Evaluation of Atmospheric Transmittance for Composite Climate

[1]M. Jamil Ahmad, G.N. Tiwari
Centre for Energy Studies, Indian Institute of Technology Delhi,
Hauz Khas, New Delhi-11 00 16, India.
[1]Corresponding author email: jamil.amu@gmail.com

ABSTRACT

In this paper, an attempt has been made to estimate the cloudiness/haziness factors and atmospheric transmittances for the composite climate of New Delhi (latitude:28.58° N; longitude: 77.02° E; elevation: 216 m above msl). To predict the hourly variation of beam and diffuse radiation on a horizontal surface for any day, atmospheric transmittances for beam and diffuse radiation have been introduced to take into account the uncertain behaviour of atmospheric conditions. For the present study, the hourly data of global and diffuse solar radiation on a horizontal surface for a period of 11 years (1991–2001) have been used and analyzed using polynomial regression analysis. The data have been obtained from the Indian Meteorological Department, Pune, India. It has been observed that there is about 11% maximum and 01% minimum root mean square error between predicted and observed values of hourly varying beam radiation for clear (blue sky) weather condition.

Keywords: Solar radiation, cloudiness/haziness factor and atmospheric transmittance, India

1. INTRODUCTION

Solar energy has diurnal and seasonal variability. Based on climatic parameters and atmospheric transmission, a large number of radiation models have been proposed and tested. In order to determine direct normal irradiance (DNI) in terrestrial regions, the concept of turbidity coefficients was introduced by various scientists. These refer to:

- The Linke turbidity factor, T_L (broadband): Linke (1922), Gueymard (1993, 2003), Kasten (1980) and Grenier (1994).
- Angstrom turbidity parameters α and β (spectral band): Pinazo (1995),Tadros (2002) and Gueymard (2003).
- The Shuepp coefficient, B (broadband).
- The Unsowrth–Monteith turbidity factor, T_U (broad-band), etc: Unsowrth (1972).

The above models are applicable only to clear (cloudless) sky condition.

Nayak [1992] has reviewed the developed models to estimate the monthly average of daily total and diffuse radiation on a horizontal surface.

Kasten [1965, 1989] has studied in detail the attenuation of solar radiation in terms of air mass, optical thickness of clear and dry atmosphere and Linke turbidity factor. Ineichen and Perez [2002] have attempted the formulation of air mass independent turbidity coefficients to evaluate beam radiation. Skartveit et al. [1998] and Perez et al. [1990] have developed direct conversion models to estimate direct radiation from global radiation.

It has been observed by Hawas and Muneer (1984) and Muneer et al (1998) that the selection of a model for estimating the hourly beam and diffuse radiation at ground level on a horizontal surface is difficult and such a model is rarely available, particularly for composite climate (one of the Indian climatic conditions). Both the hourly beam and diffuse radiation depend on a number of factors, such as (i) accuracy of estimation, (ii) average climatic conditions, (iii) latitude, (iv) seasonal variations and (v) the earth–sun angles. The hourly beam and diffuse radiation on a horizontal surface are the basic need for any solar energy system for optimization of parameters before fabrication.

Singh and Tiwari [2005] have developed a simple linear model to evaluate the hourly varying beam and diffuse radiation from measured hourly global and diffuse radiation data for the following weather conditions:

(a) Clear day (blue sky): If diffuse radiation is less than or equal to 25 % of global radiation and sunshine hour is more than or equal to 9 hours.
(b) Hazy day(fully): If diffuse radiation is less than 50 % or more than 25 % of global radiation and sunshine hour is between 7 to 9 hours.
(c) Hazy and cloudy (partially): If diffuse radiation is less than 75% or more than 50 % of global radiation and sunshine hour is between 5 to 7 hours.
(d) Cloudy day (fully): If diffuse radiation is more than 75 % of global radiation and sunshine hour is less than 5 hours.

The above four weather conditions constitute the composite climate of New Delhi.

In this communication, an attempt has been made to develop a polynomial (order 2) model to evaluate the hourly varying beam and diffuse radiation from measured hourly global and diffuse radiation data for the above weather conditions. The results obtained are compared with Singh and Tiwari (ST) model.

2. PRESENT APPROACH

In terms of air mass m, integrated Rayleigh scattering optical thickness of atmosphere ε and Linke turbidity factor T_R, the terrestrial beam radiation received on a horizontal surface is expressedin classical equation form as:

$$I_{HB} = I_N \cos\theta_Z = I_{ON}.\exp(-m.\varepsilon.T_R).\cos\theta_Z \quad (1a)$$

where $I_{ON}(W/m^2)$ is the normal extraterrestrial solar radiation and is expressed by

$$I_{ON} = I_{SC}[1.0 + 0.033\cos(360n/365)] \quad (1b)$$

I_{HB} is the hourly beam radiation on the horizontal surface derived from hourly global and diffuse radiation (Table 1); θ_Z is the solar zenith angle at a given time (Eq. (1.13) of [19]). The parameters m and ε [12,13] are expressed as:

$$m = [\cos\theta_Z + 0.15\times(93.885 - \theta_Z)^{-1.253}]^{-1} \quad (2)$$

and

$$\varepsilon = 4.529\times10^{-4}.m^2 - 9.66865\times10^{-3}.m + 0.108014 \quad (3)$$

The Linke turbidity factor T_R for clear blue sky condition (type 'a') has been calculated by linear regression analysis using Eq. (1a). The results for hourly variation of beam radiation on horizontal surface (Eq. (1a)) by using the obtained Linke turbidity factor T_R are shown in Fig. 1. The raw data of hourly variation of beam radiation on a horizontal surface from Table 1 are also shown in the same figure for comparison. These figures indicate that there is a significant deviation between predicted (by using calculated T_R) and given data (Table 1).

The Linke turbidity factor T_R, which is a measure of the vertically integrated amounts of aerosol and other suspended particulate matter in the atmosphere, is different at different times on even the same day. Since m and ε are computed from theoretical assumptions, Eq. (1a) does not accommodate the level of cloudiness/haziness (condition types 'a–d'), and transient and unpredictable changes in the atmospheric conditions. To accommodate the additional depletion in DNI in terrestrial regions due to cloudiness/haziness, and transient and unpredictable changes, atmospheric transmittance for beam radiation, β have been introduced in Eq. (1a) as

$$I_{HB} = I_{ON}.\exp[(m.\varepsilon)^2 T_{RO} + (m.\varepsilon)T_R + \alpha].\cos\theta_Z \quad (4)$$

This additional depletion in DNI can be considered to be due to the following main reasons:
1. Transient change of aerosol level (dust) in terms of content as well as size;
2. Unpredictable movements and disturbances in the upper atmosphere due to temperature difference between the layers.

