SOLAR RADIATION MAPS FOR ETHIOPIA

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ABSTRACT

Estimates of solar radiation maps for Ethiopia are prepared from measured solar radiation data of 6 sites and estimates from sunshine hour records of 136 sites. The estimates for the 136 sites are determined from their sunshine hour data using the Angstrom's linear correlation for the inland regions and that of Schuepp's for the coastal regions where extreme high and low daily sunshine occurs frequently. The 136 sites are classified into the three climatic zones defined by the EMS and suitable regression constants assigned to each site to estimate the global solar radiation level. From the maps prepared it could be seen that sizable portion of the Country receives on the average a radiation level of about 5500 wh/m^2 day^{-1}, thus signifying the solar power potential of the country.

INTRODUCTION

Information on the solar radiation level at a location is of significant use in the design and efficient utilization of solar conversion devices, in agricultural studies and weather forecasting. Measured solar radiation data is the best source of information; however, measured solar radiation data are available only for few places due to the high cost of the measuring equipment and its periodical up-keep. Attempts have therefore been made to develop emperical relations for estimating insolation from weather data: temperature, humidity, sunshine hour, coludiness and precipitation, which are actually easier to measure and are available at many locations. Alternatively, for a particular location the solar radiation level may also be evaluated by carrying out a monthwise regression analysis of data of existing neighbouring sites with similar latitude, topography and other climatic conditions.

A global as well as regional estimates of the distribution of solar radiation have been studied by many researchers [2]. However, since solar radiation reaching the earth's surface depends on many factors which are not of global character, a study of solar radiation under local climatic conditions is essential. The aim of the present work is to provide information on the global solar radiation iucident on a horizontal surface in Ethiopia.

Ethiopia lies between latitudes 3°N to 17.5°N and longitudes 33°E to 47.5°E, and is a region with high solar irradiance throughout the year. De Carli *et al* and CESEN [3,4] have calculated the mean daily global solar radiation for Ethiopia using the Angstrom's modified and linear relations and those of Schuepp's. For each of the methods they used a single set of regression constant for the entire region. The regression constant used in the modified Angstrom's relation were by Frere, and in the linear Angstrom's and Schuepp's relations were those suggested by the World Meteorological Organization. The precision of the results achieved by the three relations have been checked with only one-year measured radiation data of Addis Ababa. In the present work measured values of global solar radiation at 6 sites shown in Fig. 1 and radiation estimates calculated from percent possible sunshine for 136 sites are employed in preparing the solar radiation map of the Country. In the evaluation of the radiation estimates for the 136 sites, the modified Angstrom's relation with suitable regression constants are employed after a careful climatic classification of the sites.

CORRELATION FORMULATION AND CLASSIFICATION OF DATA BASE

Solar radiation data measurement have been started very recently in Ethiopia. For the 6 sites shown in Fig. 1, Addis Ababa has 12 years data and the rest 2-5 years only. However, sunshine hours have been recorded over varying periods by both the Ethiopian Meteorological Service (EMS) and the UN Food and Agricultural Organization (FAO) in Rome for a total of 142 stations shown in Fig. 1.

A number of emperical relations are available to estimate global solar radiation from meteorological and geographical data. However, Modi and Sukhatme after analysing a number of meteorological data of 12 stations in India [1], have confirmed the results of other researchers that percent possible sunshine is the best periodictor of solar radiation as compared with the meteorological data such as sunshine hour, temperature, humidity, cloudiness, vapour pressure, wind speed and precipitation. In this paper the global solar radiation over Ethiopia is estimated from percent possible sunshine which is evaluated from sunshine hour data recorded by the EMS/FAO and checked and compiled by De Carli *et al* and CESEN [3,4].

The Angstrom's linear correlation is the foremost that utilizes the percent possible sunshine for estimating daily global solar radiation (2).

$$H_G = H_c(a_1 + b_1 (S/S_o)) \quad (1)$$

where H_G is the monthly average daily global radiation on a horizontal surface,
H_c is the daily global radiation on a horizontal surface on a fine cloudless day, or clear sky radiation,
S is the monthly average of daily hours of bright sunshine
S_o is the maximum daily bright hours of sunshine assuming no obstruction in the horizon,
S/S_o is the percent possible sunshine, and
a_1 and b_1 are regression constants, and for Ethiopia (tropical region)
the suggested values are $a_1 = 0.30$ and
$b_1 = 0.70$. [4].

