EMPIRICAL MODELS FOR ESTIMATING NET RADIATIVE FLUX: A CASE STUDY FOR THREE MID-LATITUDE SITES WITH OROGRAPHIC VARIABILITY

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Abstract. Based on a 4-year REKLIP data-set of global solar radiation G, shortwave surface albedo a, air temperature T_a and net radiative flux R_n, four types of regression models for the estimation of net radiative flux for three sites at different altitudes, located in the southern Upper Rhine valley have been proposed. In order to make for the limitation associated with the basic regression model (BRM) which relates net radiative flux over a surface to only incoming shortwave radiation, a longwave exchange coefficient λ has been introduced thus giving rise to the modified regression model (MRM). During daytime, the longwave exchange coefficient is observed to be negative for all three sites averaging about –0.20. The suitability of MRM over BRM becomes particularly obvious with respect to the mountainous site of Feldberg where the mean absolute error between measured and simulated R_n using MRM amounts to just half of that observed using BRM. Furthermore the role of clearness index and air temperature in the estimation of the net radiative flux have each been examined. The incorporation of the former is to make up for the effect of cloudiness on the net radiative flux budget, while the latter is an independent variable arising from the effective terrestrial radiation which thus allow for the estimation of the net radiative flux during all hours of the day. The regression models been proposed here have each been validated and their efficiency in reproducing actual measurements have been reported.

1. Introduction

The net radiative flux of the underlying surface R_n is given by the difference between the absorbed radiant energy and that emitted by the underlying surface, the atmosphere or by the earth-atmosphere system. It constitutes the fundamental parameter which governs the climate of the lower atmosphere. Hence its study is crucial to synoptic meteorology. In particular, the problem of the formation and transformation of air masses, the calculation of evaporation and snow melting as well as studies on atmospheric turbidity, among others, all require adequate information about the net radiative flux. Inspite of the profound information that can be derived from sustained and uninterrupted measurements of the net radiative flux over a surface, data on surface radiative fluxes collected at standardised radiometric observatories on divers terrain are still relatively sparse (Miller, 1981; Tovar *et al.*, 1995; Garratt and Prata, 1996; Wenzel *et al.*, 1997; Jegede, 1997; Calvet *et al.*, 1998; Snyder *et al.*, 1998; Calvet *et al.*, 1998; Kessler and Jaeger, 1999). Con-

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sequently, the lack of observations on radiative fluxes has been a persistent problem in studies of atmospheric and landsurface processes (Thornton and Running, 1999).

To address the problem of lack of experimental observations, R_n needs to be estimated from empirical relations based on physical considerations and other meteorological data. From a practical point of view, it is essential that R_n can be determined from relationships which are universally applicable and relatively easy to utilise. Consequently, numerous attempts have been made to calculate the net radiation R_n from global radiation values among others. The basis for an entirely empirical approach is found in the high correlation between net radiation and global solar radiation flux documented by some investigators (Schulze, 1970; Petzold, 1980; Clothier *et al.*, 1982; Hu and Lim, 1983; Linacre, 1992; Snyder *et al.*, 1998). Most of these works are, however, carried out with reference to a singular experimental site and often for a relatively short time-span. Reports on the simultaneous measurement and estimations of surface radiative and energy fluxes for locations with orographical variability within a scale of 100 km are still rare (Tovar *et al.*, 1995; Kalthoff *et al.*, 1999).

Orographic forcing influences weather and climate. In view of this, Semazzi (1980) conducted a series of numerical experiments based on a barotropic model to investigate the influence of large-scale orographic forcing on the climate of Africa while Semazi and Sun (1997) reported on the role of orography in determining the sahelian climate. Owing partly to its considerable heterogeneity arising from orographic variability, the Upper Rhine valley region, which extends from Karlsruhe, Germany in the north to Basel, Switzerland in the south, is characterised by a pronounced temporal and spatial variability in its climatic characteristics. Consequently local differences in the radiative balance as well as in the microclimates within this region are anticipated (Wenzel *et al.*, 1997; Kalthoff *et al.*, 1999). In view of this, the Regio-Klima-Project (regional climate project) otherwise known as REKLIP (REKLIP, 1995), which encompasses a network of 36 meteorological sites located in Germany, France and Switzerland was inaugurated in 1991 with the task of investigating the long term regional, temporal and altitudinal variability of climating conditions and energy balance components within the Upper Rhine valley as well as the surrounding mountainous areas. The meteorological data for most of the experimental sites were taking over a period ranging from 1991 to 1996.

The objective of the present work is to parameterise the net radiative flux using the global solar irradiance G and a few other meteorological quantities with particular reference to three meteorological sites located in Bremgarten (47°54′35″ N, 7°37′18″ E), Geiersnest (47°55′03″ N, 7°51′31″ N, 8°00′11″ E) and Feldberg (47° 52′31″ N, 8°00′11″ E) based at different altitudes (212 m a.s.l., 870 m a.s.l., 1489 m a.s.l. respectively) within the southern part of the Upper Rhine valley region. The sites were maintained by the Meteorological Institute of University of Freiburg within the framework of REKLIP. In effect, the simultaneous parameterisations of net radiative flux for these three locations would be based on a sufficiently long term REKLIP data-set (1992–1995). This is highly desirable, since comparable measurement and data analysis of atmospheric quantities over long periods of time and from many different strategic locations are crucial to the universal compilation of climatological features which in turn would promote a better understanding of global climate change. Apart from investigating the general empirical relationship between R_n and G, this study would also attempt to propose other highly predictive and widely applicable regression models. In view of the significance of R_n in determining the magnitude of energy available for the transport of sensible and latent heat to the atmosphere and the surface below, the necessity of a reliable estimation of the net radiative flux becomes a mandatory obligation.

