Clear Skies at Sebele, Botswana

J. Andringa* and P.V.C. Luhanga [¥]
Faculty of Science. University of Bouwana
p\bag 0022 Gaborone. Botswana

ABSTRACT

The distribution of the clearness index at Sebele, Botswana, is presented for the period 1977 to 1992. Botswana lies in the mid-latitudes, between the tropical and temperate zones. Additionally the country has a semi-arid savannah-like climate. The monthly means of the daily clearness index K_{AVG} are between 44% and 75%. When the averages of the monthly means of K_{AVG} (K_{avg}) are taken for each month, it is noted that these clearness indices range from 57% to 68%. During the rainy season, relatively low values of the clearness index K_{AVG} are experienced. In the winter period, the cumulative frequency distribution of the clearness index is relatively high for the months of May, June, July and August.

The maximum value of the monthly average clearness index K_{max} has been calculated by many researchers using expressions based on K_{AVG} only. In this paper it is shown that the method used by Hollands and Huget produces results that show a better correspondence to the observed data for Botswana than the method of Saunier.

1. INTRODUCTION

Solar radiation data are essential in design purposes for solar energy and are used in the fields of agriculture and architecture, in solar chemical and solar thermal conversions. One of the parameters that indicate the availability of sunshine is the clearness index K. The clearness index gives the ratio of the incoming global radiation G, to the extraterrestrial global radiation G_0,

$$K = G/G_0 \tag{1}$$

The advantages of using the clearness index instead of the global radiation is that the ratio G/G_0 is dimensionless and therefore cloudy or clear conditions of the sky can be noted immediately. The daily values of the clearness index, K_T, are averaged for each month to get K_{AVG}, and these K_{AVG} are used to determine monthly trends and other features.

The values of K_T vary considerably from very low for overcast conditions, to very high for clear skies. K_{min} is the minimum value and K_{max} the highest value of K_T in a particular month.

Researchers and designers would like to find a model of the probability distribution of the clearness index in order to predict monthly trends and other features of the pattern of the global radiation. Several attempts have been made to arrive at such a probability function and cumulative frequency distribution of the clearness index. In most forms the boundary conditions on K_T need to be

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* ISES member.

¥ author to whom correspondence should be addressed.

known; for which value of K_T the probability function is zero. If there would be a day with no incoming radiation, the value of K_{min} would be zero. Even on a very dark and cloudy day there is always some light and $K_{min} = 0.05$ has been proposed by Bendt et al. [1]. The highest value of K_T would be $K_{max} = 1$, but this would be realized only outside the atmosphere. Two proposals for the maximum value of K_T will be investigated, both depend upon the value of K_{AVG}. Hollands and Huget [2] suggest the relationship:

$$K_{max} = 0.6313 + 0.267\, K_{AVG} - 11.9\, (K_{AVG} - 0.75)^3 \quad (2)$$

Since these authors used data from only the northern part of America, it is debatable if their results can be generalised outside this region, especially for tropical areas with very different climatic conditions; these could well need a different approach. Saunier et al [3] observed that there exists an approximately linear relationship between K_{AVG} and K_{max} for several Asian locations, and proposed the following relationship:

$$K_{max} = 0.362 + 0.597\, K_{AVG} \quad (3)$$

to be used in a generalised probability density function of the clearness index as described by Bendt et al. [1].

In this paper the clearness index is first used to indicate the climatic conditions of Botswana, showing possible annual trends. Secondly, values of K_{max} are calculated from the monthly values of K_{AVG}, using the two relationships of Hollands and Huget [2] and Saunier [3], and these are then compared with the actually observed values of K_{max} for Botswana.

2. CLIMATE OF BOTSWANA

Botswana in Southern Africa lies between 18°S and 27°S at an elevation of about 1 km. The Kalahari, a semi-desert, covers most of its area. The climate is characterised by erratic rainfall during the summer period and clear skies during winter. The monthly mean of the bright sunshine hours is above 8 hours per day throughout the year. The average annual global irradiation is quite high with values of 20 to 22 MJ m^{-2} per day throughout the country [4]. Lower values occur in winter and higher values in summer, but the latter fluctuate from day to day due to occasional spells of cloudy weather. The temperatures vary from sometimes just below zero on a winter night to over 40°C in the afternoon in summer. The air is normally quite dry. The annual rainfall ranges from 290 mm in the South West to 680 mm in the North East of the country. The rainfall occurs often in thunderstorms in summer. The eastern part of Botswana sometimes receives enough rainfall to sustain crop farming. Large areas of the country are used for cattle farming and substantial areas are dedicated to wildlife. Most of the 1.3 million people live in rural areas in the east of the country.

