).

Since the incoming shortwave and longwave radiation could be regarded as equal at all sites, the distribution of the net radiation was investigated from the distribution of the total outgoing radiation as constructed above. As a common reference the measurements of the Kipp & Zonen CM11 and the PIR at site 9 were taken. Differences of +30 W m$^{-2}$ to –40 W m$^{-2}$, with considerable scatter (Fig. 14) were found. The effect of irrigation was notable: all the negative excursions were related to the two periods of irrigation; the response to irrigation was mainly caused by $R_{\mathrm{lo}}$, since an albedo effect was not obvious. Interestingly, the diurnal behaviour of $R_{\mathrm{li}}$ from day to day showed a pattern similar to that of $R_{\mathrm{lo}}$, thereby offering some compensation. A similar pattern was found in the behaviour of the air temperature. Irrigation affected the soil temperature, the soil temperature had its effect on the air temperature, and, since $R_{\mathrm{li}}$ is coupled to the air temperature, the longwave components reacted *grosso modo* in a similar fashion.

*Conclusion:* The CNR1 and Schulze–Däke instruments agreed within 20 W m$^{-2}$ with the sum of the components. The Q*7 instruments showed larger deviations; in particular, they underestimated the net radiation during the day by 20–40 W m$^{-2}$ and overestimated at night by 10–20 W m$^{-2}$. Significant differences of several tens of W m$^{-2}$ were observed across the field, which were at least partly due to spatial differences in vegetation cover. During the periods of irrigation, differences exceeding 50 W m$^{-2}$were observed.

## 6 Conclusions: recommendation for net radiation

The sensor types in order of quality are: shortwave, longwave and net radiation, with WMO specifications and standardised calibration procedures existing only for

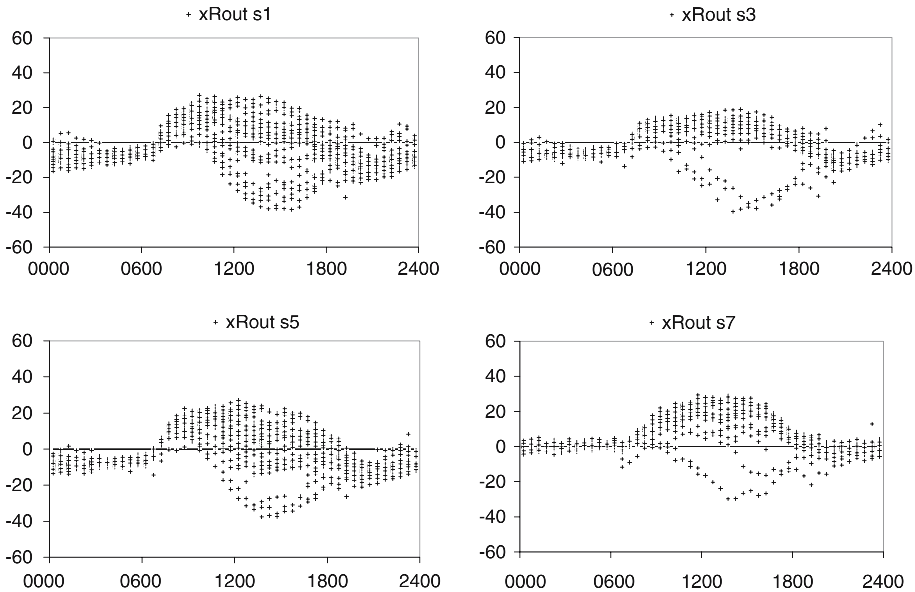


**Fig. 14** Distribution of the total outgoing radiation differences (vertical axes, in W m$^{-2}$) versus time (horizontal axes) at sites 1, 3, 5 and 7. The longwave component is from the PIR instruments, the shortwave component from the PSP instruments. As a reference the CM11/PIR combination at site 9 is taken. All half-hour averages are given. The negative deviations are related to the irrigation events

the shortwave instruments. The limiting factor in the accuracy of pyranometers is the thermal offset, which, during the day, is still uncertain. The calibration of pyranometers that are used to measure the outgoing radiation is a matter of concern since these instruments are calibrated in the upward looking position. Longwave instruments suffer from dome effects and non-standardised calibration procedures; however, their accuracy may approach that of the pyranometer by careful calibration of the thermopile, proper inclusion of dome properties in the pyrgeometer algorithm, and careful exposure procedures (ventilation and using a shading disc). The situation regarding net radiometers is less favourable: calibration procedures are not well established and reports in the literature on their accuracy are partly contradictory.