2. The Radiation Balance Equation

Close to the earth's surface, the net radiative flux R_n is generally represented by the geometric sum of both the downward and upward components of shortwave radiative fluxes R_{ns} (in the range from 0.3 μm to 3 μm) and longwave radiative fluxes R_{nl} (in the range from about 3 μm to 100 μm). Hence the radiation balance equation is given by:

$$R_n = R_{ns} + R_{nl} = (G - R_k) + (A - R_l - E) \qquad (1)$$

where G represents the global solar irradiance, R_k is the shortwave reflected irradiance and R_l is the longwave reflected radiation which is negligibly small (Kessler and Jaeger, 1999). Furthermore, A represents the atmospheric downward longwave radiation component while E denotes the outgoing terrestrial longwave radiation. In Equation (1), while the radiative fluxes which are directed away from the earth surface constitute loss parameters and are consequently assigned negative, those directed towards the earth surface are gain parameters and are therefore assigned positive. Equation (1) can be further reduced to

$$R_n = G(1 - a) + R_{nl} = G(1 - a) - E_{eff} \qquad (2)$$

where

$$E_{eff} = -R_{nl} = E + R_l - A \text{ and } a = \frac{R_k}{G}.$$

In Equation (2), E_{eff} is the effective terrestrial radiation, while a represents the shortwave albedo. In effect, the product $G(1 - a)$ is the absorbed short-wave radiation. In some published reports, a is either assumed as constant for a given surface (More, 1976; Sterlin *et al.*, 1978; Allen *et al.*, 1994; Snyder *et al.*, 1998) or estimated for example according to Dong *et al.* (1992) such that

$$a = 0.00158\theta + 0.386 \exp(-0.0188\theta) \qquad (3)$$

with θ been the solar altitude and $a = 0.26$ for $G/E_0 \leq 0.375$, where E_0 is the extra-terrestrial radiation.

3. Experimental Sites, Measurement Methods and General Climatic Conditions in the Area of Investigation

Bremgarten lies within the plains of the Upper Rhine valley area, while Geiersnest and Feldberg are located within the outskirts and peaks of the Black forest respectively. The underlying surface of the sites are grasslands. All shortwave radiation were measured by pyranometers (Type CM11 from Kipp and Zonen) while the total upward and downward radiation were measured by pyrradiometer (according to Schulze, 1954) in frequency of 0.1 Hz. Air temperature and humidity were measured by means of a psychrometer at 2 m above the surface. The data acquisition system was based on a 21X Campbell micro data logger. This study focuses mainly on a 4-year data-base extending from 1992–1995.

The Upper Rhine valley region lies in the transition area from maritime to continental climate thus possessing a relatively mild and moderately humid climate in which the average air temperature of the warmest months lies below 22 °C. Warm and humid air masses of the Mediterranean area from SW has an easy access to this area through the Belfort gap. Due to the free conditions at high altitude, the experimental sites at Geiersnest and Feldberg experiences strong wind which weakens warming process by day and cooling by night. This phenomenon as well as the greater cloudiness at these heights particularly during the summer gives rise to lower daily range of surface and air temperature at these sites. On the other hand, Bremgarten which lies in the southern Upper Rhine plains records relatively weak wind due to the screening effect of surrounding mountains and thus higher daily air and surface temperature range.

Generally the annual precipitation variation within the Upper Rhine valley shows a maximum in July (due to thermal convection) and December (owing to westerly maritime air masses). According to the low pressure systems propagating to the east, perpendicular to the orientation of the Rhine valley and the mountain ridges, a pronounced variation of precipitation within a few kilometres – from the valley to the mountain crests – has been observed (Fiedler, 1995).

4. Results and Discussions

4.1. Estimating Daily Average of Net Radiative Flux Using the Basic Regression Model (BRM)

Values published in various studies (for example, Gay, 1971; Kasten, 1977; Czeplak *et al.*, 1995) indicate that R_{nl} remains small and constant when compared to the large range of R_{ns}. Monteith and Szeicz (1961, 1962) showed that R_n could be fitted empirically as

TABLE I

Basic regression model, correlation coefficient and standard error for the estimation of daily averages of net radiative flux as a function of only global solar radiation for Bremgarten (Be), Geiersnest (Ge) and Feldberg (Fe) in the southern Upper Rhine Valley with orographic variability based on 1992–1995 REKLIP data-set

Site code	Basic regression model (with R_n and G in Wm^{-2})	Correlation coefficient R	Standard error S_{R_n}
Br	$\left\langle [R_n]_n^\tau \right\rangle = 0.60 \left\langle [G]_n^\tau \right\rangle - 23.23$	0.981	9.7
Ge	$\left\langle [R_n]_n^\tau \right\rangle = 0.61 \left\langle [G]_n^\tau \right\rangle - 30.31$	0.952	15.2
Fe	$\left\langle [R_n]_n^\tau \right\rangle = 0.57 \left\langle [G]_n^\tau \right\rangle - 32.62$	0.841	25.9

$$R_n = G \frac{(1-a)}{(1+\beta)} + L_0 \tag{4}$$

where β is the heating coefficient, and L_0 is the balance of long-wave radiation between the surface and atmosphere when the incoming shortwave radiation from the sun and the sky is zero. This linear relationship which is here referred to as the basic regression model (BRM) has been reported to yield correlation coefficient better than 0.9 for many surfaces (Davies, 1967; Linacre, 1992; Dong *et al.*, 1992). In addition the values of β and L_0 have been observed to vary only slightly for different surfaces (Stanhill *et al.*, 1966; Idso, 1971) such that G and a primarily controls R_n.

