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A COMPARISON OF THE ANGSTROM-TYPE CORRELATIONS AND THE ESTIMATION OF MONTHLY AVERAGE DAILY GLOBAL IRRADIATION *

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ABSTRACT

Linear regression analysis of the monthly average daily global irradiation and the sunshine duration data of 8 Zambian locations has been performed using the least square technique. Good correlation $(r > 0.95)$ is obtained in all the cases showing that the Angstrom equation is valid for Zambian locations. The values of the correlation parameters thus obtained show substantial unsystematic scatter. The analysis was repeated after incorporating the effects of (i) multiple reflections of radiation between the ground and the atmosphere, and (ii) not burning of the sunshine recorder chart, into the Angstrom equation. The surface albedo measurements at Lusaka were used. The scatter in the correlation parameters was investigated by graphical representation, by regression analysis of the data of the individual stations as well as the combined data of the 8 stations. The results show that the incorporation of none of the two effects reduces the scatter significantly.

A single linear equation obtained from the regression analysis of the combined data of the 8 stations is found to be appropriate for estimating the global irradiation over Zambian locations with reasonable accuracy from the sunshine duration data.

1. INTRODUCTION

A reasonably accurate knowledge of the availability of the solar resource at any place is required by solar engineers, architects, agriculturists and hydrologists in many applications of solar energy. The most important parameter which is often needed is the long-term average daily global irradiation. Unfortunately the measurements for this parameter are done only at a few places. For places where no measured values are available, a common practice has been to assess this parameter using appropriate correlations which are empirically established by using the measured data at some selected places. These correlations estimate the values of $\bar{H}$ from the more readily available meteorological, climatological and geographical parameters such as the sunshine duration, humidity, temperature, latitude.

2. CORRELATIONS

The first correlation proposed for estimating the monthly average daily global irradiation is due to Angstrom [1]. It uses the sunshine duration data for estimating the global irradiation. Prescot [2] put Angstrom correlation in a more convenient form by replacing H_c by H_o.

$$\bar{H} = \bar{H}_o\,(a+b\;\bar{S}/\bar{S}_o) \qquad (1)$$

Though a number of other correlations, which include more parameters, have been developed by different workers [3], [4], eqn (1) has been found to be very convenient, applicable to a large number of locations and the most widely used correlation. The usual method is to establish the values of the regression parameters a and b using eqn (1) for places where the measured values of the global irradiation and the sunshine duration are available. These values of a and b can then be used to estimate the values of these parameters for other locations on the basis of their climatological and geographical similarities. Finally, the sunshine duration data at these places can be used to generate the values of the global irradiation with the help of eqn (1).

One of the difficulties with eqn (1) is that one often encounters a substantial temporal as well as spatial scatter in the values of the regression parameters even for nearby and climatologically similar locations [5-8]. This makes the task of assigning the values of a and b for other locations rather hard. To circumvent this difficulty, Hay [9] proposed to incorporate the effects of (i) the multiple reflections between the ground and the atmosphere, and (ii) not burning of the sunshine recorder chart when the elevation of the sun is less than 5^o. He used the modified equation

$$\bar{H}' = \bar{H}_o\,(a+b\;\bar{S}/\bar{S}_o') \;, \qquad (2)$$

where

$$\bar{H}' = \bar{H}\,[1-\alpha\,\{0.25\;\bar{S}/\bar{S}_o' + 0.6\,(1-\bar{S}/\bar{S}_o')\}] \qquad (3)$$

and

$$\bar{S}_o' = \frac{2}{15}\;\cos^{-1}\left(\frac{\cos 85 - \sin\phi\,\sin\delta}{\cos\phi\,\cos\delta}\right) \;. \qquad (4)$$

