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Estimating Daytime Net Radiation Using Routine Meteorological Data in Jamaica

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ABSTRACT.—**An empirical scheme is formulated for estimating daytime net radiation in Jamaica by adjusting the net long-wave radiation component in the radiation balance equation. The adjustment incorporates the effect of soil surface temperature and sunshine in terms of global short-wave radiation. The net radiation estimated using the scheme agrees well with the measured net radiation. The correlation coefficients are between 0.98 and 1.0, and the root mean square errors for the correlations between the measured net radiation and the estimated net radiation are 10 percent or less of the average measured net radiation. The scheme adapts well to different climatic areas, surface moisture conditions, soil types, and seasons. The comparisons between the measured hourly average net radiation and the estimated values, with and without the adjustment, demonstrate that the contribution from the adjustment is very important during daytime, except in the morning and late afternoon hours. This is so because surface heating is weak due to low global short-wave radiation fluxes, and sunshine is low during the morning and late afternoon.**

INTRODUCTION

Net radiation is an important component in the surface radiation balance. It can be measured with reliable instruments. In the absence of direct measurements, net radiation can be obtained using the radiation balance equation if the other components are known. The radiation balance equation (Eq. 1) is:

$$Rn = Rs\ (1 - \alpha) + \varepsilon_s Rld - \varepsilon_s \sigma Ts^4$$

where Rn is the net radiation, Rs is the global short-wave radiation, α is the surface albedo, ε_s is the surface emissivity, Rld is the downward long-wave radiation, σ is the Stefan-Boltzmann constant, Ts is the temperature of the ground in Kelvin, and the term $\varepsilon_s \sigma Ts^4$ represents the upward long-wave radiation (usually denoted by Rlu). The expression $\varepsilon_s Rld - \varepsilon_s \sigma Ts^4$ in Eq. 1 represents the net long-wave radiation (usually denoted by Rnl). The global short-wave radiation consists of direct solar radiation and diffuse sky radiation in the wavelength range 0.1 to 4 μm. The long-wave radiation is the radiation emitted by the atmospheric constituents and the earth, in the wavelength range from 4 to about 100 μm.

Knowing the other values, Eq. 1 can be used to estimate the net radiation (Rn). The global short-wave radiation component, Rs, can be readily measured. Rs is much easier to measure than Rn. The component Rld can be measured with reliable instruments, such as a calibrated pyrgeometer. The surface temperature Ts is rarely known. In most instances, the upward long-wave radiation is calculated using the air temperature near the surface instead of Ts (Brutsaert, 1982). The α and ε_s values for different types of surfaces are available in Brutsaert (1982). The albedo α can be measured with an albedometer. When direct measurements of the components are not available, values of Rs and Rld are estimated by simple empirical schemes.

Two schemes to estimate the net radiation (Rn), and use Eq. 1 as the basis, are Holtslag and Van Ulden (1983) and Chen (1992). The former carried their work in central Netherlands, a temperate region. Their work indicated the importance of the difference between surface temperature and air temperature. Holtslag and Van Ulden (1983) measured the surface temperature, Ts, with an infrared radiation thermometer and used the measurements to parameterize the upward long-wave radiation component (Eq. 2) as follows:

$$\sigma Ts^4 = \sigma T^4 + 4\sigma T^3 (Ts - T),$$

where T is the air temperature and the second term on the right is approximately 0.12Rn.

The work of Chen (1992) was done in Jamaica and involved the parameterization of net long-wave radiation, Rnl, and the global radiation in terms of the sunshine percentage. His parameterizations were given by the equations (Eq. 3 and 4):

$$Rnl = \varepsilon_s \sigma \, [c + d\,(n/N)]\,[1.24(e/T)^{1/7} T^4 - Ts^4]$$

$$Rs = 11.574\,[a + b\,(n/N)]\,Ho$$

The quantity (n/N) in Eq. 3 and Eq. 4 is the ratio of the monthly average number of instrument-recorded bright-sunshine hours per day to the average day length. In Eq. 3, the coefficients c and d depend on the season, with values of $c = 0.717$ and $d = 1.164$ for the summer (August to September) of 1989, and $c = 0.425$ and $d = 0.627$ for the winter (January to February) of 1990. The quantity e in Eq. 3 represents the vapor pressure at air temperature T and $1.24(e/T)^{1/7}$ is the effective atmospheric emissivity for clear sky theoretically derived by Brutsaert (1975). In Chen (1992), the surface temperature, Ts, was assumed to be approximately equal to T. In Eq. 4, the Ångström coefficients a and b were 0.170 and 0.585, respectively, and Ho is the average daily solar radiation in MJm^{-2} day^{-1} which would reach a horizontal surface in the absence of the atmosphere. Ho can be calculated for a given latitude and time of the year knowing the solar constant.