In line with Equation (4), the dependence of net radiative flux R_n upon global solar radiation G can be expressed using some form of empirical linear regression model given by

$$R_n = A \cdot G + B \tag{5}$$

where A and B are constants of regression. Based on daily mean values of measured R_n and G for Bremgarten (Br), Geiersnest (Gr) and Feldberg (Fe) averaged over a period of four years (1992–1995), Table I presents the equivalent of the basic regression model BRM (Equations (4) and (5)), correlation coefficients and standard error for R_n obtained for the respective sites. In Table I, the indices τ and n represent time in hours and whole day (24 hrs) respectively.

As shown in Table I, the high correlation coefficient ($R \to 1$) and relatively small standard errors observed in the estimates of daily average of net radiation using BRM particularly for Bremgarten and Geiersnest are in support of Equation (5) and do confirm that, on a general basis R_{nl} has negligible variation when compared to that of G. Consequently, BRM is a fairly good predictor of R_n on general basis. The relatively low correlation coefficient ($R = 0.841$) and somewhat high standard error obtained for the regression model of Feldberg could be attributed mainly to the dominant effect of snow cover and the resulting radiative processes during the winter period. At the high elevation of Feldberg (and to a lesser extent Geiersnest), especially under winter and late autumn anticyclonic inversion conditions, the atmosphere is transparent possessing high clearness index and good visibility. Solar radiation is hence essentially unimpeded and stronger at these sites in comparison to Bremgarten. In spite of the relatively high solar radiation at Feldberg during this period, the high values of albedo emanating from pronounced snow cover gives rise to comparatively lower R_{ns}, higher E_{eff} and hence small R_n which in turn is not strictly proportional to the relative high G during this period. Consequently the combined effects of snow cover during the winter period and to some degree, convective cloudiness during summer, both of which may lead to a non-proportionality between R_n and G, explain the reason for the lower R and higher S_{R_n} associated with the regression model reported for Feldberg in Table I (see also Table IV). In general, each of the basic regression models in Table I is an index of the surface radiative exchange processes pertinent to each site.

Taking the median of the coefficients A and B from twenty-three empirical models for the estimation of R_n over grass, similar to Equation (5), proposed by Shaw (1956) for Iowa; Clothier *et al.* (1982) for New Zealand; Hu and Lim (1983) for Malaysia; Montheith and Szeicz (1961) for England and likewise for 19 more sets of results (Linacre, 1992), the following equation results:

$$\left\langle [R_n]_n^\tau \right\rangle = 0.66 \left\langle [G]_n^\tau \right\rangle - 28. \tag{6}$$

In addition, measurements published by Berliand (1970) taken worldwide during the International Geophysical Year in 1957/1958 produced the relationship

$$\left\langle [R_n]_n^\tau \right\rangle = 0.63 \left\langle [G]_n^\tau \right\rangle - 40. \tag{7}$$

The basic regression models presented in Table I for the three sites under investigation are in good agreement with those reported by other investigators as summarised in Equations (6) and (7).

4.2. Estimating hourly values of daytime net radiative flux under all sky conditions

4.2.1. *Applying the basic regression model*

Since the leading component of the daytime (with $G > 0$) net radiation is the global solar radiation, further attempt was made to model daytime hourly values of R_n by utilising only G. The regression models and correlation coefficients using instantaneous daytime measurements (represented here by index d) of R_n and G under all sky conditions for Bremgarten (Br), Geiersnest (Ge) and Feldberg (Fe) over a four-year period (1992–1995) is presented in Table II. The mean absolute error (MAE)

TABLE II

Regression models and correlation coefficients using instantaneous hourly daytime measurements of R_n and G under all sky conditions for Bremgarten (Br), Geiersnest (Ge) and Feldberg (Fe) in southern Upper Rhine Valley, based on 1992–1995 REKLIP data-set

Site code	Basic regression model for daylight R_n (fluxes in Wm^{-2})	Correlation coefficient R
Br	$[R_n]_d^\tau = 0.63[G]_d^\tau - 25.7$	0.984
Ge	$[R_n]_d^\tau = 0.63[G]_d^\tau - 29.6$	0.964
Fe	$[R_n]_d^\tau = 0.55[G]_d^\tau - 23.6$	0.914

TABLE III

Annual mean albedo a, longwave exchange coefficient λ and applications of the regression models of Equation (12) and (10) for the three sites Bremgarten (Br), Geiersnest (Ge) and Feldberg (Fe) using all hourly daytime measurements from 1992 to 1995 (with R_n, R_{ns} and R_{nl} in Wm^{-2})

Site code	a (%)	λ	Modified Regression Model (MRM)		
			Regression model (12)	R	Regression model (10)
Br	22	–0.20	$[R_n]_d^\tau = 0.80[R_{ns}]_d^\tau - 24.5$	0.986	$[R_{nl}]_d^\tau = -0.20[R_{ns}]_d^\tau - 24.5$
Ge	26	–0.19	$[R_n]_d^\tau = 0.81[R_{ns}]_d^\tau - 25.7$	0.980	$[R_{nl}]_d^\tau = -0.19[R_{ns}] - 25.7$
Fe	36	–0.22	$[R_n]_d^\tau = 0.78[R_{ns}]_d^\tau - 17.8$	0.978	$[R_{nl}]_d^\tau = -0.22[R_{ns}] - 17.8$

TABLE IV

Mean absolute error (MAE) between R_n (measured) and R_n (estimated by BRM, MRM and CIRM) based on all daytime hourly values from 1992 and 1995 for Bremgarten, Geiersnest and Feldberg in Southwest Germany