Since Eq. (4) accommodates the precipitable water level in the lumped atmosphere, henceforth, T_{RO} and T_R will be defined as cloudiness/haziness factors for the lumped atmosphere.

If the value of T_{RO} becomes zero, then equation (4) reduces to linear model proposed by Singh and Tiwari (2005).

2.1 Regression Analysis for Cloudiness/Haziness Factors (T_{RO} and T_R) and Atmospheric Transmittance α for Beam Radiation

Eq. (4) can be rewritten after normalization as

$$\frac{I_{HB}}{I_{ON}.\cos\theta_Z} = \exp[(m.\varepsilon)^2 T_{RO} + (m.\varepsilon)T_R + \alpha]$$

or

$$\log\left[\frac{I_{HB}}{I_{ON}.\cos\theta_Z}\right]=(m.\varepsilon)^2T_{RO}+(m.\varepsilon)T_R+\alpha \qquad (5)$$

Comparing Eq. (5) with the standard polynomial equation of order 2

$$y=ax^2+bx+c \qquad (6)$$

we can write

$y=\log\left[\frac{I_{HB}}{I_{ON}.\cos\theta_Z}\right]$; x=m. ε; a=T_{RO}

$b=T_R$ and $c=\alpha$

By regression analysis of y and x, regression coefficients a, b, c and hence the Cloudiness / haziness factors (T_{RO} and T_R) and atmospheric transmittance for beam radiation α can be evaluated.

2.2 Regression Analysis for Perturbation Factors and Background Diffuse Radiation for Lumped Atmosphere

In order to evaluate hourly diffuse radiation on the horizontal surface, a well known expression is given [19] by

$$I_{HD}=\frac{1}{3}(I_{ON}-I_N).\cos\theta_Z \qquad (7a)$$

The above equation can be used to determine hourly diffuse radiation with the help of Eq. (1a,b). Its variation for the clear sky (type 'a') condition for typical winter and summer months have been shown in Fig. 1. It is evident that there is a significant difference between calculated hourly values of diffuse radiation and the given data of Table 1. Hence, there is a strong need to modify Eq. (7a).

Eq. (7a) can be rewritten in terms of constants K_0, K_1 and K_2 as

$$I_{HD}=K_0\left((I_{ON}-I_N).\cos\theta_Z\right)^2+K_1(I_{ON}-I_N).\cos\theta_Z+K_2 \qquad (7b)$$

where I_N (W/m2) is the normal terrestrial solar radiation at ground level.

The constants K_0, K_1 and K_2 can be defined as atmospheric transmittances for diffuse radiation and can be evaluated using regression analysis for given data of hourly variation in diffuse radiation (Table 1) and known hourly values of I_{ON} (Eq. (1b)), I_N and $\cos\theta_Z$ (Equation (1a)).

Further, the constant K_0 and K_1 can be interpreted as the 'perturbation factors' for describing scattering out of a beam traversing the lumped atmosphere, and K_2 can be referred to as 'background diffuse radiation'.

If the value of K_0 becomes zero, then equation (7b) reduces to linear model proposed by Singh and Tiwari (2005).

After obtaining the hourly beam (Equation (4)) and diffuse (Equation (7a,b)) radiation on the horizontal surface, the total radiation for a solar thermal device of any inclination and orientation can be evaluated using the Liu and Jord en formula [20].

2.3 Root Mean Square Error (RMSE) and Mean Bias Error (MBE)

The closeness of hourly predicted values of solar radiation, using the evaluated parameters T_{RO}, T_R, α , K_0 , K_1 and K_2 to the experimental average data has been presented in terms of root mean square error (RMSE) and mean bias error (MBE).

Root mean square error: The root mean square error is defined as

$$RMSE = \left\{ \left[\sum \left(I_{i,pre} - I_{i,obs} \right)^2 \right] / n \right\}^{1/2} \qquad (8)$$

where $I_{i,pre}$ is the ith predicted value, $I_{i,obs}$ is the ith observed value, and n is the total number of observations. The RMSE is always positive, a zero value is ideal. This test provides information on the short-term performance of the models by allowing a term by term comparison of the actual deviation between the calculated value and the measured value. However a few large errors in the sum can produce a significant increase in RMSE.

Mean bias error: The mean bias error is defined as

$$MBE = \left[\sum (I_{i,pre} - I_{i,obs}) \right] / n \qquad (9)$$

This test provides information on the long-term performance. A low MBE is desired. Ideally a zero value of MBE should be obtained. A positive value gives the average amount of over-estimation in the calculated value and vice versa. One drawback of this test is that over-estimation of an individual observation will cancel under-estimation in a separate observation.

3. EXPERIMENTAL DATA

For the present study, data of the hourly global and diffuse solar radiation (W/m^2) on a horizontal surface for a period of 11 years (1991–2001) have been used. The data have been obtained from the India Meteorological Department, Pune, India. The data for the composite climate of New Delhi have been obtained using a thermoelectric pyranometer with (diffuse) and without (global) a shade ring. The shade ring factor (SRF) has been used to make corrections for shaded sky assuming that sky radiation is isotropic. The pyranometers used are calibrated once a year with reference to the World Radiometric Reference (WRR). The estimated uncertainty in the measured data is about $\pm$ 5%. For the computation of T_{RO}, T_R, α , K_0 , K_1 and K_2 the beam radiation data have been derived from the measured hourly global and diffuse radiation data. For every month over the period of 11 years, the average number of days falling under different weather conditions has been given in Table 2. The average number of days falling under different weather conditions in each month has been obtained on the basis of recorded weather observations, given total sunshine hours and daily global radiation. Table 1 gives the average hourly measured data for total and diffuse radiation for the typical months of January (winter conditions) and June (summer conditions), respectively. The data of Table 1 have been used in evaluating T_{RO}, T_R, α, K_0, K_1 and K_2. Similar data for other months have also been obtained and used.

4. RESULTS AND DISCUSSION

In order to evaluate T_{RO}, T_R and α of Eq. (4), for the month of January and June, Eq. (6) has been used for regression analysis. For regression analysis, the data of Table 1 have been used. Similarly T_{RO}, T_R and α for other months have also been obtained. The results for each month and all weather conditions (types 'a-d') are given in Table 3 and shown in Fig. 2 to 5, which can be used to generate the hourly beam and diffuse radiation data for New Delhi.