The schemes of Chen (1992) were used to estimate average net radiation, average global radiation, and the average daily evapotranspiration for the studied summer and winter periods in Jamaica. However, some aspects were overlooked in the schemes. The first was the substitution of T instead of Ts in the analysis. This was an oversimplified assumption, if one considers the importance of the temperature difference noted by Holtslag and Van Ulden (1983). Certainly, we would expect the temperature difference to be more significant in a tropical region, where radiation levels are generally higher and therefore surface heating is more intense. The second was, in principle, that under clear sky conditions the value of n/N converges to 1.0 and (c + d) in Eq. 3 needs to converge to 1.0 so that Rnl approaches Rnlc, which is the net long-wave radiation under clear sky conditions. The clear sky net long-wave radiation, Rnlc, is given by (Brutsaert, 1982) (Eq. 5):

$$Rnlc = \varepsilon_s \sigma \, [1.24(e/T)^{1/7} T^4 - Ts^4]$$

The term $1.24\sigma(e/T)^{1/7} T^4$ in Eq. 5 is the clear sky downward long-wave radiation component Rldc. In Chen (1992), the summer period (c + d) was 1.881 and the winter period (c + d) was 1.052. Thus, the summer period value was higher than expected. Thirdly, the results given by Eq. 3 and Eq. 4 were established at a particular site and therefore their applicability over a wider area is questionable. Chen et al. (1994) show that the Ångström a and b coefficients are dependent on station characteristics.

An empirical scheme is presented herein that can be used to estimate the daytime net radiation in Jamaica. This scheme uses global radiation, air temperature, and vapor pressure at screen height (1.5 m to 2.5 m from the ground). The scheme was developed by adding a term to the clear sky net long-wave radiation component, Rnlc, given by Eq. 5. This term was formulated empirically and incorporated the effect of the surface temperature and the sunshine. The scheme applies to a wider area than the study presented by Chen (1992) and explains why (c + d) in the Chen (1992) scheme did not converge to 1.0. The applicability and accuracy of the scheme was examined using several independent data sets.

METHODS

Site Characteristics and Data Collection

Data were collected at Mona, St. Catherine, and Munro in Jamaica, West Indies. The distance from Mona to St. Catherine is 35 km and from Mona to Munro is 130 km. The latitude, longitude, altitude, and average annual rainfall, respectively, for the sta-

TABLE 1. Data collection periods, parameters measured, and height of measurement above ground.

Site	Data collection period	Parameters[1]	Height of measurement (m)
Mona	January-February 1994	Rn, Rs, α	2.0
		e and θ	1.5
	September 1994	Rn, Rs, RH and θ	2.0
	March 1997	Rs	15.0
		θ	1.6
		θ_s	-0.005[2]
St. Catherine	March and August 1989, and January-February 1990	Rn, Rs	2.0
		e and θ	1.5
Munro	July 1996-August 1997	Rn, Rs, RH and θ	2.5

[1] Rn = net radiation, Rs = global short-wave radiation, α = surface albedo, e = vapor pressure, θ = air temperature, θ_s = soil surface temperature, RH = relative humidity.

[2] 5 mm below the surface.

tions are as follows: 17°58′ N, 76°45′W, 150 m and 1000 mm for Mona. 17°58′N, 77°5′W, 150 m and 1000 mm for St. Catherine. 17°58′N, 77°45′W, 800 m and 2500 mm for Munro. The altitude and the rainfall values are from Morrissey (1994). The sites were fields with grass about 10 cm tall. The top soil surface at Mona and St. Catherine was mainly loam, but at Munro it was red bauxite mixed with limestone. The fields at Mona and St. Catherine were irrigated at regular intervals except in March of 1997 and 1989. At these times the fields were drier than usual. The ground at Munro was moist due to high rainfall throughout the year. The site for the global short-wave radiation measurement in March 1997 was the weather station of the Department of Physics, Mona Campus, UWI. This station is situated on the concrete roof of a building 15 m high. It is 500 m away from the site used in March 1997 for the surface temperature measurement.

The data collection periods, the parameters measured, and height of measurement are given in Table 1. Measurements were done at screen height except for the global short-wave radiation and the soil surface temperature in March 1997 at Mona.