Site code	MAE between R_n (measured) and R_n (estimated by BRM)	MAE between R_n (measured) and R_n (estimated by MRM)	MAE between R_n (measured) and R_n (estimated by CIRM)
Br	0.18	0.17	0.14
Ge	0.24	0.23	0.17
Fe	0.50	0.25	0.37

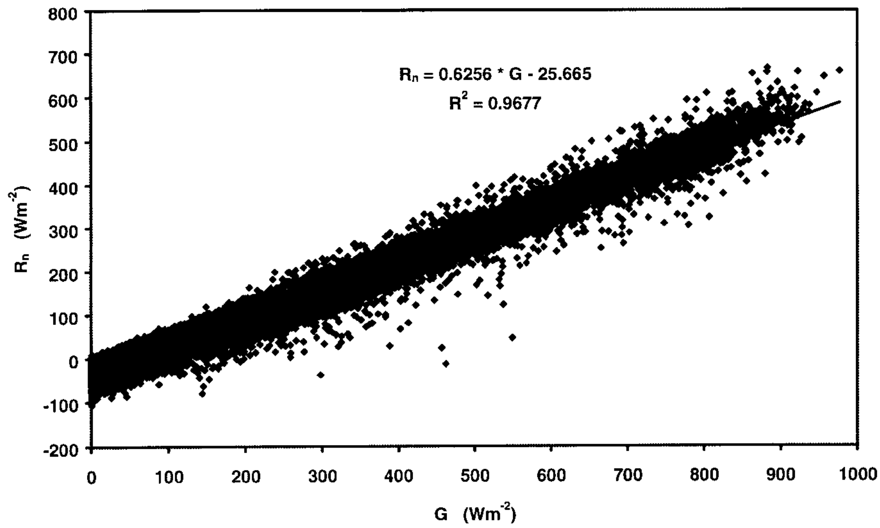

Figure 1. Plot of hourly values of net radiative flux R_n versus shotwave solar radiation G during daytime for Bremgarten, Southwest Germany (1992–1995).

between measured hourly R_n and those estimated by the basic regression models in Table II are later presented in Table IV.

It might be expected that the constants A and B of the regression model given in Table II would be different for averaging period less than 24 hours, because of the difference between daytime and nocturnal radiation conditions since there is no shortwave radiation at night. However, reduction of G, by including the zero value after sunset to obtain a 24-hour mean as in Table I, offsets the negative net irradiance during the night so that the constants A and B observed in Table II are much similar to those in Table I. It should be emphasised here that the constants of regression A and B in Tables I and II do not represent $(1 - a)$ and R_{nl} respectively (Gay, 1971) since R_{ln} will not necessarily remain constant over irradiated surfaces, but instead may vary with R_{ns}. However, the relative lower constant of regression A obtained for Feldberg in Tables I and II is indicative of the higher annual mean surface albedo at this site in comparison to the other two sites.

Linacre (1992) reports that the median of the coefficients A and B from empirical models for the estimation of daytime instantaneous values of R_n over various surfaces (e.g. grass, pasture, vineyard) as proposed by 10 different Workers (including Kalma, 1972 for Australia; Nkemdirim, 1972 for Canada and Penney, 1981 for South Australia) yields

$$[R_n]_d^\tau = 0.63[G]_d^\tau - 23. \quad (8)$$

Again this result is in agreement with those presented in Table II. Figure 1 presents the correlation between daylight measurements of net radiative flux and global solar radiation for Bremgarten.

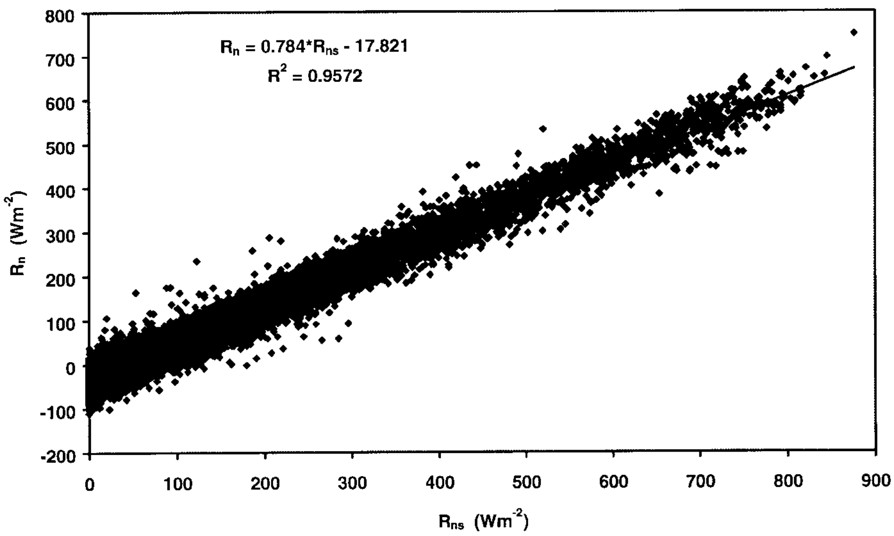

Figure 2. Plot of daytime hourly values of net radiative flux R_n versus absorbed shortwave radiation R_{ns} for Feldberg, Southwest Germany (1992–1995).