The atmospheric transmittances K_0, K_1 and K_2 for diffuse radiation in Eq. (7b) have again been obtained by regression analysis from the data of Table 1 and other months. The results for K_0, K_1 and K_2 for each month and all weather conditions (types 'a-d') are given in Table 4 and shown in Fig. 2 to 5.

From Table 3, it can be seen that the cloudiness/haziness factors T_{RO} and T_R are maximum for cloudy days (type 'd') due to attenuation of radiation in the atmosphere, unlike for clear days (type 'a'). The values of T_{RO} and T_R for other weather conditions (types 'b' and 'c') lie between these two extreme values, as expected.

The values of atmospheric transmittance for beam radiation α are higher for cloudy conditions (type'd', Table 3), as expected.

The values of K_0, K_1 and K_2 for each month vary according to the weather conditions and instability in them (Table 4).

Figs. 2 to 5 give the hourly variation in observed and predicted beam and diffuse radiation (by both models) for the typical months of January (winter) and June (summer), respectively and for weather types a, b, c and d respectively. It is inferred that there is a 1–11% RMSE between observed and predicted values of beam radiation by present model (JT) for clear days (type 'a'), as shown in Fig. 2 and Table 5. This RMSE is more dominant for the type'd' weather condition, as expected.

There is a 1–13% RMSE between observed and predicted values of beam radiation by Singh and Tiwari model (ST) for clear days (type ‘a’), as shown in Fig. 2 and Table 5. This RMSE is more dominant for the type d’ weather condition, as expected

For both models, Singh-Tiwari (ST) and Jamil-Tiwari (JT), the evaluated values of percentage root mean square error (RMSE) and percentage mean bias error (MBE) for beam radiation have been given in Table 5 for each month and each type of weather. JT model gives slightly better results in terms of RMSEs and MBEs during all months of the year and for all the four types of weather.

For both models, Singh-Tiwari (ST) and Jamil-Tiwari (JT), the evaluated values of percentage root mean square error (RMSE) and percentage mean bias error (MBE) for diffuse radiation have been given in Table 6 for each month and each type of weather. JT model gives slightly better results in terms of RMSEs during all months of the year and for all the four types of weather.

Both models generally give better results for clear sky conditions of Indian regions. The low MBEs are particularly remarkable. Therefore, their use is recommended for composite climate of Indian regions.

5. CONCLUSIONS AND RECOMMENDATION

From the present studies, it is evident that by defining T_{RO} and T_R as the cloudiness/haziness factors and introducing atmospheric transmittance for beam radiation α , the perturbation factors K_0, K_1 and background diffuse radiation K_2 for diffuse radiation provide a simple model for the prediction of hourly beam and diffuse radiation on a horizontal surface for the composite climate of New Delhi. The present studies should be extended to the other climatic conditions of India.

6. ACKNOWLEDGEMENTS

The authors are grateful to the Indian Meteorological Department, Pune, India for providing the hourly global and diffuse radiation data for the period of 11 years from 1991 to 2001.

7. REFERENCES

Grenier J.C., Casiniere A.D.L. and Cabot T. 1994. A spectral model of Linke’s turbidity factor and its experimental implications. Solar Energy. 52(4):303–13.

Gueymard C. 1993. Critical analysis and performance assessment of clear sky solar irradiance models using theoretical and measured data. Solar Energy. 51:121–38.

Gueymard C. 2003. Direct solar transmittance and irradiance predictions with broadband models. Part-I: detailed theoretical performance assessment. Solar

Energy.74:355–79.
Gueymard C. 2003. Direct solar transmittance and irradiance predictions with broadband models. Part-II: validation with high-quality measurements. Solar Energy.74:381–95.
Gueymard C. 2003. Importance of atmospheric turbidity and associated uncertainties in solar radiation and luminous efficacy modeling. Edinburgh.
Hawas M. M. and Muneer T. 1984. Study of diffuse and global radiation characteristics in India. Energy Conversion and Managemen. 24(2):143–9.
Ineichen P. and Perez R. 2002. A new air mass independent formulation for the Linke turbidity coefficient. Solar Energy. 73(3):151–7.
Kamal R. Maheshwari K.P. and Sahney R.L. 1992. Solar energy and energy Conservation. New Delhi, Wiley Eastern Limited.
Kasten F. 1980. A simple parameterization of two pyrheliometric formulae for determining the Linke turbidity factor. Meter Rdsch. 33:124–7.
Kasten F. 1965. A new table and approximate formula for relative optical air mass. Arch Meteorol Geophys Bioklimatel Ser B. 14:206–23.
Kasten F. and Young A.T. 1989. Revised optical air mass tables and approximation Formula. Appl Opt. 28: 4735–8.
Linke F. 1922. Transmission koeffiezient and turbid ity factor. Beitr Phys Fr Atom. 10:91–103.
Liu B.Y.H. and Jordan R.C. 1960. The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. Solar Energy. 4(3):1–19.
Muneer T., Gul M. and Kambezedis H. 1998. Evaluation of an all-sky meteorological radiation model against long-term measured hourly data. Energy Coversion and Management. 39(3/4):303–17.
Perez R., Ineichen P., Maxwell E., Seals R. and Zelenka A. 1990. Dynamic global to direct conversion models. ASHRAE Trans. 98:354–69.
Pinazo J. M., Canada J. and Bosca J.V. 1995. A new method to determine Angstrom's turbidity coefficient: its application for Valencia. Solar Energy. 54(4):219–26.
Skartveit A., Olseth J.A. and Tuft M.E. 1998. An hourly diffuse fraction model with correction for variability and surface albedo. Solar Energy. 63(3):173–83.
Singh H.N. and Tiwari G. N. 2005. Evaluation of cloudiness/haziness factor for composite climate. Energy. 30:1589-1601.
Tadros M.T.Y., El-Metwally M. and Hamed A.B. 2002. Determination of Angstrom coefficients from spectral aerosol optical depth at two sites in Egypt. Renewable Energy. 27:621–45.
Tiwari G.N. 2002. Solar energy fundamentals, design, modeling and applications. USA, CRC Press.
Unsowrth M.H. and Monteith J.L. 1972. Aerosol and solar radiation in Britain. QJR Meteorol Soc. 98: 778–97.

