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ESTIMATION OF DAILY TOTAL AND DIFFUSE INSOLATION IN INDIA FROM WEATHER DATA

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Abstract—Insolation and weather data for a large number of cities in India is analysed and correlated. Correlations based on a citywise regression analysis indicate that daily total insolation correlates best with sunshine duration, all clouds and precipitation. However these relations are not useful for predicting insolation at locations where this data is not measured. Monthwise correlations which are valid over a region are more useful. Hence such correlations have been developed for Indian conditions. In order to increase the accuracy of prediction of these correlations, India is divided into two regions on the basis of the climatic characteristics of the winter monsoon.

Finally the Liu and Jordan model for predicting daily diffuse radiation from daily total radiation has been tested and found to be applicable for Indian conditions. However the numerical values obtained are very different from those obtained for conditions in the United States.

1. INTRODUCTION

Data on the monthly averages of the daily total and diffuse solar radiation at a location is of significant use in the design of most equipment using solar energy. Actual measurements of insolation are generally made only at a few places because of the cost of the equipment required and the care needed for maintaining it. Attempts have therefore been made to develop statistical relations for estimating insolation from various surface weather observations most of which are usually made at many locations. Angstrom[1] suggested the use of per cent possible sunshine hours as a parameter to predict radiation. Lund[2] correlated 9 yr of daily insolation observations with measurements of temperature, snow cover, wind, sunshine, sky cover, pressure and precipitation at Blue Hill, Massachusetts. He found that sunshine observations were the best specifiers of insolation in all months of the year. Sky cover was the second best for most of the months. Norris[3] reviewed attempts to divide cloud reports into classes of transmissivity for use of prediction. He reported poor correlations and concluded that it is probably impossible to predict solar radiation from such measurements. Bennett[4] brought out the usefulness of opaque sky cover as an important correlate of insolation. It is to be noted that the relations obtained in the above investigations have been derived from observations at a single location and have limited predictive capacity for other locations.

In many places, only the total radiation is measured. This results in a need for developing relationships for estimating diffuse radiation. In a pioneering study, Liu and Jordan[5] analyzed the data of many locations in the United States and calculated the values of the two parameters (H_{av}/H_0) and (D_{av}/H_0). They studied the relationship between the two and presented their results in a table from which one can obtain D_{av} knowing H_{av}. Chaudhury[6] tested the Liu and Jordan model for the data of New Delhi and found generally good agreement although his experimental data showed a higher diffuse ratio for a given cloudiness index. Tuller[7] applied and Liu and Jordan method to 4 stations in Canada and found the method good for predicting long term expected values. He reported that error is introduced by transferring the relationship established at one station to another. Ruth and Chant[8] also applied the Liu and Jordan method to Toronto, Montreal, Goosebay and Resolute Bay using 7 yr of data. They concluded that the correlations provided by Liu and Jordan are not universally applicable. In general, these relations vary from place to place.

Reddy[9] proposed an empirical method for computing daily total solar radiation using sunshine hours, humidity, and rainfall data. He tested his equation for only 2 locations, Poona and Trivandrum. His equation gave large errors when tested at other locations. Mani and Chacko[10] plotted the results of solar radiation measurements made at a network of 13 stations in India. Maps with constant solar radiation curves plotted at intervals of 50 cal/cm^2-day were drawn for each month on the basis of the above data.

The aim of the present investigation is to study the radiation and weather data of several Indian cities with a view to developing predictive relations for solar radiation over India.

2. DATA AVAILABLE

Monthly averages of the daily total and diffuse solar radiation and the sunshine hours per day were available from the Indian Meteorological Department for twelve locations, viz. Ahmedabad, Bhavnagar, Calcutta, Goa, Jodhpur, Madras, Nagpur, New Delhi, Poona, Shillong, Trivandrum and Vishakhapatnam. The number of years for which the monthly averages of the data were available generally ranged from six to eleven. Also the above data with the exception of the daily diffuse radiation was available for Bangalore, Kodaikanal, Hyderabad, Mangalore, Minicoy and Srinagar. It will be seen from Fig. 1 that the above locations are reasonably well distributed over the whole country.