4.2.2. *Modified regression model (MRM)*

Equation (5) can be modified by regressing R_n on the absorbed shortwave radiation in place of incoming solar radiation to yield

$$R_n = X(1 - a)G + Y = XR_{ns} + Y \tag{9}$$

where X and Y are again the constants of regression. This regression model which is here described as the modified regression model (MRM) is expected to perform better than the basic regression model (BRM) of Equations (4) and (5) since it includes shortwave albedo which varies with surface conditions, solar elevation and altitude above sea level. This negates the supposition of Allen *et al.* (1994) and Snyder *et al.* (1998) that surface albedo could be assumed as constant in radiative computations. Taking surface albedo to be constant would overlook the role that albedo may play in generalizing the regression relations developed over surfaces with different surface reflectance. In view of this, the inclusion of surface albedo as in Equation (9) is justifiable and indeed recommended to enhance more predictive relations.

By combining Equations (1) and (9), R_{nl} can be expressed as a linear function of R_{ns} thus

$$R_{nl} = (X - 1)R_{ns} + Y. \tag{10}$$

Defining dR_{nl}/dR_{ns} as λ (the longwave exchange coefficient), Equation (10) yields

$$\lambda = dR_{nl}/dR_{ns} = (X - 1) = (R_{nl} - Y)/R_{ns}. \tag{11}$$

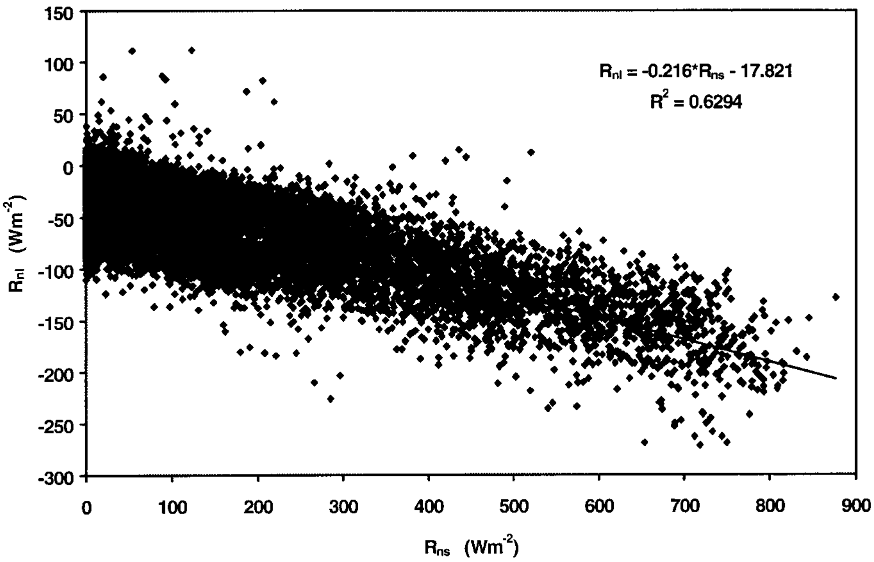

Figure 3. Plot of daytime longwave net radiation R_{nl} versus absorbed shortwave radiation R_{ns} for Feldberg, Southwest Germany (1992–1995).

With $G = 0$, $R_{nl} = L_0$ such that $Y = L_0$ in Equation (10). Adding R_{ns} to both sides of Equation (10) gives

$$R_n = (1 + \lambda)R_{ns} + L_0. \tag{12}$$

λ can be considered as an index to surface thermal response. Thus $\lambda = 0$ would imply that an increase in R_{ns} is completely partitioned into evapotranspiration such that the surface temperature remains unchanged and that R_{nl} does not change with an increase in R_{ns}. Figure 2 presents the plot of daytime hourly net radiative flux as a function of the absorbed shortwave radiation for Feldberg, while Figure 3 presents the plot of the corresponding daytime hourly values of longwave net radiative flux versus the absorbed shortwave radiation for Feldberg. The relative lower correlation coefficient of Figure 3 is partly due to the fact that G does not play the explicit role of a sole independent variable here. For more details, Table III presents the values of the longwave exchange coefficient λ and the results emanating from the modified regression models as given by Equation (12) and (10) for the three sites Bremgarten (Br), Geiersnest (Ge) and Feldberg (Fe) using hourly daytime measurements from 1992 to 1995 (with R_n, R_{ns} and R_{nl} in Wm^{-2}). The computed annual average of surface albedo a during the 4-year period is also presented in the table. As shown in Table III, the longwave exchange coefficient is seen to be negative for all three sites averaging about –0.20. The implication of this is that R_{ns} increases more rapidly than does the energy flux that is partitioned into evapotranspiration at the surface. The excess of sensible heat flux that is made available at the surface in this way subsequently gets transformed into convection

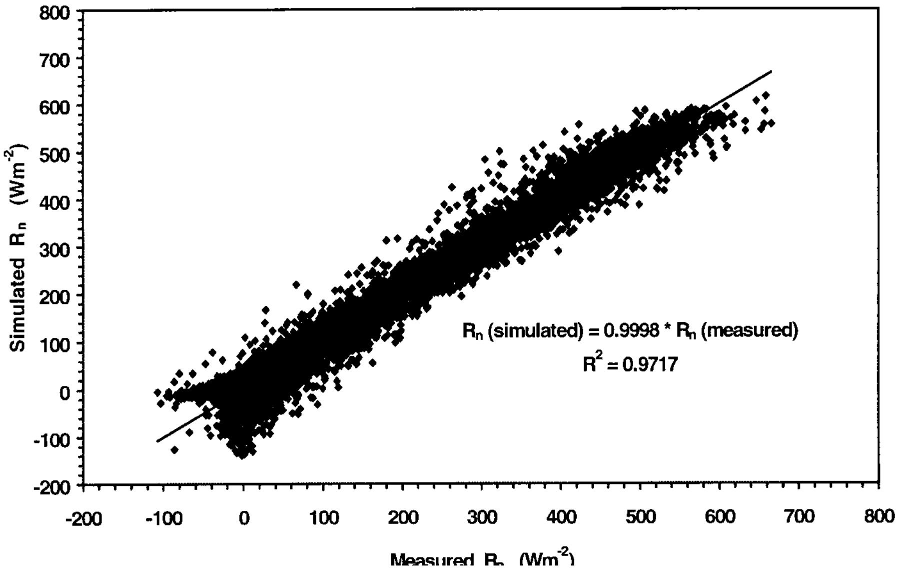

Figure 4. Hourly values of daytime measured R_n and computed R_n using CIRM model for Bremgarten, Southwest Germany (1992–1995).