By using eqn (2), Hay [9] observed a substantial reduction in the scatter of the data for Canadian locations. However, recently Jain [10] used eqn (2) for analysing the global irradiation and the sunshine duration data of 30 Italian locations. He also tested two more equations by incorporating each of the above-mentioned two effects separately, viz. the incorporation of the effect of the multiple reflection alone gives

$$\bar{H}' = \bar{H}_o\,(a+b\;\bar{S}/\bar{S}_o) \qquad (5)$$

and that of not burning of the sunshine recorder chart when the elevation of the sun is less than 5^o, would give

$$\bar{H} = \bar{H}_o\,(a+b\;\bar{S}/\bar{S}_o') \;. \qquad (6)$$

His results showed that the use of none of the eqns (2), (5) or (6) offered any advantage over the use of simpler Angstrom equation. However, Jain's analysis was open to question in one respect. Because of the non-availability of the surface albedo values, he assumed a common constant value of 0.2 for all seasons and all the locations. The present analysis is meant to compare the efficiency of eqns (1), (2), (5) and (6) more conclusively by using the actually measured values of the surface albedo at Lusaka.

3. DATA ANALYSIS AND RESULTS

3.1 Effect of multiple reflections and not burning of the sunshine recorder chart on the scatter

The global irradiation, the sunshine duration and the surface albedo data for Zambian locations are used in the analysis. Though the sunshine duration, temperature and humidity data are available for fairly long duration for about 20 Zambian locations, the measurements of the solar radiation data first started only in 1977. At present there are only 8 stations that measure the global radiation. Table 1 lists the geographical details of the stations together with the duration of the global radiation data available and used in the present analysis. The sunshine duration data in this analysis is taken for the same duration as that for the global radiation. It is essential that the two data should be for the same duration. The locations of the various stations inside the country, the pattern of variation of the meteorological parameters - the maximum temperature, humidity and the sunshine duration - are available in an earlier work [11].

Table 2 presents the measured values of H and S used in the present analysis. The values of H_o, S_o and S_o' were easily obtained from the table recently compiled by Jain [12] and are presented in Table 2. The mean of the surface albedo values for each month as measured at Lusaka during 1982-84 are presented in Table 3. There are no measurements of the surface albedo values at other locations. However, it may be seen that the variation of the surface albedo values for Lusaka during the year is quite small - between 0.23 and 0.28 only. Also, in view of the fact that the whole country has nearly the same kind of vegetation, ground and climatological conditions, the surface albedo values at Lusaka would indeed be expected to be representative of those of other locations as well. Using these values of the surface albedo and Eq. (3), the values of H' were computed and are presented in Table 2 along with other values.

Linear regression analysis using the least square technique was done on the ICTP computer Gould 32/87 for the four equations (1), (2), (5) and (6) and for each of the 8 locations. The values of the regression parameters a and b, and the coefficient of correlation r were computed. These are presented in Table 4. The mean μ, the sample standard deviation σ_{n-1} and the coefficient of variation V, defined as the ratio σ_{n-1}/μ, were also computed and are presented in the same Table.

To study the scatter from a different viewpoint, the sunshine duration data and the global irradiation data of the 8 locations were grouped together, i.e. $12 \times 8 = 96$ sets of values were obtained for each of S/S_o, H/H_o, S/S_o' and H'/H_o. Linear regression analysis using the equations (1), (2), (5) and (6) was done for this data and the values of a, b and r were computed. These are presented in Table 5.

To show the scatter pictorially, Figs. 1 and 2 are drawn to show the plots of the 96 pairs of points, S/S_o vs. H/H_o and S/S_o' vs. H'/H_o, respectively.

3.2 Global irradiation estimation

To find if a single set of regression parameters can be used to estimate the global irradiation over Zambian locations, we chose the single set of regression parameters obtained for the combined data of the 8 locations and used the equation

$$H = H_o\,(0.240 + 0.513\,S/S_o) \tag{7}$$

for estimating the global irradiation for the 8 locations. The magnitude of the percentage error in the estimate was calculated using the expression

$$\text{Error} = \frac{|H_e - H_m|}{H_m} \times 100$$

For each of the months. The 12-months average of these magnitudes were calculated and are about 4%, 3%, 6%, 3%, 4%, 9%, 3% and 5% respectively for Mbala, Mansa, Ndola, Lusaka, Livingstone, Luangwa, Kasama and Mongu.