A non-linear relationship is also suggested by Schuepp that correlates H_G with percent possible sunshine and the clear sky radiation [3,4].

$$H_G = H_C \ (a' + b' \ 1/2 \ S/S_o \ (1 + S/S_o)) \quad (2)$$

where a' and b' are regression constants and for tropical regions the suggested values are: $a' = 0.25$ and $b' = 0.75$. [3]

Accurate measurement of the maximum daily bright hours of sunshine (S_o) is a practical problem since during sunrise and sunset the direct radiation of the sun is too weak to activate sunshine recorders and the water vapour content of the atmosphere could also affect the threshold above which the temperature burns the paper in the recorders. Hence, the practice is to replace S_o by Z, astronomical length of the day (5).

$$Z = 2/15 \cos^{-1} (-\tan\phi \tan\delta) \quad (3)$$

where is the locations latitude in degrees

$$= 23.45° \text{ Sin } (360(284 + n)/365) \quad (4)$$

is the solar declination, and
n is the day of the year given for each month

In the Angstrom's correlation, because of the difficulty in defining a clear day, H_G is replaced by H_O (extraterrestrial radiation), and the correlation in Eq. 1 is modified as (7).

$$H_G = H_O \ (a + b \ (S/Z)) \quad (5)$$

where a and b are regression constants dependant on location and site's climatic conditions.

A number of researchers have suggested values for the regression constants a and b. Black *et al* [8] after analysing the sunshine records for 32 meteorological stations between geographical latitudes 30°S to 60°N have suggested the values for $a = 0.23$ and $b = 0.48$. Frere *et al* [9] have proposed a graphical relationship between the constants a and b and the annual percent possible sunshine for areas between latitudes 35°S to 50°N. Glover and McCulloch [10] have noted that the constant a is dependant on latitude; whereas, the constant b is more or less fixed with a value of 0.52. They suggested that the constant a is related to the latitude by

$$a = 0.29 \cos\phi \quad (6)$$

Studying the values of the regression constants suggested by these researchers over the wide range of latitudes and actual values obtained on local or regional level by other researchers [9, 11-17], one can see quite a large variations, and hence for better results local or regional radiation records should be employed to evaluate the coefficients.

For the 6 sites with measured solar radiation data the least square method was used to calculate the regression coefficients a and b of Eq. [5] and the correlation coefficient r. The results are presented in Table 1. The correlation is good for all the sites except Massawa which is a port with $r = 0.67$. This could be expected since the site being in a coastal region there is a varying radiation intensity during different periods of the day due to the influence of the sea that contributes to poor correlation. Hence, a non-linear correlation, Schuepp's, is chosen and the comparison between the measured and estimated global solar radiation values as shown in Table 2 is excellent.

The regression constants suggested for tropical regions in the Angstroms's correlation and those by Frere *et al*, Black *et al*, and Glover and McCulloch have been tried in the estimation of the global solar radiation with the remaining 5 sites if they could provide error levels between the measured and estimated radiation values within $\pm$ 10%. The result is shown in Table 3.

Regression constant values of $a = 0.29$ and $b = 0.50$ is suggested in this work and the maximum error involved between the measured and calculated values is also shown in Table 3.

From Table 3 it can be seen that the suggested regression constants: $a = 0.29$ and $b = 0.50$ provide error less than $\pm$ 10% in four of the sites except Dire Dawa. According to the climatic classification by EMS, Dire Dawa is in a semi-arid Zone [18-19], and infact with sand dust during the dry-months period, September to May, that makes solar radiation intermittent. The remaining four sites are in tropical zones.

Representing the five sites by a single set of regression constant is impossible. Hence for best result our suggestion is to use the site's regression constants of $a = 0.358$ and $b = 0.501$ for Dire Dawa, and $a = 0.29$ and $b = 0.50$ for for the other four sites.

Table: 1 Regression and Correlation coefficients

Site	Altitude (m) a.s.l	Location Lat.	Long.	Regression a	Constants b	Correlation Coefficient
Addis Ababa	2408	9.02°N	38.45°E	0.255	0.532	0.992
Asmara	2325	15.17°N	38.55°E	0.306	0.545	0.989
Awassa	1750	7.04°N	38.30°E	0.242	0.389	0.985
Bahar Dar	1890	11.36°N	37.24°E	0.336	0.383	0.969
Dire Dawa	1210	9.36°N	41.52°E	0.358	0.501	0.887
Massawa	10	15.37°N	39.27°E	0.530	0.085	0.670

Table 2: Measured and Estimated Global Solar Radiation for Massawa

Month	Global Solar Radiation (KJ/m^2) Measured	Calculated [4]	Error (%)
January	14603	14599	0.03
February	15981	15977	0.0
March	19517	19541	-0.10
April	22597	22591	0.0
May	22258	22252	0.0
June	22735	22729	0.0
July	21236	21230	0.0
August	21636	21630	0.0
September	21875	21869	0.0
October	19128	19123	0.0
November	16573	16569	0.0
December	15293	15289	0.0