and change in storage. With a more rapid increase in surface temperature, R_{nl} becomes more negative thus giving rise to negative longwave coefficient λ at the three sites. Moreover, it follows from Table III, that with an increase from 0 to 1.0 Wm^{-2} in R_{ns}, an increase $\Delta R_n = 0.8$ Wm^{-2} is recorded in Bremgarten and Geiersnest and a corresponding $\Delta R_n = 0.78$ Wm^{-2} in Feldberg. Apart from the fact that the MRM (Equation 12) takes cognisance of the surface albedo, the higher correlation coefficient in comparison to Table II also attests to its suitability over the BRM expressed in Equations (4) and (5).

4.2.3. *Clearness index regression model (CIRM)*

Another possible means of modelling daytime net radiative flux abounds in the incorporation of clearness index K_T into the basic regression model of Equation (5). K_T is here given by G/E_0 where E_0 is the extraterrestrial irradiance. E_0 was computed on hourly basis for each of the sites according to VDI (1994) and Badescu (1997). This form of empirical model (CIRM) which couples G with K_T would be particularly helpful for locations where measurements of shortwave albedo are not available. The notion of introducing K_T is justified by its dependence on sky conditions and atmospheric turbidity both of which affect the net radiative budget at the surface. Consequently, by inputting hourly mean values of measured G (in Wm^{-2}) and computed K_T obtained in the period from 1992 to 1995, measured daytime hourly net radiative flux (in Wm^{-2}) at the sites of investigations have been modelled and found to yield the following relations.

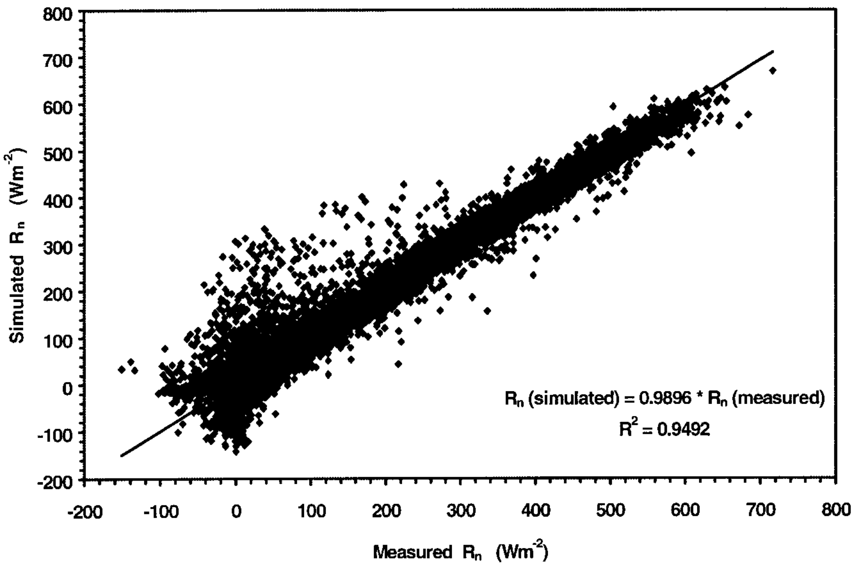

Figure 5. Hourly values of daytime measured R_n and simulated R_n using CIRM for Geiersnest, Southwest Germany (1992–1995).

$$[R_n(\mathrm{Br})]_d^\tau = 0.76[G]_d^\tau - 147.5[K_T]_d^\tau - 4 \tag{13}$$

$$[R_n(\mathrm{Ge})]_d^\tau = 0.77[G]_d^\tau - 146[K_T]_d^\tau - 6 \tag{14}$$

$$[R_n(\mathrm{Fe})]_d^\tau = 0.81[G]_d^\tau - 160[K_T]_d^\tau - 28. \tag{15}$$

Figures 4 and 5 present measured versus simulated values of R_n for Bremgarten and Geiersnest on applying CIRM (in this case, Equations 13 and 14 respectively). There is a close agreement between the magnitude of R_n computed from the above relations and those obtained from measurements as indicated by the regressions equation and coefficients.

4.2.4. *Mean absolute error between actual measurements and those emanating from the foregoing proposed regression models*

The mean absolute error (MAE) between R_n (measured) and R_n (estimated by applying BRM, MRM and CIRM) based on all daytime hourly values from 1992 to 1995 is presented in Table IV. The mean absolute errors between measured R_n and estimated R_n (using MRM) are smaller for all sites when compared to those between measured R_n and estimated R_n using BRM although the difference is just slight for Bremgarten and Geiersnest where the surface albedo is relatively low. On the other hand, the wide margin between the mean absolute error (MAE) with respect to BRM and MRM (Δ MAE = 0.25) for Feldberg stresses the role played by albedo on the net radiative budget of this mountainous site. All the aforementioned factors favour MRM more than BRM for a more predictive estimation of R_n at the sites. In addition, the MAE emanating from the application of CIRM are the smallest (when compared to BRM and MRM) for Bremgarten and Geiersnest been 0.14 and 0.17 respectively. In view of this, CIRM appears to be the most suitable of the three aforementioned regression models for estimating the daytime net radiative flux for Bremgarten and Geiersnest. For Feldberg, MRM, which takes cognisance of albedo, possesses the least mean absolute error (as compared to CIRM and BRM) and hence recommended over the other two.

