ELSEVIER Agricultural and Forest Meteorology 90 (1998) 257–263

AGRICULTURAL AND FOREST METEOROLOGY

Inconsistencies in net radiation estimates from use of several models of instruments in a desert environment

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Received 28 December 1996; received in revised form 26 January 1998; accepted 5 February 1998

Abstract

Studies of surface energy and water balance generally require an accurate estimate of net radiation and its spatial distribution. A project quantifying both short term and seasonal water use of shrub and grass vegetation in the Jornada Experimental Range in New Mexico prompted a study to compare net radiation observations using two types of net radiometers currently being used in research. A set of 12 REBS net radiometers were compared with each other and one Swissteco, over wet and dry surfaces in an arid landscape under clear skies. The set of REBS exhibited significant differences in output over both surfaces. However, they could be cross calibrated to yield values within 10 W m^{-2}, on average. There was also a significant bias between the REBS and Swissteco over a dry surface, but not over a wet one. The two makes of instrument could be made to agree under the dry conditions by using regression or autoregression techniques. However, the resulting equations would induce bias for the wet surface condition. Thus, it is not possible to cross calibrate these two makes of radiometer over the range of environmental conditions observed. This result indicates that determination of spatial distribution of net radiation over a variable surface should be made with identical instruments which have been cross calibrated. The need still exists for development of a radiometer and calibration procedures which will produce accurate and consistent measurements over a range of surface conditions. © 1998 Elsevier Science B.V.

1. Introduction

Net radiation (R_n) is the source of energy for biophysical processes at the surface and greatly impacts climatic processes at all scales. It is the most fundamental variable for surface energy balance studies. For micrometeorological measurements, accurate R_n observations are required for the Bowen Ratio approach and are useful for evaluating energy balance closure when using eddy covariance techniques for estimating latent and sensible heat fluxes (e.g., Stannard et al., 1994).

Direct measurements of R_n generally use a thermopile device enclosed by hemispherical windshields or domes to protect it from environmental conditions, such as precipitation and variable convective cooling. A variety of instruments exist from different manufacturers, though the basic design remains largely the same. Two widely used net radiometers are

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0168-1923/98/$19.00
PII S0168-1923(98)00062-8

manufactured by the Radiation and Energy Balance Systems[1] (REBS, Seattle, WA) and Swissteco (Oberriet, Switzerland). The main difference between the net radiometers is that the REBS have thicker polyethylene domes which are self-supporting and durable. In contrast, the Swissteco domes are thin and require pressurization for maintaining dome support. The REBS domes are advantageous for long-term monitoring, but the thicker dome may substantially affect sensitivities to longwave versus shortwave radiation, as indicated by past studies evaluating the performance of various net radiometers (e.g., Wright and Oliver, 1990; Field et al., 1992; Halldin and Lindroth, 1992; Duchon and Wilk, 1994).

Significant discrepancies in estimates of R_n between different net radiometers has been reported by Field et al. (1992), Halldin and Lindroth (1992) and Duchon and Wilk (1994). Field et al. (1992) found 10–15% variations in daytime R_n and greater differences at night with instruments from four different manufacturers. Halldin and Lindroth (1992) compared instruments from six different manufacturers, noting differences with a four component net radiation system ranging from 6 to 20%. They also found on site calibration of the instruments varied by as much as 30% from the manufacturers' calibration. Stannard et al. (1994) compared R_n observations using a four-way net radiation system, a thin domed net radiometer requiring pressurization similar to the Swissteco and a REBS Q*6. Their results showed that differences can nearly reach $100\ \mathrm{W\ m^{-2}}$ when $R_n \sim 700\ \mathrm{W\ m^{-2}}$. Results reported by Smith and Hodges (1997) and Smith et al. (1997) suggest that under high radiation conditions, estimates from nine different net radiometer systems from seven different manufacturers can vary up to 25%.