Table 3: Choice of Regression Coefficients for the Five Sites

Site	Angstrom Corr	Modified Angstrom Correleation			
	a=.30; b=.70 Error (%)	Black *et al* a=.23; b=.48 Error (%)	Frere *et al* Error (%)	Glover/McCulloch a=.29;Cos ;b=.52 Error (%)	Suggested Values a=.29; b=.50 Error (%)
Addis Ababa	-4.2 to 5.4	-9.3	a=.3, b=.42 -3 to 5.2	-17.8	-9.7
Asmara	19.1	-21.8	a=.32, b=.41 13.5	8.8	9.9
Awassa	18.2	-16.2	a=.31, b=.41 13.2	-3 to .9	-3 to 2.4
Bahar Dar	39.2	-5.1	a=.31, b=.41 3.18	-8.4	-7.5
Dire Dawa	28.6	-23.3	a=.32, b=.41 22.4	16.7	18.5

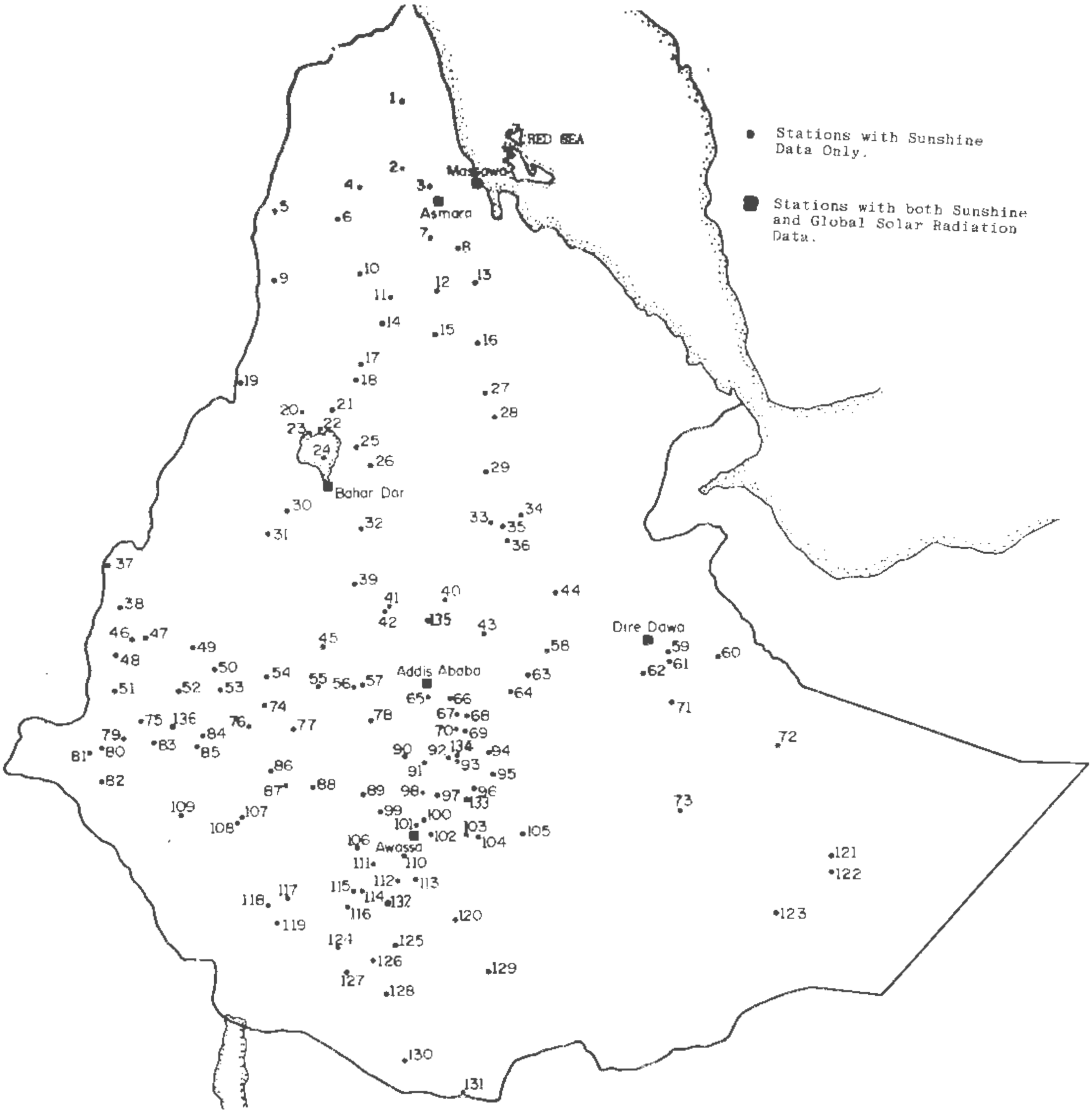

Fig. 1 Data Sites

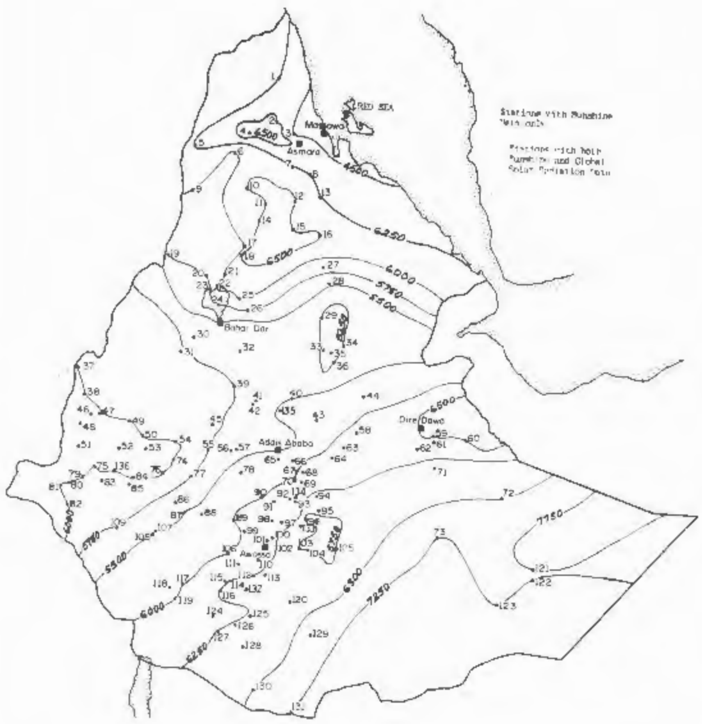

Fig. 2 Mean Daily Global Solar Radiation (wh/m^2) for January.

Fig. 3 Mean Daily Global Solar Radiation (wh/m^2) for February.

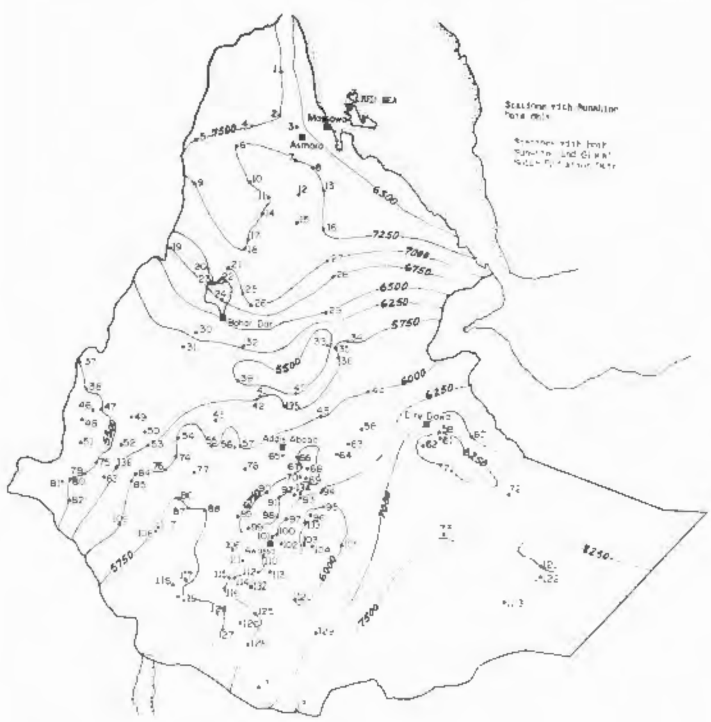

Fig. 4 Mean Daily Global Solar Radiation (wh/m^2) for March.

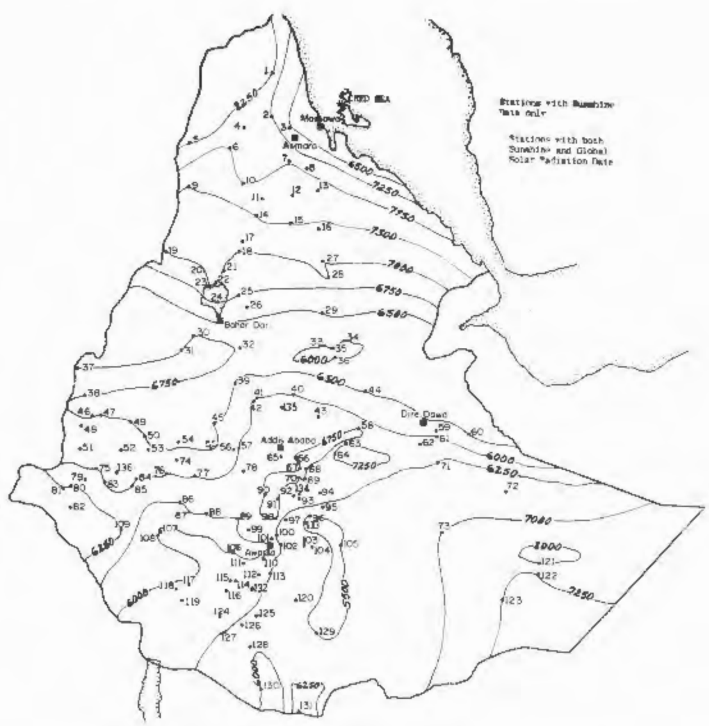

Fig. 5 Mean Daily Global Solar Radiation (wh/m^2) for April.