The basic choice for EBEX-2000 is whether the net radiation should be obtained from the net radiometers (CNR1, Schulze–Däke, Q*7) or from the sum of single component instruments. The comparisons as discussed in Sect.5 indicate that the sum of the components is to be preferred over the Q*7 net radiometer. The same cannot be said of the CNR1 and the Schulze–Däke on the basis of the EBEX-2000 data alone, however there are other arguments that favour the sum of the components: the CNR1 longwave sensor is known to have a dome heating effect and the CNR1 shortwave sensors are of a lower class than either the Eppley PSP or the Kipp & Zonen CM11 or CM21. It is true that the CNR1 shortwave and longwave errors partly compensate, but it does not really add to the quality of the sensor since the compensation may differ from one situation to the other. Regarding the Schulze–Däke, we have to be conservative since the manufacturer's calibration procedure is not known in detail. As to the sensor used in EBEX, there is a difference between the older calibration and the most recent one (which was applied in EBEX-2000) of 6% that was not explained by the present manufacturer. Since the Schulze–Däke instrument measures the incoming and outgoing radiation components separately, it is possible to analyse these components separately and compare them to, for instance, a CM21/PIR combination. Such an analysis showed a difference of a few W $m^{-2}$ during the night, but at daytime the differences were larger, as may be expected from Fig. 12.

Taking all factors into consideration, it is concluded that, consistent with BSRN practice, in EBEX-2000 the sum of the components is the most accurate method of determining the net radiation. In the specific case of EBEX-2000, the all-wave incoming component of the net radiation can be assumed to be the same for all sites. Thus, one pyranometer (preferably the CM21) and one pygeometer (preferably the PIR) suffice. The outgoing radiation was not homogeneously distributed over the field due to differences in vegetation cover and irrigation practice, and must be determined per site from the downlooking pyranometer (in order of preference: CM14, CM21, CM11, PSP) and the downlooking PIR pyrgeometer.

The accuracy of the net radiation is estimated as follows:

- Incoming shortwave: max (5 W $m^{-2}$, 1% of value)
- Incoming longwave: 10 W $m^{-2}$ (daytime), 5 W $m^{-2}$ (nighttime)
- Outgoing shortwave: max (5 W $m^{-2}$, 6% of value)
- Outgoing longwave: 10 W $m^{-2}$ (daytime), 5 W $m^{-2}$ (nighttime)

Adding up, and giving some account for non-correlated errors, the error in the net radiation per site is estimated at max (25 W $m^{-2}$, 5%) at day and 10 W $m^{-2}$ at night.

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## References

Brock FV, Richardson SJ (2001) Meteorological measurement systems. Oxford University Press, New York, 290 pp

Brotzge JA, Duchon CE (2000) A field comparison among a domeless net radiometer, two four-component net radiometers, and a domed net radiometer. J Atmos Oceanic Technol 15:1569–1581

Chess RD, Qian T, Sun M (2000) Consistency tests applied to the measurement of total, direct and diffuse shortwave radiation at the surface. J Geophys Res 105(D20):24881–24887

Dehne K, Bergholter U, Kasten F (1993) IEA comparison of longwave radiometers. International Energy Agency Rep. IEA-SHCP-9F-3, 72 pp. [Available from: Morse Associates, Inc., 236 Massachusetts Ave. NE, Suite 605, Washington DC 20002, USA]