Parameters and instruments used in the measurements are given in Table 2. Surface and air temperature during March 1997

TABLE 2. Parameters measured and instruments used.

Parameter[1]	Instrument
Rn[2]	Fritschen (model 3032) and Swissteco type S-1 (model CH9463) net radiometers
Rs	Li-Cor Inc. (model LI-200SZC) pyranometer 2 Kipp and Zonen (type CM10) radiometers in March 1997[3]
α	Kipp and Zonen (type CM7) albedometer
RH and θ	Campbell Scientific Inc. (model 207) temperature and relative humidity probe
e and θ	Cooled mirror dew point hygrometer and fine wire thermocouple (0.001 inch chromel-constantan) system which formed a part of Campbell Scientific Inc. (Dew-10 series) Bowen ratio system
θ in March 1997	Thermocouple (0.021 inch chromel-constantan) made in the Department of Physics, Mona Campus
θ_s in March 1997[4]	2 thermocouples (0.021 inch chromel-constantan) made in the Department of Physics, Mona Campus

[1] Parameters are the same as those defined in Table 1.

[2] Both radiometers were used in January-February of 1990 and 1994.The average of the two radiometers was used in these periods. In the other instances only the Fritschen radiometer was used.

[3] The average of the two radiometers was used in the analysis.

[4] The average of the two thermocouples was used in the analysis.

were measured with 0.021 inch chromel-constantan thermocouples made in the Department of Physics, Mona Campus, UWI. One thermocouple was used to measure air temperature and two thermocouples were used to measure soil surface temperature. The thermocouple used to measure air temperature was mounted in a model 207 relative humidity probe housing to prevent direct heating of the junction by solar radiation, and also to provide adequate ventilation. The thermocouples used to measure soil surface temperature were buried 5 mm below the surface to prevent direct solar radiation on the junctions. The two junctions were 50 cm apart. In the computation of surface temperature, an average from the two thermocouples was taken. The thermocouples were used in March 1997 to measure soil surface temperature, since more suitable instruments like infrared radiation thermometers were not available. The data were collected for ten days. The global radiation during this period was measured with two Kipp and Zonen radiometers. The average of the two radiometers was taken for the analysis. The readings from the two radiometers agreed to within one percent and the readings from the two thermocouples buried in the soil agreed to within 1°C.

Data were stored on-site in a datalogger (Campbell Scientific Inc. 21X micrologger) and downloaded to a computer for analysis. At Munro and at the weather station of the Physics Department, Mona Campus, data were stored hourly. In the other instances data were stored in 20 min averages.

Formulation of The Adjustment Term

The radiation balance equation for clear sky can be written using Eq. 1 and Eq. 5, as (Eq. 6):

$$Rn = Rs\,(1 - \alpha) + \varepsilon_s \sigma 1.24(e/T)^{1/7}\, T^4 - \varepsilon_s \sigma Ts^4$$

In a tropical region, the radiation levels are high and we can expect Ts to be significantly higher than the air temperature T. Thus, in the absence of direct measurements of Ts, the use of $\varepsilon_s \sigma Ts^4$, with Ts = T, for the upward long-wave radiation component, Rlu, may not be suitable. To correct for this, the upward long-wave radiation component was expressed as in Eq. 7, below. This adjustment is similar to the one in Holtslag and Van Ulden (1983).

$$Rlu = \varepsilon_s\,(\sigma T^4 + B)$$

where B is an adjustment term that accounts for the temperature difference. The term B must be related to a readily measurable parameter if the adjustment is to be practical.

The downward long-wave radiation component is generally affected by cloudiness. As discussed by Brutsaert (1982), the cloudiness effect can be considered using one of two procedures. The first is to adjust the Rldc, which is the clear sky downward long-wave radiation component, using fractional cloud cover or percentage of sunshine. The second is to adjust the clear sky net long-wave radiation component, Rnlc, using fractional cloud cover or percentage of sunshine. We preferred the first procedure, as Eq. 7 provides an adjustment to the upward long-wave radiation component, and the downward long-wave radiation component is the one affected directly by cloudiness. To accomplish the adjustment, the downward long-wave radiation component, Rld, was expressed as in Eq. 8 below, which includes a term for cloudiness effect of the sky.

$$Rld = Rldc + A$$

where A is an adjustment term to the clear sky downward long-wave radiation component, Rldc. The term A can be made to depend on cloudiness or sunshine. Here it was treated as a function of sunshine. A similar adjustment term was used by Holtslag and Van Ulden (1983), based on cloud cover, which they took from Paltridge and Platt (1976). The application of Eq. 7, and adding the term A to the Rldc term in Eq. 6, provides the equation (Eq. 9):

$$Rn = Rs\,(1 - \alpha) + \varepsilon_s \sigma\,[1.24(e/T)^{1/7}\, T^4 - T^4] - \varepsilon_s\,(B - A)$$

In Eq. 9 the clear sky net long-wave radiation component has been adjusted to account for the effect of sunshine and temperature difference (Ts - T). This equation can be used to estimate Rn when the term (B - A) is known in terms of a readily measurable parameter. An empirical evaluation of (B - A) appears in the results section.