Fig. 6 Mean Daily Global Solar Radiation (wh/m^2) for May.

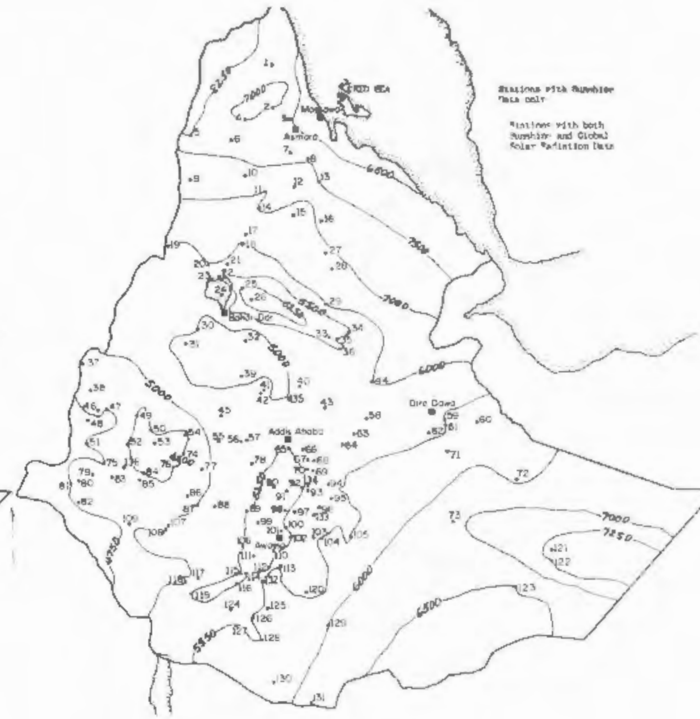

Fig. 7 Mean Daily Global Solar Radiation (wh/m^2) for June.

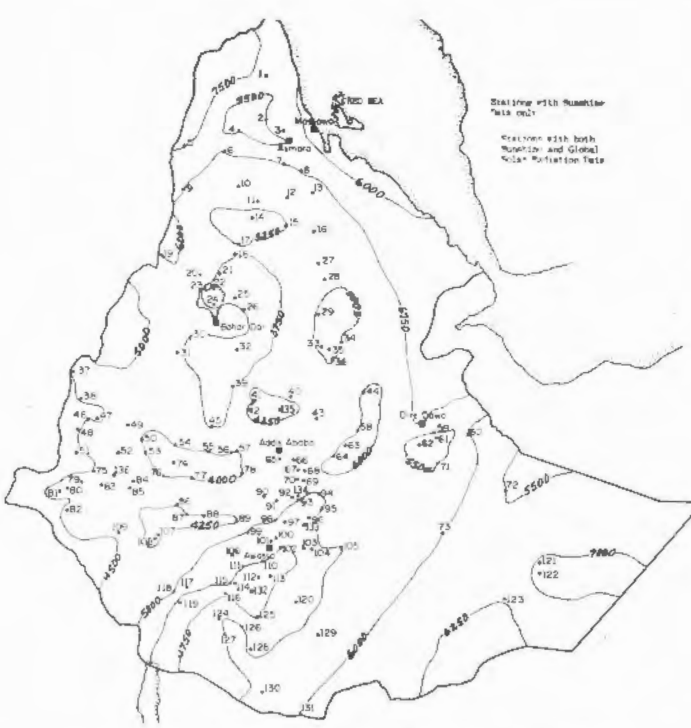

Fig. 8 Mean Daily Global Solar Radiation (wh/m^2) for July.

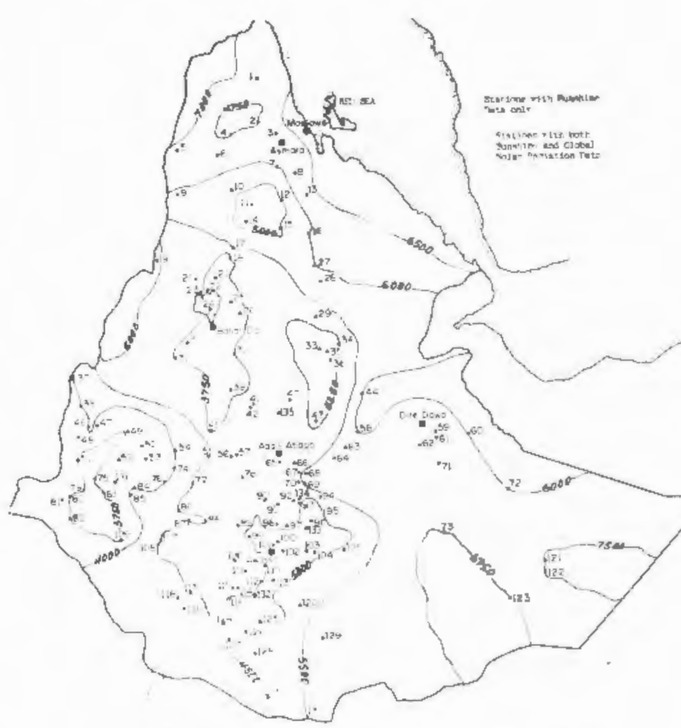

Fig. 9 Mean Daily Solar Radiation (wh/m^2) for August.

