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Estimation of solar radiation from temperature and rainfall observations

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ABSTRACT

An attempt has been made to evaluate the accuracy and applicability of nine models for estimating daily solar radiation (Q) from commonly measured meteorological variables in Hyderabad region of India using three types of input parameters: only temperature, only rainfall and both temperature and rainfall data. The STATISTICA software was used for non-linear multi variate regression. To overcome the seasonal heterogeneity of error, all equations were divided by daily extra terrestrial radiation. The r^2 between estimated Q and measured Q was 0.35-0.69, 0.15-0.54 and 0.38-0.72; RMSE was 2.44-4.93, 2.68-5.33 and 2.42-4.84 MJ m^{-2} for the model that included temperature (minimum and maximum) and rainfall and both rainfall and temperature, respectively. In general, the models using both temperature and rainfall, and only temperature gave similar results. Also, the model which expressed rainfall as a binary quantity (1 for rainfall> 0, 0 for rainfall = 0) does not perform better than those using amount of rainfall (mm). The performance of the models were also compared with the Angstrom equation (r^2 = 0.18-0.28, RMSE = 4.76-5.79 MJ m^{-2}) which use the daily sun shine hours. All nine models performed better than the Angstrom's equation. But to substantiate this, all the models should be tested at some other stations of India.

Key words: Solar radiation, Rainfall, Air temperature

Solar radiation is the fundamental source of energy, activating not only vital biological processes on the earth but also all meteorological systems on micro and macro scales. Daily solar radiation (Q) is required by most models that simulate crop growth based on the photosynthetic process. However, it is an infrequently measured meteorological variable, compared to other parameters like temperature and rainfall. Lack of solar radiation data is not only common in India but also in countries, such as USA (Richardson, 1985; Hook and McClendon, 1992), Australia (Liu and Scott, 2001) and Canada (De Jong and Stewart, 1993), and can be a major limitation to the use of crop growth simulation models.

The need for solar radiation data for crop models has led researchers to develop a number of methods for simulating such data. Some crop modelers (e.g., Rosenthal *et al.*, 1989) have incorporated stochastic weather generators to simulate solar radiation and other weather inputs based on probabilistic criteria. Sharpley and Williams (1990) adopted this approach to generate radiation data using only the monthly means of daily radiation as input. Stochastic generated data may be useful to explore possible model scenarios for an average theoretical situation of long term simulation. It has limitations when used for model validation and simulation analysis for a specific period of time as the method may not generate the data to match the actual weather extremes (Wallis and Griffiths, 1995).

A number of techniques are available for estimating solar radiation. These vary in sophistication from simple empirical formulations based on common weather or climate data to complex radiative transfer schemes that explicitly model the absorption and scattering of the solar beam as it passes through the atmosphere. These more complex models are capable of highly accurate estimates of incoming solar radiation. However, they tend to be too complex and data - intensive for operational use, or are limited by requirements for site specific data which are unavailable outside of a few locations (Goodin *et al.*, 1999).

Using empirical relationships requires the development of a set of equations to estimate solar radiation from the commonly measured meteorological variables. A number of formulae and methods have been reported using this approach (Fitzpatrick and Nix, 1970; Bristow and Campbell, 1984; Richardson, 1985; Hook and McClendon, 1992; De Jong and Stewart, 1993). Daily total extraterrestrial radiation (Q_O) is often included in the relationships. The underlying approach is to express solar radiation reaching the earth surface (Q) as a fraction of Q_O. This is based on the attenuation of incoming radiation through the atmosphere. Hayhoe (1998) recently evaluated the empirical approaches for estimating solar radiation and compared them to stochastic weather generation (Sharpley and Williams, 1990). He found that an empirical model based on temperature and rainfall provided better estimates than the stochastic model.

The aim of the present study was to evaluate the accuracy and applicability of several models for estimating daily values of solar radiation (Q) for different situations: (a) only rainfall data available, (b) only temperature data available, and (c) both rainfall and temperature data available, for the Hyderabad region of India. The performance of the models was also compared with the Angstrom (1924) equation where daily sunshine hours were used as input.