The advantage of Eq. 9 is that it does not demand knowledge of the soil surface temperature Ts, a parameter that is not readily measured. The soil surface temperature may depend on various factors, such as soil moisture, soil composition, soil heat capacity, and soil type. Therefore, a scheme to estimate soil surface temperature in terms of soil properties is not straightforward. Furthermore, in the given form Eq. 9 accounts for the effect of sunshine.

RESULTS

The Schemes for The Adjustment Term (B - A) and The Net Radiation, Rn.

A scheme to evaluate (B - A) was formulated in terms of Rs, a readily measurable parameter. The process was done in three stages. First, the relation given by Eq. 7 was validated using the measurements of air and soil temperatures performed in March 1997. The results are shown in Figure 1. The B term for this data set was best represented by (Eq. 10):

$$B = 4\sigma T^3 (Ts - T) + 6\sigma T^2 (Ts - T)^2$$

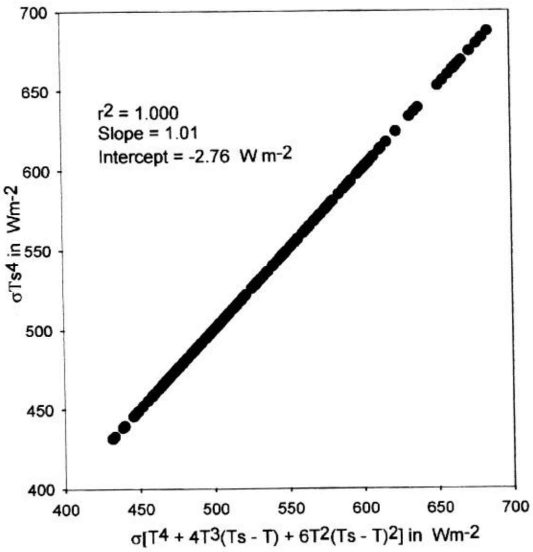

FIG. 1. Linear relationship between σTs^4 and $\sigma[T^4 + 4T^3 (Ts - T) + 6T^2 (Ts - T)^2]$, validating Eq. 7, using air and surface temperatures in March 1997.

The average air and soil temperatures, measured during daytime in March 1997, were 27.0°C and 37.7°C, respectively. A study of the hourly B and Rs values showed that they can be correlated. The correlation coefficient was 0.89. This result was useful because it indicated dependence of B on Rs.

Secondly, a comparison of A and B magnitudes was done using March 1997 averages of air and soil temperatures in Eq. 7 to calculate B, and using that calculated value of B with January-February 1994 averages of Rn, Rs, e, T and α in Eq. 9 to calculate A. The averages of Rn, Rs, e, T and α in January-February 1994 were respectively 276.6 Wm^{-2}, 447.6 Wm^{-2}, 23.5 mb, 299.8 K, and 0.2. The B value thus calculated was 68 Wm^{-2} and A was 48 Wm^{-2}. In the calculations, 0.98 was used for ε_s (Brutsaert, 1982). These calculated values demonstrated that A and B are of comparable magnitudes and therefore considering both is important. A similar comparability of the adjustment terms was evident in Holtslag and Van Ulden (1983). The March 1997 and January-February 1994 data sets were suitable to use in this part of the exercise because both sites were located in the same area (Mona) and the annual variation of climatic conditions at a given area in Jamaica is not very significant. Furthermore, all the measurements required to calculate B and A were available in these data sets.