4. DISCUSSION

Table 4 shows that high values of the correlation coefficient $(r > 0.95)$ are obtained for all the 8 Zambian locations. This means that the Angstrom equation is valid fairly accurately for Zambian locations. However, it is also seen from the same Table that substantial unsystematic scatters are obtained in the values of the regression constants. To study the extent of the scatter, Table 4 also lists the mean, the standard deviation and the coefficient of variation of the parameters. It may be cautioned that the standard deviation alone should not be used to judge the relative scatter of two samples with different mean values.

The parameter which should be compared is the coefficient of variation V, which is the ratio of the standard deviation and the mean. It can be seen from Table 4 that for the parameter a, the value of V is 0.165 for eqn (1), considerably higher for eqns (2) and (5) and a little lower for eqn (6). For the parameter b, the value of V is almost the same for eqns (1) and (6) and little lower for eqns (5) and (2). This shows that the use of eqns (2), (5) or (6) does not cause any systematic and significant reduction in the scatter amongst the values of the regression parameters.

Table 5 offers another way of looking at the scatter. This table lists the results of the linear regression analysis when the data of all the 8 locations are grouped together. It is seen that the values of the coefficient of correlation for eqns (1), (2), (5) and (6) are 0.917, 0.930, 0.928 and 0.918, respectively. This shows a slight improvement in the coefficient of correlation by the use of eqns (2) and (5), but the improvements are too small to be of any significance. Therefore the use of eqns (2), (5) or (6) does not offer any significant advantage over the use of eqn (1) for Zambian locations. Essentially the same conclusions are drawn by looking at Figs. 1 and 2 where no reduction in the scatter of points is evident in Fig. 2.

As the actually observed values of the surface albedo have been used in the present analysis, this study establishes more conclusively than the previous study by Jain [10] that the incorporation of the two effects studied here into the Angstrom equation, collectively or singly, does not universally offer a significant advantage over the simpler Angstrom equation. However, Hay's [9] study clearly shows a considerable reduction in the scatter by the use of eqn (2). It therefore appears that the effect of the multiple scattering is significant under some conditions. This effect appears to be important in regions where the surface albedo is high for some part or the whole of the year, for example, due to snow cover. For places where the surface albedo remains upto about 0.3, it does not appear to play a significant role.

The effect of not burning of the sunshine recorder chart for small elevation of the sun, though theoretically appealing and described by several workers, does not seem to play any important role in reducing the scatter. As is expected and can be easily seen from Table 1 of Ref. [12], the difference between S_o and S'_o is higher for higher latitudes. Since the Zambian locations are situated at low latitudes, one may tend to think that this effect may be important for locations with high latitudes. However, in his study of the Italian locations, which have latitude values in the range about $40^{\circ} - 45^{\circ}$N, Jain [10] showed that this effect did not contribute at all in reducing the scatter. Since the study of this effect was not based on the

surface albedo value, which had been assumed, the study was conclusive in this respect. Even Hay's [9] study would not show anything about this factor alone. He studied the two effects collectively. The reduction in the scatter in his case could have been solely due to the incorporation of the effect of the multiple scattering. It is therfore highly doubtful if the incorporation of the effect of not burning of the sunshine recorder chart plays any role in reducing the scatter.

Jain [11] has already discussed that the variation in the values of a and b for Zambian locations do not depend either on the latitude, as suggested by Glover and McCulloch [13], or on the value of S/S_o as suggested by Fre're et al [14]. He did obtain empirical correlations of the parameters with the station heights. These correlations were supposed to hold for the stations with medium elevation only (about 950 m to 1500 m). It is in fact seen in this study as well that such a correlation exists for six of the stations which are situated in the elevation range of 950 m and 1500 m. The correlation does not hold for Mbala and Luangwa which have elevations of 1673 m and 570 m, respectively. The cause of the scatter therfore remains rather illusive. At this point we may simply comment that these variations are perhaps real variations caused by some subtle variations in the climatological conditions. The climatological and the atmospheric conditions of any two places, even though it may appear to be the same strictly speaking, are never the same. Even for the same place these conditions would not be exactly the same from year to year. Any such changes are bound to reflect in the variations of the regression parameters.