MATERIALS AND METHODS

Three years (1996-98) daily meteorological data collected at Hayatnagar Farm of Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad (17°27'N, 78°28'E) were used to get the constants of the equations. The farm situation represents semi-arid tropical region of Peninsular India with an average annual rainfall of 733 mm and potential evapotranspiration of 1754 mm (Ramana Rao *et al.*, 1993). Nearly 70 percent of the total precipitation is received during the southwest monsoon season (June to

September). Daily weather data of minimum temperature, maximum temperature, rainfall and solar radiation were recorded by automatic weather station (Campbell Inc. Logan, USA) with a CR-10 Data Logger installed in the farm. The automatic station was equipped with LI-COR silicon-cell photodiode Pyranometer for measuring solar radiation (MJ m^{-2} d^{-1}), thermister-thermometer (calibrated to Stevenson screen measurement) for minimum and maximum air temperature measurement and tipping bucket rainguage for rainfall measurement.

Estimation of solar radiation using temperature

Bristow and Campbell (1984) developed a model for estimation of solar radiation reaching the earth's surface (Q), based on the fraction of daily total atmospheric transmittance of the extra-terrestrial solar radiation (Q_0), which is determined by the range of daily air temperature extremes (D) as

$$Q = Q_0 a(1 - \exp(-bD^c)) \qquad (1)$$

where a, b, and c, are empirical coefficients, determined for the particular site from measured solar radiation data. D is diurnal range of air temperature and is calculated as

$$D = T_{max} - \frac{T_{min}(j) + T_{min}(j-1)}{2}$$

where T_{max} is the daily maximum temperature (°C), $T_{min}(j)$ and $T_{min}(j+1)$ the daily minimum temperature (°C) on the day and the next day, respectively. Bristow and Campbell (1984) included an adjustment for the measured D on the rainy days, by setting D equal to 0.75 times the measured D as the rainfall can be another manifestation of cloud cover. However, this has not been included as an adjustment for estimating radiation.

Two other models estimating solar radiation from temperature data were Eq. (2) (Richardson, 1985) and Eq. (3) (Hargreaves *et al.*, 1985):

$$Q = Q_0 a (T_{max} - T_{min})^b \qquad (2)$$

$$Q = Q_0 a \sqrt{T_{max} - T_{min}} + b \qquad (3)$$

where a, b are the coefficients.

Estimation of solar radiation using rainfall

McCaskill (1990a) reported a method using Fourier series with incorporated rain-day information as

$$Q = a + b\cos(0) + c\sin(0) + d\cos(20) + e\sin(20) + fR_{j-1} + gR_j + hR_{j+1} \qquad (4)$$

where q is the day of the year converted to radian, R the transformed rainfall data and its subscripts j - 1, j and j + 1 refer to the previous, current and next days and a, b, c, d, e, f, g and h are the coefficients determined by regression. The transformation used to calculate R (rainfall) data was to encode rain-days: if P > 0, R = 1; P = 0, R = 0, where P is precipitation.

Eq. (4) does not include Q_0, but the site-specific coefficients (a, b, c, d, and e) with the functions of Fourier series, will empirically describe the seasonal changes of radiation at the site where the data were collected. In another report, McCaskill (1990b) related Q to Q_0 and rain-day information as

$$Q = aQ_0 + bR_{i-1} + cR_i + dR_{i+1} \quad (5)$$

where a, b, c and d are coefficients determined by regression and R is as defined in Eq.(4). The coefficient a is the atmospheric transmittance with no rainfall recorded on the day, the day before or the day after, while b, c, and d are the amounts of radiation reduction (MJ m^{-2}) when it rained on the day before, on the day and on the day after, respectively.

Estimation of solar radiation using both temperature and rainfall

De Jong and Stewart (1993) used precipitation and the range of daily temperature extremes for estimation of solar radiation as

$$Q = aQ_0D^b(1 + cP + dP^2) \quad (6)$$

where P is the total precipitation (mm) on the day, D is defined as in Eq.(1). Eq. (6) expressed the effect of precipitation on radiation as multiplicative.

Hunt *et al.*, (1998) developed Eq. (7) to include the effect of P as an additive formula:

$$Q = aQ_0\sqrt{T_{max} - T_{min}} + bT_{max} + cP + dP^2 + e \quad (7)$$

where a, b, c, d, e are the coefficients.