4.3. EXTENDED REGRESSION MODEL (ERM): INCORPORATING AIR TEMPERATURE

Comparing Equations (9) and (5) with (1) it becomes obvious that the significance of the effective terrestrial radiation has been undermined. Consequently BRM, MRM and CIRM are best suitable for the daytime estimate of R_n and thus limited in their applications. The effective terrestrial radiation E_{eff} dominates the net radiative budget at night due to the deficit of global solar radiation during this period. Assuming that the longwave reflected radiation is negligible, E_{eff} then amounts to the difference between E and A. The outgoing longwave terrestrial radiation E, which is a function of the surface temperature, is given by $\varepsilon\sigma T_s^4$ where ε, T_s and σ denote the surface emissivity, surface temperature and Stefan-Boltzmann constant respectively. On the other hand the atmospheric counter radiation A is a function of cloudiness, air temperature T_a, CO_2 and water vapour content of the underlying surface.

For a clear sky condition, A can be expressed as $f(\sigma T_a^4, VP)$ where VP denotes water vapour pressure. Since cloud amount, CO_2 and water vapour content of the atmosphere are somewhat indicative of the air temperature, it can be assumed that the air temperature plays a dominant role in determining A. Furthermore, since the atmosphere is essentially transparent to shortwave solar radiation, but absorbs outgoing longwave radiation from the surface, it follows that the atmosphere is heated from below. Consequently air temperature is dependent on the surface temperature. From the foregoing, it becomes evident that the air temperature is the major independent variable for the effective terrestrial radiation. In light of this, the regression model giving in Equation (9) can be further extended to include air temperature for estimating the net radiative flux during all hours of the day viz:

$$R_n = M(1-a)G + N\sigma T_a^4 + P = MR_{ns} + N\sigma T_a^4 + P \quad (16)$$

where M, N and P are constants of regression.

Applying the extended regression model (ERM) given in Equation (16) the following relations were obtained for the three sites.

$$[R_n(\mathrm{Br})]_n^\tau = 0.82[(1-a)G]_n^\tau - 0.027\sigma[T_a^4]_n^\tau - 37 \quad (17)$$

$$[R_n(\mathrm{Ge})]_n^\tau = 0.855[(1-a)G]_n^\tau - 0.028\sigma[T_a^4]_n^\tau - 38.4 \quad (18)$$

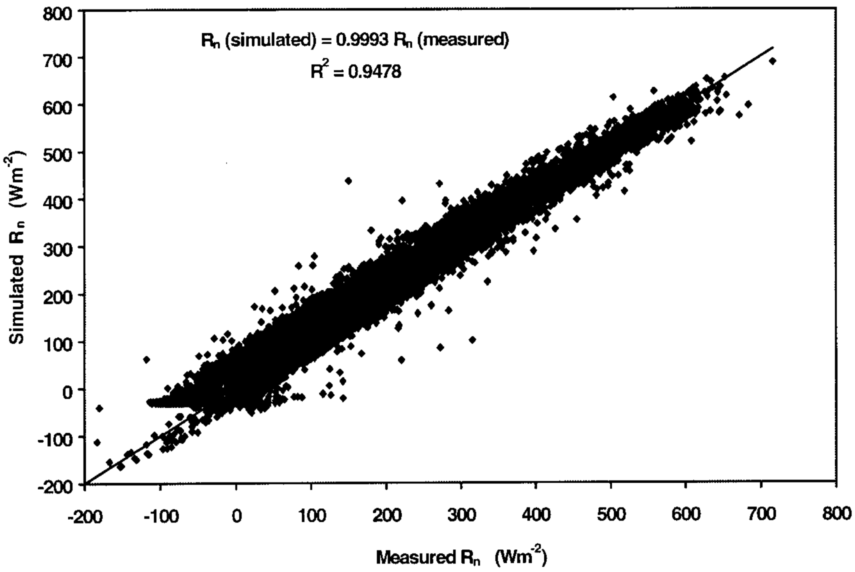

Figure 6. Hourly values of measured R_n and simulated R_n using ERM for Geiersnest, Southwest Germany (1992–1995).

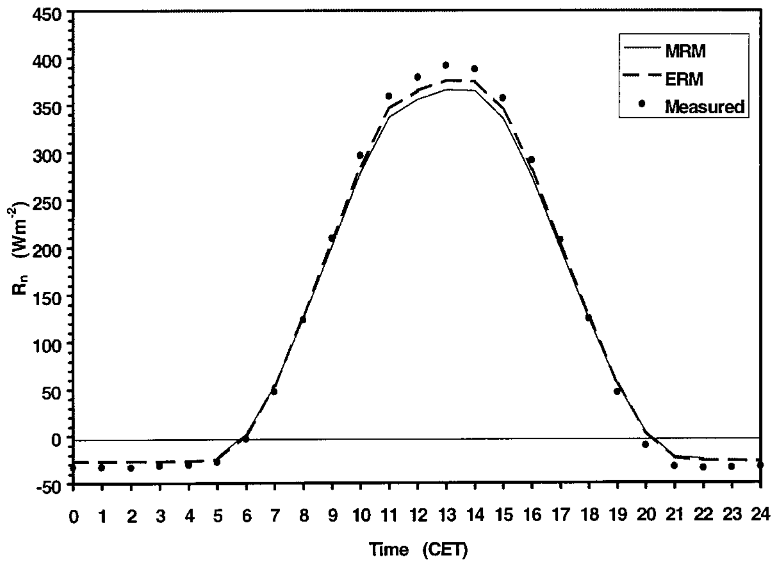

Figure 7. Monthly mean diurnal variation of net radiative flux R_n as measured and simulated by MRM and ERM for the month of June for Bremgarten, Southwest Germany (1992–1995).