Fortunately, it has still been possible to find a way to estimate the global irradiation at Zambian locations to a fair degree of accuracy. Though there are considerable scatters in the values of a and b, the scatter in the value of the sum a+b is much smaller. This has enabled the use of the same eqn(7) for all the Zambian locations. As is mentioned in Subsec. 3.2, the estimated values, on the average, differ by a margin of about 4-5% from the measured values. It may be stressed that the use of eqn(7) is not, however, in estimating the global irradiation for the 8 locations where the measured values of the irradiation already exist. The exercise was done to simply assess the efficiency of the use of eqn (7). The real use of this equation is in the estimation of the global irradiation for any other Zambian location where only the sunshine duration data are available

5. SUMMARY AND CONCLUSIONS

Linear regression analysis of the global irradiation and the sunshine duration data of 8 Zambian locations using the least square technique shows that the Angstrom equation is valid for the Zambian locations. Substantial unsystematic scatters are obtained in the values of the regression parameters. The incorporation of the effects of, (i) multiple reflections between the ground and the atmosphere, and (ii) not burning of the sunshine recorder chart for small elevation of the sun, collectively or singly, does not reduce the scatter significantly. While the effect of the multiple reflections could be important only for places where the surface albedo value is high, for example due to snow cover, the effect of not burning of the sunshine recorder chart is not of significant importance anywhere in reducing the scatter.

The linear equation $H = H_o (0.240 + 0.513\ S/S_o)$, obtained from the regression analysis of the combined data of 8 Zambian locations is recommended for estimating the global irradiation over all those Zambian locations where the sunshine duration data are available.

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NOMENCLATURE

a,b	regression parameters
H	monthly average daily global irradiation
H_c	monthly average daily global irradiation on a clear day
H_e	estimated monthly average daily global irradiation
H_m	measured monthly average daily global irradiation
H_o	monthly average daily extraterrestrial irradiation
H'	monthly average daily global irradiation that first hits the ground before undergoing multiple reflections
S	monthly average daily sunshine duration
S_o	maximum possible monthly average daily sunshine duration
S'_o	maximum possible monthly average daily sunshine duration recorded on a Campbell-Stoke's sunshine recorder
r	coefficient of correlation
V	coefficient of variation
α	surface albedo
δ	declination
ϕ	latitude
σ_{n-1}	sample standard deviation
μ	mean

TABLE 1

Station	Latitude	Longitude	Elevation (meters)	Duration of data
Lusaka	$15^{\circ}19'$	$28^{\circ}27'$	1154	Jan 1978 - Dec 1984
Livingstone	$17^{\circ}49'$	$25^{\circ}49'$	986	Jan 1977 - Nov 1984
Ndola	$13^{\circ}00'$	$28^{\circ}39'$	1270	Jan 1978 - Dec 1984
Mansa	$11^{\circ}06'$	$28^{\circ}51'$	1259	Jan 1981 - Dec 1984
Mongu	$15^{\circ}15'$	$23^{\circ}09'$	1053	Jan 1981 - May 1983
Luangwa	$13^{\circ}16'$	$31^{\circ}56'$	570	Jun 1981 - Dec 1984
Kasama	$10^{\circ}13'$	$31^{\circ}08'$	1384	Aug 1981 - Dec 1984
Mbala	$08^{\circ}51'$	$31^{\circ}21'$	1673	Jan 1983 - Dec 1984