By analyzing various forms with both temperature and rainfall variables across Australia, Liu and Scott (2001) proposed two equations in the form of

$$Q = Q_0a(1 - \exp(-bD^c))(1 + dR_{i-1} + eR_i + fR_{i+1}) + g \quad (8)$$

$$Q = Q_0a(1 - \exp(-bD^c)) + dR_{i-1} + eR_i + fR_{i+1} + g \quad (9)$$

where a, b, c, d, e, f and g are the coefficients and D and R are as defined in Eqs. (1) and (4), respectively.

Calculation of daily extraterrestrial solar radiation (Q_0)

Each day's Q_0 was determined as a function of site latitude using the equation given by Gates (1980):

$$Q_0 = 86400S_0(\bar{d}/d)^2(h_s \sin\phi \sin\delta + \cos\phi \cos\delta \sin h_s)/1000000\pi$$

Where S_0 is the solar constant (1360 W m^{-2}), $\bar{d}$ is the mean value of the distance from sun to earth, d is the distance from sun to earth, h_s is the half day length, ϕ is the latitude of the location of interest, δ is the solar declination. Solar declination and latitude, and hence daylength, are in radians. The $(\bar{d}/d)^2$ never differs by more than 3.5% from unity (Gates, 1980) and was therefore taken as unity.

$$h2 = \pi/2 - ATAN(X/\sqrt{1 - X^2})$$

(Campbell and Diaz, 1988)

ATAN is arctangent, the angle whose tangent is in radians

$X = \sin \phi \sin \delta \;/(\cos \phi \cos \delta)$

$\delta = 0.39785\sin(4.869 + 0.0172\, J_d + 0.03345\sin(6.224 + 0.0172\, J_d))$

J_d = days of the year (Julian)

Angstrom (1924) equation was used as base to evaluate the performance of other models

$Q = Q_0(a + bn/N)$

Q_0 = Daily extra-terrestrial radiation, Q = Solar radiation, n/N = ratio between actual and possible hours of bright, sunshine, a and b are constants varying with the station, a = 0.14, b = 0.55 for Hyderabad (17.4° N) (Gangopadhayay, *et al.*, 1970).

Calculation of N (Jones *et al.*, 1986)

N = 7.639 Acos (DLV)
Acos = arccosine of a number.
$DLV = (-\sin\phi\sin\delta - 0.1047)/(\cos\phi\cos\delta)$
ϕ latitude in radians, δ is solar declination

Data analysis

The STATISTICA software (Statsoft, 1998) was used for nonlinear multivariate regression to determine the constants. In order to overcome the seasonal heterogeneity of error, all equations were divided by Q_o. The coefficients of models were validated using the second set of data of the year 1995 and 1999 for the same station. Goodness of fit for validations was assessed by squared correlation coefficients (r^2) between the estimated Q and recorded Q and the root mean square error (RMSE) associated with the estimation. Willmott (1982) proposed an 'index of agreement' (D) to evaluate model performance. The value of D is calculated as follows

$$D = 1 - [\Sigma (P - O)^2 / \Sigma(|P - \overline{O}| + |O - \overline{O}|)^2]$$

where $\overline{O}$ = mean of observed values, P = predicted value, O = observed value.

Willmott also suggested the use of both systematic (MSE_s) and unsystematic (MSE_u, random) error terms. The Mean Square Error (MSE) is made up then of the systematic and the unsystematic portion that is MSEs and MSEu, respectively:

$MSE = MSE_s + MSE_u$,

$MSE_s = n^{-1}\Sigma(P_i - O)^2$,

$MSE_u = n^{-1}\Sigma(P - P_i)^2$

where $P_i = a + bO$; n is the number of observations; and a and b are regression coefficients of the intercept and slope, respectively. Systematic error is related to the model performance and random error is related to observations or measurements.