It seems that although various net radiometers all use the same general design, they often yield significantly different values for a given surface. This unfortunate situation presents two related problems. First, it is not clear which instrument produces the most accurate number, or for that matter, what is the 'true' value of R_n. Second, there will be a lack of consistency in a set of measurements which includes several different models of instruments. We shall consider the second issue here.

Since regional scale studies of the surface energy balance often require a spatial array of measurements, it is important that any differences resulting from inconsistency of the instruments be separated from true spatial differences. Since previous studies suggest that the differences between the various instruments are dependent upon the surface conditions, this may not be a trivial issue.

Our goal here is to quantify the inconsistencies resulting from the use of the two popular instruments, REBS and Swissteco, in an arid landscape. Two different surface conditions, wet and dry soil are considered in order to simulate spatial differences in surface energy balance for such an ecosystem. Three questions are addressed:

1. What are the differences between the instruments for both dry and wet surfaces?
2. Can the instruments be cross calibrated so that they all yield the same values for any condition?
3. What are the implications of the above for energy balance studies at the regional scale?

We do not attempt to address the issue of which instrument most closely matches the 'true' value of R_n. This would require an independent set of measurements which are universally accepted as a standard for accuracy. For example, Halldin and Lindroth (1992) note that the problem of varying instrument sensitivity to shortwave and longwave radiation can only be addressed with certainty when the scientific community can agree upon a longwave calibration procedure and a measurement standard.

2. Materials and methods

In this study we used several models of REBS net radiometers including the Q*6, Q*7 and Q*7.1, as well as a Swissteco over a bare soil surface in the Jornada Experimental Range in New Mexico (32° 40′ N Latitude, 106° 45′ West Longitude). Data were collected during JORNEX (Jornada Experiment), a multi disciplinary study evaluating the utility of remote sensing for quantifying variability of vegeta-

[1] Company and trade names are given for the benefit of the reader and imply no endorsement of the products by the USDA-ARS or Utah State University.

tion cover and related surface fluxes over a desert ecosystem (Ritchie et al., 1996).

2.1. Experimental design

On April 30, 1996 (Day of Year, DOY 121) a bare soil site was prepared for the net radiometer intercomparison. The bare soil was raked to create a relatively smooth and uniform surface. The dimensions of the bare soil plot were about 100 m east–west by 75 m north–south. Net radiometers were positioned facing south at 30 cm above the soil surface. At this height, it was calculated that an area of approximately 3 m in diameter contributed 95% of the signal seen by the net radiometers. Table 1 lists the radiometers used in the study. There were six Q*7.1 models, one with a ventilator unit (Q*7.1vent), four Q*7 models; two using original coefficients (Q*7orig) and two using coefficients from a new calibration procedure by the manufacturer (Q*7new), two Q*6 models and one Swissteco net radiometer.

The design of the Q*7.1 and Q*7 are similar except that a different black paint was used for the Q*7.1 transducer having a more consistent emissivity over the entire electromagnetic spectrum. Furthermore, the Q*7.1 is calibrated using a new 'partial shading technique' resulting in ≈16% increase in positive (daytime) R_n estimates and ≈9% decrease in the magnitude of negative (night-time) R_n estimates relative to the original calibration procedure used for the Q*7 model (C. Fritschen, personal communication).

The 13 net radiometers were separated by approximately 30 cm in an east–west direction. It was assumed that any effects due to reflection and shadows by the instruments were negligible and would effect each radiometer equally. A large inner tube was connected to the Swissteco to pressurize the thin domes. Manufacturers' calibration coefficients were used in converting instrument voltage output to W m^{-2}. Studies by Field et al. (1992) and Halldin and Lindroth (1992) indicate manufacturers' calibration coefficients from REBS and Swissteco instruments agree to within a few percent of on site calibrations.

Measurements were recorded every 10 s and the values averaged on a half-hourly basis. Skies were clear for all the measurement days. Wind speed at the same height as the net radiometers was measured with an RM Young Model 10002 photochopper anemometer (RM Young, Ann Arbor, MI) with a 0.25 m s^{-1} velocity threshold. Wind speed data were used to compute a wind correction for the REBS net radiometers.