TABLE 2

Station	Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Lusaka	S	6.01	5.84	6.42	7.62	8.93	9.00	8.61	9.99	9.75	8.53	7.21	5.46
	S_o	12.80	12.45	12.07	11.64	11.28	11.11	11.15	11.49	11.89	12.32	12.70	12.89
	S'_o	12.06	11.77	11.38	10.94	10.55	10.35	10.43	10.77	11.20	11.62	11.97	12.14
	H	18.54	17.20	18.46	18.11	17.95	17.03	17.12	21.62	22.07	22.36	21.20	18.45
	H_o	40.94	39.85	37.09	32.88	28.78	26.59	27.41	30.76	34.96	38.41	40.34	41.01
	H'	16.64	15.52	16.69	16.44	16.67	15.82	15.90	20.14	20.50	20.51	18.88	16.41
Livingstone	S	7.53	6.99	7.26	9.27	10.00	9.87	9.93	10.29	9.99	8.61	7.15	7.10
	S_o	12.94	12.56	12.08	11.58	11.16	10.95	11.04	11.40	11.87	12.38	12.81	13.05
	S'_o	12.18	11.84	11.38	10.87	10.41	10.17	10.28	10.67	11.17	11.67	12.08	12.28
	H	22.83	22.13	20.70	20.77	19.91	19.61	20.68	21.57	23.28	22.39	21.01	21.95
	H_o	41.47	39.97	36.72	32.03	27.62	25.32	26.18	29.78	34.37	38.34	40.73	41.64
	H'	20.73	20.13	18.83	19.14	18.65	18.38	19.44	20.15	21.67	20.56	18.70	19.77
Ndola	S	5.10	5.28	6.10	7.64	9.30	9.51	9.64	10.20	9.79	8.53	7.16	5.15
	S_o	12.67	12.41	12.06	11.70	11.40	11.25	11.31	11.57	11.91	12.27	12.59	12.75
	S'_o	11.94	11.70	11.37	11.00	10.67	10.50	10.57	10.86	11.22	11.58	11.86	12.01
	H	17.56	18.33	18.56	18.35	18.34	17.48	17.65	19.69	20.64	20.45	19.33	17.79
	H_o	40.40	39.67	37.39	33.63	29.81	27.75	28.51	31.64	35.45	38.42	39.91	40.35
	H'	15.67	16.46	16.73	16.64	17.04	16.30	16.51	18.36	19.18	18.78	17.22	15.79

TABLE 2 (a)

Station	Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Mansa	S	4.90	5.40	7.63	8.43	9.43	9.95	10.10	10.10	9.28	8.43	6.83	4.63
	S_o	12.57	12.34	12.05	11.75	11.49	11.36	11.41	11.64	11.92	12.23	12.50	12.64
	S'_o	11.85	11.64	11.37	11.05	10.76	10.61	10.68	10.93	11.24	11.54	11.78	11.90
	H	19.06	18.36	18.96	19.46	20.37	20.33	20.60	22.07	22.56	22.02	20.56	18.32
	H_o	39.91	39.48	37.58	34.19	30.63	28.66	29.37	32.30	35.80	38.38	39.52	39.78
	H'	16.97	16.51	17.17	17.77	18.94	19.01	19.33	20.54	20.88	20.20	18.27	16.20
Mongu	S	6.47	6.80	6.50	9.10	9.97	10.10	10.20	10.10	9.30	8.40	5.30	8.20
	S_o	12.79	12.48	12.07	11.64	11.29	11.11	11.19	11.49	11.89	12.32	12.69	12.89
	S'_o	12.05	11.77	11.38	10.94	10.55	10.35	10.43	10.77	11.20	11.62	11.96	12.14
	H	19.51	20.83	18.28	20.98	19.10	18.70	20.06	20.86	20.98	20.03	17.05	21.43
	H_o	40.93	39.85	37.10	32.91	28.81	26.63	27.45	30.79	34.97	38.41	40.32	40.99
	H'	17.59	18.93	16.52	19.29	17.87	17.55	18.87	19.45	19.42	18.36	14.92	19.49
Luangwa	S	5.73	6.17	7.90	8.90	8.55	9.05	8.55	9.65	9.38	9.20	7.60	6.80
	S_o	12.68	12.42	12.06	11.69	11.39	11.24	11.30	11.56	11.91	12.27	12.60	12.76
	S'_o	11.95	11.71	11.37	11.00	10.66	10.49	10.56	10.85	11.22	11.58	11.87	12.02
	H	20.71	21.76	25.06	23.01	20.84	20.75	20.97	23.36	24.18	25.24	24.00	22.77
	H_o	40.46	39.69	37.36	33.55	29.70	27.63	28.39	31.55	35.40	38.42	39.96	40.42
	H'	18.56	19.68	22.90	21.12	19.24	19.26	19.44	21.68	22.40	23.28	21.47	20.49

