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Report on the radiation measurements of EBEX

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1 Introduction

EBEX-2000 was an experiment that concentrated on the closure of the energy balance. In the '90-s it was more and more realized that the energy balance at the earth's surface was often not closed. In the literature of that time various explanations were offered, varying from instrumental shortcomings to failure of understanding all the transport processes. EBEX-2000 was primarily designed to assess the instrumental accuracies over an 'ideal' terrain, a terrain with little inhomogeneities covered with a well-evaporating, closed vegetation. The site that was chosen for EBEX was a cotton field of 800mx1600m near the town of Hampton, CA, USA. From the beginning on, it was realized that the terrain was not perfect. Gradients in the soil water due to the irrigation scheme may have caused gradients in the evapotranspiration. In the wider surroundings of the cotton field different soil coverings were present, also bare soil. Gradients on larger scale may have given rise to meso-scale type circulations.
These limitations were partly met by the installation of many micrometeorological stations over the field. Before the start of the main experiment, a comparison study was done where several stations were located close together. More information can be found in Oncley et al., 2002.

This report deals with the radiation measurements. In the EBEX project the net radiation is one of the most important quantities. Therefore much attention was paid to its measurement. Net radiation can be measured in several ways: by means of the measurement of its four components (shortwave, longwave, upward and downward), and directly by means of a net radiometer. All these methods were applied in EBEX, and often with instruments of different manufacturers. At nine sites a so-called dark horse was installed on which the instruments were mounted (Fig. 1). The dark horses were oriented East-West and were 2 m high. The instruments they carried varied. Table 1 gives a survey of the radiation instruments, and Table 2 their position in the field. Some of the dark horses also carried an infrared thermometer. This measurement has a very local character and has been left out of this analysis.
The weather conditions during EBEX were in so far unique 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.

2 Discussion of the instruments.

2.1 Shortwave radiation

Three instrument types were employed:
1. Eppley Precision Spectral Pyranometer (PSP)
2. Kipp&Zonen pyranometer type CM11, CM14 and CM21
3. Kipp&Zonen net radiometer CRN1, shortwave component

The first two instruments have double domes. The CM14 is usually applied as a pair for the measurement of the albedo. The difference with the CM11 is in the shape of the radiation screen of the instrument that measures the reflected radiation. 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 Table 3). Eppley classifies their PSP as a WMO First Class Radiometer, which is one rank lower than a secondary standard. However, the specifications are much closer to that of the secondary standard than to the First Class. The CRN1 is a net radiometer, with separate measurement of the 4 components. The shortwave sensor (CM3) has a single spherical dome and meets the WMO requirements for a Second Class pyranometer.

A pyranometer is often ventilated to prevent dew formation on the dome. In EBEX some instruments were ventilated, others not. Next to the advantage of dew suppression, ventilation may also force the dome temperature closer to the temperature of the instrument housing. This will reduce errors due to convective or radiative heat transport between dome and sensor. However, ventilation may have the disadvantage of a more rapid deposition of dirt on the dome , especially in a polluted environment, and more frequent cleaning may be necessary.

One of the main concerns nowadays in the measurement of downward shortwave radiation is the off-set due to differences in dome and sensor temperature. It is well known that pyranometers give a negative reading of several Wm^{-2} during clear nights, and this is commonly ascribed to the colder dome, which radiates in the infrared against the cold sky. It is debatable whether this nighttime offset can be used for correction over day (Chess et al., 2000). On one hand, on a clear day the dome looses infrared radiation against the cold sky, like at night, but on the other there might be a slight heating due to absorption of solar radiation.

2.2 Longwave radiation

Two instrument types were employed:

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

Longwave radiometers, or pyrgeometers, have an optical filter that rejects the shortwave radiation and transmit 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. The total effect can be 10 to 20 Wm^{-2} at bright sunshine. Forced ventilation helps in reducing the effect since it reduces the temperature difference between dome and thermopile.

Thus, in order to arrive at the atmospheric radiation, three quantities have to be known: the thermopile voltage, the thermopile's upper surface temperature and the dome temperature. Eppley's PIR has a dome-shaped optical filter and has signal outputs for the thermopile, the body temperature and the dome temperature. The latter temperature is commonly sensed near the base of the dome, but on request sensors can be installed on other positions. The difference between the body temperature and the thermopile 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. Another electric circuit, which is powered by an internal battery, provides a signal that is proportional to the radiation emitted by the body, and by adding this signal to the thermopile signal a single output is obtained. Most users, however, prefer to not using this option and record the body temperature and the thermopile separately.

Kipp&Zonen's CNR1 longwave sensor (CG3) has a flat optical filter and lacks the measurement of the filter temperature. As a consequence of the design, the cosine response is not so 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.

Calibration of the pyrgeometers is a complex issue. There exists no international agreement on a longwave radiation standard and calibration procedure as with the shortwave pyranometers. Neither is there 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). They only give a response coefficient for the thermopile (or the combination of thermopile and the electric equivalent of the body emission). A correction for the dome temperature is left to the user. Besides Eppley, there are a number of other institutes that perform infrared calibration. Philippona et al. (1998) report on a comparison experiment involving five PIR's and eleven laboratories Of these institutes, six reported a responsivity that was within 2% of the median. One of these institutes was Eppley (Eplab), another the World Radiation Center (WRC). Kipp&Zonen was not included. These institutes are mentioned here specifically because of their relevance to EBEX. At the WRC is not only the response of the thermopile measured, but also the effect of the dome. The pyrgeometer formula recommended by the WRC incorporates three calibration factors: the response of the thermopile, a factor by which the black body emission of the body has to be multiplied, and a factor ("b") by which the difference between the black body emission at the dome temperature and at the body temperature has to be multiplied. Kipp&Zonen calibrate against a constant temperature source; details are not given.
Extensive literature exists on the pyrgeometer formula. As just noted, the formula of Philipona et al. (1995) has three fit parameters. The second fit parameter, that for the black body emission of the body, was independently questioned by Kohsiek and van Lammeren (1997), and by Fairall et al. (1998). They both argue that it should be identical to one. The application of the respective formulas may result in a disagreement of a few Wm^{-2}.

Philipona et al. (1995) also considered the effect of shortwave radiation that is transmitted by the longwave optical filter. The argument is that there is no perfect gap between the shortwave and longwave radiation spectrum and consequently radiation in this region could be counted twice: by the pyranometer and by the pyrgeometer. Philipona et al. introduced a factor (f) that, multiplied by the shortwave radiation, give the correction for the longwave measurement. They do not quantify f in their publication. 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. The Bayreuth group (for the link between the research groups and the instruments, see Table 3) used the observed temperature differences across the dome of the PIR as a characterization of the shortwave radiation error. They determined the f factor once during EBEX by shading the pyrgeometer. The so-obtained corrections can be 15 Wm^{-2}, which is rather high in view of other studies. It should be noted that the interpretation of shading experiments is delicate since the temperature of the dome changes as well. Moreover, since the thermal equilibrium of the instrument changes, internal thermal lags may complicate the interpretation of the experiment.

2.3 Net radiation

In EBEX, three different radiometers were employed:

1. Kipp&Zonen CNR1
2. REBS Q*7
3. Schulze

The CNR1 is a 4-component system. The sensitivities of the four sensors are matched, so they may be added electrically to give 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. The signal is generated by a thermopile with hot junctions facing upward and cold junctions facing down. Two polyethylene half domes protect the thermopile from wind, rain etc. These domes are 0.25 mm thick and require no pressurising to maintain shape. The domes are ventilated by the natural wind only. The instrument is calibrated by the manufacturer by means of 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.

The Schulze has separate thermopiles for the upward and downward radiation. Also the body temperature is measured (a Pt100 resistance element). It is therefore a 3-signal instrument. From these signals, the total upward radiation and the total downward radiation can be calculated. The instrument has two 0.1 mm thick self-supporting protection domes of a polyethylene called Lupolen. These domes have a transmission of over 95% over the entire spectrum, with the exception of isolated absoption bands at 3.5, 6.9 and 14 µm. The body of the instrument and the two domes are ventilated by a forced air stream that is heated some degrees C above ambient. According to the manufacturer's calibration sheet, the shortwave calibration is done by means of comparison with another Schulze radiometer under an artificial light source; the "reference" is in turn calibrated against a pyrradiometer (single sided total radiation) of the Meteorological Institute at Potsdam. Longwave calibration is done with a black body. The manufacturer gives 4 calibration factors, respectively for the shortwave, longwave, upward and downward component. These factors differ by4% at most. In EBEX, a calibration factor was adopted that was the average of the shortwave upward and downward factor, weighed with an albedo of 0.16. The error thus introduced is less than 5 Wm^{-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 measurement of its four components. An important reason is that the measurement of the shortwave component can be done with relative 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 heat transfer between dome and thermopile surface (c) unequal sensitivity for shorwave 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's Lupolen domes have higher transmission because they are much thinner. Also, ventilation helps to keep the dome temperature close to the thermopile temperature, thus reducing the convective heat exchange. Calibration poses problems that the other radiation instruments do not have. For instance, a method to infer the shortwave responsivity is by comparison against a pyranometer under an artificial light source in the laboratory. When doing so, it is important to keep the longwave environment constant, which is far from easy. Furthermore, one has to correct for the longwave cut-off of the pyranometer. A small part of the solar radiation that lies in the mid infrared is not directly sensed by a pyranometer like the CM21, but included as a constant fraction (about 1%) in the calibration factor. When comparing an all-wave sensitive instrument to a pyranometer under a light source in which this mid infrared portion is absent, the correction fraction should be subtracted from the reading of the pyranometer.
Another way is to calibrate outside against a pyranometer by means of shading both instruments repeatedly from direct sunlight on a very clear, cloudless day. Such procedure causes the upper surface of the thermopile to change temperature from above the body's housing to below, thus invoking a significant change in the thermal equilibrium between housing, thermopile and dome. If convective heat exchange between dome and thermopile occurs, it may compromise the comparison.
The situation regarding an internationally accepted calibration procedure is even worse than that for the longwave instruments; for instance, inter-comparisons between laboratories were not made for net radiometers.

Net radiometry has been the subject of some recent publications. Halldin and Lindroth (1992) made a study of six different designs among which the Schulze and a Q*4 of REBS, an earlier version of the Q*7. They judge the performance of the Schulze superior over that of the others. Brotzge and Duchon (2000) report on a field comparison of a domeless net radiometer, a Q*7 and a CNR1. Their reference is an Eppley PSP/PIR combination. The Q*7 shows an underestimate of about –50 Wm^{-2} at midday and several tens of Wm^{-2} overestimate at night. The CNR1 performs 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) report on a similar study of the Schenk (not used in EBEX), Schulze , REBS Q*7 and CNR1 net radiometer in a series of field experiments in Europe. The reference is a Kipp&Zonen CM11/Eppley PIR combination. They find that the performance of the instruments is not very significantly different from one another. The differences between the 7 Schulze's of this study seem to be larger than suggested by the study of Halldin and Lindroth.

2.4 Summary

In EBEX a multitude of radiation instruments was employed. In order of quality we have: shortwave, longwave and net radiation. Only for the shortwave instruments WMO specifications exist. The limiting factor in the accuracy of pyranometers may well be the response to thermal radiation. Longwave instruments suffer from filter effects and non-standardised calibration procedures. However, their accuracy may approach that of the pyranometer by careful calibration of thermopile and filter properties (including spectral transmission), and careful exposure procedures (preferably 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.