Table 1
Description and symbol definitions for the net radiometers used in the intercomparison

Manuf.[a]	Model	Quant.	Description	Symbol
REBS	Q*6	2	Thick polyethylene domes with white and black striping on thermopile designed to balance longwave and shortwave calibration coefficients.	Q*6
REBS	Q*7	2	Thick polyethylene domes with all black painted thermopile. Using original coefficients calibrated so that output matched R_n from a 4 component system. Different calibration coefficients for R_n>0 (daytime) and R_n<0 (night-time).	Q*7orig
REBS	Q*7	2	Thick polyethylene domes with all black painted thermopile. Using new coefficients derived from new calibration procedure used with the Q*7.1 model. Different calibration coefficients for R_n>0 (daytime) and R_n<0 (night-time).	Q*7new
REBS	Q*7.1	5	Thick polyethylene domes with an improved all black painted thermopile providing more consistent emissivity across the entire spectrum. Different calibration coefficients for R_n>0 (daytime) and R_n<0 (night-time). Most recent REBS model.	Q*7.1
REBS	Q*7.1	1	Has an attached ventilator unit blowing air over domes to reduce dew formation.	Q*7.1vent
Swissteco	S-1	1	Thin polyethylene domes requiring pressurization with all black thermopile	Swissteco

[a] REBS: Radiation and Energy Balance Systems, Seattle, WA.
Swissteco: Swissteco Instruments, Stegweg, Eichenwies, Obberriet SG, Switzerland.

After several days of measurements under very dry soil moisture conditions, water was applied to the bare soil with a radius of least 4 m north–south and east–west of each sensor. The first application was on DOY 124 at approximately 15.30 Mountain Standard Time (MST) and again the following morning on DOY 125 at approximately 07.00 MST. The dry and wet surface provided a unique opportunity to study the behavior of the net radiometers under the extremes in surface conditions that would typically exist in this desert ecosystem.

2.2. Wind corrections

The effect of wind on net radiometer output design has been evaluated by Kano et al. (1973), who reported a decrease on the order of 10% in the output signal from the zero wind case. However, once the wind speed reached ≈1 m s^{-1} a negligible variation was observed. REBS supplies wind correction equations, while Swissteco provides no information pertaining to wind effects on their instrument. Preliminary results from Smith and Hodges (1997) indicate less than a +2% change from the 1 m s^{-1} case in the Swissteco output (wind speeds from 2 and 8 m s^{-1}) while the output from the Q*6 and Q*7.1 were typically within ±3%. They also found that wind speed effects on sensor output varied with net radiometer design and the magnitude of incoming radiation. Further details are provided in Smith et al. (1997).

Wind speed correction factors supplied by REBS as well as those used by Campbell Scientific (Swiatek, personal communication) were applied to the REBS instruments. The various correction equations produced results within a few percent of one another. Smith and Hodges (1997) found that wind speed effects were not always positive for the REBS Q*6 and Q*7.1 and did not find monotonically increasing behavior for the wind correction. During the intercomparison study, the winds typically ranged from 1 to 5 m s^{-1} during the daytime causing an increase in the calculated net radiation of 4–6%, while at night the winds were typically less than 1 m s^{-1} resulting in corrections of generally 1% or less. More studies are needed to examine wind speed effects on the net radiometer output based on instrument design to more fully understand the implications of these corrections on net radiation estimates.

3. Results

3.1. Consistency between instruments

Differences among similar models of REBS net radiometers were relatively small, typically less than 5% between individual net radiometers. Differences among the various REBS models (see Table 1) tended to be larger ranging from 5 to 15%. For example, the Q*7orig significantly underestimated R_n compared to all other REBS sensors (Fig. 1), especially when no wind correction was applied. For R_n between 300 and 500 W m^{-2}, which mainly represents dry soil conditions, differences among REBS models (except for the Q*7orig) were generally within 50 W m^{-2}. For low radiation conditions, R_n<300 W m^{-2} and for R_n>500 W m^{-2}, which mainly represents high radiation under wet soil conditions, differences among REBS models (except for the Q*7orig) were within 25 W m^{-2}.