In the next stage, we used Eq. 9 and the (B–A) term was expressed as (Eq. 11):

$$D = 1/\varepsilon_s \{Rs (1 - \alpha) - Rn - \varepsilon_s \sigma T^4 [1 - 1.24(e/T)^{1/7}]\}$$

where D = (B - A). Equation 11 was used with January-February 1994 data to calculate D. The values of D calculated were regressed with the Rs values measured during January-February of 1994. We obtained a correlation coefficient (r) of 0.92 in the regression analysis and the result was (Eq. 12):

$$D = 0.140 Rs - 41.5$$

The standard error in the slope was 0.0026 and in the intercept was 1.38 Wm^{-2}. The regression of D with Rn had a lower correlation coefficient (0.89). The use of Eq. 12 in Eq. 9, resulted in (Eq. 13):

$$Rn = Rs\,(1 - \alpha) + \varepsilon_s[1.24\sigma(e/T)^{1/7}\,T^4 - \sigma T^4 - 0.140\,Rs + 41.5]$$

The expression for the net radiation without the correction term would be (Eq. 14):

$$Rn = Rs\,(1 - \alpha) + \varepsilon_s\sigma T^4\,[1.24(e/T)^{1/7} - 1]$$

Estimation of Rn Using Other Data Sets

Equation 13 and Eq. 14 were used to calculate the net radiation Rn, with six independent data sets including that of January-February, 1994, collected at Mona. The data sets are described in Table 1. The values of Rn obtained were compared by performing a linear regression analysis between the measured and calculated values of Rn. This was done to examine the applicability and the skill of the scheme, given by Eq. 13, and to examine the effectiveness of the adjustment term given by Eq. 12. Tables 3 to 7 present the results of the correlation between the measured net radiation, Y, and the estimated net radiation, X, for 20 min and hourly values, and hourly average values.

The vapor pressure values, e, used in Eq. 13 and Eq. 14 were either measured or calculated using the measured relative humidity and the calculated saturation vapor pressure (SVP). The SVP was calculated using the result of Lowe (1977) which is given in Eq. 16, below.

$$SVP = a_o + a_1\theta + a_2\theta^2 + a_3\theta^3 + a_4\theta^4 + a_5\theta^5 + a_6\theta^6$$

In Eq. 16, θ is the air temperature, the values of coefficients a_o to a_6 depend on the unit chosen for temperature, degrees C or K, and the SVP is in mb. Vapor pressures were calculated at Munro, and in September 1994 at Mona. In all the other instances the vapor pressures were measured. In Table 7, Mona and St. Catherine are considered together because they are at the same altitude and have similar climate. However, the results for March 1989 were separated because that period was drier. Figures 2 to 4 illustrate the variation of the daytime hourly average net radiation, measured and estimated using Eq. 13 and Eq. 14, versus time. Figure 2 shows Mona and St. Catherine without March 1989, Figure 3 shows March 1989 at St. Catherine, and Figure 4 shows Munro. The results in Table 7 correspond to the data in these figures.

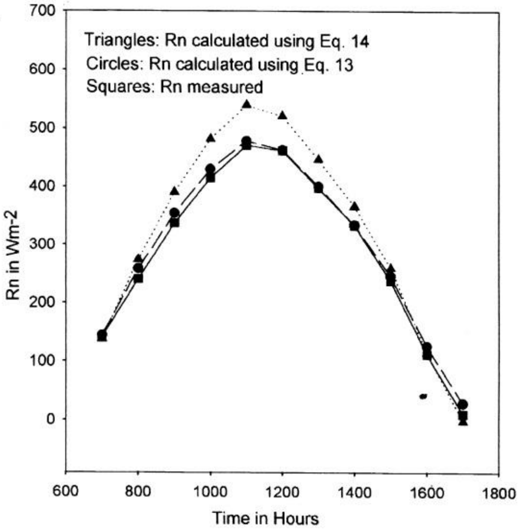

FIG. 2. Comparison of the measured hourly average net radiation with the hourly average net radiation estimated using Eq. 13 and Eq. 14, for Mona and St. Catherine under wet surface conditions.

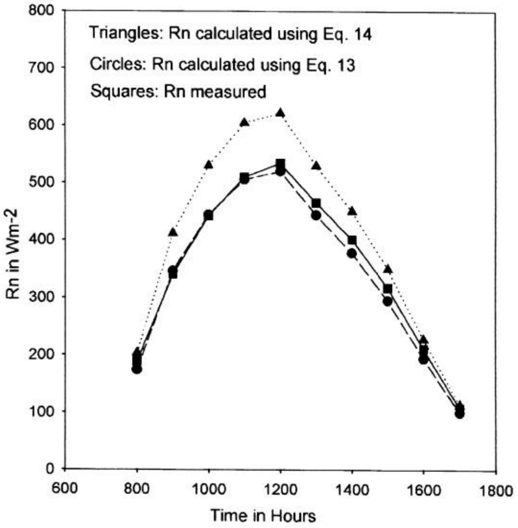

FIG. 3. Comparison of the measured hourly average net radiation with the hourly average net radiation estimated using Eq. 13 and Eq. 14, for St. Catherine under dry surface conditions in March 1989.