3 Comparison of instruments

3.1 Downward shortwave radiation

It is reasonable to assume that the downward shortwave radiation is the same at all sites, thus all instruments can be compared. As reference the Kipp&Zonen CM21 pyranometer #239 of the Basel University is adopted. This choice is 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) consequent cleaning routine at the Basel site.
All radiation data of the Basel group were shifted a half hour in advance to synchronise with the data of all other participants. The comparison reveals the following:

a. the Basel CM21 #009 and the NCAR PSP (both at site 9) agree within +/- 10 Wm^{-2} with the reference, disregarding a few outlyers (Fig. 3). Since the global radiation reaches a maximum value of about 900 Wm^{-2}, the agreement is within 1%.
b. the Bayreuth CM14 shows about 15 Wm^{-2} larger values in the afternoon, and there are a few outlyers of + and -40 Wm^{-2} (Fig. 3)
c. other NCAR PSP's and the CM21 showed larger deviations (Fig.4). This is likely related to cleaning procedures. Notable are the effects of cleaning on 16 August: a jump of ≈50 Wm^{-2} in the CM21 (site 7), and on 21 August, a jump of ≈80 Wm^{-2} in the PSP at site 8 (these effects are not well shown by Fig.4, but are apparent from the time series). However, a dirty dome does not explain the up to ≈30 Wm^{-2} positive deviations of the PSP at site 7. This instrument may have had problems. Measurements up to 8 August 11h were deleted from the comparison because of very unrealistic values.
d. the two CNR1's show lower radiation values (Fig. 5). The Basel CNR1 on the average about –20 Wm^{-2} in the afternoon, the one of Bayreuth about –40 Wm^{-2} in the morning with some outlyers down to –60 Wm^{-2}
e. night-time values of the Basel instruments are exactly zero. Presumably, this is an electronic cut-off. Other instruments show night-time values of –2 to –4 Wm^{-2}, with the exception of the Bayreuth CM14 which was ≈3 Wm^{-2} (positive) at night

Conclusion:
The regularly cleaned instruments at site 9 (two CM21, one PSP) agree within their specifications (1%). Other PSP's show larger deviations. This may partly be due to dirty domes. The PSP at site

7 gives values that are about 4% larger than the reference (the CM21 #239 at site 9), which can not be explained by dirt. The CM14 agrees within 2% for most of the time, with some isolated outlyers, thereby marginally matching its specifications. The CNR1's perform within their specification.

3.2 Downward longwave radiation

We have two types of instruments here: the Eppley PIR (NCAR, Bayreuth, Basel) and the Kipp&Zonen CNR1 (Bayreuth and Basel). The manufacturer calibrated the CNR1's. Regarding the PIR's, the Basel group had theirs calibrated at the WRC and apply an instrument specific dome correction. They did not apply a shortwave (f) correction. Bayreuth had their instrument calibrated by the WRC as well. They do correct for shortwave radiation by means of the temperature distribution over the dome. In their original data set, Bayreuth employs calibration constants that differ from the ones that were given at a later time. The data set was re-calculated according to these latest coefficients. NCAR had their instruments calibrated by NOAA. Their data file contains the thermopile output (in Wm^{-2}), the dome temperature and the case temperature, but not the longwave radiation. Initially, there were problems with the temperature measurement. The data could be corrected afterwards. We calculated the longwave radiation by addition of the thermopile output, the black body emission of the instrument case and using dome correction factors as provided by NCAR (also at a later stage).
Furthermore, there are differences in ventilation policy: Bayreuth and NCAR ventilated, Basel did not.
As a reference for comparison, the Basel PIR was adopted, but equally well the Bayreuth PIR could have been taken.

The comparison of the PIR's shows a diurnal behaviour where at midday the Bayreuth values are about 5 to 15 Wm^{-2} larger than the Basel values, and the NCAR values are 0 to 10 Wm^{-2} larger (Fig. 6). At night, the Bayreuth values are 5 to 10 Wm^{-2} larger than the Basel values, NCAR shows 0 to 10 Wm^{-2} larger values. The Bayreuth values discussed here are the ones **without** f correction. Inclusion of this correction would lead to a more pronounced diurnal behaviour of the difference with Basel with about 5 Wm^{-2} smaller values at midday. The diurnal behaviour points to an over-correction of the dome emission and/or of the transmitted solar radiation. In commenting on the large f correction, Bayreuth noted that this f factor was probably too large. More likely, it lies in between the smaller value found at European sites and the present one. In a comparison experiment done after EBEX it was found that the Basel instrument was biased by – 5 Wm^{-2} with respect to the Bayreuth instrument, which is in line with the present observations. The bias is ascribed to problems with the body and dome temperature.
The NCAR PIR values are about 5 Wm^{-2} 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 could explain such difference since then it would then have to be as large as 10%. The radiation difference corresponds to a temperature difference of about 1 °C.

The CNR1 instruments compare very well with each other. When compared to the Basel PIR we see a pronounced daily pattern (Fig.7). At night, the CNR1's are a few Wm^{-2} larger than the PIR, at mid day they are about 25 Wm^{-2} larger. Taking the simplicity of the instrument into account, this is surprisingly good. The diurnal pattern points to an effect of solar heating of the dome. Kipp&Zonen specify a solar heating effect of 25 Wm^{-2} at 1000Wm^{-2} normal solar radiation, thus the present findings agree with their spec's.

Conclusion

At day, the Eppley PIR's show significant differences from one another, up to 20 Wm^{-2}. This is likely due to dome heating and dome shortwave transmission effects. At night, a bias is noted which may be related to inaccuracies in the measurement of the dome and body temperature. The f correction of Bayreuth appears to be an over-correction. The Kipp&Zonen CNR1's show a distinct solar heating effect. Application of the manufacturer's filter heating correction would improve the quality of the instrument.

3.3 Upward shortwave radiation

Comparison of instruments is not so straightforward because it cannot be assumed that the surface is homogenous. In fact, at all sites instruments were installed with the objective to investigate the distribution of the albedo over the field. Multiple measurements were done at all sites except site 8. This section is divided into three parts: comparison of instruments at a common site, a discussion of the albedo and the distribution of the shortwave radiation across the field.

3.3.1 Comparison of instruments

At stations 1-6 NCAR had installed PSP and CM21 downlooking pyranometers. The ratio PSP/CM21 as a function of time shows a broad plateau between 0.90 and 0.97, which corresponds to a difference of about 17 to 5 Wm^{-2} at midday (Fig. 8). These differences exceed the specifications of the instruments. No explanation can be offered.

We continue with the upward shortwave radiation at sites 7 and 9. At site 7 we have the CNR1 of Bayreuth, the PSP of NCAR and the CM14 also of Bayreuth. As a reference we take the CM14. At midday the PSP has on the average about 10 Wm^{-2} lower values than the CM14, whereas the CNR1 is about 15-20 Wm^{-2} lower than the PSP in the morning and afternoon (Fig. 9). Given the fact that the absolute value of the shortwave radiation at midday is about 170 Wm^{-2}, these are differences of several per cent for the PSP-CM14 difference and about 10% for the CNR1-CM14 difference, thereby exceeding the specifications of these instruments. It could be that the differences are due to differences in the vegetation cover right below the instruments. The "dark horse" on which the instruments were mounted was positioned above a row of cotton plants. These plants have dimensions that are not very small as compared to the area seen by the instruments. The maximum deviations of the CNR1 in the morning and afternoon suggests a contribution of internally reflected radiation at lower sun angles.

At site 9 the same features are observed regarding the CNR1 (Fig. 10). The reference here is the CM11 of Basel . However, the data are shifted to more positive values as compared to site 7. The pattern of the PSP is different from that at site 7. At midday, the PSP is about 10 Wm^{-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 boost the CM11 values: this would bring more order in the observed differences at all sites, at the price of a worse CNR1. However, one could also argue that if the values of the CM14 would be lowered by a certain fraction, there would be more agreement between sites 7 and 9, and an acceptable CNR1. Neither case can be proven from these data alone.

Since the pattern of the differences of the CNR1 at site 7 is the same as at site 9, it is not likely that a non-homogenous vegetation cover is interfering here.

3.3.2 Albedo

There was one albedometer employed in EBEX, that of Bayreuth at site 7 (Kipp&Zonen CM14). Also sites 8 and 9 were equipped with upward and downward pyranometers. However, downward looking "regular" pyranometers can be influenced by internal reflections at low sun angles. The albedo shows a daily course with a minimum of about 0.17 (Fig. 11). The increase near sunrise and sunset is probably a real effect because the reflection of most materials increase with increasing angle of incidence. Depending on the combination of instruments, one sees at site 7 a value between 0.16 and 0.18 (Fig.12) and at site 9 (Fig.13) an albedo between 0.15 and 0.16 at 12h15 local time (half hour average. Site 9 is more dry than the other sites, and the vegetation less dense. Soil has a lower reflectivity than vegetation, which explains the lower albedo of site 9. Remarkedly, the order by which the measurements differ at site 9 is different from that at site 7: at site 9, the PSP gives the highest albedo, followed by the CNR1 and the CM11/CM21, whereas at site 7 the order is CM14, CNR1, PSP. This is an indication of the precision of the measurement: about 10% of the value.

The irrigation water reached site 7 at 2 August and 16 August, and site 8 one day thereafter. It is seen from Figs. 12 and 13 that the albedo decreases after irrigation, especially on 2/3 August. Irrigation leads to a decrease of the reflected shortwave radiation since the albedo of water (0.04 at normal incidence) is lower than that of cotton (0.17). The effect on 16/17 August is less obvious presumably because the vegetation was denser at that time.

3.3.3 Distribution of the shortwave upward radiation

Considering the PSP data at site 1 to 9 as a function of time of the day appreciable differences are visible (Fig.14). The spread of the data at midday is about 40 Wm^{-2}, or 25% of the absolute value This spread may be due to the delay by which the irrigation front reaches the respective sites. As a fraction of the net radiation, the spread is about 5%.

Conclusion

The upward shortwave radiation is not uniformly distributed over the site at all times. Differences up to 40 Wm^{-2} were observed. The differences may partly be related to the irrigation scheme. There are also instrumental or observational shortcomings that exceed the specifications of the instruments.

The albedo of the cotton field is about 0.17 at midday and has maximum values near sunrise and sunset.

3.4 Upward longwave radiation

Also here we compare instruments at a common site, and analyse the distribution of the radiation across the field. But first a few notes on the measurements.

Bayreuth did not correct for the dome. Since the dome temperature of the down looking instruments is close to the body temperature, such a correction would be small anyhow.

The data of site 3 after 14 August 07:15 LT were left out since the instrument was moved to the bare soil location at that day. Multiple measurements at a single site with PIR instruments were not done. At site 7 and 9 a PIR and a CNR1 were installed.

3.4.1 Comparison of instruments

The two CNR1's (site 7 and 9) compare well with their companion PIR's. The Basel CNR1 is generally between +5 and 0 Wm^{-2} higher than the PIR, the Bayreuth CNR1 is between –6 and -2 Wm^{-2} as compared to the PIR (Fig.15). Had Bayreuth applied a dome correction to their PIR, this would probably have brought the two instruments closer together

3.4.2 Distribution of the longwave radiation

When comparing all PIR's to the one of Basel, one notes that the differences show a daily course that roughly lies between 0 and –50 Wm^{-2} (Fig. 16). Thus, Basel is the hottest spot at daytime. The differences may be related to the irrigation strategy, like in the case of the upward shortwave radiation. Some features are indeed noticeable around the days of irrigation. However, the shortwave radiation showed also some variations from day to day, and it is not possible to distinguish between a change in surface temperature due to the intrusion of water and due to changes of the incoming shortwave radiation. Instrumental effects are not thought to exceed 10 Wm^{-2}.