Weather data for India is available for about 180

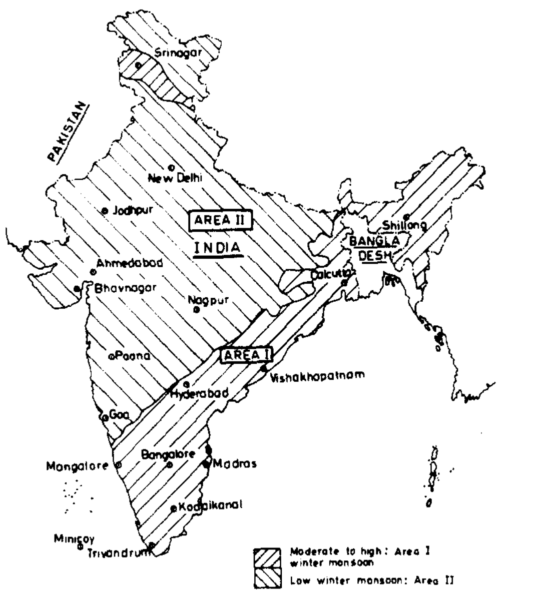

Fig. 1. Regions into which India is divided for monthwise regression analysis.

locations and is published every 30 yr by the Indian Meteorological Department[11]. The monthly averages of the daily values are averaged over the 30 yr. Observations are made at 0830 hr and 1730 hr IST. In the present study, the arithmetic mean of the two observations was taken for the purpose of regression analysis.

Unlike Lund[2], the data was not normalized because the ultimate aim is to use these equations for prediction. As suggested by Bennett[4], the quantity estimated was (H_{av}/H_0). This ratio is used as an insolation variable to eliminate the time of the year as a significant variable in the relationships. For a given location and day, the value of H_0 is calculated as described by Duffie and Beckman[12].

The independent variables (units in parenthesis) used for prediction were: (i) sunshine hours (hr); (ii) per cent possible sunshine (ratio of sunshine hr to day length, dimensionless); (iii) all clouds (oktas); (iv) low clouds (oktas); (v) average station pressure (mbars); (vi) arithmetic mean of the maximum and minimum temperature (°C); (vii) difference between the maximum and minimum temperature (°C); (viii) average relative humidity (per cent); (ix) average vapour pressure (mbars); (x) mean wind speed (kmph); (xi) precipitation (number of days in the month with precipitation ≥ 0.3 mm)

3. CITYWISE REGRESSION ANALYSIS

A regression analysis was carried out for each city using 12 data points, one for each month. A least square line of the type

$$(H_{av}/H_0) = A + BX \tag{1}$$

was fitted to each city separately and the coefficients A and B were evaluated. The values obtained for the coefficients A and B along with the coefficient of determination (r^2) and the mean of the actual error ($\bar{e}$) are given in Table 1 for the 4 independent variables which gave the least errors.

From Table 1, it is seen that per cent possible sunshine emerges as the best predictor. It has been found to be the best predictor by previous investigators also. The next best predictor is absolute hours of sunshine. Precipitation followed by all clouds are third and fourth best variables for prediction. The other variables gave significantly high errors with the mean of the actual error

Table 1. Regression coefficients A and B of eqn (1), coefficient of determination (r^2) and mean per cent error ($\bar{e}$) for citywise regression

	% possible sunshine				Sunshine hours				All clouds				Precipitation			
	100A	100B	$100r^2$	$\bar{e}$	100A	100B	$100r^2$	$\bar{e}$	100A	-100B	$100r^2$	$\bar{e}$	100A	-100B	$100r^2$	$\bar{e}$
Ahmedabad	28	480	94	3.0	26	45	91	3.7	76	45	96	2.0	70	15	94	1.0
Bangalore	18	640	95	3.9	16	57	94	4.4	86	59	91	5.0	69	15	95	5.4
Bhavnagar	28	470	96	2.8	28	41	88	5.3	78	49	88	5.1	71	20	96	3.7
Calcutta	28	420	99	1.3	24	41	97	1.8	68	36	93	3.1	63	09	99	3.7
Goa	30	480	98	2.1	28	43	96	2.9	84	59	87	5.6	69	10	98	3.5
Jodhpur	33	460	92	2.0	25	48	78	3.8	80	47	79	2.7	74	21	92	2.0
Kodaikanal	32	550	95	2.9	31	47	93	3.1	90	67	89	4.6	75	14	95	4.1
Madras	30	440	87	3.5	27	40	94	2.6	78	42	84	3.9	66	11	87	3.8
Mangalore	27	430	94	4.2	25	39	95	4.0	78	49	83	7.4	65	09	94	5.7
Minicoy	26	390	96	1.4	25	39	95	2.0	75	48	91	2.7	60	08	96	2.9
Nagpur	27	500	98	1.6	24	46	96	2.7	79	-48	92	4.4	70	12	98	3.0
New Delhi	25	570	93	3.0	15	60	82	4.8	77	52	84	4.2	71	17	93	2.4
Poona	31	430	98	1.9	29	39	99	1.2	76	44	94	3.6	70	11	98	2.3
Shillong	22	570	98	3.0	18	53	91	5.2	83	64	83	6.5	65	10	98	7.5
Srinagar	35	400	81	4.7	39	26	82	4.7	70	37	44	8.3	57	22	81	10
Trivandrum	37	390	89	2.5	35	35	88	2.6	77	22	94	2.1	66	07	89	2.8
Vishakhapatnam	28	470	98	1.2	26	42	93	2.6	80	48	93	3.4	68	14	98	6.0
Average				2.6				3.4				4.6				4.1