RESULTS AND DISCUSSION

The values of each coefficient used in nine models (Eq.1- Eq.9) were used (Table 1) to compare the model performance by comparing with the recorded daily solar radiation data for the year 1995 and 1999 at the same station. The performance of the nine models along with results from Angstrom equation is presented in Fig.1 (Eq. 1 to Eq. 9) and Table 2. The performance of the model for 1995 varies with the year 1999. One possibility is that there may be inconsistency of

Table 1: Values of each constant, used in different models (Calculated by using STATISTICA Software)

No.	Equations	a	b	c	d	e	f	g	h
1	$Q = Q_0 a(1-\exp(-bD^c))$	0.5069	0.0673	1.2858					
2	$Q = Q_0\, a\, (T_{max} - T_{min})^b$	0.1367	0.4285						
3	$Q = Q_0\, a\sqrt{T_{max} - T_{min}} + b$	0.0902	2.7519						
4	$Q = a + b\cos(\theta) + c\sin(\theta) + d\cos(2\theta) + e\sin(2\theta) + fR_{i-1} + gR_i + hR_{i+1}$	13.9524	-1.3994	0.6523	-1.0793	-0.3525	-1.0483	-1.933	-0.6579
5	$Q = aQ_0 + bR_{i-1} + cR_i + dR_{i+1}$	0.4263	-1.5550	-2.3037	-1.4254				
6	$Q = aQ_0 D^b(1 + cP + dP^2)$	0.1396	0.4258	-0.0105	0.00009				
7	$Q = Q_0\, a\sqrt{T_{max} - T_{min}} + bT_{max} + cP + dP^2 + e$	0.0767	0.8380	-0.1440	0.0012	1.7744			
8	$Q = Q_0 a\,(1-\exp(-bD^c))\,(1 + dR_{i-1} + eR_i + fR_{i+1}) + g$	0.4146	0.0467	1.4734	0.0197	-0.0905	-0.0259	2.2811	
9	$Q = Q_0 a(1-\exp(-bD^c)) + dR_{i-1} + eR_i + fR_{i+1} + g$	0.4074	0.0528	1.4125	0.1914	-1.0506	-0.3047	2.5849	

Table 2: Statistics for testing the model performance

Equation No.	Year	r^2	RMSE ($MJ\ m^{-2}$)	D Index	MSE_s ($MJ\ m^{-2}$)	MSE_u ($MJ\ m^{-2}$)
1	1995	0.692	4.576	0.730	18.585	2.358
	1999	0.394	2.545	0.709	3.101	2.887
2	1995	0.690	4.723	0.687	20.801	1.511
	1999	0.347	2.544	0.663	3.971	2.024
3	1995	0.676	4.931	0.654	18.585	1.717
	1999	0.356	2.437	0.654	3.101	1.889
4	1995	0.472	5.332	0.603	26.652	1.771
	1999	0.149	2.684	0.555	4.899	2.047
5	1995	0.538	5.065	0.649	23.124	2.530
	1999	0.178	2.819	0.586	4.769	2.866
6	1995	0.716	4.668	0.705	23.124	1.734
	1999	0.377	2.530	0.676	4.769	2.270
7	1995	0.687	4.846	0.682	20.169	1.569
	1999	0.389	2.419	0.679	3.814	1.854
8	1995	0.681	4.737	0.708	21.963	2.171
	1999	0.399	2.440	0.712	3.748	2.539
9	1995	0.678	4.751	0.709	20.391	2.176
	1999	0.404	2.432	0.715	3.103	2.506
Angstrom Eq.	1995	0.278	5.786	0.704	9.649	23.824
	1999	0.177	4.757	0.530	5.328	17.302

*All r^2 values are statistically significant at 1% level

recorded data itself. The 1:1 line in Fig.1 indicated that most of the models overestimated in lower values of solar radiation but underestimated in higher ranges in 1995 but all the models overestimated for 1999. Among the three models using temperature data only (Eqs.1-3), Eq. 1 (Bristow and Campbell, 1984) had higher values of r^2 and lower RMSE. Das and Pujari (1993) also found that Bristow and Campbell (1984) equation was fairly accurate (70%) in estimating daily solar radiation. Eq.2 (Richardson, 1985) was more accurate than Eq. 3 (Hargreaves *et al.*, 1985). Of the models using rainfall only, the Eq. 5 performed better than Eq.4. Among the four models, which use both temperature and rainfall data (Eqs. 6-9) had similar r^2 and RMSE. The highest r^2 (0.716) was observed for Eq.