Conclusion

The upward longwave radiation is not uniformly distributed over the field at all times. Differences of up to 50 Wm^{-2} are observed.

Some of the PIR's had to be skipped from the analysis so far because of suspect behaviour. The CNR1 instruments compare favourably with their PIR companions.

3.5 Net radiation

Net radiation differs from site to site as do the upward shortwave and longwave radiation components. We will first look at the performance of the instruments themselves. At sites 7 and 9 more than one instrument was used and a direct comparison is possible. At the other sites this is not possible. However, one can construct for every site a net radiation from the local measurement of the upward shortwave and longwave radiation and taking the downward shortwave and longwave radiation from a reference site.

3.5.1 Comparison of instruments - direct

At site 7 we have the REBS Q*7, the Kipp&Zonen CNR1, the Schulze and the 4 individual components. At site 9 we have the same suite of instruments less the Schulze.
At site 7 the sum of the 4 component was taken as reference against which the other instruments were compared. In order of agreement it is seen that the CNR1 comes first, the Schulze second and the Q*7 third (Fig. 17). The deviations for both the CNR1 and the Schulze are within + and – 20 Wm^{-2}, whereas the Q*7 shows differences below –40 Wm^{-2}. The Schulze has a positive peak in the morning and a negative one in the afternoon. This could indicate a thermal lag. At night the CNR1 and the Schulze differ little from the reference, but the Q*7 is about 10 Wm^{-2} higher.
A similar comparison was done at site 9. There the CNR1 is 0-20 Wm^{-2} higher values than the sum of the components and the Q*7 differences are between –20 and 20 Wm^{-2} but at some days about –40 Wm^{-2} at midday. These are the same sort of differences as observed at site 7.
In the above sections it was noted that the shortwave sensor of the CNR1 underestimates at day, while the longwave sensor overestimates. Thus, the errors partly compensate.

3.5.2 Comparison of instruments - indirect

The reference was constructed per site as follows. At all sites the incoming shortwave radiation was taken equal to the Kipp&Zonen #239 at site 9, and the incoming longwave radiation equal to the Eppley PIR at site 9. At sites1 to 6 and 8 the outgoing shortwave radiation was that of the PSP, and the outgoing longwave radiation the NCAR PIR. At site 7 the PIR of Bayreuth was chosen, and at site 9 the Basel PIR. The outgoing shortwave radiation at sites 7 and 9 was again the PSP. The instruments to be compared are the Q*7 's. It is seen that the pattern of the deviations is the same at all sites: a weak maximum in the early morning and late afternoon, and a pronounced minimum at noon (Fig. 18). The differences are typically between 20 and –20 Wm^{-2} for the southern sites and between 20 and –40 Wm^{-2} for the northern ones. At night the Q*7's typically give 15 Wm^{-2} higher radiation values than the references. These findings are in line with the above comparison at sites 7 and 9 and also with the report of Broztge and Duchon (2000).

3.5.3 Distribution of the net radiation

Since the incoming total radiation can be regarded as the same for all sites, the distribution of the net radiation is best investigated from the distribution of the outgoing total radiation as constructed in section 3.5.2. As a common reference the measurements of the Kipp&Zonen CM11 and the PIR at site 9 are taken. The comparison shows that the differences lie between 30 and -40 Wm^{-2}, with considerable scatter (Fig. 19). This picture would thus reflect the differences that are encountered across the field. As noted above for the shortwave component, the differences are not constant in time but vary with the irrigation.

Conclusion

The CNR1 measurements compare within 20 Wm^{-2} with the sum of the components. The Schulze performs as well, but not better than the CNR1 The Q*7 measurements show larger deviations; they over-estimate the net radiation at night by 10-20 Wm^{-2} and underestimate it by day by 20-40 Wm^{-2}
Significant differences of several tens of Wm^{-2} were observed across the field, which are at least partly due to terrain differences.

4 Recommendation on the net radiation measurement of EBEX

The basic choice is whether to take net radiometers (CNR1, Schulze, Q*7) or the sum of the components. From the comparisons discussed in section 3.5 it can be concluded that the sum of the components is to be preferred over the Q*7. The same can not be said of the CNR1 and the Schulze on basis of the EBEX data alone. However, there are other arguments to prefer the sum of the components. First, it is known of the CNR1 longwave sensor to have a dome heating effect. Second, the CNR1 shortwave sensors are of a lower class than the Eppley PSP or the Kipp&Zonen CM11 or CM21. In fact the CNR1 shortwave error and longwave error partly compensate. This may be a pleasant coincidence, 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 some reserve is at place since the calibration procedure followed by the manufacturer is not known in detail. There is a difference between the older calibration and the most recent one of 6% that is not explained by the present manufacturer.

Taking these factors into consideration, it is felt that the sum of the components is the most accurate way to determine the net radiation in EBEX. The incoming component of the net radiation can be assumed to be the same for all sites. Thus, one pyranometer and one pygeometer suffice. It is proposed to use the Kipp&Zonen CM21 #239 of site 9 and the Eppley PIR of the same site to this purpose. This choice is based on the following considerations. Of all pyranometers used in EBEX, the CM21 has the best specifications. Two other CM21's were employed, a second one at site 9 and one at site 7. The differences between the two CM21's at site 9 were minor, less than 10 Wm^{-2}. The CM21 at site 7 shows deviations with respect to the other two that can be as large as -40 Wm^{-2}, which is possibly due to accumulation of dirt on the dome, so it is not preferred. Regarding the PIR's, we have two instruments at site 7 (NCAR and Bayreuth), one at site 8 (NCAR) and one at site 9 (Basel). The NCAR instruments were less regularly cleaned than the others. This leads to some preference to the Bayreuth instrument at site 7 and the Basel one at site 9. Both instruments were calibrated at the WRC. The Bayreuth PIR was ventilated and the Basel one not. Bayreuth applied a shortwave correction to the downward longwave radiation that seems to be too large, but can be ignored; Basel did not apply such a correction. There is, to the author's opinion, no preference for one instrument over the other.

The outgoing component of the net radiation differs from place to place because of differences in the terrain. In the following a recommendation is given as to how to infer the outgoing shortwave and longwave radiation at each site.

Site 1. Shortwave: average of PSP and CM21.
Longwave: PIR
Site 2. As site 1
Site 3. As site 1 up to 14 August 07h30 LT. Thereafter, no measurement because the PIR was moved to the bare soil site
Site 4. As site 1
Site 5. As site 1
Site 6. As site 1
Site 7. Shortwave: average op PSP and CM14 (Bayreuth)
Longwave: PIR (Bayreuth)
Site 8. Shortwave: PSP
Longwave: PIR
Site 9. Shortwave: average of PSP and CM11 (Basel)
Longwave: PIR (Basel)
All instruments are of NCAR, unless specified otherwise.

The accuracy of the net radiation is estimated as follows.
Shortwave down: max(5 Wm^{-2}, 1% of value)
Longwave down: 10 Wm^{-2} (daytime), 5 Wm^{-2} (nighttime)
Shortwave up: max(5 Wm^{-2}, 2% of value)
Longwave up: 10 Wm^{-2} (daytime), 5 Wm^{-2} (nighttime)

Adding up, and giving some account for non correlated errors, the error in the net radiation is estimated at 20 Wm^{-2} at day and 10 Wm^{-2} at night. This does not include uncertainties due to terrain inhomogeneity.

References

Brotzge, J.A. and C.E. Duchon (2000), "A field comparison among a domeless net radiometer, two four-component net radiometers, and a domed net radiometer", J. Atmos. and Oceanic Technol. **15**, 1569-1581.

Chess, R.D., Qian, T. and M. Sun (2000), "Consistency tests applied to the measurement of total, direct and diffuse shortwave radiation at the surface. J. Geoph. Res., 105, No. D20, 24881-248887.

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

Fairall, C.W., Person, E.F. Bradley, R.E. Payne and S.P. Anderson (1998), "A new look at calibration and use of the Eppley Precision Infrared Radiometers. Part 1: Theory and application", J. Atmos. and Oceanic Technol. **15**, 1229-1242.

Fritschen, L.J. and C.L. Fritschen (1991), "Design and evaluation of net radiometers", Seventh Symp. Meteorological Observations and Instrumentation, New Orleans, USA. 113-117.

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

Kohsiek, W. and A.C.A.P. van Lammeren (1997), "Pyrgeometer formula", Appl. Optics **36**, 5984-5986.

Oncley, S.P., Foken, Th., Voght, R., Bernhofer, Ch., Kohsiek, W., Liu, H., Pitacco, A., Grantz, D., Ribeiro, L., Weidinger, T. (2002). *The energy balance experiment EBEX-2000*. Proc. 15th Symposium on Boundary Layers and Turbulence, 15-19 July 2002, Wageningen, The Netherlands, pp. 1-4.

Philipona, R., C. Fröhlich and Ch. Betz (1995),"Characterization of pyrgeometers and the accuracy of atmospheric long-wave radiation measurements", Appl. Optics **34**, 1598-1605.

Philipona, R., C. Fröhlich, K. Dehne, J. DeLuisi, J. Augustine, E. Dutton, D. Nelson, B. Forgan, P. Novotny, J. Hickey, S.P. Love, S. Bender, B. McArthur, A. Ohmura, J.H. Seymour, J.S. Foot, M. Shiobara, F.P.J. Valero and A.W. Strawa (1998), "The Baseline Surface Radiation Network pyrgeometer Round-Robin calibration experiment", J. Atmos. and Oceanic Technol. **15**, 687-696.

Vogt, R. (2000), "Aspekte der Strahlungsbilanzmessung", Berichte des Meteorologischen Institutes der Universität Freiburg, Nr. 5, 173-183.

Websites
EBEX: www.atd.ucar.edu/rtf/projects/ebex2000
Eppley: www.eppleylab.com
Kipp&Zonen: www.kippzonen.com

Table 1. List of instruments

$K_E^{\uparrow}$ Eppley PSP pyranometer, upward radiation
$K_E^{\downarrow}$ Eppley PSP pyranometer, downward radiation
$K_{11}^{\uparrow}$ Kipp&Zonen CM11 pyranometer, upward radiation
$K_{14}^{\uparrow}$ Kipp&Zonen CM14 pyranometer, upward radiation
$K_{21}^{\uparrow}$ Kipp&Zonen CM21 pyranometer, upward radiation
$K_{14}^{\downarrow}$ Kipp&Zonen CM14 pyranometer, downward radiation
$K_{21}^{\downarrow}$ Kipp&Zonen CM21 pyranometer, downward radiation
$K_C^{\uparrow}$ Kipp&Zonen CNR1 net radiometer, shortwave upward component
$K_C^{\downarrow}$ Kipp&Zonen CNR1 net radiometer, shortwave downward component
$K_E^{\uparrow}$ $K_E^{\downarrow}$ $K_{21}^{\downarrow}$ Q_R^{*}Eppley PIR pyrgeometer, upward component
$L_E^{\uparrow}$ Eppley PIR pyrgeometer, upward radiation
$L_E^{\downarrow}$ Eppley PIR pyrgeometer, downward radiation
$L_C^{\uparrow}$ Kipp&Zonen CNR1 net radiometer, longwave upward component
$L_C^{\downarrow}$ Kipp&Zonen CNR1 net radiometer, longwave downward component
Q_C^{*} Kipp&Zonen CNR1 net radiometer
Q_R^{*} REBS $Q^{*}7$ net radiometer
Q_S^{*} Schulze net radiometer