8. NOMENCLATURE

I_{HB}	terrestrial beam solar radiation on a horizontal surface at ground level (W/m^2)
I_{HD}	diffuse solar radiation on a horizontal surface at ground level (W/m^2)
I_{ON}	normal extraterrestrial solar radiation (W/m^2)
I_N	normal terrestrial solar radiation at the ground level (W/m^2)
I_{Sc}	solar constant (W/m^2)
K_0, K_1	perturbation factors
K_2	background diffuse radiation (W/m^2)
m	air mass (dimensionless)
n	day of the year, starting from 1st January
T_{RO}, T_R	cloudiness/haziness factor
RMSE	root mean square error
MBE	mean bias error

Greek letters

α	atmospheric transmittance for beam radiation
ε	integrated Rayleigh scattering optical thickness
θ_z	solar zenith angle

Table 1. Average hourly global and diffuse radiation (W/m^2) in (a) January (b) June for all weather types at New Delhi

Time	Weather type							
	a		b		c		d	
	Total	Diffuse	Total	Diffuse	Total	Diffuse	Total	Diffuse
(a) January								
8	132.99	52.60	119.58	52.75	71.11	64.16	51.20	48.16
9	355.56	86.28	332.50	102.57	235.55	146.66	140.11	107.67
10	554.69	107.29	516.25	123.09	360.00	195.56	237.11	175.66
11	680.73	121.53	650.41	149.46	457.78	220.00	301.78	221.00
12	726.74	126.39	708.75	155.32	515.55	226.12	379.92	246.50
13	733.85	136.63	723.33	161.18	515.55	226.12	379.92	255.00
14	656.08	128.30	650.41	155.32	462.22	210.84	328.72	240.83
15	500.00	110.94	498.75	128.94	353.34	180.28	261.36	187.00
16	311.46	90.28	315.00	96.71	217.78	122.22	161.67	138.83
17	106.42	41.84	110.84	46.88	71.11	51.94	45.80	42.50
(b) June								
8	436.67	123.89	433.34	198.33	358.33	277.77	235.12	169.56
9	637.22	149.44	641.34	250.83	555.56	350.70	350.12	251.31
10	802.22	157.22	794.45	277.08	727.78	378.47	454.88	360.31
11	915.00	158.89	912.89	297.50	816.67	416.66	595.44	405.72
12	951.67	167.78	999.55	300.42	833.33	434.03	672.12	454.17
13	946.11	185.00	996.66	335.41	861.11	423.61	682.34	481.42
14	882.78	180.56	912.89	315.00	763.89	402.78	631.22	448.11
15	765.56	176.11	808.89	291.67	688.89	385.41	536.66	393.61
16	611.67	142.78	635.55	274.17	538.89	347.22	426.78	330.03
17	420.00	116.11	416.00	207.08	333.33	246.53	281.12	260.39

Table 2. Average number of days under different weather types in different months during 1991-2001 for New Delhi

Weather	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
a	3	3	5	4	4	3	2	2	7	5	6	3
b	8	4	6	7	9	4	3	3	3	10	10	7
c	11	12	12	14	12	14	10	7	10	13	12	13
d	9	9	8	5	6	9	17	19	10	3	2	8

Table 3. Evaluated cloudiness/haziness factors (T_R and α) and atmospheric transmittance (β) for (a) weather type ‘a’, (b) weather type ‘b’, (c) weather type ‘c’ and (d) weather type ‘d’ at New Delhi

Parameter	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Weather type ‘a’												
T_R	-0.43	-0.66	-1.01	11.28	13.48	27.09	-29.27	-5.24	26.69	15.28	7.40	5.35
α	-2.01	-2.47	-2.48	-6.43	-7.66	-10.29	5.63	-0.99	-12.40	-9.23	-6.84	-6.02
β	-0.10	-0.13	-0.19	0.06	0.13	0.25	-0.93	-0.53	0.53	0.36	0.30	0.31
Weather type ‘b’												
T_R	0.652	-0.26	-1.41	3.01	-7.47	21.11	-38.53	-9.65	8.37	-1.96	15.27	3.33
α	-2.67	-2.65	-2.37	-4.16	-3.26	-10.84	5.46	-2.48	-6.37	-3.68	-12.89	-5.24
β	-0.10	-0.15	-0.18	-0.09	-0.31	0.21	-0.98	-0.39	-0.05	-0.31	0.67	0.13
Weather type ‘c’												
T_R	-1.41	-0.76	-2.26	-37.81	-62.45	29.36	-69.57	-10.12	0.92	-4.21	-135.55	5.77
α	-5.14	-5.97	-5.27	4.45	9.45	-19.08	12.81	-4.93	-5.93	-5.65	45.67	-9.18
β	-0.35	-0.41	-0.44	-1.22	-1.37	0.52	-1.76	-0.72	-0.45	-0.26	-5.38	0.08
Weather type ‘d’												
T_R	21.42	13.65	10.20	-31.75	-85.69	-129.62	-0.010	-52.06	-25.21	93.72	32.08	14.37
α	-20.43	-12.33	-9.39	-0.95	11.91	24.69	-8.21	7.32	-0.29	-55.00	-31.07	-18.27
β	0.46	-0.71	-0.15	-0.83	-1.85	-3.12	-1.26	-2.23	-1.58	3.75	2.38	0.57

Table 4. Evaluated perturbation factors (K_1, K_2) and background diffuse radiation (K_3) for (a) weather type 'a', (b) weather type 'b', (c) weather type 'c' and (d) weather type 'd' at New Delhi

Parameter	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Weather type 'a'												
K_1	-0.0004	-0.0001	-0.0003	0.0003	0.0008	0.0003	-0.0001	0.0002	0.0003	0.0004	0.0004	0.001
K_2	0.63	0.43	0.55	0.03	-0.48	0.005	0.49	0.24	-0.007	-0.07	0.008	-0.18
K_3	-27.6	-10.6	-32.7	84.2	206.4	84.9	-62.9	-18.3	78.8	67.5	47.7	50.2
Weather type 'b'												
K_1	0.0003	-0.0002	-0.0003	0.000	0.000	0.0002	0.0003	0.0002	0.0006	0.000	0.0002	0.0008
K_2	0.35	0.63	0.70	0.44	0.46	0.21	0.20	0.15	-0.13	0.43	0.21	0.01
K_3	-4.6	-40.3	-44.5	-8.7	-2.6	82.5	43.5	74.1	116.7	-12.4	33.3	37.1
Weather type 'c'												
K_1	-0.0001	-0.0002	-0.0001	-0.0001	0.0009	-0.0003	-0.0001	-0.0002	0.0003	0.000	0.0002	0.0006
K_2	0.48	0.51	0.47	0.47	-0.67	0.94	0.58	0.64	0.06	0.33	0.12	-0.04
K_3	-29.0	-41.1	-28.2	-19.3	351.5	-162.2	-90.4	-52.3	126.9	-6.7	43.4	50.0
Weather type 'd'												
K_1	0.0001	0.0001	0.000	0.0005	0.0002	0.0005	0.000	-0.0001	0.0004	0.0003	0.0001	0.0003
K_2	0.27	0.19	0.43	-0.25	0.15	-0.40	0.35	0.65	-0.23	0.03	0.19	0.08
K_3	-11.1	20.5	-34.3	203.4	84.2	285.3	-23.4	-147.7	184.9	84.3	39.1	35.4