De Luisi J, Dehne K, Vogt R (1992) First Results of the Baseline Surface Radiation Network (BSRN) broadband infrared radiometer intercomparison at FIRE II. *In* International radiation symposion (IRS '92), Tallinn, Estonia, 3–8 August 1992, pp 559–564

Eppley (1995) Instruction sheet for the Eppley Precision Infrared Radiometer (Model PIR), Available from The Eppley Laboratory, Inc., P.O. Box 419, Newport, RI 02840, USA, 8 pp

Fairall CW, Persson POG, Bradley EF, Payne RE, Anderson SP (1998) A new look at calibration and use of the Eppley Precision Infrared Radiometers. Part 1: Theory and application. J Atmos Oceanic Technol 15:1229–1242

Fritschen LJ, Fritschen CL (1991) Design and evaluation of net radiometers. *In* seventh symposium on meteorological observations and instrumentation. New Orleans, USA, pp 113–117

Gilgen H, Whitlock CH, Koch F, Müller G, Ohmura A, Steiger D, Wheeler R (1995) Technical plan for BSRN data management version 2.1, WMO/TD-No. 443

Halldin S, Lindroth A (1992) Errors in net radiometry: comparison and evaluation of six radiometer designs. J Atmos Oceanic Technol 9:762–783

Halldin S (2004) Radiation measurements in integrated terrestrial experiments. In: P. Kabat et al. (eds) Vegetation, water, humans and the climate. Springer, pp 167–171
Kohsiek W, van Lammeren ACAP (1997) Pyrgeometer formula. Appl Opt 36:5984–5986
Ohmura A, Dutton EG, Forgan B, Fröhlich C, Gilgen H, Hegner H, Heimo A, König-Langlo G, McArthur B, Müller G, Philipona R, Pinker R, Whitlock CH, Dehne K, Wild M (1998) Baseline Surface Radiation Network (BSRN/WCRP): new precision radiometry for climate research. Bull Amer Meteorol Soc 79:2115–2136
Oncley SP, Foken Th, Vogt R, Bernhofer Ch, Kohsiek W, Liu H, Pitacco A, Grantz D, Ribeiro L, Weidinger T (2002) The Energy Balance Experiment EBEX-2000. Proceedings 15th symposium on boundary layers and turbulence 15–19 July (2002), Wageningen, The Netherlands, pp 1–4
Oncley SP, Foken T, Vogt R, Kohsiek W, Debruin HAR, Bernhofer Ch, Christen A, Gorsel E, Grantz D, Lehner I, Liebethal C, Liu H, Mauder M, Pitacco A, Ribeiro L, Weidinger T (2006) The Energy Balance Experiment EBEX-2000. Part I: Overview and energy balance. Boundary-Layer Meteorol this issue
Pérez M, Alados-Arboledas L (1999) Effects of natural ventilation and solar radiation on the performance of pyrgeometers. J Atmos Oceanic Technol 16:174–180
Philipona R, Fröhlich C, Betz Ch (1995) Characterization of pyrgeometers and the accuracy of atmospheric long-wave radiation measurements. Appl Optics 34:1598–1605
Philipona R, Fröhlich C, Dehne K, DeLuisi J, Augustine J, Dutton E, Nelson D, Forgan B, Novotny P, Hickey J, Love SP, Bender S, McArthur B, Ohmura A, Seymour JH, Foot JS, Shiobara, M., Valero FPJ, Strawa AW (1998) The Baseline Surface Radiation Network pyrgeometer Round-Robin calibration experiment. J Atmos Oceanic Technol 15:687–696
Reda I, Hickey J, Long C, Myers D, Stoffel T, Wilcox S, Michalsky JJ, Dutton EG, Nelson D (2005) Using a blackbody to calculate net longwave responsivity of shortwave solar pyranometers to correct for their thermal offset error during outdoor calibration using the component sum method. J Atmos Oceanic Technol 22:1531–1540
Vogt R (2000) Aspekte der Strahlungsbilanzmessung. Berichte des Meteorologischen Institutes der Universität Freiburg 5:173–183