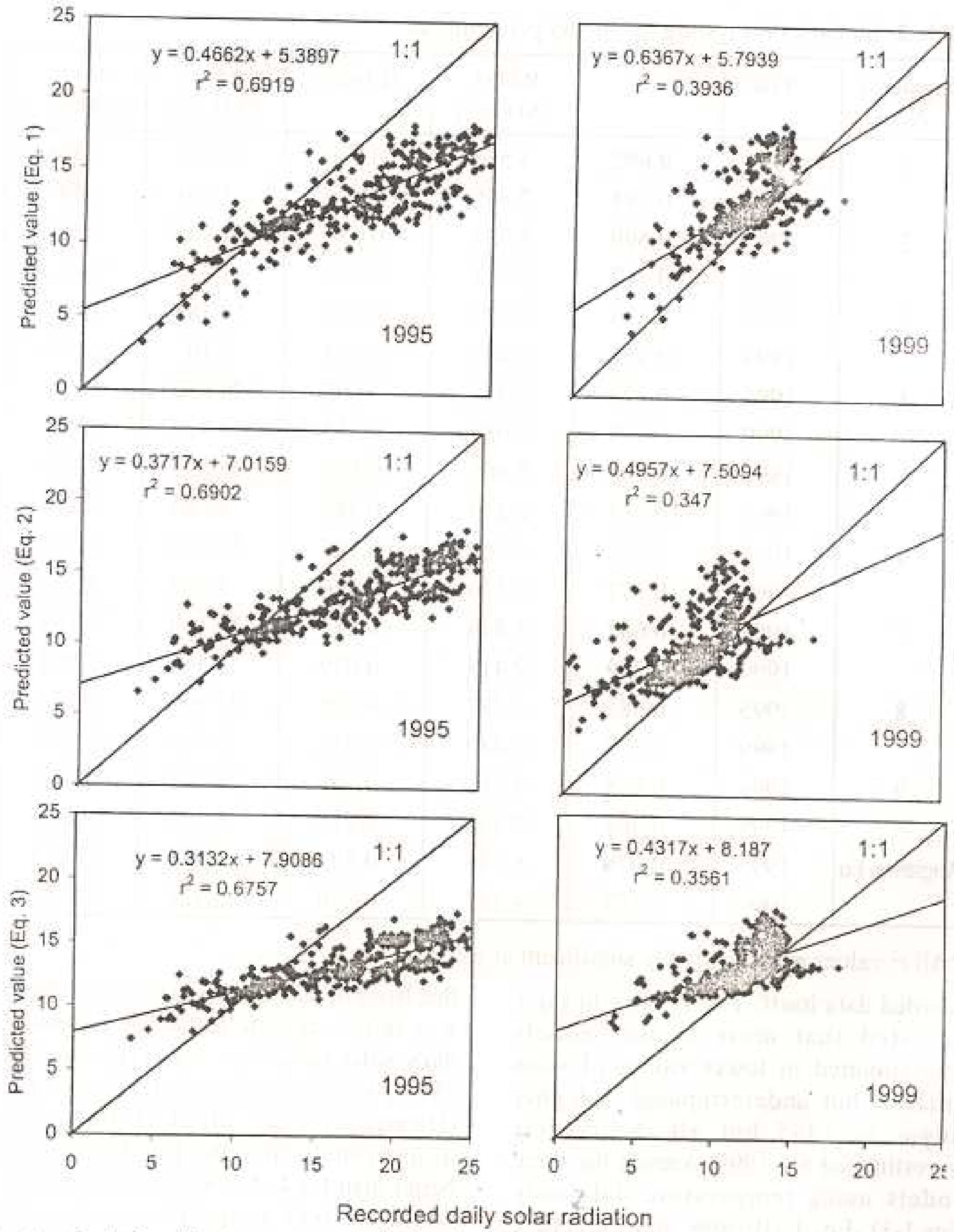

Fig.1a : Relationship between recorded and predicted daily solar radiation (MJ m^{-2} d^{-1}) at Hyderabad using equations (Eq.1 - Eq.3)