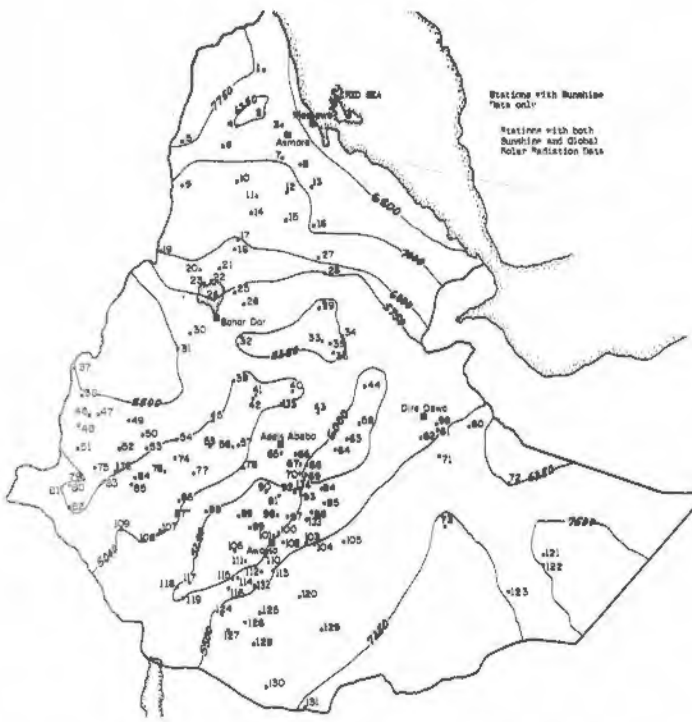

Fig. 10 Mean Daily Global Solar Radiation (wh/m^2) for September.

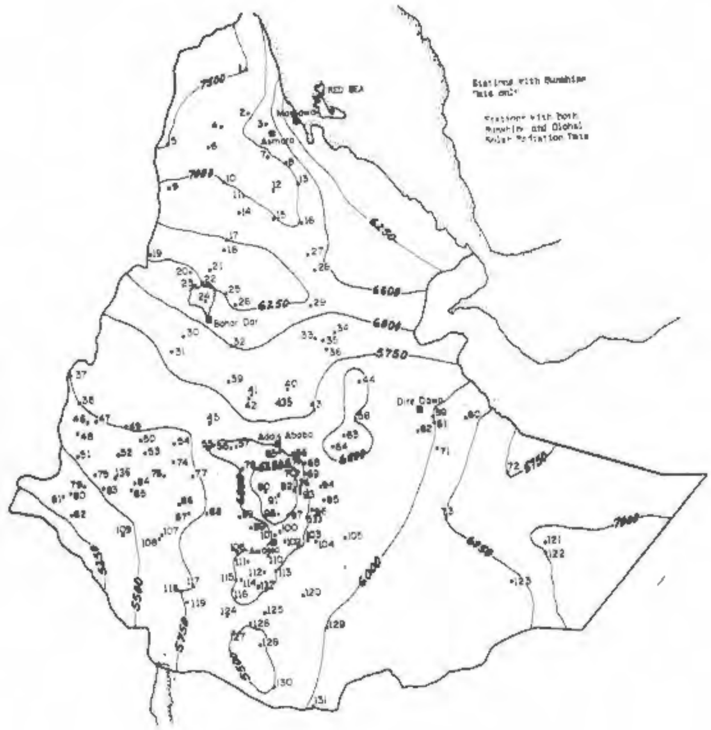

Fig. 11 Mean Daily Global Solar Radiation (wh/m^2) for October.