Table 2. Instrument location

site	Furrow/ Row	NCAR	Basel	Bayreuth	KNMI/ WU
1	R	$K_{21}^{\uparrow}$ $K_E^{\uparrow}$ $L_E^{\uparrow}$ Q_R^{*}			
2	R	$K_{21}^{\uparrow}$ $K_E^{\uparrow}$ $L_E^{\uparrow}$ Q_R^{*}			
3	R	$K_{21}^{\uparrow}$ $K_E^{\uparrow}$ $L_E^{\uparrow}$ Q_R^{*}			
4	F	$K_{21}^{\uparrow}$ $K_E^{\uparrow}$ $L_E^{\uparrow}$ Q_R^{*}			
5	F	$K_{21}^{\uparrow}$ $K_E^{\uparrow}$ $L_E^{\uparrow}$ Q_R^{*}			
6	R	$K_{21}^{\uparrow}$ $K_E^{\uparrow}$ $L_E^{\uparrow}$ Q_R^{*}			
7	R	$K_E^{\uparrow}$ $K_E^{\downarrow}$ $K_{21}^{\downarrow}$ Q_R^{*}		$K_{14}^{\uparrow}$ $K_{14}^{\downarrow}$ $L_E^{\uparrow}$ $L_E^{\downarrow}$ Q_C^{*}	Q_S^{*}
8	R	$K_E^{\uparrow}$ $K_E^{\downarrow}$ Q_R^{*} $L_E^{\uparrow}$ $L_E^{\downarrow}$			
9	R	$K_E^{\uparrow}$ $K_E^{\downarrow}$ Q_R^{*}	$K_{11}^{\uparrow}$ $K_{21}^{\downarrow}$ $K_{21}^{\downarrow}$ $L_E^{\uparrow}$ $L_E^{\downarrow}$ Q_C^{*}		

Table 3. Instrument characteristics

instrument	Owner	accuracy	calibration	ventilation	cleaning
Eppley PSP	NCAR	1%?	?	x(site 8)	occasional
Kipp CM11	Basel	1%	K&Z		daily
Kipp CM14	Bayreuth	1%	K&Z 9.6.1997	x	?
Kipp CM21	NCAR	1%?	?	x	occasional
Kipp CM21 #239	Basel	1%	WRC 3.12.1996		daily
Kipp CM21 #009	Basel	1%	K&Z 8.4.1997		daily
Eppley PIR	NCAR	5 Wm^{-2}	NOAA	x	occasional
Eppley PIR	Basel	5 Wm^{-2}	WRC		daily

Eppley PIR	Bayreuth	5 Wm^{-2}	WRC 24.09.1997	x	?
Kipp CNR1	Basel	20 Wm^{-2}	K&Z 1999		daily
Kipp CNR1	Bayreuth	20 Wm^{-2}	K&Z 20.11.1997		?
REBS Q^*7	NCAR	20 Wm^{-2}?	?		occasional
Schulze	KNMI	10 Wm^{-2}	Käseberg 19.12.2000	x	daily

Notes:

1. The stated accuracies are merely indications. The are partly from the manufacturer's specs, partly from the author's experience. Regarding the many factors that affect the accuracy of an instrument, just one figure is often an over-simplification.
2. NCAR cleaned their instruments at sites 1-8 only a few times. Site 9 was cleaned daily. $L_E^{\uparrow}$ was moved to the bare soil location on 14 August.

Table 4. WMO Classification of pyranometers

Characteristic	Secondary standard	First class	Second class
Resolution (smallest detectable change in Wm-2)	±1	±5	±10
Stability (percentage of full scale, change/year	±1	±2	±5
Cosine response (percentage deviation from ideal at 10° solar elevation on a clear day)	<±3	<±7	<±15
Azimuth response (percentage deviation from the mean at 10° solar elevation on a clear day)	<±3	<±5	<±10
Temperature response (percentage maximum error due to change of ambient temperature within the operating range)	±1	±2	±5
Non-linearity (percentage of full scale)	±0.5	±2	±5
Spectral sensitivity (percentage deviation from mean absorptance 0.3 to 3 μm	±2	±5	±10
Response time (99% response)	< 25 s	< 1 min	< 4 min

Figure captions

Fig. 1 "dark horse" with radiation instruments.

Fig. 2 Daily course of the 4 radiation components on 14 August 2000 at site 9 (Basel data). Time is local time.

Fig. 3 Daily course of downward shortwave radiation differences. The CM21 #009 (site 9), the PSP (site 9) and the CM14 (site 7) with respect to the CM21 #239 (site 9).

Fig. 4 Daily course of downward shortwave radiation differences. The PSP at sites 7, 8 and 9 relative to the CM21 #239.

Fig. 5 Daily course of downward shortwave radiation differences. The CNR1 at sites 7 and 9 relative to the CM21 #239.

Fig. 6 Daily course of downward longwave radiation differences. The PIR at sites 7 and 8 relative to site 9 PIR. The PIR at site 7 is given with the shortwave (f) correction included, and without this correction.

Fig. 7 Daily course of the downward longwave radiation differences. The CNR1 at sites 7 and 9 relative to the PIR at site 9.

Fig. 8 Daily course of the upward shortwave radiation. Ratio of the PSP and the CM21 at sites 1 to 6.

Fig. 9 Daily course of upward shortwave radiation differences at site 7. The PSP and the CNR1 relative to the CM14.

Fig. 10 Daily course of upward shortwave radiation differences at site 9. The PSP and the CNR1 relative to the CM11.

Fig. 11 Daily course of the albedo at site 7. Instruments: CNR1 (up and down), CM14 (up and down) and PSP (up and down).

Fig. 12 The albedo at site 7 at 12:15 local time from day to day. Instruments as in Fig. 11.

Fig. 13 The albedo at site 9 at 12:15 local time from day to day. Instruments: CNR1 (up and down), CM11 (up)and CM21 (down) and PSP (up and down).

Fig. 14 Distribution of the upward shortwave radiation. All PSP's relative to the CM11 at site 9.

Fig. 15 Daily course of the upward longwave radiation differences CNR1 – PIR at site 7 and 9.

Fig. 16 Distribution of the upward longwave radiation. All PIR instruments compared to the one at site 9.

Fig. 17 Daily course of net radiation differences at site 7. The CNR1, Q*7 and the Schulze relative to the sum of the four components (CM14 and PIR).

Fig. 18 Daily course of the differences between the Q*7 and the sum of the four components. All sites.

Fig. 19 Distribution of the total upward radiation. The longwave component is from the PIR instruments, the shortwave component from the PSP's. As a reference the CM11/PIR combination at site 9 is taken.

Fig. 1

Fig. 2

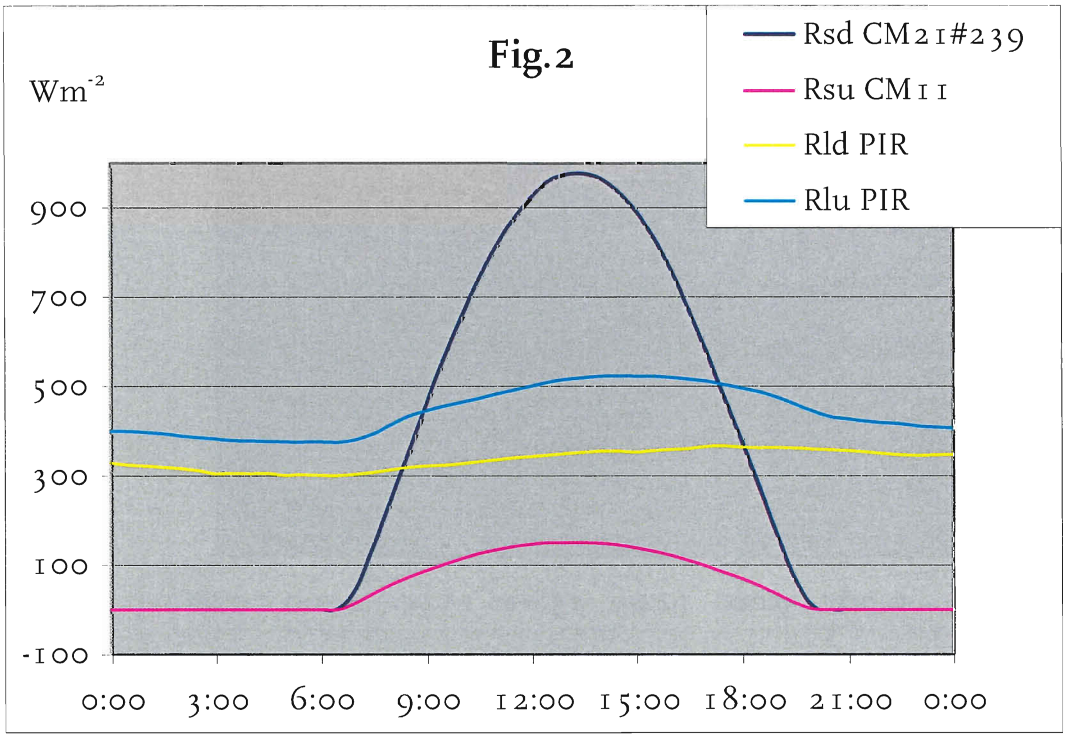

Wm-2
Rsd CM21#239
Rsu CM11
Rld PIR
Rlu PIR
900
700
500
300
100
-100
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00