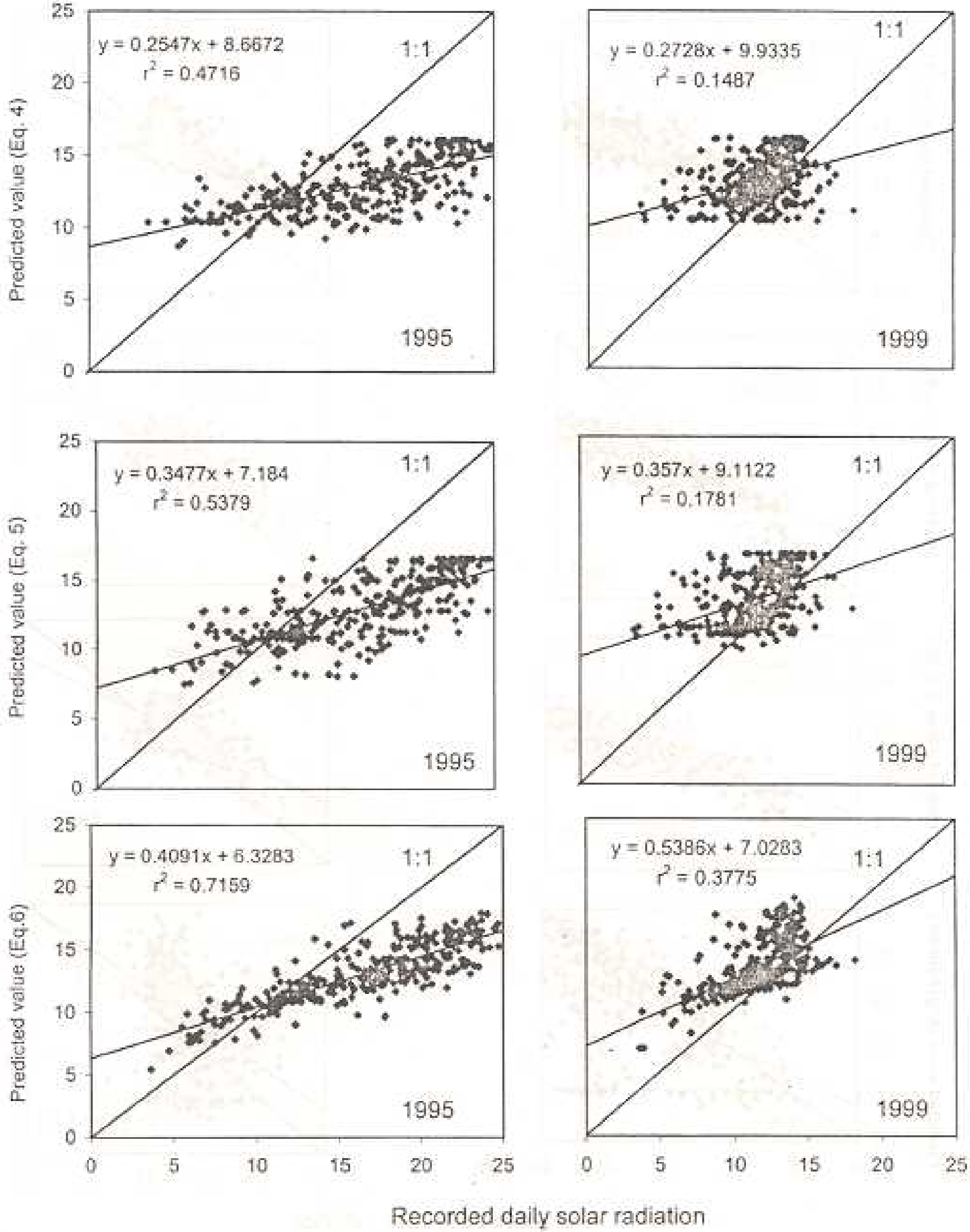

Fig. 1b : Relationship between recorded and predicted daily solar radiation (MJ m^{-2} d^{-1}) at Hyderabad using equations (Eq.4 - Eq.6)