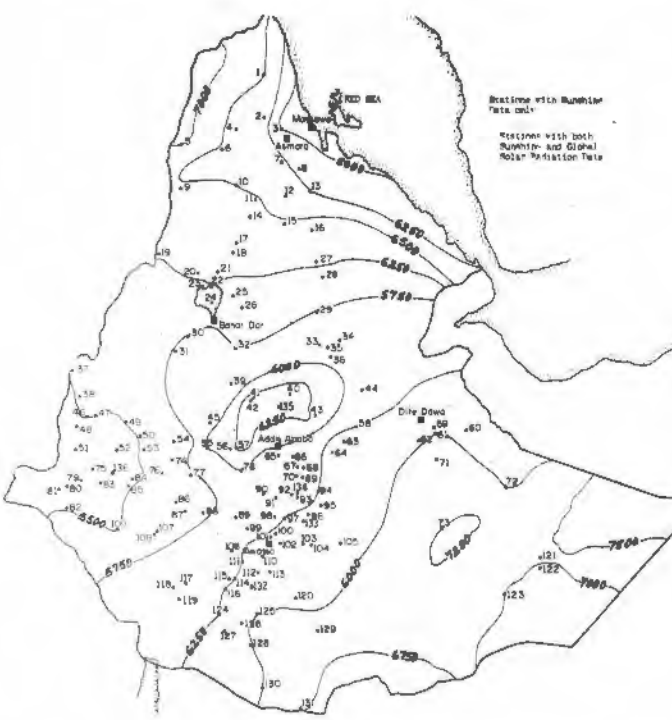

Fig. 12 Mean Daily Global Solar Radiation (wh/m^2) for November.

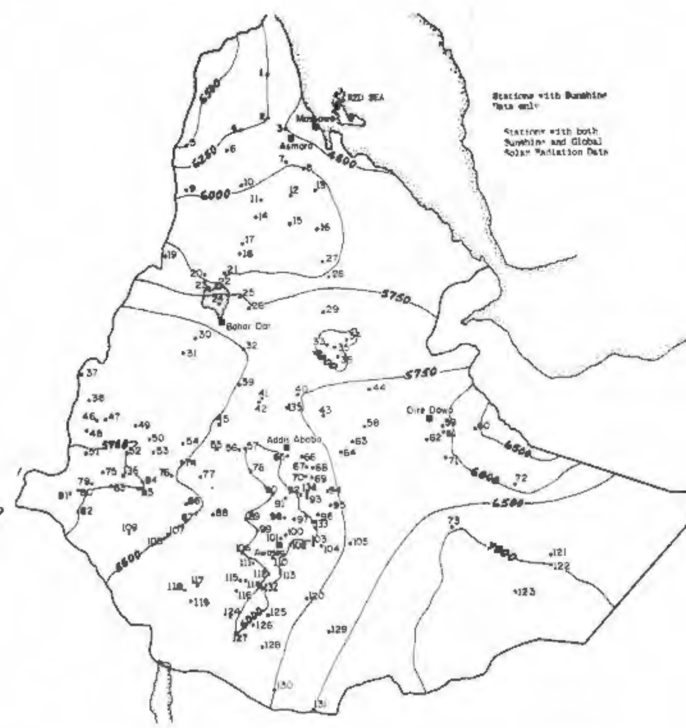

Fig. 13 Mean Daily Global Solar Radiation (wh/m^2) for December.

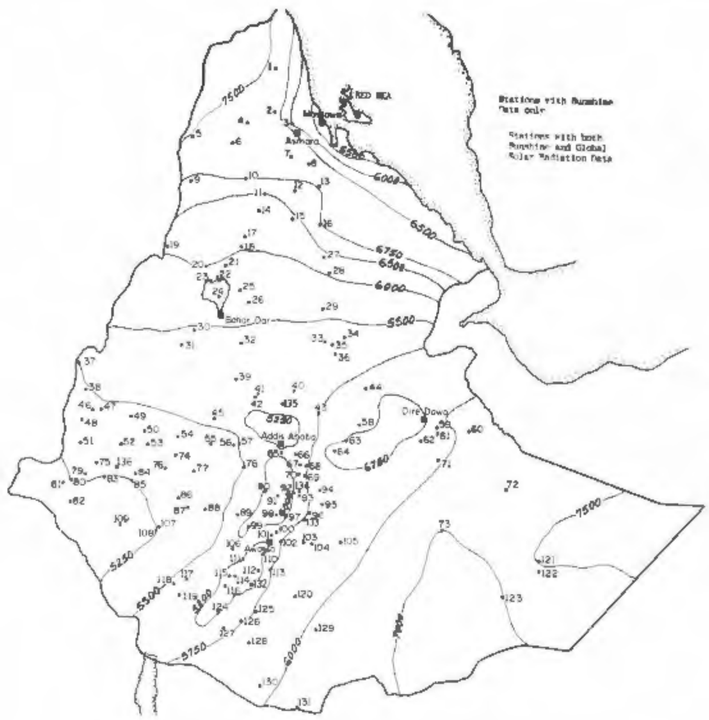

Fig. 14 Annual Mean Daily Global Solar Radiation (wh/m²).