Station / Month		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Kasama	S	4.20	5.43	6.50	7.80	8.90	9.47	10.60	9.55	9.38	7.67	7.50	5.38
	S_o	12.52	12.32	12.05	11.77	11.53	11.42	11.47	11.66	11.93	12.21	12.46	12.58
	S'_o	11.80	11.62	11.37	11.07	10.81	10.67	10.73	10.96	11.25	11.52	11.74	11.85
	H	16.91	17.61	20.09	19.78	19.92	19.42	19.59	21.14	22.80	21.16	20.86	17.72
	H_o	39.66	39.37	37.66	34.44	31.01	29.09	29.78	32.61	35.96	38.35	39.32	39.50
	H'	15.02	15.65	15.16	17.95	18.42	18.08	18.48	19.63	21.11	19.30	18.66	15.76
Mbala	S	4.01	5.30	6.20	7.50	9.25	9.60	8.75	8.30	9.40	7.85	5.80	4.25
	S_o	12.45	12.25	12.04	11.79	11.60	11.49	11.54	11.71	11.94	12.18	12.39	12.50
	S'_o	11.77	11.59	11.36	11.11	10.88	10.76	10.81	11.01	11.26	11.50	11.68	11.77
	H	17.16	18.04	19.84	19.51	20.78	20.20	19.15	20.41	24.11	19.22	16.77	17.10
	H_o	39.28	39.19	37.76	34.81	31.56	29.72	30.38	33.01	36.16	38.28	39.00	39.05
	H'	15.16	16.22	17.90	17.67	19.27	18.80	17.76	18.69	22.32	17.55	14.77	15.07

TABLE 2 (b)

TABLE 3

JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
0.24	0.23	0.24	0.26	0.24	0.24	0.23	0.25	0.24	0.24	0.28	0.25

TABLE 4

Location	Using eqn (1)			Using eqn (2)			Using eqn (5)			Using eqn (6)		
	a	b	r	a	b	r	a	b	r	a	b	r
Lusaka	0.198	0.551	0.986	0.151	0.516	0.990	0.147	0.556	0.990	0.202	0.511	0.986
Livingstone	0.187	0.613	0.964	0.135	0.579	0.968	0.127	0.628	0.965	0.195	0.565	0.967
Ndola	0.286	0.386	0.980	0.231	0.375	0.982	0.229	0.402	0.981	0.287	0.360	0.982
Mansa	0.265	0.476	0.975	0.210	0.457	0.978	0.208	0.489	0.976	0.267	0.445	0.977
Mongu	0.188	0.556	0.973	0.139	0.526	0.977	0.133	0.568	0.976	0.194	0.515	0.975
Luangwa	0.253	0.588	0.955	0.196	0.556	0.962	0.194	0.595	0.959	0.256	0.549	0.959
Kasama	0.268	0.454	0.977	0.215	0.434	0.982	0.213	0.466	0.982	0.270	0.424	0.977
Mbala	0.245	0.505	0.950	0.194	0.479	0.955	0.193	0.511	0.954	0.247	0.473	0.951
μ	0.236	0.516	0.970	0.184	0.490	0.974	0.181	0.527	0.973	0.240	0.480	0.972
σ_{n-1}	0.039	0.075	0.013	0.037	0.067	0.012	0.039	0.074	0.012	0.037	0.069	0.012
V	0.165	0.145	0.013	0.201	0.137	0.012	0.215	0.140	0.012	0.154	0.144	0.012

TABLE 5

Independent variable	S/S_o	S/S'_o	S/S_o	S/S'_o
Dependent variable	H/H_o	H'/H_o	H'/H_o	H/H_o
Intercept a	0.240	0.187	0.184	0.243
Slope b	0.513	0.487	0.524	0.478
Coefficient of correlation r	0.917	0.930	0.928	0.918

TABLE CAPTIONS

Table 1	Geographical parameters and the duration of the data of the Zambian locations.
Table 2	Solar radiation and meteorological data of the Zambian locations used.
Table 3	Surface albedo values for Lusaka.
Table 4	Results of the linear regression analysis for the data of 8 Zambian locations.
Table 5	Results of the linear regression analysis for the combined data.