All the REBS models could be recalibrated to read similarly by choosing one as the reference or the

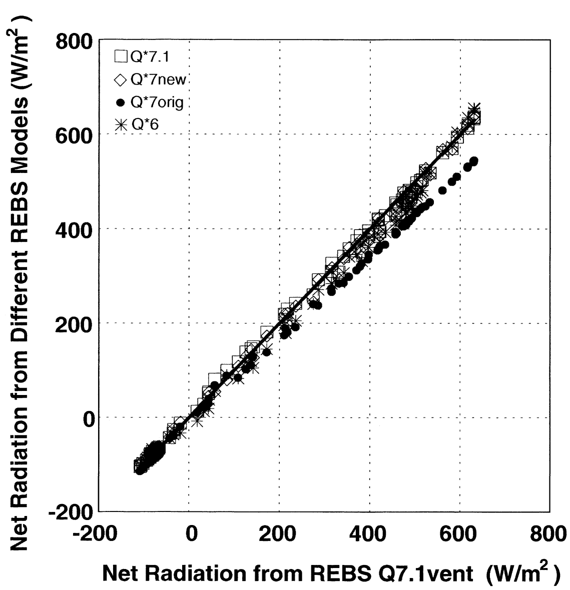

Fig. 1. Comparison of wind corrected R_n estimates from the various REBS radiometer models over the whole range of observations (approximately −100 to 700 W m^{-2}). All REBS models are plotted against the Q*7.1vent (chosen arbitrarily). The data for each REBS model/type (see Table 1) is an average of the individual instrument values. The line represents perfect agreement with Q*7.1vent estimates.

dependent variable and then performing an ordinary least squares regression with each of the other sensors as the independent variable. This procedure resulted in a set of self-consistent cross calibration coefficients valid under both wet and dry conditions. After such a recalibration, the REBS radiometers demonstrated an average root-mean-square-error, RMSE, (Willmott, 1982) of $\approx$10 W m^{-2}. Therefore, it appears that internal inconsistencies within a set of radiometers of a given manufacturer can be effectively removed by a cross calibration at the site of interest.

3.2. Variations between the two makes of radiometers

In order to compare the Swissteco and REBS radiometers, the data were divided into the dry and wet surfaces. Since the differences between the Swissteco and the various REBS radiometer models were similar, one was arbitrarily chosen (Q*7.1vent) to display the results. For this analysis, no wind corrections were applied to the REBS radiometers for the following reasons:

1. wind correction generally increased differences with the Swissteco;
2. no wind correction algorithm is available for the Swissteco;
3. results from Smith and Hodges (1997) indicate inconsistencies in wind correction algorithms.

The data for the dry and wet conditions each were again split randomly into 2 sets to insure independence and to validate consistency in the proposed adjustments (Montgomery and Peck, 1982). Fig. 2 illustrates the relationship between the REBS and Swissteco radiometer for dry conditions. It is clear that there is a definite bias present, with the REBS estimates being larger than the Swissteco by approximately 30 W m^{-2}, on average. The bias increases greatly with radiation level or time indicating serial correlation (Draper and Smith, 1981). The RMSE value was $\approx$40 W m^{-2} for both dry sets.