Table 5. Percentage Root Mean Square Error (RMSE) between predicted results and observed monthly-mean hourly beam radiation for location New Delhi

		'a' type weather		'b' type		'c' type		'd' type	
		JT	ST	JT	ST	JT	ST	JT	ST
Jan	RMSE	4.09	4.13	1.33	1.27	5.29	5.69	27.43	15.28
	MBE	-0.09	-0.04	0.02	-0.05	0.04	0.30	-0.96	-1.10
Feb	RMSE	2.23	2.30	1.42	1.43	9.33	9.32	43.71	28.38
	MBE	-0.002	0.03	-0.002	0.01	-0.45	-0.40	-8.17	0.07
Mar	RMSE	1.14	1.17	0.74	0.84	2.92	2.94	19.81	12.10
	MBE	-0.007	0.01	0.002	0.03	-0.03	0.03	-1.23	1.49
Apr	RMSE	3.56	3.26	1.30	1.38	1.77	4.13	6.09	7.72
	MBE	-0.03	-0.16	-0.01	-0.05	-0.02	0.53	-0.11	0.54
May	RMSE	3.24	3.14	1.30	1.40	3.65	6.99	9.63	10.60
	MBE	-0.03	-0.14	-0.01	0.05	-0.06	0.57	-0.45	0.72
Jun	RMSE	3.05	3.18	3.67	3.76	8.39	7.48	18.02	15.68
	MBE	-0.04	-0.17	-0.05	-0.18	-0.18	-0.47	-1.68	-0.74
Jul	RMSE	2.75	3.82	3.76	3.93	6.18	7.81	13.01	13.01
	MBE	-0.04	0.06	-0.09	0.08	-0.19	0.12	-0.90	-0.90
Aug	RMSE	4.97	4.98	2.37	2.47	7.41	7.72	12.37	13.82
	MBE	-0.11	-0.07	-0.05	0.03	-0.31	-0.21	-0.77	-0.27
Sep	RMSE	6.29	6.31	5.97	5.49	6.66	6.57	16.83	18.10
	MBE	-0.11	-0.86	-0.04	-0.26	-0.001	-0.03	-1.47	-0.49
Oct	RMSE	10.87	11.93	0.93	1.33	2.49	4.17	40.20	39.98
	MBE	-0.58	-2.43	-0.02	0.26	0.085	0.86	3.46	-20.06
Nov	RMSE	9.82	13.10	5.88	24.20	14.18	26.76	32.66	39.07
	MBE	-0.16	-4.64	0.65	-9.63	-1.07	-17.86	3.89	-26.78
Dec	RMSE	10.23	11.07	6.70	9.21	10.46	9.12	21.92	38.41
	MBE	0.61	-4.71	0.17	-3.37	-0.70	-3.83	1.36	-18.61

Table 6. Percentage Root Mean Square Error (RMSE) between predicted results and observed monthly-mean hourly diffuse radiation for location New Delhi.

		'a' type weather		'b' type		'c' type		'd' type	
		JT	ST	JT	ST	JT	ST	JT	ST
Jan	RMSE	6.1	6.2	3.4	3.7	2.4	2.7	6.4	6.6
	MBE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feb	RMSE	5.7	5.7	6.8	6.8	3.3	3.7	7.4	7.6
	MBE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mar	RMSE	1.2	1.5	1.6	1.7	1.8	2.0	3.0	3.0
	MBE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Apr	RMSE	5.6	5.7	2.4	2.4	3.6	3.7	4.5	5.5
	MBE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
May	RMSE	8.6	8.9	1.2	1.2	5.7	6.6	4.9	5.0
	MBE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jun	RMSE	6.0	6.1	8.0	8.0	3.7	3.9	12.7	13.2
	MBE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jul	RMSE	5.2	5.2	2.3	2.4	2.4	2.5	4.1	4.1
	MBE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aug	RMSE	6.3	6.4	1.5	1.6	2.9	3.2	5.0	5.2
	MBE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sep	RMSE	9.3	9.4	12.1	12.6	8.3	8.6	10.8	12.1
	MBE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Oct	RMSE	26.9	27.3	0.9	0.9	1.7	1.7	11.8	13.0
	MBE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nov	RMSE	28.5	28.9	3.0	4.3	15.3	16.0	29.7	29.8
	MBE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dec	RMSE	26.8	29.7	17.8	19.1	13.6	16.0	12.6	14.6
	MBE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

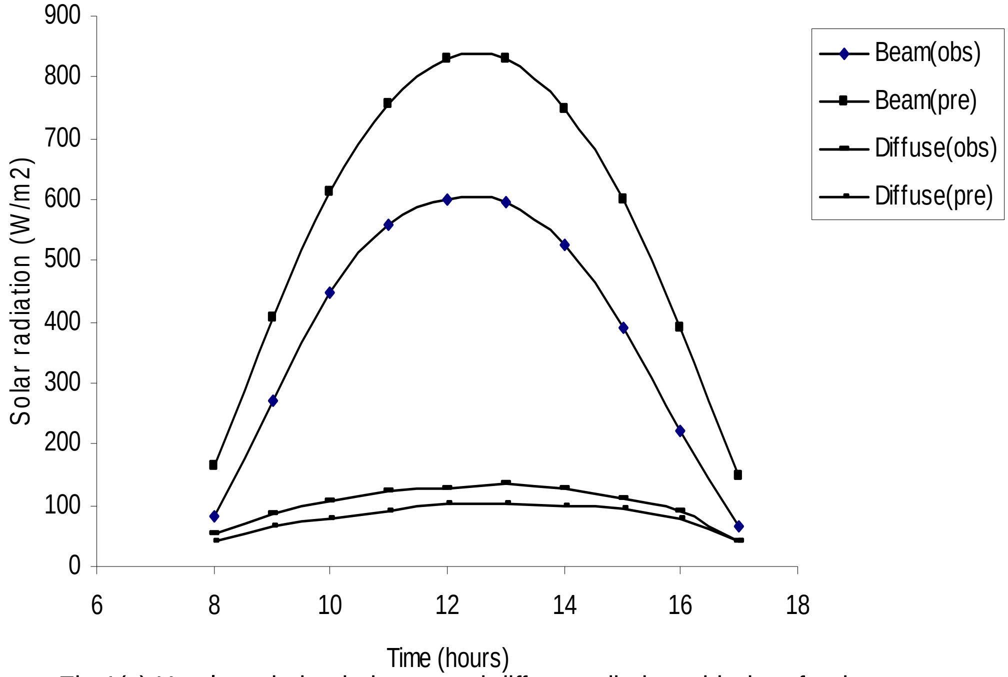

Fig 1(a) Hourly variation in beam and diffuse radiation with time for the months of January (type 'a' weather condition) using Linke turbidity coefficient