Fig.3

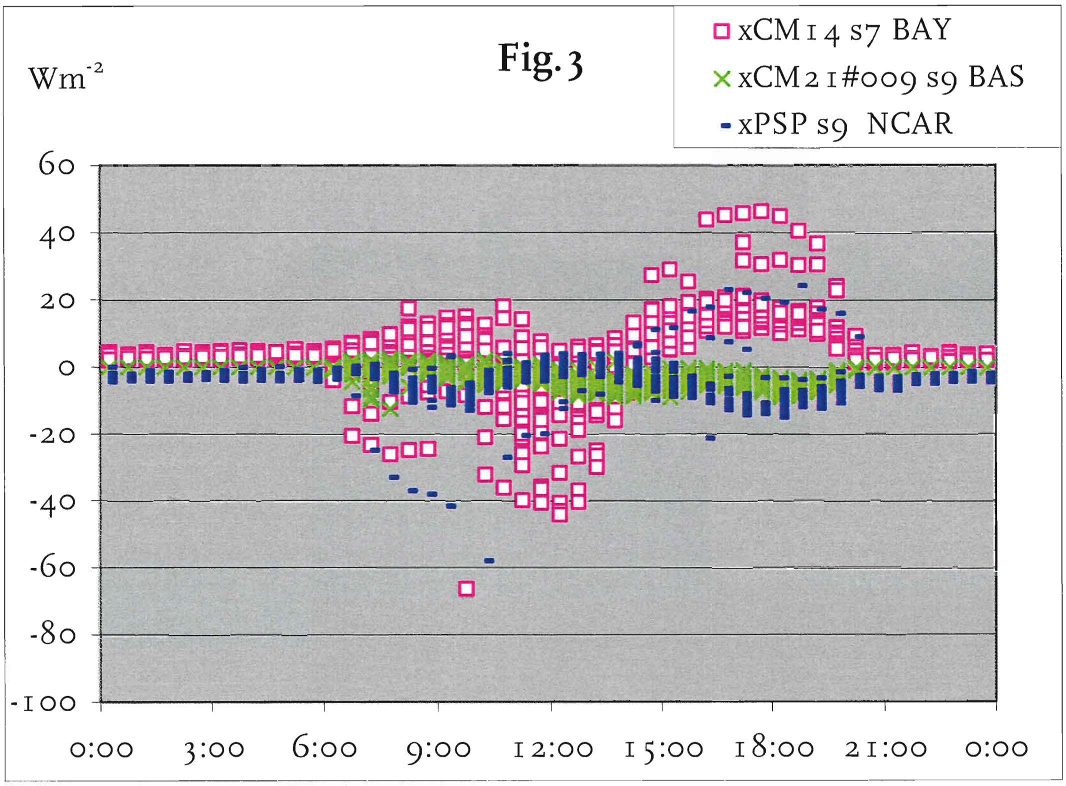
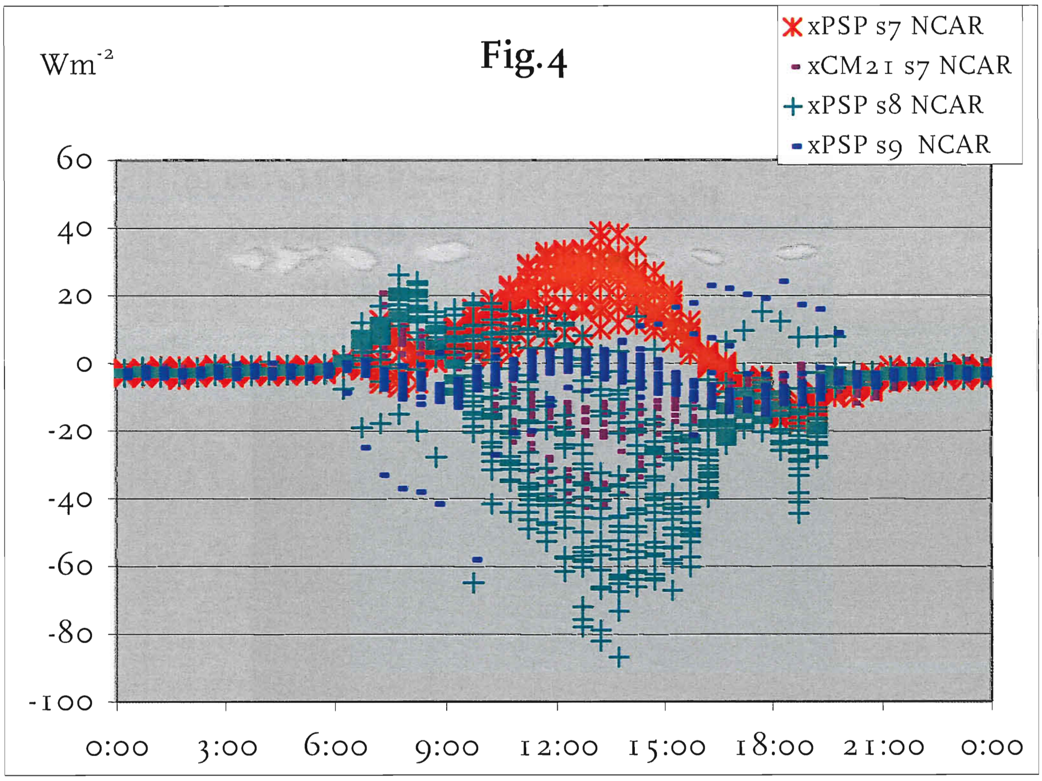

Wm^{-2}
□ xCM14 s7 BAY
× xCM21#009 s9 BAS
- xPSP s9 NCAR
60
40
20
0
-20
-40
-60
-80
-100
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00

Fig.4


Wm^{-2}
✶ xPSP s7 NCAR
- xCM21 s7 NCAR
+ xPSP s8 NCAR
- xPSP s9 NCAR
60
40
20
0
-20
-40
-60
-80
-100
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00

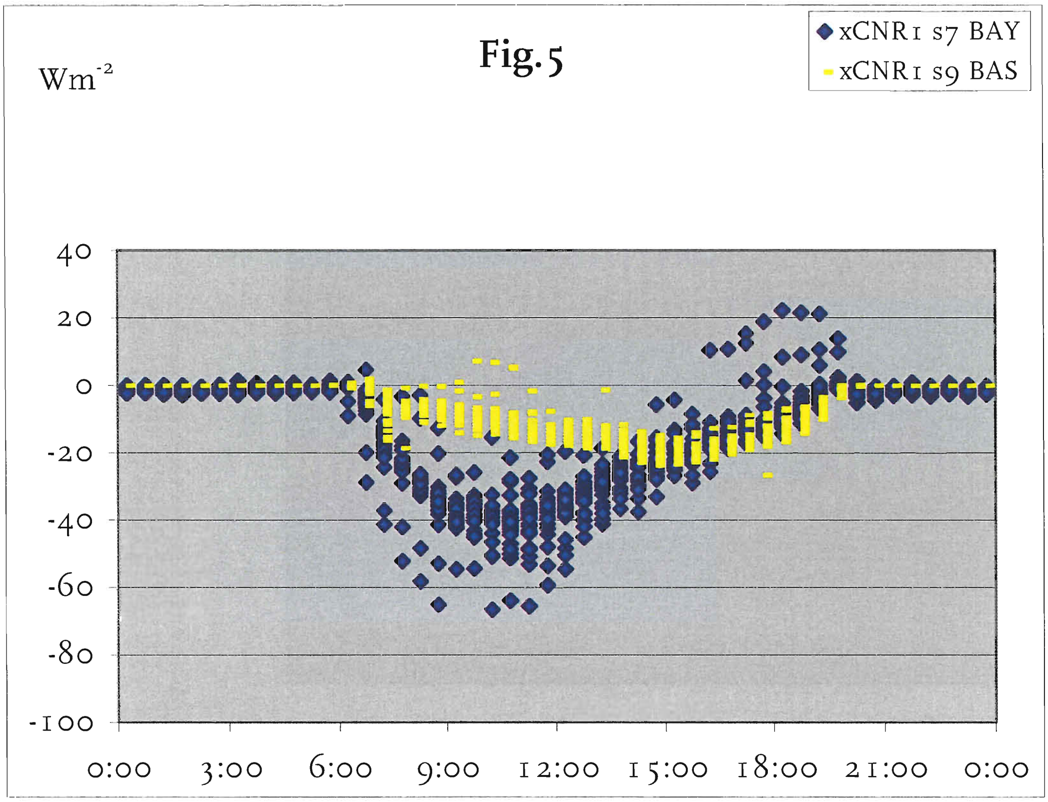


Fig.5
Wm^{-2}
◆ xCNR1 s7 BAY
- xCNR1 s9 BAS
40
20
0
-20
-40
-60
-80
-100
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00

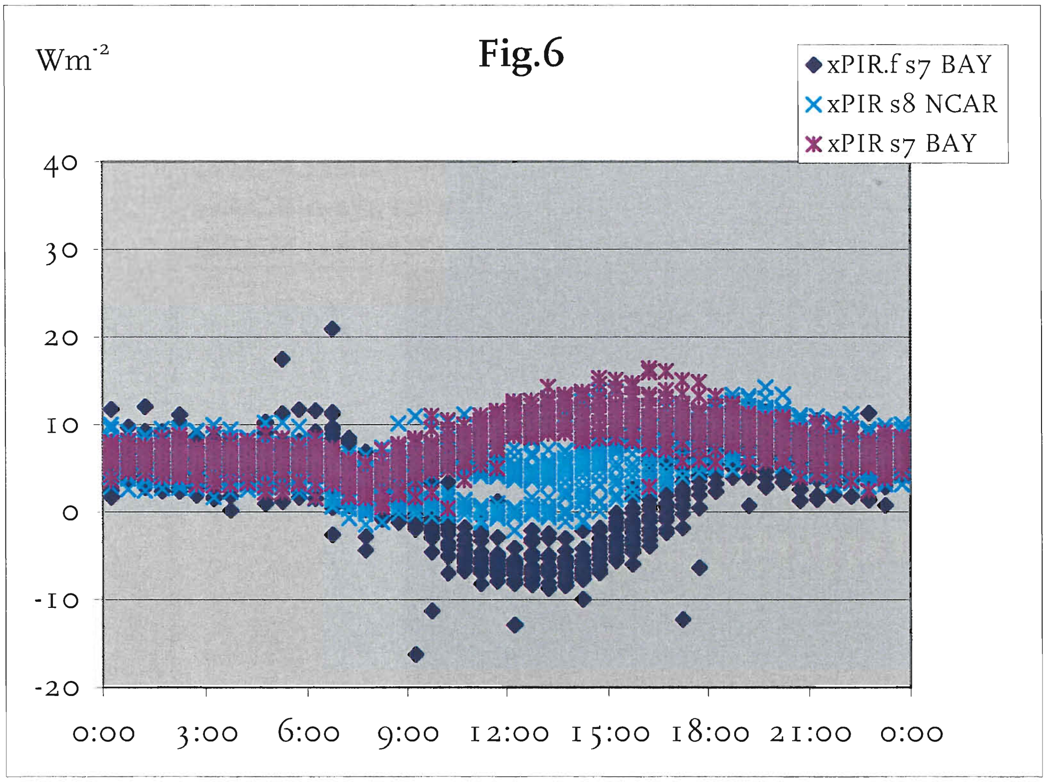


Fig.6
Wm^{-2}
◆ xPIR.f s7 BAY
× xPIR s8 NCAR
✱ xPIR s7 BAY
40
30
20
10
0
-10
-20
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00

Fig.7

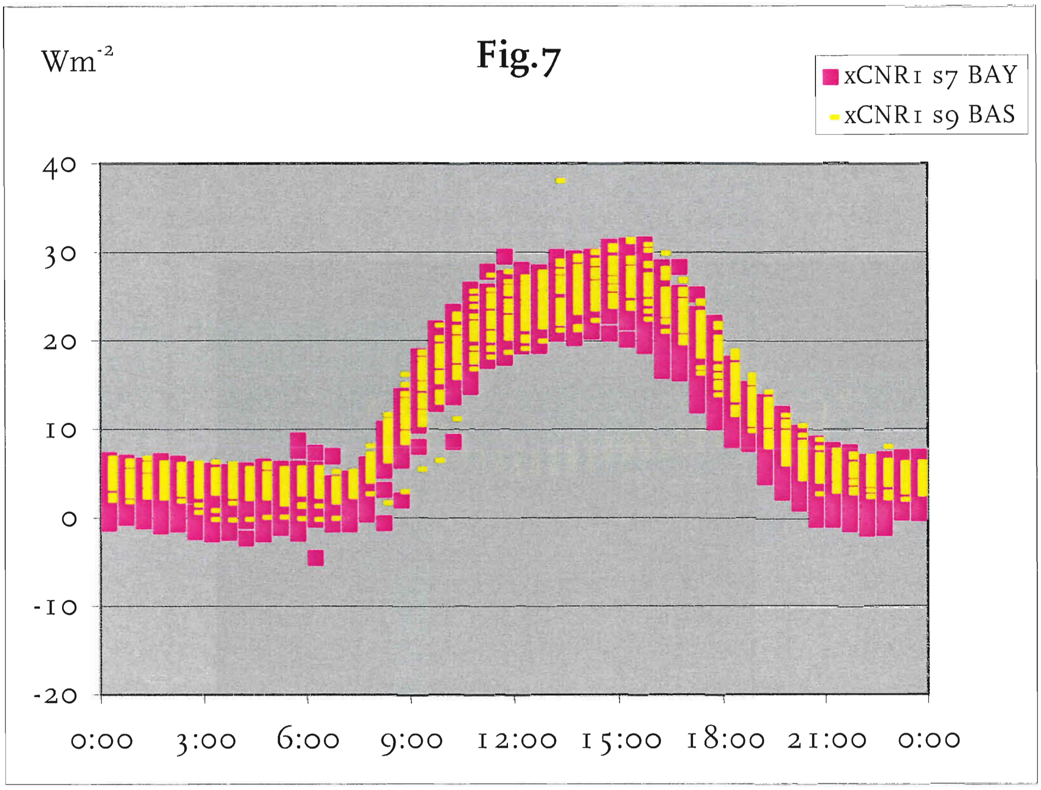

Wm^{-2}
xCNR1 s7 BAY
xCNR1 s9 BAS
40
30
20
10
0
-10
-20
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00