exceeding five per cent. The results of the regression analysis for these variables have been presented in Ref. [13].

4. MONTHWISE REGRESSION ANALYSIS

A study of Table 1 shows that the values of the regression coefficients generally vary significantly with geographic location and it is difficult to decide what values one might use for prediction purposes at a place where radiation data is not available. The citywise regression analysis is thus not useful in providing a suitable method of prediction. An alternative approach could be a month-wise regression analysis which could be applicable to a region as a whole. However if climatic conditions over the region vary considerably, then the errors in the fit will be large.

Keeping this in mind, India has been divided into two regions for the purposes of the monthwise regression analysis. The winter monsoon has been used as the basis for making this division since the summer monsoon is received almost throughout the country though with some degree of variation. On the other hand, the winter monsoon is completely absent or negligible over a large part of the country, and is significant in the rest of the country. It is also observed that in the part receiving the winter monsoon, the radiation quantity is lower by about 15 per cent. The two regions are shown in Fig. 1. The region with a moderate to high winter monsoon is shown as Area I, while the region with a low winter monsoon is shown as Area II. A monthwise regression analysis carried out separately on these two regions would obviously result in a better fit than if the country were treated as one region.

The locations in Area I for which data is available are Hyderabad, Mangalore, Calcutta, Madras, Bangalore, Vishakhapatnam and Trivandrum. The corresponding locations in Area II are Ahmedabad, Bhavnagar, Goa, Jodhpur, New Delhi, Nagpur and Poona. It will be noted (by comparison with the locations mentioned in Section 2) that four locations, viz. Kodaikanal, Shillong, Srinagar and Minicoy have been deleted. The reasons for deleting Kodaikanal, Shillong and Srinagar are that although they fall within Area I, they are all at high altitudes (greater than 1500 m). At these altitudes, other factors like reduced air mass, low dust content and snow cover come into play and affect the radiation. On the other hand, Minicoy has been deleted because it is an island far from the mainland, receives rain almost throughout the year and has very different climatic characteristics.

A monthwise regression analysis was carried out on the locations in Area I using the data of the seven cities that fall in this area. A least square line of the type

$$(H_{av}/H_0) = a + bX \tag{2}$$

was fitted for each month separately and the coefficients a and b were evaluated. The values obtained for the coefficients a and b along with the mean of the actual error ($\bar{e}$) are given in Table 2 for the three independent variables which gave the least errors. The results for other weather parameters may be referred to in [13]. Looking at the errors in the prediction, it can be seen that all clouds is the best specifier. It is followed by per cent possible sunshine and precipitation which are the second and the third best. For the purpose of prediction normally one would use the parameter known to give the least error. However the choice may also be dictated by the availability of data.

A similar analysis has been carried out on the locations in Area II using the data of the seven cities that fall in this area. A least square line, eqn (2), was again fitted for each month separately. The values obtained for the coefficients a and b along with the mean of the actual error ($\bar{e}$) are given in Table 3 for the 3 independent variables which gave the least errors. Looking at the errors, it can be seen that per cent possible sunshine and precipitation are the best specifiers. They are followed by all clouds which is the second best. The errors in Area

Table 2. Regression coefficients a and b in eqn (2) and mean per cent error ($\bar{e}$) for monthwise regression on Area I locations