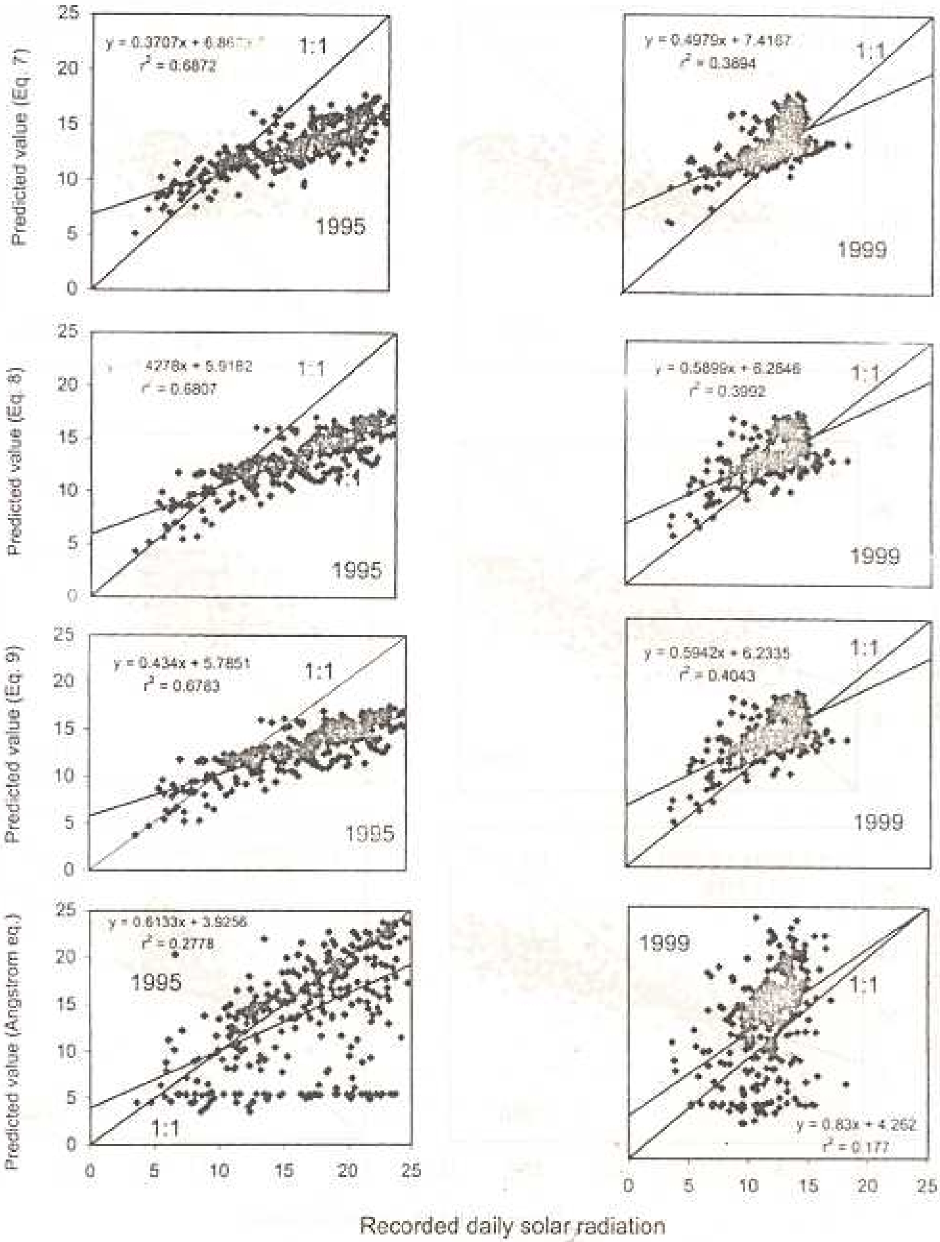

Fig.1c : Relationship between recorded and predicted daily solar radiation (MJ m^{-2} d^{-1}) at Hyderabad using equations (Eq.7 - Eq. 9)

6 in 1995 data set. It has also been noted that higher correlation coefficient values do not necessarily coincide with lower RMSE.

In general, the models using both temperature with rainfall and only temperature gave similar type of results. Also, the model which expressed rainfall as a binary quantity (1 for rainfall> 0, 0 for rainfall = 0) does not perform better than those using amount of rainfall (mm). Because in tropics, rainfall generally occurs for short period may be for one or two hours and remaining period of the day is mostly partly cloudy or clear. D index (index of agreement) performed better than r^2. But among the error components, major portion of error is contributed by systematic error (MSEs) rather than random error (MSEu), which indicate that none of the models perform well in Hyderabad region. Also all nine models performed better than the Angstrom equation in respect of r^2 but in Angtrom equation only major error is contributed by random error, which is related to observation or measurements. But to come to valid conclusions all the models should be tested at some other stations of India.

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