Fig.8

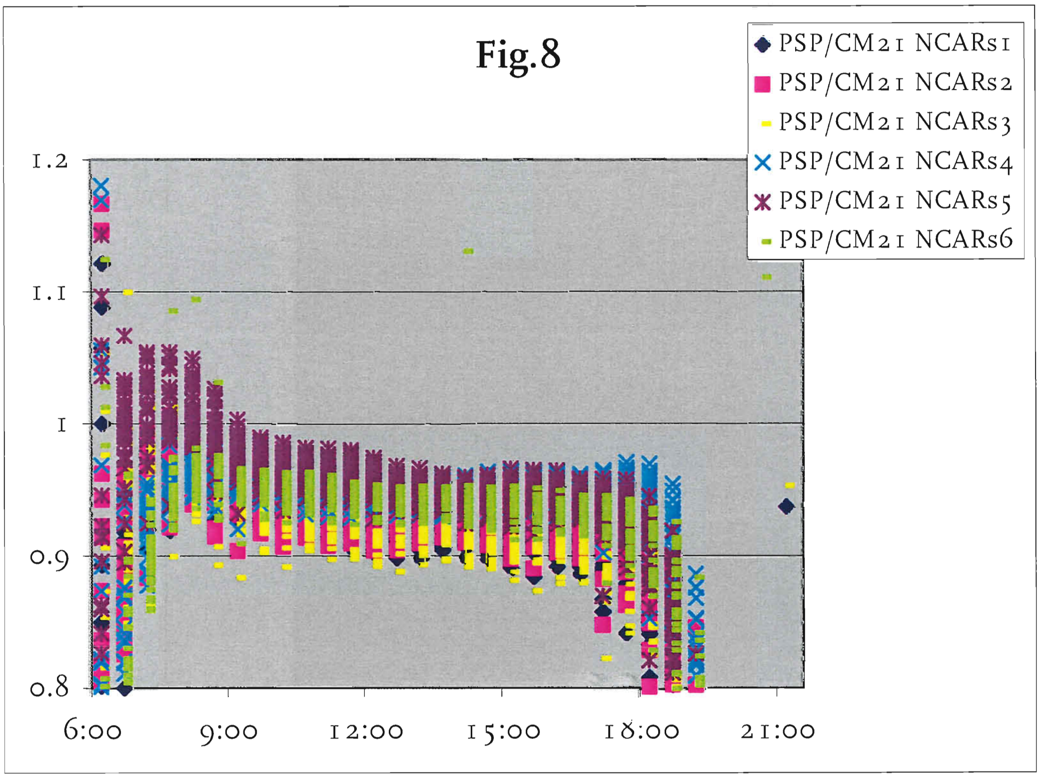

PSP/CM21 NCARs1
PSP/CM21 NCARs2
PSP/CM21 NCARs3
PSP/CM21 NCARs4
PSP/CM21 NCARs5
PSP/CM21 NCARs6
1.2
1.1
1
0.9
0.8
6:00
9:00
12:00
15:00
18:00
21:00

Fig.9

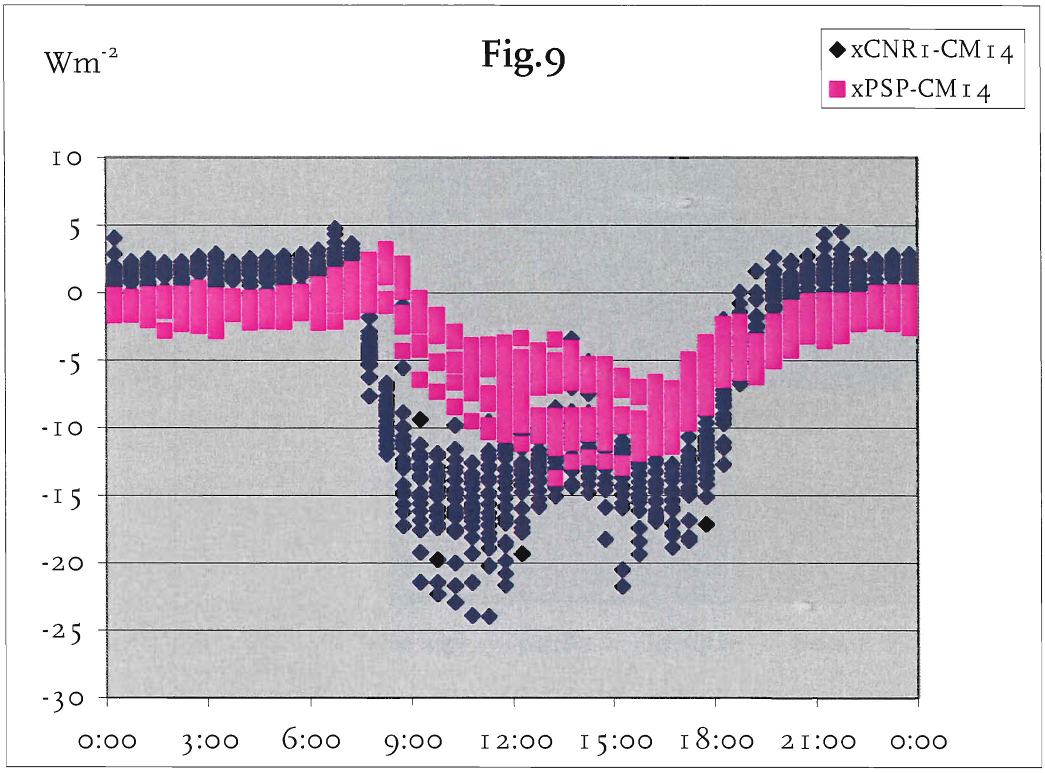
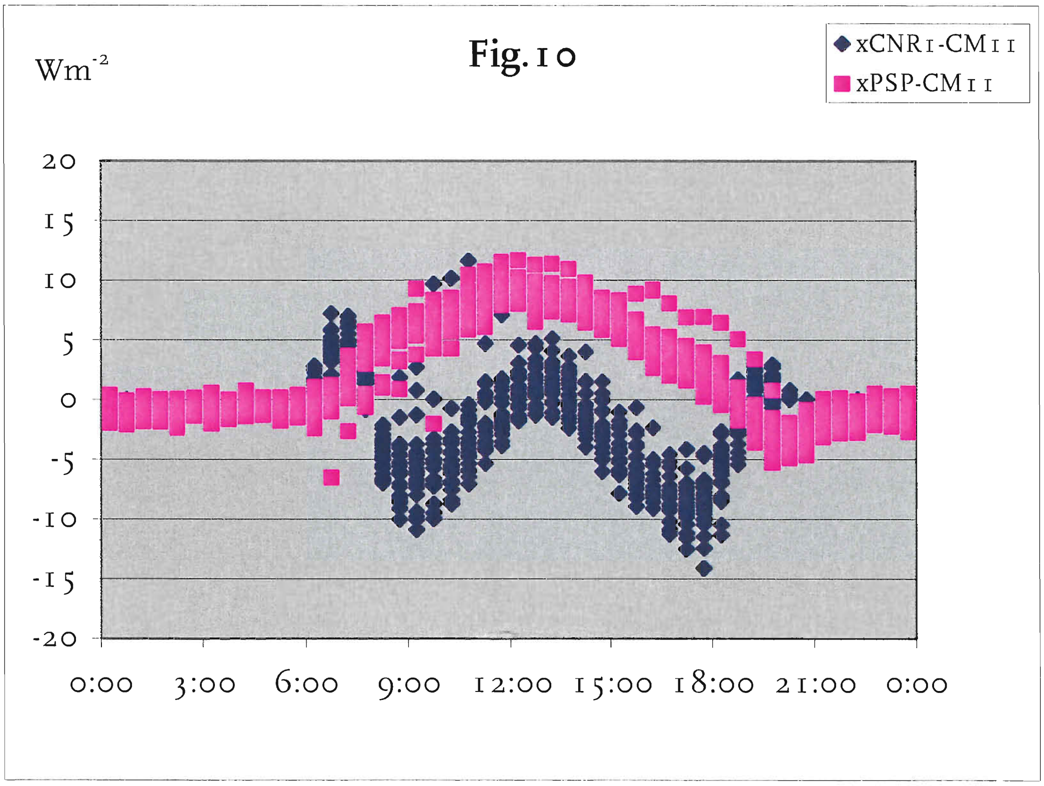

Wm-2
◆ xCNR1-CM14
■ xPSP-CM14
10
5
0
-5
-10
-15
-20
-25
-30
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00

Fig.10


Wm-2
◆ xCNR1-CM11
■ xPSP-CM11
20
15
10
5
0
-5
-10
-15
-20
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00