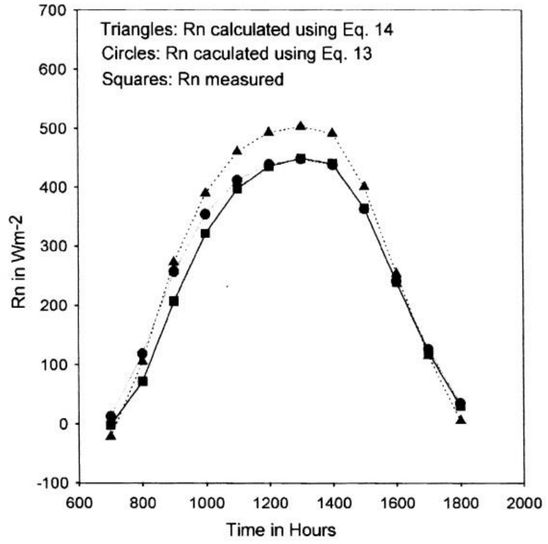

FIG. 4. Comparison, for Munro, of the measured hourly average net radiation with the hourly average net radiation estimated using Eq. 13 and Eq. 14.

A value of 0.20 (Brutsaert, 1982) was used for the surface albedo, α, except for the period of January-February 1994. In this period the surface albedo was measured and these values were used in the analysis. The measured values of α varied from 0.17 to 0.22. A value of 0.98 (Brutsaert, 1982) was used for the surface emissivity in all the data sets.

DISCUSSION

We have presented a scheme, given by Eq. 13, that can be used to estimate the daytime net radiation in Jamaica. The data included two climates (Munro is wetter and at higher altitude), two seasons (winter and summer), two surface moisture conditions (March 1989 was drier), and two soil types. The scheme is simple because it consists of a few readily measurable parameters: air temperature, vapor pressure or relative humidity, and global short-wave radiation. In the absence of direct measurements of Rs, the average values can be estimated using schemes dependent on percentage of sunshine (Brutsaert, 1982; Chen, 1992; Chen et al., 1994). The surface albedo and surface emissivity can be obtained from the appropriate tables (Brutsaert, 1982).

The overall success of the scheme for estimating net radiation is apparent when one examines the correlation coefficients, the slopes, and the other quantities given in Tables 3 to 7. The correlation coefficients are high (0.98 to 1.0), the slopes of the lines of observed net radiation versus the net radiation estimated using Eq. 13 are close to 1.0 (0.95 to 1.03), and the intercepts and the root mean square errors are 10 percent or less of the average measured net radiation. A 10 percent is acceptable in our work, when we consider the different types of conditions (climate, seasons, surface moisture, soil type) that the data covered. No attempt was made to adjust the clear sky net long-wave radiation component to incorporate these different conditions.

Tables 3 to 7 present the results of the correlation between the measured net radiation and the net radiation estimated using Eq. 14, without the adjustment term. The

TABLE 3. Linear regression results of the 20 min values of measured net radiation and estimated net radiation using Eq. 13 (values outside parentheses) and Eq. 14 (values inside parentheses), at Mona.

Parameter[1]	January-February, 1994	September, 1994
M	582	182
S	0.996(0.83)	0.98(0.81)
P (Wm^{-2})	0.562(30)	-20(13)
Y_{av} (Wm^{-2})	277	265
r	0.995(0.996)	0.999(0.999)
η (Wm^{-2})	18(48)	28(67)
η / Y_{av}	0.06(0.17)	0.10(0.25)

[1] M = number of data points, S = slope of the linear regression line of the measured net radiation versus estimated net radiation using Eq. 13 and Eq. 14, P = intercept that corresponds to the slope S, Y_{av} = average value of the measured net radiation, r = correlation coefficient, and η = root mean square error calculated using Eq. 15: $\eta = [\Sigma(Y - X)^2 / M]^{1/2}$.

TABLE 4. Linear regression results of the 20 min values of measured net radiation and estimated net radiation using Eq. 13 (values outside parentheses) and Eq. 14 (values inside parentheses), at St. Catherine.