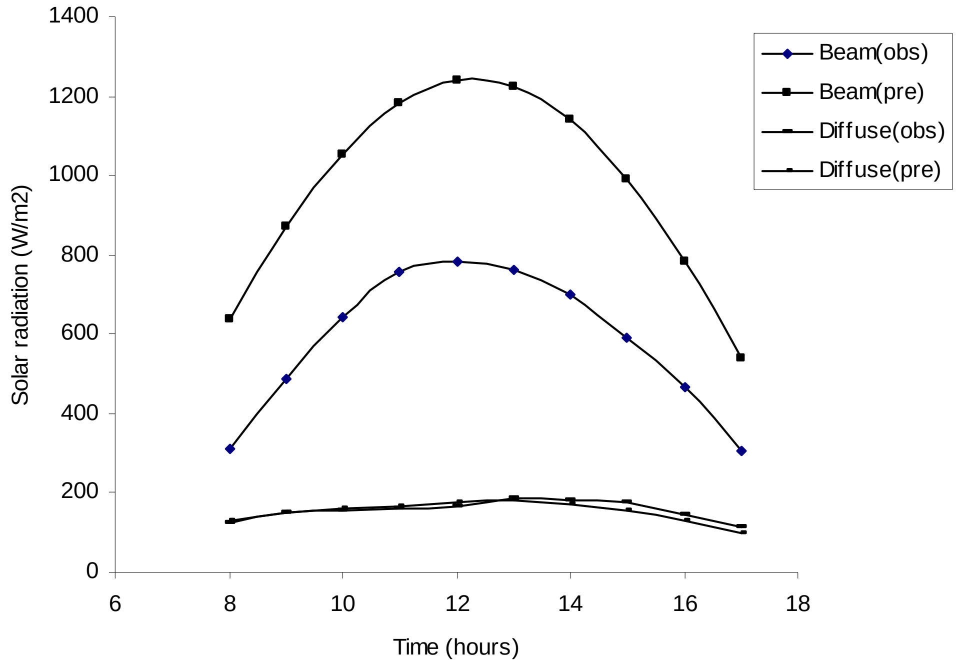

Fig 1(b) Hourly variation in beam and diffuse radiation with time for the months of June (type 'a' weather condition) using Linke turbidity coefficient

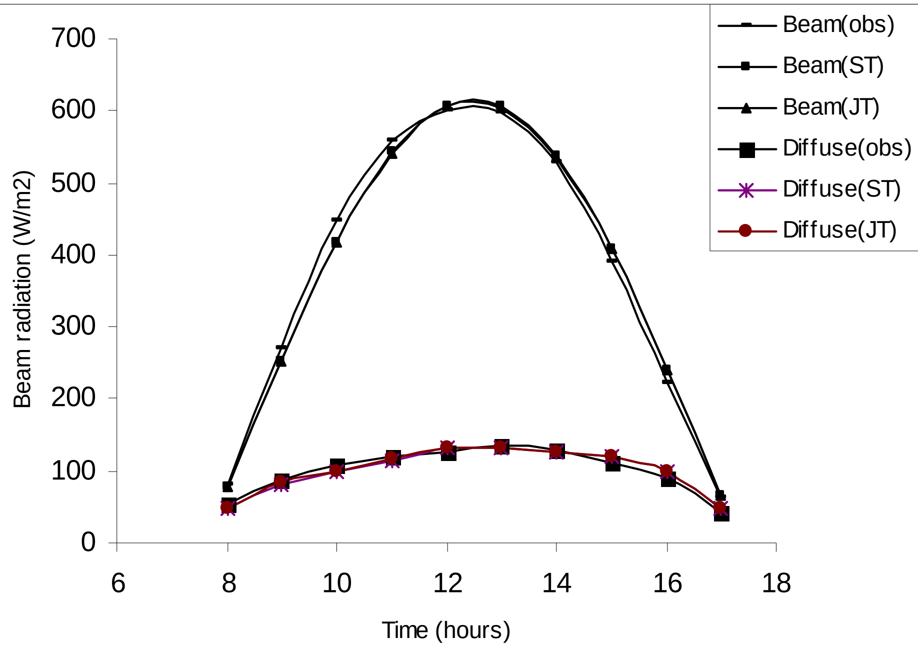

Fig 2(a) Hourly variation in beam radiation w ith time for the month of Jan (w eather type 'a') using cloudiness/haziness factor and atmospheric transmittances