FIGURE CAPTIONS

Fig. 1 Relationship between S/S_o and H/H_o for 8 Zambian locations.

Fig. 2 Relationship between S/S_o' and H'/H_o for 8 Zambian locations.

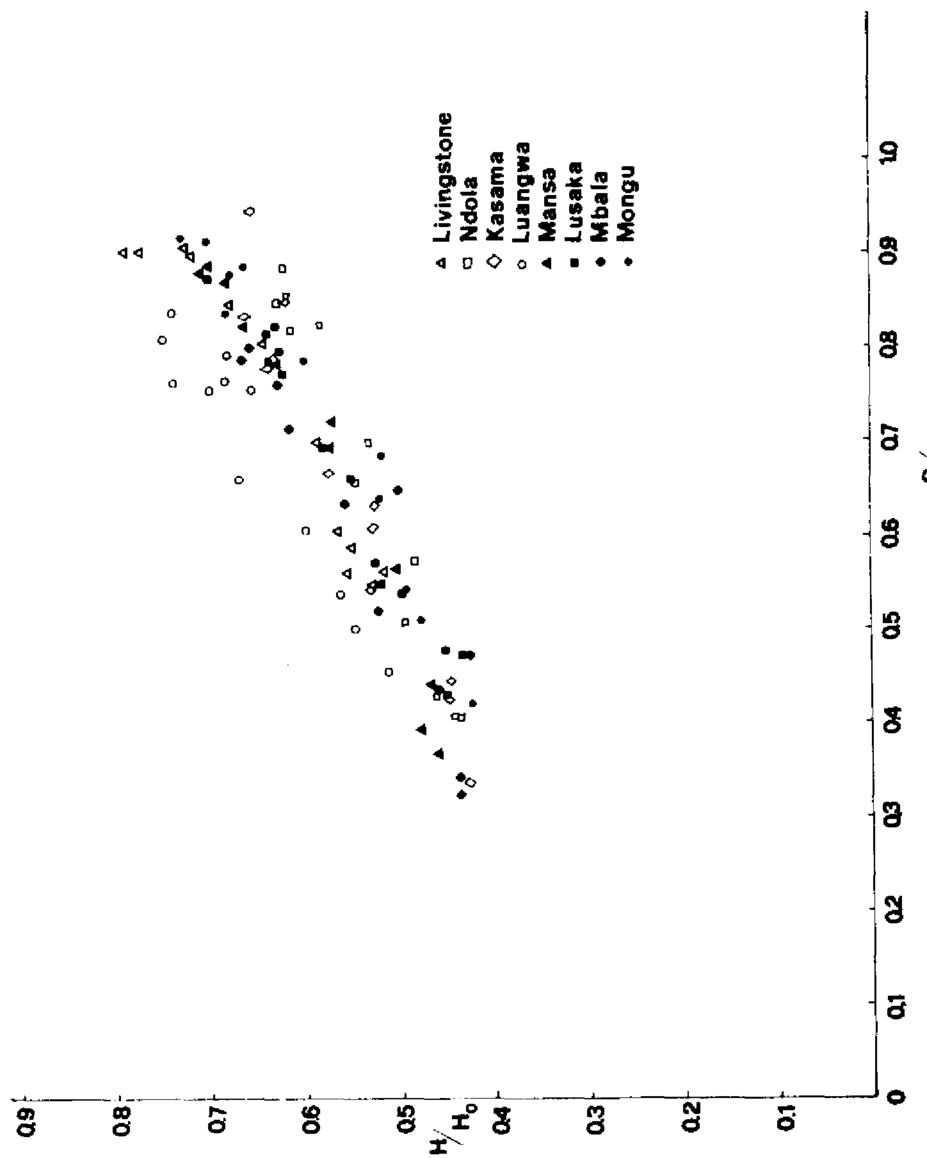

Fig.1