Parameter[1]	March, 1989	August-September, 1989	January-February, 1990
M	519	428	640
S	0.96(0.79)	1.02(0.84)	0.98(0.81)
P (Wm^{-2})	5(34)	-29(4.2)	1.72(30)
Y_{av} (Wm^{-2})	390	413	318
r	0.99(0.99)	0.98(0.98)	0.99(0.99)
η (Wm^{-2})	27(78)	50(91)	24(58)
η / Y_{av}	0.07(0.20)	0.12(0.22)	0.070(0.18)

[1] See Table 3 for the letters and symbols used for the parameters.

values of the slopes are smaller than 1.0 and lie between 0.8 and 0.87. The root mean square errors are higher. These indicate that the adjustment term, given by Eq. 12, improves the accuracy of the scheme given by Eq. 13. It brings the measured net radiation and the net radiation estimated using Eq. 13 closer to each other. The effectiveness of the adjustment term is evident when one examines the variation of the hourly average values of the net radiation over time, as illustrated in Figures 2 to 4. During the period of 900 to 1600 hours there was a difference between the measured net radiation and the net radiation estimated using Eq. 14, whereas there is good agreement between the net radiation estimated using Eq. 13 and the measured net radiation. During mid-day the difference is 25 percent. However, in the early hours and in the late afternoon there is a tendency for the values estimated using Eq. 14 to approach the measured and estimated values of the net radiation using Eq. 13. Perhaps this is because during morning and late afternoon hours the global radiation, Rs, is low. Low Rs causes weak heating of the surface, resulting in small temperature differences, (Ts - T), and correspond to low sunshine. Thus, the contribution from the adjustment term, given by Eq. 12, may be unimportant. This is evident in Figure 5, which illustrates the variation of the hourly average global radiation with time for Munro. The Munro data set covers almost a year, and therefore is a better data set to present the average values. From Figure 5, it is apparent that the average global radiation increases to a value of 300 Wm^{-2} around 830 hours and drops again to 300 Wm^{-2} around 1630 hours, with a maximum at 1300 hours. A careful consideration of Eq. 12 reveals that our adjustment term approaches zero as Rs approaches about 296 Wm^{-2}, which corresponds to the edges of our early and late afternoon hours.

Evaluation of the adjustment term, given by Eq. 12, at Rs values lower than 296 Wm^{-2} indicates that the adjustment term acquires negative values. This is so because the surface temperature approaches the air temperature and crosses it in the morning and late afternoon. This results in Ts becoming less than T. Such a situation was illustrated by Brutsaert (1982). When Ts becomes less than T, the B term acquires negative values. However, our data are not adequate enough to provide a conclusive explanation

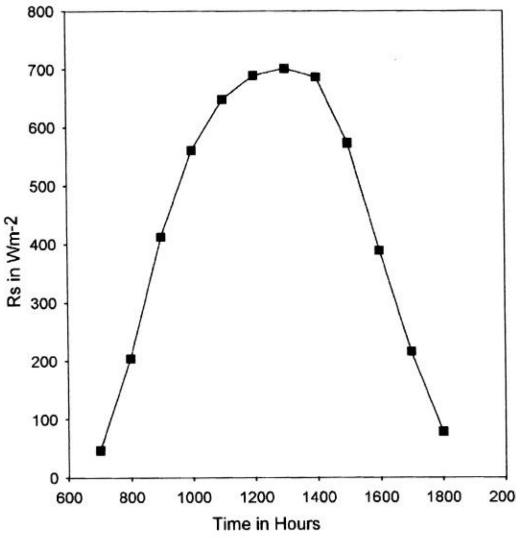

FIG. 5. Variation, for Munro, of the hourly average global short-wave radiation with time.

TABLE 5. Linear regression results of the hourly values of measured net radiation and estimated net radiation using Eq. 13 (values outside parentheses) and Eq. 14 (values inside parentheses), at Mona and Munro.

Parameter[1]	Mona: January-February, 1994	Mona: September, 1994	Munro: July, 1996 to August, 1997
M	151	53	2899
S	0.99(0.82)	0.98(0.81)	1.01(0.84)
P (Wm^{-2})	1.93(32)	-19(14)	-18(13)
Y_{av} (Wm^{-2})	307	269	257
r	0.99(0.99)	0.99(0.99)	0.99(0.99)
η (Wm^{-2})	15(46)	27(65)	35(60)
η / Y_{av}	0.04(0.15)	0.10(0.24)	0.14(0.23)

[1] See Table 3 for the letters and symbols used for the parameters.

of the behaviour of the adjustment term, given by Eq. 12, in the early hours (earlier than about 800 hours) and in the late afternoon hours (later than about 1700 hours), and also to indicate the exact times of the day at which the air temperature exceeds the surface temperature.