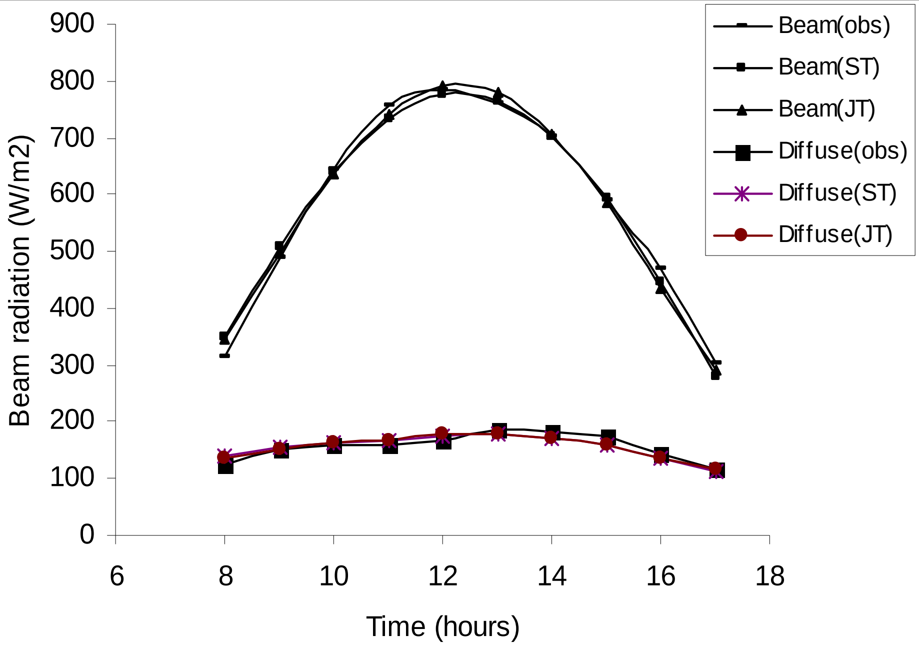

Fig 2(b) Hourly variation in beam radiation with time for the month of June (weather type 'b') using cloudiness/haziness factor and atmospheric transmittances

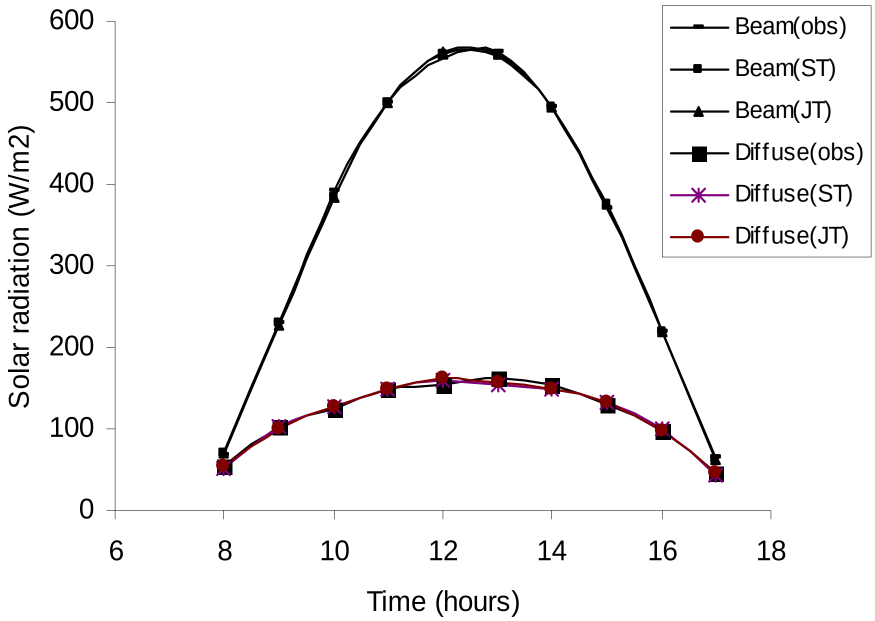

Fig 3(a) Hourly variation in beam and diffuse radiation with time for the month of January (weather type 'b') using cloudiness/haziness factor and atmospheric transmittances

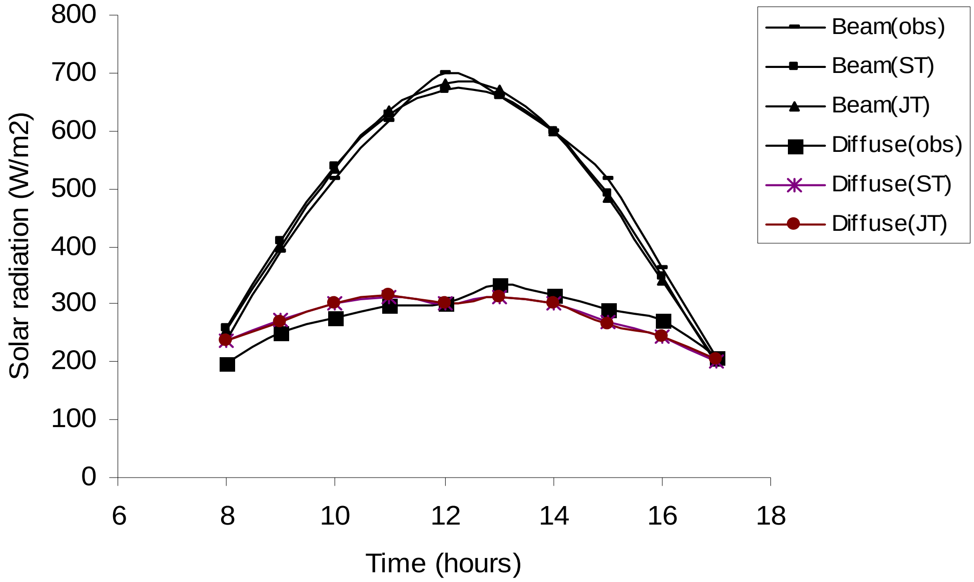

Fig 3(b) Hourly variation in beam and diffuse radiation with time for the month of June (weather type 'b') using cloudiness/haziness factor and atmospheric transmittances

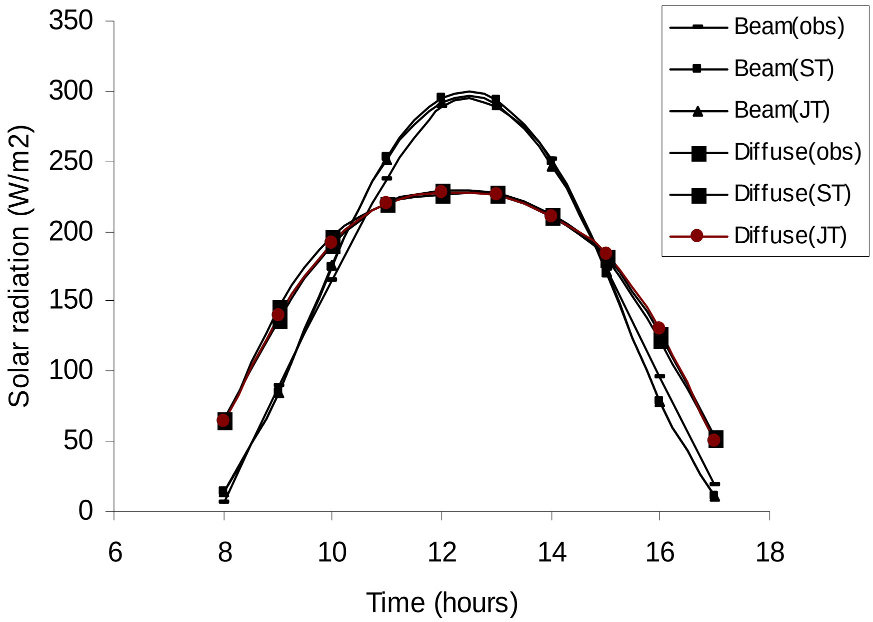

Fig 4(a) Hourly variation in beam and diffuse radiation with time for the month of January (weather type 'c') using cloudiness/haziness factor and atmospheric transmittances