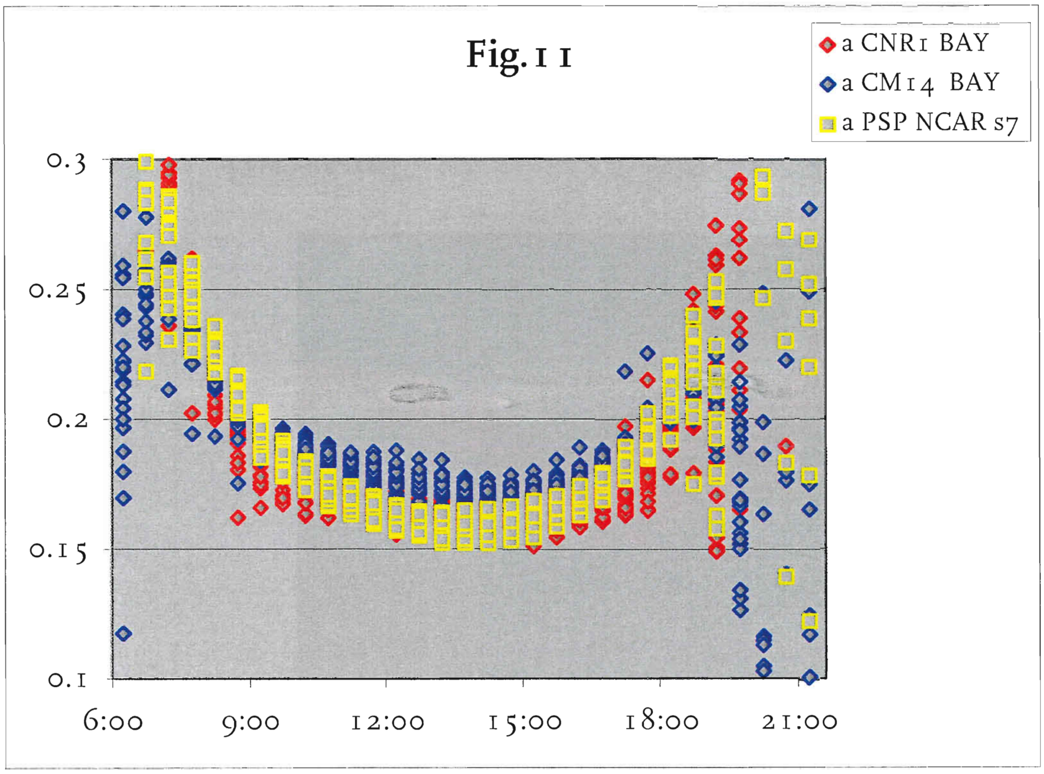


Fig. 11

◆ a CNR1 BAY
◆ a CM14 BAY
▨ a PSP NCAR s7
0.3
0.25
0.2
0.15
0.1
6:00
9:00
12:00
15:00
18:00
21:00

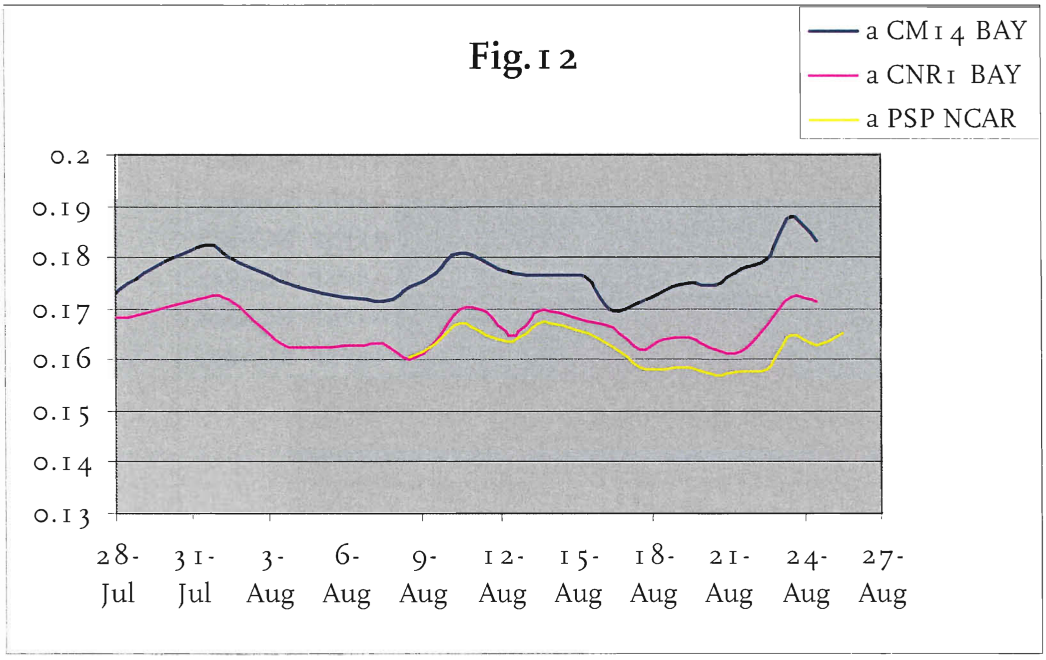


Fig. 12
a CM14 BAY
a CNR1 BAY
a PSP NCAR
0.2
0.19
0.18
0.17
0.16
0.15
0.14
0.13
28-Jul
31-Jul
3-Aug
6-Aug
9-Aug
12-Aug
15-Aug
18-Aug
21-Aug
24-Aug
27-Aug

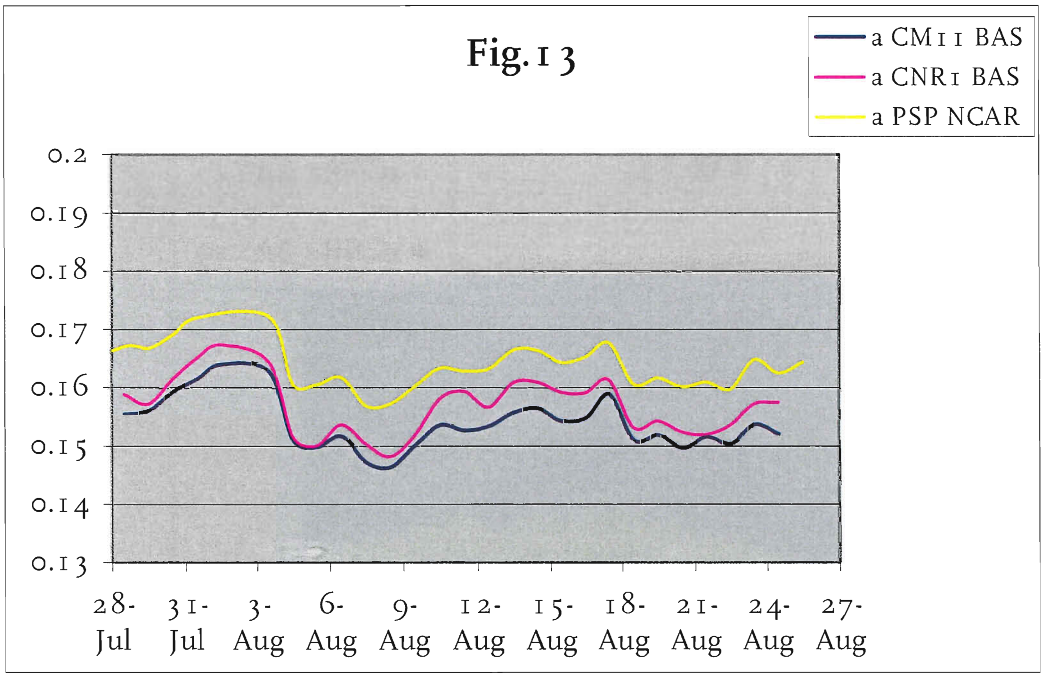


Fig. 13
a CM11 BAS
a CNR1 BAS
a PSP NCAR
0.2
0.19
0.18
0.17
0.16
0.15
0.14
0.13
28-Jul
31-Jul
3-Aug
6-Aug
9-Aug
12-Aug
15-Aug
18-Aug
21-Aug
24-Aug
27-Aug

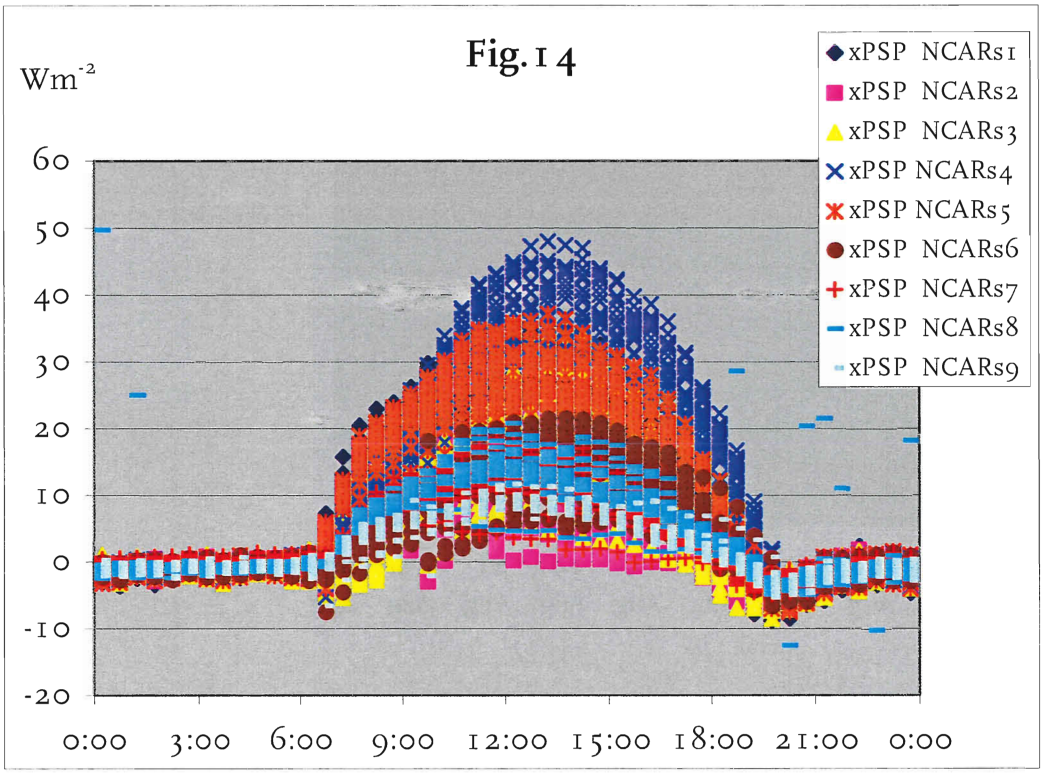


Fig. 14

Wm^{-2}
60
50
40
30
20
10
0
-10
-20
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00
◆ xPSP NCARs1
■ xPSP NCARs2
▲ xPSP NCARs3
× xPSP NCARs4
✳ xPSP NCARs5
● xPSP NCARs6
+ xPSP NCARs7
− xPSP NCARs8
- xPSP NCARs9

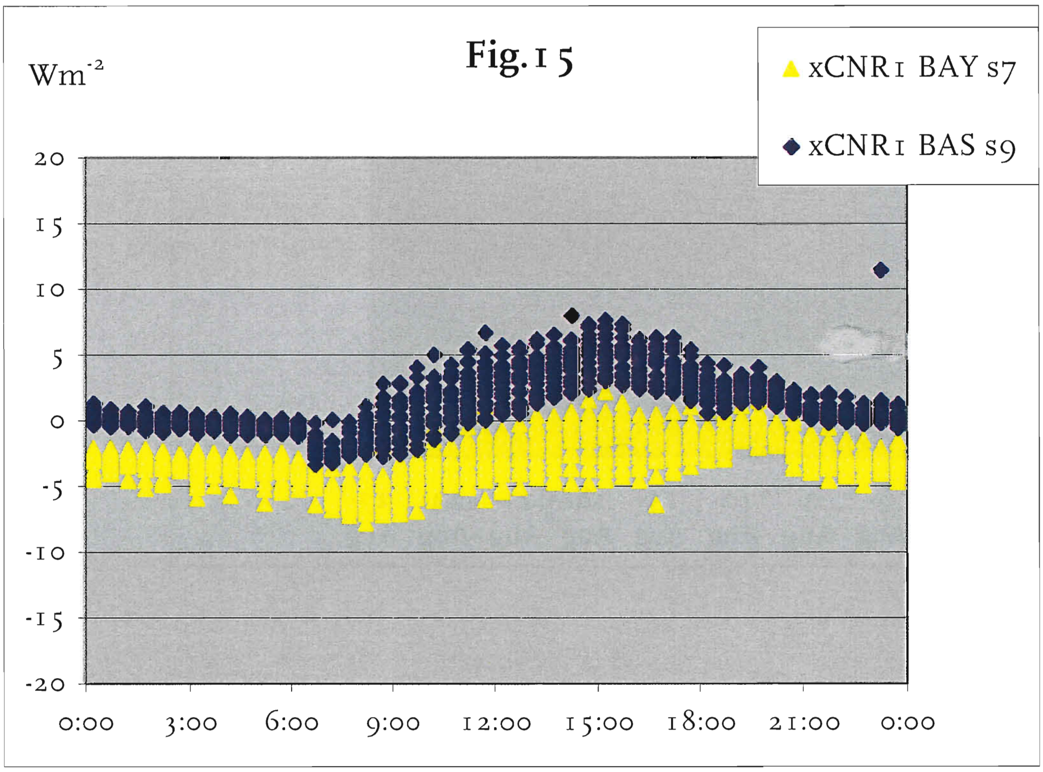


Fig. 15

Wm^{-2}
20
15
10
5
0
-5
-10
-15
-20
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00
▲ xCNR1 BAY s7
◆ xCNR1 BAS s9