1.	Nakfa	28.	Alamata	55.	Bako	82.	Abobo	109.	Tepi
2.	Keren	29.	Woldia	56.	Guder	83.	Bure	110.	Wondo A.
3.	Faghena	30.	Dangla	57.	Ambo	84.	Metu	111.	Bilate
4.	Akordat	31.	Chagne	58.	Melka Werer	85.	Gore	112.	Dila
5.	Tesseney	32.	Mota	59.	Alemaya	86.	Agaro	113.	Hagere Selam
6.	Barantu	33.	Desie	60.	Jijiga	87.	Jima	114.	Mierab
7.	Adi Ugri	34.	Bati	61.	Harar	88.	Asendabo	115.	Chenca
8.	Adi Keyih	35.	Kombolcha	62.	Grawa	89.	Hossana	116.	Arba Minch
9.	Humera	36.	Chafa	63.	Awash	90.	Butajira	117.	Felege Newaye
10.	Sheraro	37.	Kurmuk	64.	Metehara	91.	Ziway	118.	Bulki
11.	Indaselasie	38.	Asosa	65.	Akaki	92.	Ogelcho	119.	Bako Jinka
12.	Adwa	39.	Debre Markos	66.	Debre Zeit	93.	Asela	120.	Adola
13.	Adigrat	40.	Alem Ketema	67.	Mojo	94.	Dixis	121	Kebri Dehar
14.	Tekeze	41.	Goha Tsion	68.	Nazreth	95.	Robi	122.	Korrahie
15.	Abiy Adi	42.	Filiklik	69.	Wonji	96.	Ticho	123.	Gode
16.	Mekele	43.	Debre Berhan	70.	Koka Dam	97.	Munesa	124.	Bako Jinka
17.	Debivar	44.	Gewani	71.	Migdalola	98.	Langano	125.	Hagere Mariam
18.	Dabat	45.	Fincha	72.	Degeh Bur	99.	Alaba K.	126.	Burji
19.	Metema	46.	Bambesi	73.	Hamaro	100.	Kuyera	127.	Konso
20.	Aykel	47.	Mendi	74.	Arjo	101.	Wendo G.	128.	Yabelo
21.	Gondar	48.	Begi	75.	Dembi Dolo	102.	Kofele	129.	Negele
22.	Kola Diba	49.	Nejo	76.	Bedele	103.	Dodola	130.	Mega
23.	Gorgora	50.	Gimbi	77.	Amago	104.	Adaba	131.	Moyale
24.	Zeigie	51.	Gidami	78.	Weliso	105.	Goba	132.	Yirga Chefe
25.	Addis Zemen	52.	Yubdo	79.	Gambela	106.	Sodo	133.	Bekoji
26.	Debre Tabor	53.	Dedisa	80.	Poko	107.	Wush Wush	134.	Kulumsa
27.	Maichew	54.	Nekemte	81.	Itang	108.	Bonga	135.	Fitche
								136.	Atnago

The 136 stations are classified by EMS into three broad catagories: Tropical climate (coldest month above 18°C), Tropical highlands (coldest month between 3°C to 18°C), and Arid climate (desert and steepe), [18-19]. The sites: Addis Ababa, Asmara, Awassa and Bahar Dar which are in tropical type of climate stretch over 1300 Kms distance with different altitudes and latitudes, but still represented by the same regression constants. Other stations in the neighbourhood along these sites and with the same climatic classification are assigned the same regression constants. The arid zone which comprises mostly the northern end and the coastal region is assumed to receive radiation level identical to that of the Massawa area. The semi-arid sites which are found at isolated spots and mostly in the south-eastern part of the Country are assigned the same regression constants as that of Dire Dawa if the particular site satisfies the climatic and topographic conditions of Dire Dawa. I.e., in this paper a site classified as semi-arid by the EMS if it satisfies the conditions: percent possible sunshine > 0.6, altitude < 1500m, rainfall < 500mm/yr, and in addition considering the site's neighbouring zones

it takes the regression constants of Dire Dawa. Otherwise, it is classified as tropical. Based on these classifications the global solar radiation for each month and the average for the year is calculated for all the 136 sites, and the results are mapped in Figs. 2-14.

CONCLUSION

The main features of the solar radiation maps shown in Figs. 2-14 are as follows:

i) The highest radiation level in the Country is received by the north-western and south-eastern regions, and the lowest level by the western regions.

ii) In all the months there is solar radiations gradient from the north to the centeral region.

iii) The highest radiation level in the Country is between the months April to June and the lowest level in July and August; corresponding to the dry and rainy seasons, respectively.

iv) Throughout the year a great portion of the Country receives an average of 5500 wh/m^2 day^1 of radiation. This radiation level is quite high and signifies that the Country has a great potential of solar power for energy production.

The solar radiation maps prepared from the sunshine hour data of the 136 sites and actual solar data of the 6 sites could provide information on the insolation level in the Country and may also help in system sizing of solar devices. With actual solar radiation data measurements at these and other additional sites, in particular along the Red Sea coast, south-eastern and north western regions of the Country, a more complete and accurate map could be prepared.

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