To correct for the bias, two statistical models were used. First, an ordinary least squares regression equation was fit using half of the dry condition data. REBS data were treated as the independent variable and the Swissteco data as the dependent variable. The resulting regression parameters were then used to modify

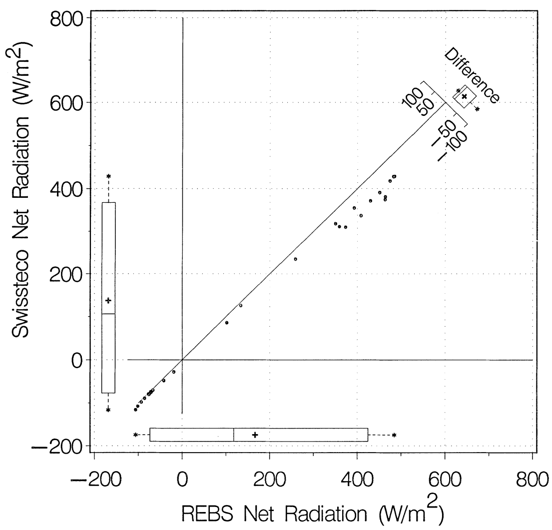

Fig. 2. Berg (1992) plot of the REBS versus Swissteco radiometer data for one of the two dry condition data sets. The box plots generated for the x (REBS) and y (Swissteco) variables and the box plot for the differences ($y-x$) display the quartiles, the mean (+), the maximum and minimum values (∗) and the 5th and the 95th percentiles (- - -).

the other half of the data set. Fig. 3 illustrates the results. Clearly bias between the two types of instruments is essentially removed, with the RMSE reduced to about 10 W m^{-2}.

Since there is a strong correlation of the bias with radiation level or time, an autoregression model was also utilized. The equation used is:

$$y(t) = a_0 + a_1 x(t) + b_1(a_0 + a_1 x(t-1) - y(t-1)) \quad (1)$$

where t is time, $x(t)$ is the independent variable (i.e., REBS radiometer) and $y(t)$ is the dependent variable (i.e., Swissteco radiometer). As before, half the data were used to fit the equation, which was then applied to the other half of the data. The autoregression was even more effective at removing variations and bias between the two instruments under dry conditions (see Fig. 4) with the RMSE being reduced to about 5 W m^{-2}.

The relationship between the two types of radiometer was different under the wet conditions, as shown in Fig. 5. In this case, the bias is less than 10 W m^{-2} and hence is considered insignificant. In fact, the

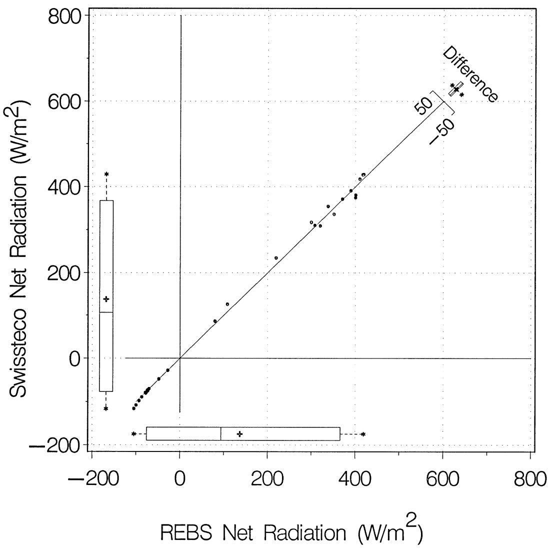

Fig. 3. Berg (1992) plot of the REBS versus Swissteco radiometer data with one dry condition data set from the REBS adjusted with ordinary least squares regression model coefficients derived from the other set (see text). See Fig. 1 for a description of the box plots.

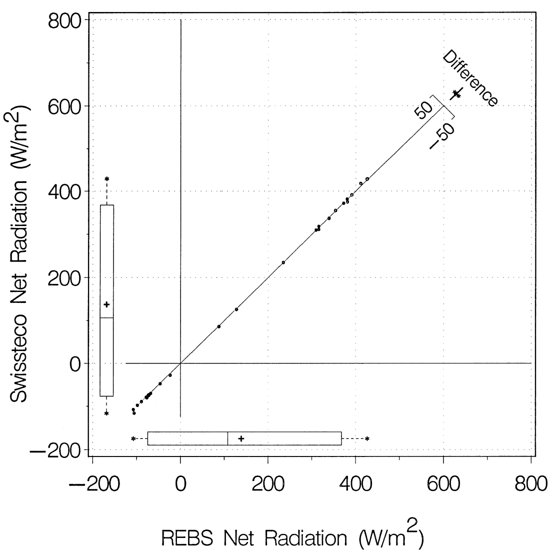

Fig. 4. Berg (1992) plot of the REBS versus Swissteco radiometer data with one dry condition data set from the REBS adjusted with autoregression model coefficients (cf. Eq. (1)) derived from the other set (see text). See Fig. 1 for a description of the box plots.

agreement is such (i.e., RMSE $\approx$15 W m^{-2}) that no further analyses are required.