	Percent possible sunshine			Precipitation			All clouds		
	$a \times 10^3$	$b \times 10^3$	$\bar{e}$	$a \times 10^3$	$-b \times 10^4$	$\bar{e}$	$a \times 10^3$	$-b \times 10^4$	$\bar{e}$
J	608	246	4.2	640	71	4.1	638	38	3.8
F	487	202	4.7	699	27	4.9	734	303	4.7
M	364	364	3.5	669	147	3.0	729	357	3.6
A	462	177	3.0	634	66	2.7	641	98	3.4
M	555	42	4.3	627	58	3.6	805	455	3.7
J	293	442	6.3	536	41	8.1	993	797	8.7
J	209	640	7.0	573	79	10.8	1234	1174	7.1
A	416	117	8.8	453	00	9.4	676	328	9.2
S	424	126	11.0	537	36	11.2	977	820	8.0
O	522	00	3.5	522	00	3.0	549	50	3.8
N	360	290	6.0	596	56	7.4	689	311	4.9
D	454	194	3.8	634	124	3.3	681	264	3.8
Average			5.5			6.0			5.4

Table 3. Regression coefficients a and b in eqn (2) and mean per cent error ($\bar{e}$) for monthwise regression on Area II locations

	Percent possible sunshine			Precipitation			All clouds		
	$a \times 10^3$	$b \times 10^3$	$\bar{e}$	$a \times 10^3$	$-b \times 10^4$	$\bar{e}$	$a \times 10^3$	$-b \times 10^4$	$\bar{e}$
J	490	239	2.0	709	147	1.4	730	200	2.0
F	567	165	0.8	717	61	0.7	730	113	0.8
M	608	119	2.3	711	98	1.9	743	241	1.8
A	561	152	2.1	697	103	1.8	722	199	1.5
M	469	263	1.6	704	135	1.3	711	172	1.4
J	352	385	2.3	641	69	1.5	702	301	4.1
J	267	532	3.7	567	69	4.0	745	481	7.2
A	271	519	3.3	491	19	8.0	826	583	4.4
S	354	387	3.7	663	82	2.8	729	333	3.2
O	289	479	1.3	711	98	1.0	725	191	2.6
N	279	487	2.2	724	224	1.6	742	283	2.0
D	442	287	2.0	693	277	2.1	690	68	2.3
Average			2.3			2.3			2.8

II are lower than those in Area I primarily because of the low variability of radiation in Area II, particularly in the months from November to May.

It is worth noting that the values of the regression coefficients would probably be applicable for the neighbouring countries of Pakistan and Bangladesh. The values for Pakistan would correspond to those obtained for Area II, while the values for Bangladesh would correspond to those obtained for Area I.

5. PREDICTION OF DAILY DIFFUSE RADIATION FROM DAILY TOTAL RADIATION

The available Indian data was analyzed and the values of the parameters (H_{av}/H_0) and (D_{av}/H_0) were obtained in a manner similar to that of Liu and Jordan. When their relationship was studied, it was observed that the basis of the Liu and Jordan approach is valid for Indian conditions but the actual coefficients are different. A plot of (D_{av}/H_{av}) vs (H_{av}/H_0) gave an excellent linear fit. The relationship can be expressed by the equation

$$(D_{av}/H_{av}) = 1.4112 - 1.6956(H_{av}/H_0)$$
$$0.34 \leq H_{av}/H_0 \leq 0.73. \quad (3)$$

Coefficient of determination $r^2 = 0.93$. The above mentioned range of (H_{av}/H_0) covers almost all values that occur in Indian conditions. Equation (3) is derived from the data of 12 cities all over India and should be generally valid for prediction anywhere in India. When the results of the above relationship were compared with those of Liu and Jordan, it was observed that the diffuse component is much larger in India, particularly for lower values of (H_{av}/H_0).

In case the values of H_{av} are not available for a particular location, one could predict these on the basis of the monthwise regression analysis discussed in Section 4.

6. CONCLUSIONS

The following conclusions can be drawn:

(a) A citywise regression analysis is useful in determining which weather parameters correlate best with insolation. However the variation in the values of the regression coefficients from one location to another is significant and consequently such an analysis is not useful from the point of view of predicting insolation.

(b) A monthwise regression analysis carried out separately over regions having some similarities in their climatic characteristics is more useful for prediction purposes.

(c) Per cent possible sunshine, all clouds and precipitation are the three parameters which could be used to estimate insolation with a low error.

(d) The Liu and Jordan model for predicting daily diffuse radiation from daily total radiation is valid for Indian conditions. However in general the value of the diffuse component in India is much larger than that suggested by Liu and Jordan for the United States.

NOMENCLATURE

D_{av} monthly average of the daily diffuse radiation on a horizontal surface

H_{av} monthly average of the daily total radiation on a horizontal surface

H_0 monthly average of the daily extraterrestrial radiation on a horizontal surface

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