Fig. 16

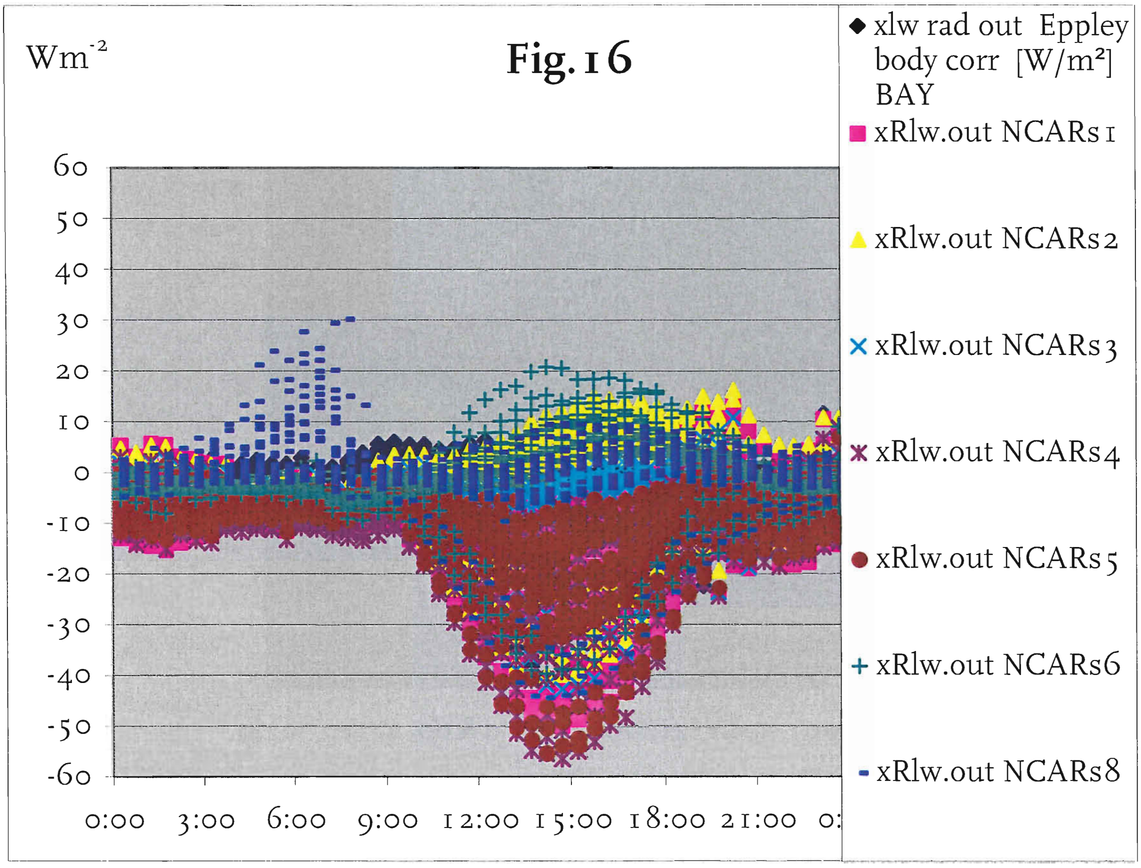
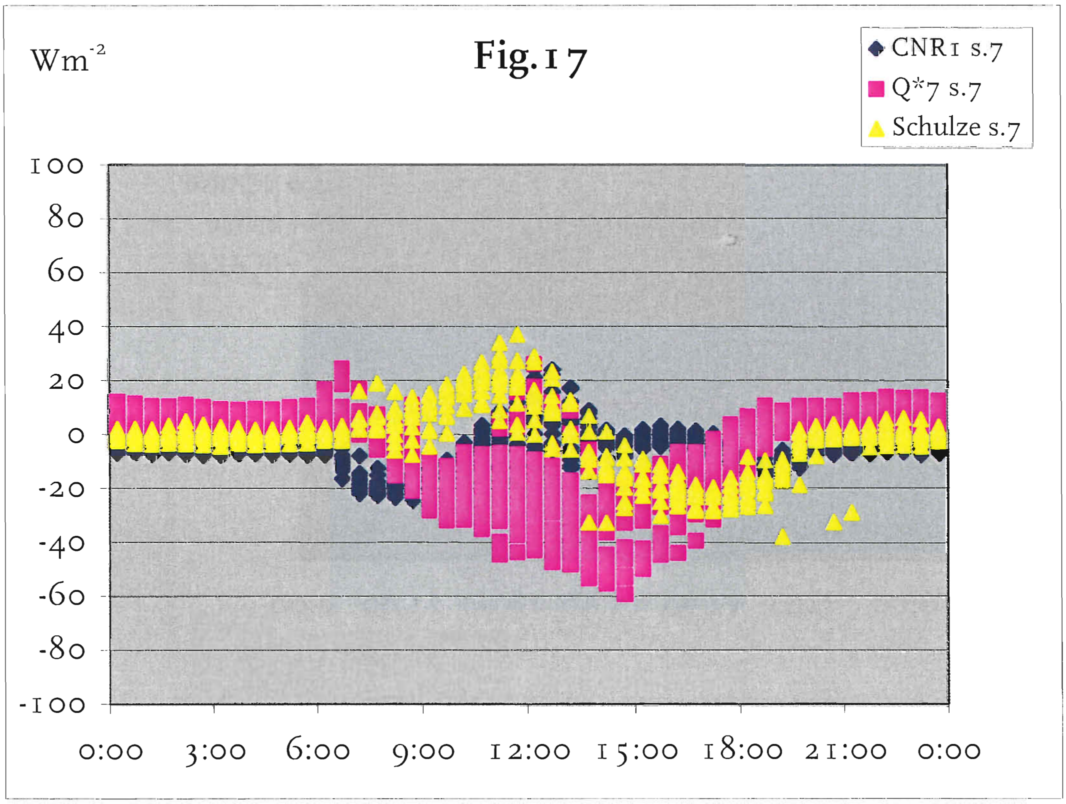

Wm-2
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:
◆ xlw rad out Eppley body corr [W/m²] BAY
■ xRlw.out NCARs1
▲ xRlw.out NCARs2
× xRlw.out NCARs3
✱ xRlw.out NCARs4
● xRlw.out NCARs5
+ xRlw.out NCARs6
- xRlw.out NCARs8

Fig. 17


Wm-2
100
80
60
40
20
0
-20
-40
-60
-80
-100
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00
◆ CNR1 s.7
■ Q*7 s.7
▲ Schulze s.7

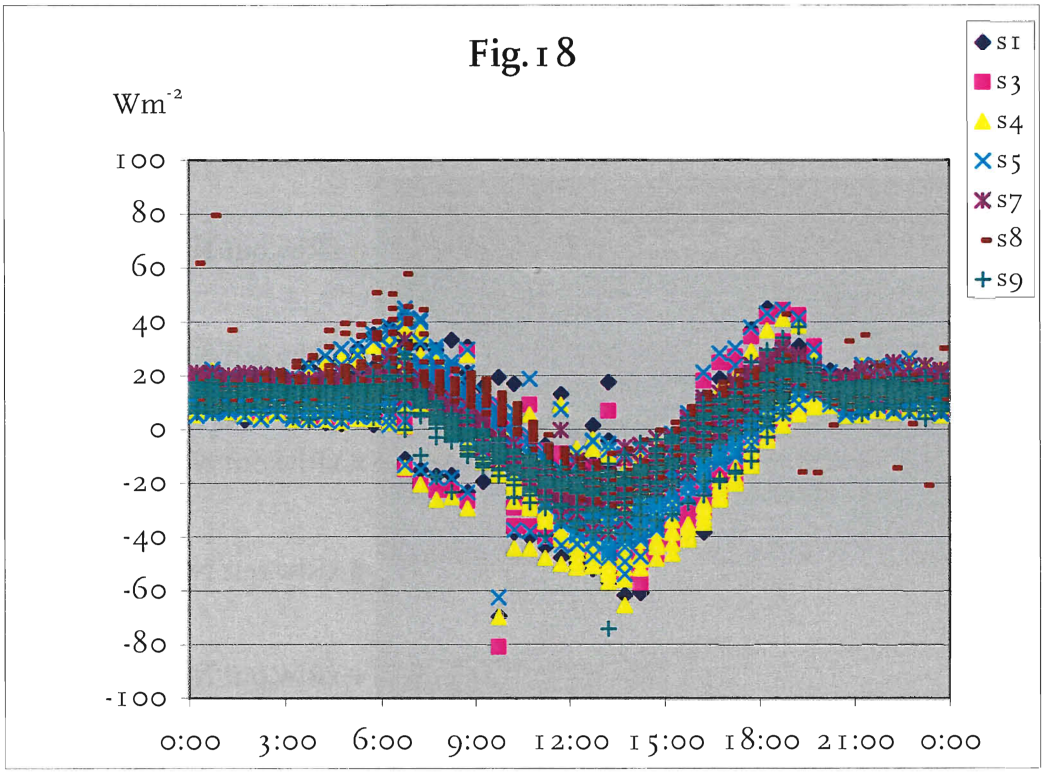


Fig. 18

Wm^{-2}
100
80
60
40
20
0
-20
-40
-60
-80
-100
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00
s1
s3
s4
s5
s7
s8
s9

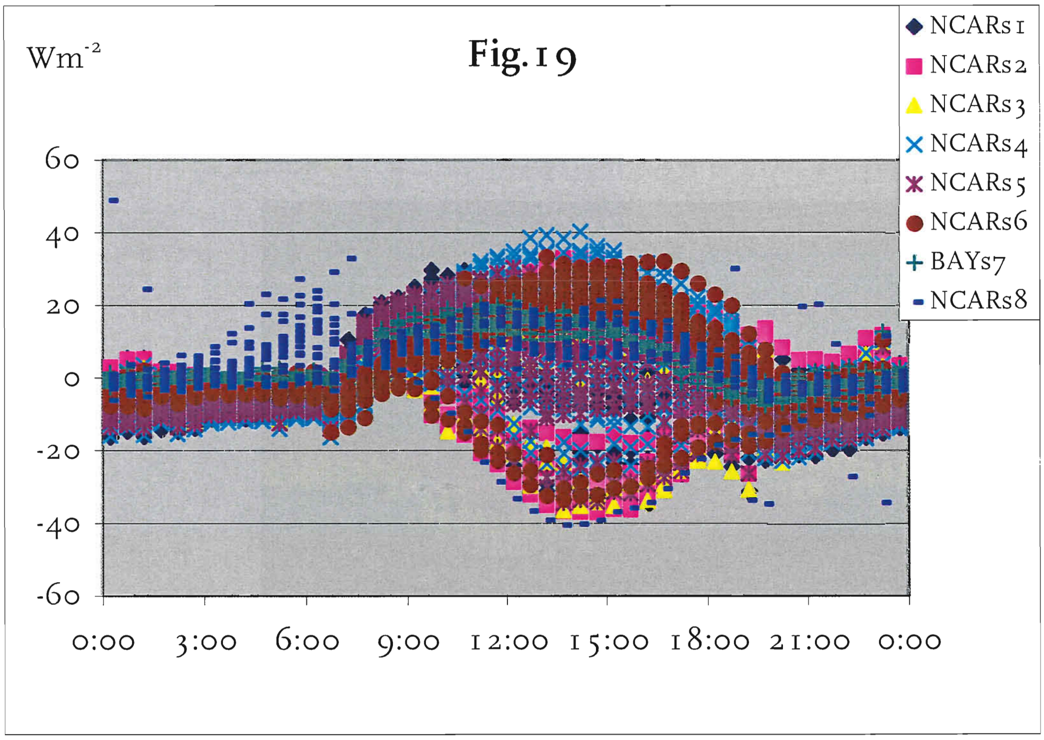


Fig. 19

Wm^{-2}
60
40
20
0
-20
-40
-60
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00
NCARs1
NCARs2
NCARs3
NCARs4
NCARs5
NCARs6
BAYs7
NCARs8