These results indicate that although the two radiometers can be cross calibrated to remove bias for dry

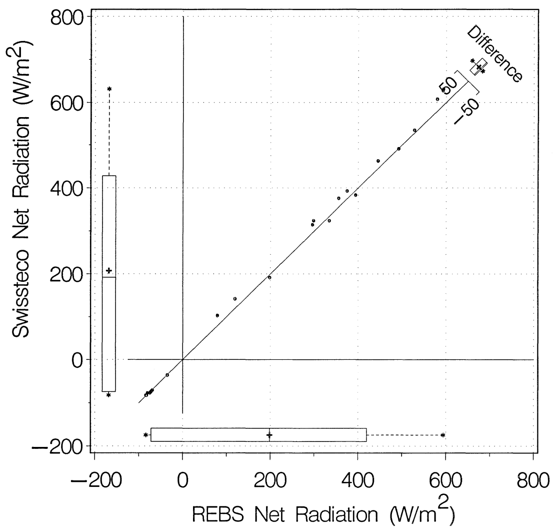

Fig. 5. Berg (1992) plot of the REBS versus Swissteco radiometer data for one of the two wet condition data sets. See Fig. 1 for a description of the box plots.

conditions, for all practical purposes no modifications are needed under wet conditions. In fact, using either regression model for dry conditions would introduce bias for wet conditions. Hence, there is no way to remove bias between the instruments for all conditions. One cannot cross calibrate the two instruments to make them read the same values under variable surface conditions.

4. Conclusions

In order to assess the spatial variations in net radiation across a landscape, the inconsistencies among a set of net radiometers should be negligible. Removing these differences requires a cross calibration over the range of surface conditions encountered on the landscape. We have shown that a set of radiometers from a given manufacturer containing several models can be cross calibrated so that differences among the instruments become negligible. This was true for both wet and dry surfaces, which represent a large change in the surface radiation balance. Because of the dependency of the differences upon the value of net radiation, an autoregression produced the best results.

However, when comparing instruments from two different manufacturers, in this case REBS and Swissteco, it was not possible to cross calibrate them for both wet and dry conditions. Regressions could induce agreement under dry conditions, but their use would introduce more bias for wet conditions. This suggests that there are fundamental differences between these two instruments in the relative response to solar and longwave radiation, which has also been indicated in other studies.

It is clear that in order to properly assess the spatial differences in net radiation of a landscape, instruments of a single manufacturer should be utilized and cross calibrated on the site. The issue of accuracy is a separate one and not explicitly addressed here. However, it is clear that the sizes of the inconsistencies between instruments reflect problems with accuracy as well.

We note that the need remains for the development of a combination of radiometer design, calibration procedures and validation under various conditions, which will provide measurements of net radiation accurate within a few per cent. Surface energy and water balance studies are very much dependent upon available energy. Further progress in these studies is limited by our present ability to make accurate measurements of net radiation.

Acknowledgements

The authors would like to thank the personnel at the USDA-ARS Jornada Experimental Range facility for their cooperation and assistance, especially Jim Lenz and Kris Havstad. The assistance of Jerry Ritchie in preparing the bare soil site is gratefully acknowledged. The authors would like to thank suggestions made by Drs. John Baker, Greg Johnson, Tom Sauer and the anonymous reviewers on early versions of this manuscript. We would also like to thank Mr. Charles Fritschen for providing a REBS Q*7.1 with ventilator unit for the intercomparison.

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