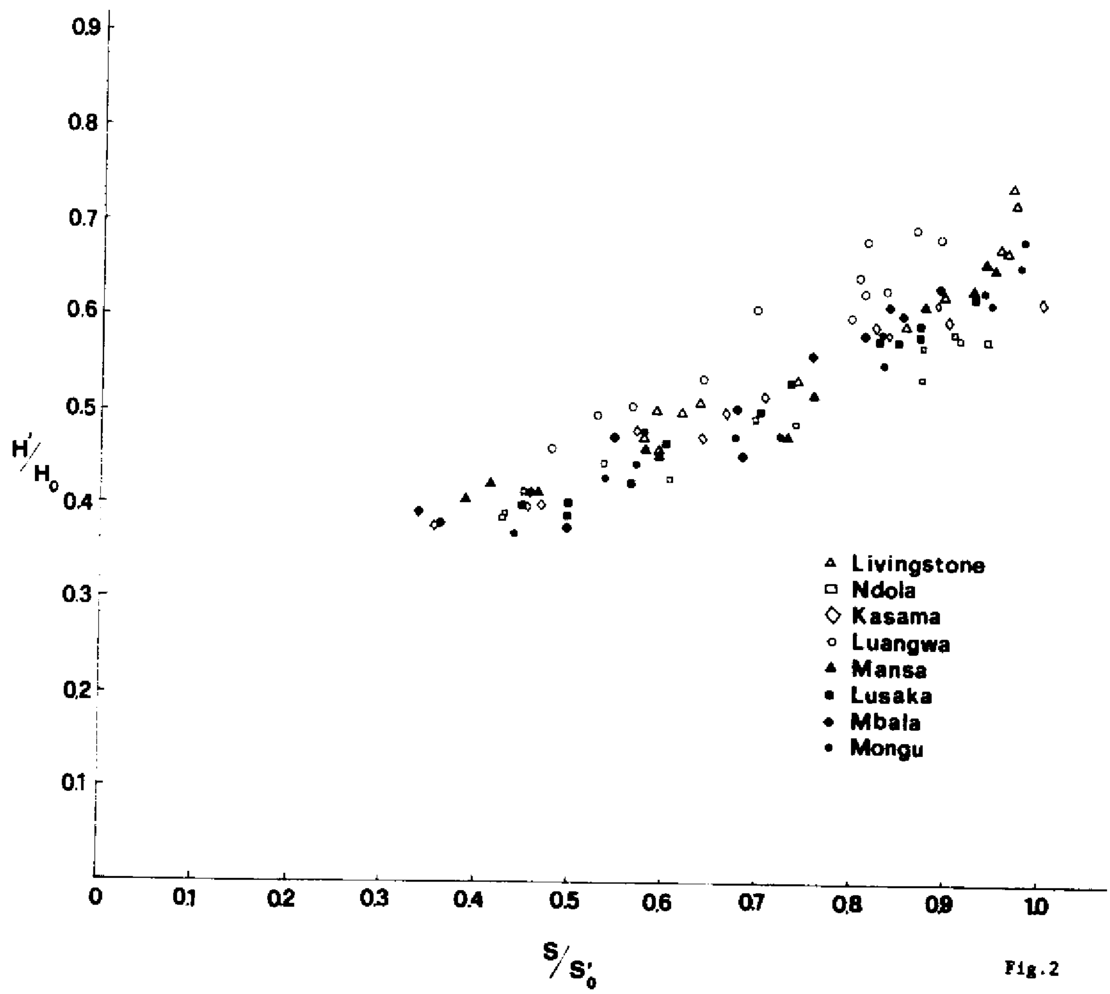
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
H'/H0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
S/S'0
Livingstone
Ndola
Kasama
Luangwa
Mansa
Lusaka
Mbala
Mongu

Fig.2