TABLE V

Summary of the regression equation {R_n (simulated) = C R_n (measured)} and regression coefficients emanating from the application of ERM to all hourly REKLIP data from 1992–1995

Site code	R_n (simulated) = C R_n (measured)	Correlation coefficient R
Br	R_n (simulated) = 0.9996 R_n (measured)	0.986
Ge	R_n (simulated) = 0.9993 R_n (measured)	0.974
Fe	R_n (simulated) = 0.9998 R_n (measured)	0.968

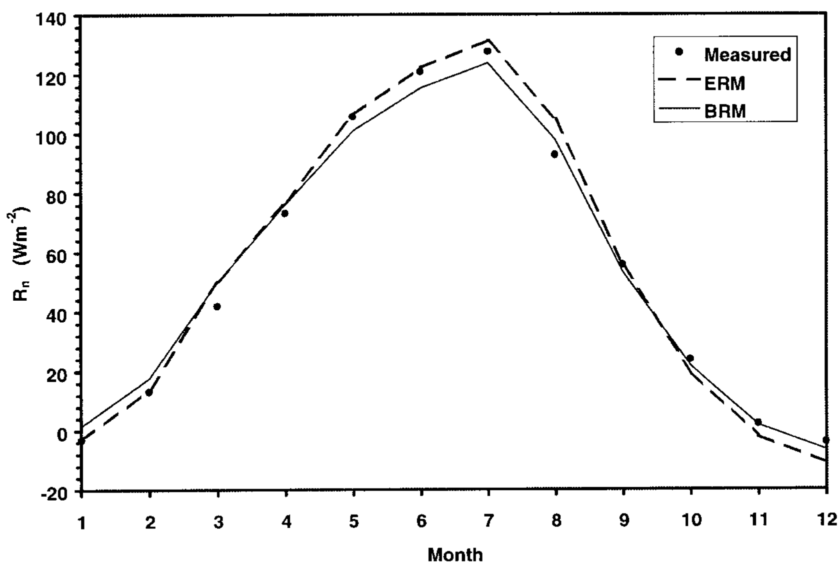

Figure 8. Monthly average of net radiative flux R_n as measured and simulated by BRM and ERM for Bremgarten, Southwest Germany (1992–1995).

$$[R_n(\text{Ge})]_n^\tau = 0.855[(1-a)G]_n^\tau - 0.028\sigma[T_a^4]_n^\tau - 38.4 \qquad (19)$$

In Equations (17) to (19), T_a is in K, while G and R_n are in Wm^{-2}. Using all hourly mean values of measured G, T_a, a and R_n for each day from 1992 to 1995, Table V presents a summary of the ratio of the measured R_n to those simulated on applying ERM as well as the corresponding correlation coefficients. Figure 6 presents the case for Geiersnest. Furthermore, Figure 7 presents the monthly mean diurnal variation of R_n for the month of June for Bremgarten using measured values and those simulated using MRM and ERM while Figure 8 presents the monthly mean daily averages simulated using both ERM and BRM. These results are quite satisfactory as there is close agreement between simulated and measured values. For instance, the diurnal and monthly mean values of R_n for Bremgarten simulated using ERM and those obtained from actual measurements are observed to agree to about 10% on a general basis.

5. Summary and Conclusions

This work proposes four types of regression models for the estimation of net radiative flux for three different sites located in an area with orographic variability. Some studies in the past have sought to relate the net radiative flux over natural surfaces to incoming shortwave radiation only. However limitations in the interpretation of such simple regression models (BRM) associated with the surface heating coefficient does exist. In order to correct this deficiency, a longwave exchange coefficient λ, which relates the change in net longwave radiation to that of absorbed shortwave radiation, has been introduced. λ was observed to amount to an average of –0.20 for Bremgarten and Geiersnest, while it amounted to –0.22 for Feldberg. Apart from the fact that the coefficient λ is affected by environmental properties, it may serve as an indicator of such surface characteristics which controls the dissipation of net shortwave radiation. Furthermore the role of clearness index and air temperature in the estimation of the net radiative flux have each been examined, thus giving rise to the clearness index regression model (CIRM) and extended regression model (ERM) respectively. The efficiency of CIRM in predicting daytime values of R_n (particularly for Bremgarten and Geiersnest with relatively lower annual albedo) is slightly higher than BRM and MRM although all three regression models have been observed to perform relatively quite well yielding mean absolute error less than 0.25 for these two sites. For the mountainous site of Feldberg, MRM which takes cognisance of albedo, yielded the least mean absolute error (as compared to CIRM and BRM) and hence recommended over the other two. Diurnal and monthly mean values of R_n arising from actual measurements and those emanating from the extended regression model (ERM) have been found to agree generally to within 10%. The extensiveness of the data-set utilised in this study coupled with the statistics between measured and simulated values of R_n lend credibility to the ensuing regression models. Having considered in this present work, such parameters as global solar radiation, surface albedo, clearness index and air temperature for estimating the net radiative flux, subsequent investigations would seek to incorporate further elements including sunshine duration and water vapour pressure to enhance more strictly predictive relations.

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