The good daytime adaptability of the adjustment term to sites with different surface conditions, suggests that the B term is weakly dependent on the surface conditions. This is so because radiation levels during daytime, outside of morning and late afternoon hours, are high (Fig. 5). High radiation levels can mask the dependence of B on the surface conditions. This topic requires further study with better surface temperature data, especially at low Rs.

Chen (1992) and our present work are closely linked because data collection procedures, instrumentation, and a site are similar. Some comparison between the two is appropriate. The site in Chen (1992) was at St. Catherine, but present work has two more sites (Mona and Munro) covering a wider region with different climatic conditions and soil types. The net long-wave radiation was studied with different equations. We used Eq. 17 and Chen (1992) used Eq. 18, given below.

$$Rnl = \varepsilon_s [1.24\sigma(e/T)^{1/7} T^4 - \sigma T^4 - 0.140\ Rs + 41.5]$$

$$Rnl = \varepsilon_s [c + d\ (n/N)]\ [1.24\sigma(e/T)^{1/7} T^4 - \sigma T^4]$$

A shortcoming of the result given in Eq. 18 was that (c + d) did not converge to 1.0 as n/N approaches 1.0 for clear sky conditions. The value of (c + d) in summer was 1.881 and in winter 1.052. The discrepancy, especially in summer, was attributed to the higher values of net radiation in the tropics. The results of our work can help to clarify this discrepancy.

An examination of Eq. 18 reveals that the function of the adjustment term, [c + d (n/N)], is to correct the net long-wave radiation for cloudiness in terms of the clear sky values. Eq. 18 can be obtained replacing Ts in Eq. 3 by T, the air temperature. From Eq. 3 and Eq. 18 we notice that the transformation from Rnlc to Rnl infers (c + d) to be 1.0

TABLE 6. Linear regression results of the hourly values of measured net radiation and estimated net radiation using Eq. 13 (values outside parentheses) and Eq. 14 (values inside parentheses), at St. Catherine.

Parameter[1]	March, 1989	August-September, 1989	January-February, 1990
M	159	122	186
S	0.95(0.79)	1.02(0.84)	0.98(0.81)
P (Wm^{-2})	9(38)	-29(3.3)	2.50(31)
Y_{av} (Wm^{-2})	404	445	326
r	0.99(0.99)	0.97(0.97)	0.99(0.99)
η (Wm^{-2})	27(79)	45(94)	19(54)
η / Y_{av}	0.07(0.20)	0.10(0.21)	0.06(0.17)

[1] See Table 3 for the letters and symbols used for the parameters.

TABLE 7. Linear regression results of the hourly average values of measured net radiation and estimated net radiation using Eq. 13 (values outside parentheses) and Eq. 14 (values inside parentheses), at Mona and St. Catherine, and Munro.

Parameter[1]	Mona and St.Catherine (winter and summer)	St. Catherine (March,1989)	Munro
M	11	10	12
S	1.02(0.84)	0.99(0.82)	1.03(0.85)
P (Wm^{-2})	-15(16)	15(20)	-22(10)
Y_{av} (Wm^{-2})	287	352	257
r	0.999(0.999)	0.997(0.997)	0.99(0.99)
η (Wm^{-2})	12(43)	15(61)	23(46)
η/Y_{av}	0.04(0.15)	0.04(0.17)	0.09(0.18)
Time interval	700–1700 hours	800–1700 hours	700–1800 hours

[1] See Table 3 for the letters and symbols used for the parameters.

under clear sky conditions only in two instances. One, when Ts is measured and used in the upward long-wave radiation term, as in Eq. 5. The other, when Ts is almost equal to T, which may happen in the tropics when surface heating is low. This occurs in early morning, late afternoon, and at night. During daytime, Ts is greater than T in the tropics. As a result, the correction term, [c + d (n/N)] in Eq. 18, includes the effects of the difference between the air and surface temperatures, as well as cloudiness. Both of these effects can be related to Rs, which correlates with n/N. Under clear sky conditions (c + d) does not need to converge to 1.0, except in the two instances that were mentioned. It should be greater than 1.0, especially in the summer, when radiation levels are higher and the surface heating is more intense.

In conclusion, we have formulated a scheme given by Eq. 13, that is dependent on readily measurable meteorological parameters, suitable to estimate daytime net radiation in Jamaica. The success of the scheme has been examined using data collected at three sites covering two climates, types of soils, surface moisture conditions, and seasons. The adjustment term, given by Eq. 12, adjusts the net long-wave radiation term for the difference between the surface and air temperatures, and also for the sunshine.

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