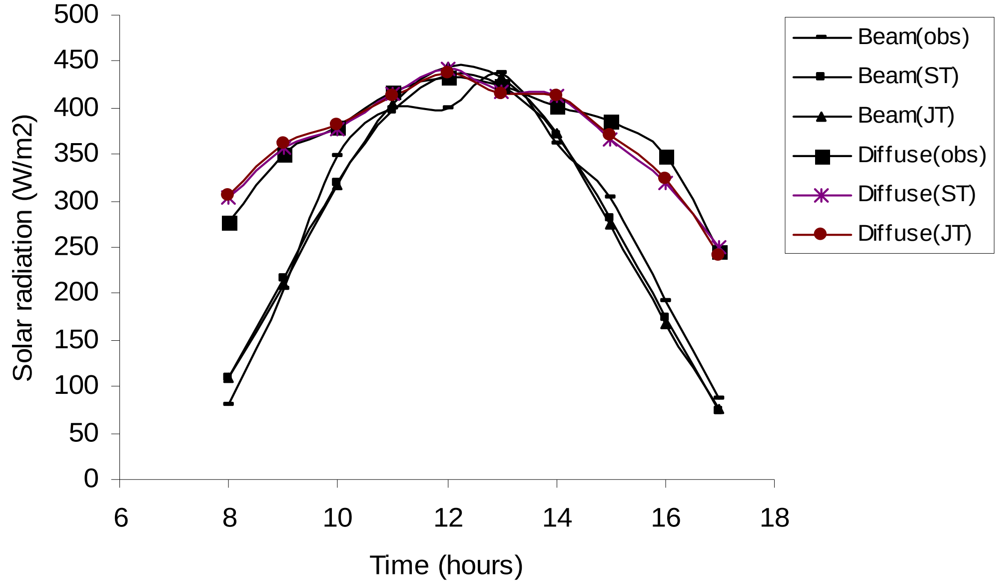

Fig 4(b) Hourly variation in beam and diffuse radiation with time for the month of June (weather type 'c') using cloudiness/haziness factor and atmospheric transmittances

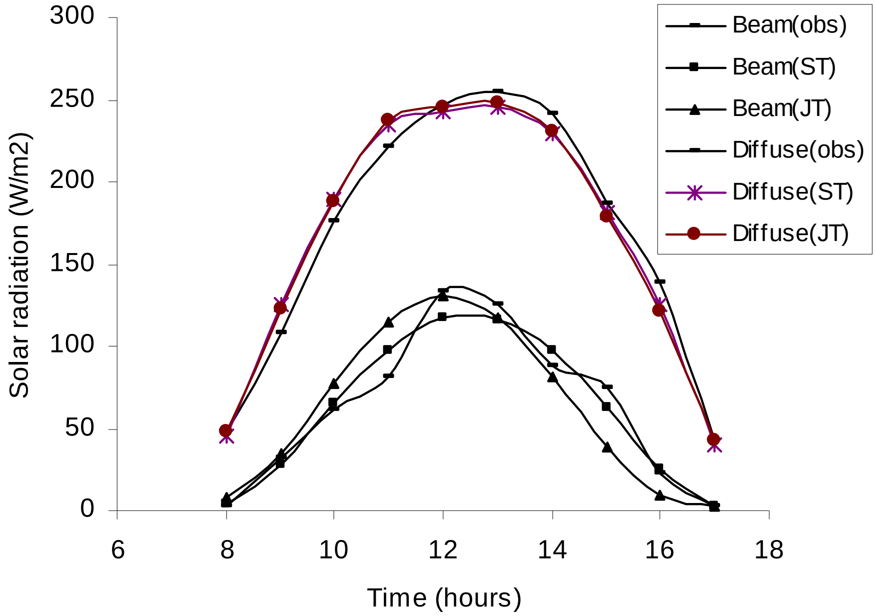

Fig 5(a) Hourly variation in beam and diffuse radiation with time for the month of January (weather type 'd') using cloudiness/haziness factor and atmospheric transmittances

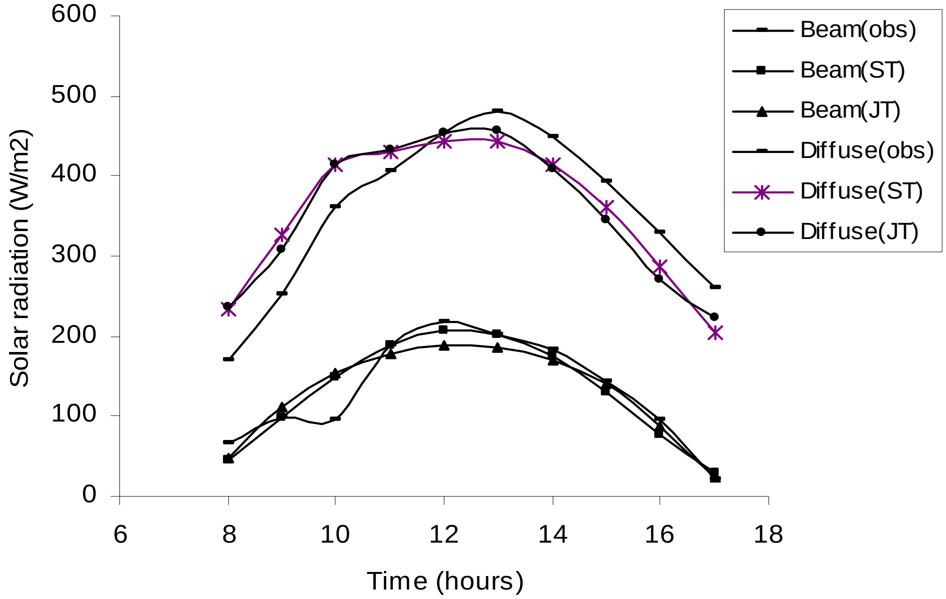

Fig 5(b) Hourly variation in beam and diffuse radiation with time for the month of June (weather type 'd') using cloudiness/haziness factor and atmospheric transmittances