Weather parameters are measured at a dozen synoptic stations spread over the whole country and processed in the capital, Gaborone. The Agricultural Research Station (ARS) at Sebele is located 10 km north of Gaborone, in the South East of the country. The station monitors weather parameters including global radiation [5].

A few characteristics of the weather parameters for Gaborone are as follows [6,7,8]. The average annual rainfall for Gaborone is 530 mm, annual totals range from a low 240 mm to a high 930 mm. The mean evaporation (class A pan) is 2.6 m per year, with monthly values varying from 110 mm to

300 mm. The average sunshine duration is 8.8 h/day; monthly values range from 8.3 to 9.6 h/day. The annual average of the daily insolation is 20 MJ m^{-2}; the monthly mean ranges from 15 MJ m^{-2} to 25 MJ m^{-2}. The average wind speed at 2 m is 1.2 m/s, (range of the monthly average: 0.9 - 1.6 m/s). The mean minimum air temperature is 13°C (range: 4 - 20°C), the maximum 28°C (range: 22 - 33°C). The relative humidity in the moming at 08:00 has a mean value of 65% (the monthly values range from 50 - 75%); in the afternoon at 14:00 the values average 35% (range: 26 - 43%). The average number of cloudy days, with cloud cover at least half the daylength, is 61 in one year. and there are 304 days with cloud cover of less than 50% of the daylength.

3. DATA PROCESSING

In Botswana the daily global irradiation has been measured with a pyranometer since 1975 at the ARS at Sebele near Gaborone. There are a few more stations with global irradiation records but their measurements are infrequent and of short duration, with only a few months or a few years of continuous data. Daily sunshine duration S has been recorded at all synoptic stations in the country. These data have been the background used to arrive at a picture of the solar radiation for Botswana [4,6]. The relationship:

$$G/G_o = a + b\,(S/S_o) \qquad (4)$$

relates the daily global radiation G with the calculated values of the extraterrestrial radiation G_o and the daylength S_o to the measured daily sunshine duration S. A similar expression is valid for the monthly averages of the quantities and this has been used to determine the long term values for the constants a and b. Based upon the screened measured monthly average values of S and G for Sebele, it was found [4] that a = 0.25 and b = 0.50.

For the present study on the clearness index, the measurements for the period 1977 to 1992 were extensively checked for data reliability. Sometimes problems occurred with the measurements of C and therefore data were not always available [9]. The process of recognizing invalid data is a difficult one and data might have been recorded without realizing that they were invalid, therefore a check is essential. The following rejection criteria are somewhat arbitrary and are based upon guidance from similar work [10,111.

There are often some months in Botswana for which all days have a sunshine duration of more than half the daylength. For such months the correlation coefficient will be low compared to months in which there is a larger range for values of S/S_o, that is for months in which there were cloudy days ($S/S_o < 0.5$) as well as sunny days ($S/S_o > 0.5$). For each month the regression coefficients a_n and b_n were calculated, and so was the correlation coefficient r_n. In this investigation, (i) data were rejected for months for which $a_n + b_n$ were either below 0.6 or above 0.9; (ii) data were rejected for months for which the correlation coefficient between S/S_o and G/G_o was below 0.8, when there were both cloudy and sunny days in that month; (iii) data were also rejected for months where the correlation coefficient was exactly equal to 1, since obviously either the S or the G values had been calculated instead of having been measured. A lucky circumstance is that Gaborone and Sebele are quite close and that the daily values of S could be verified and some data could be salvaged. Using the above criteria, about 20% of the data had to be rejected.

4. SOME OBSERVATIONS AND RESULTS

The clearness index K_T was calculated for each day. The extraterrestrial radiation G_0 depends on the declination of the sun and the latitude of the location and on the solar constant. The value for the solar constant was taken as 1.37 kW m^{-2} [12]. For each month the average value of K_T was calculated (K_{AVG}). The minimum and maximum values of K_T, K_{min} and K_{max}, were determined for each month. Then the 15-year mean values of K_{AVG}, K_{avg}, for every calendar month were established, see Table 1. The extreme values of K_{min} for each month were checked and recorded. For each month, the two lowest values appear in the table. Similarly, the two highest values of K_{max} represent the monthly maxima values of the clearness index observed for each month. The calculated values of K_{max} using equations (2) and (3) have also been included in the table for each month, for comparison.

Table 1. The monthly **clearness** indices **(in %) for Sebele.**

Month	Observed K_{avg}	Observed K_{max}			Observed K_{min}			Calculated	
		AVG	(1)	(2)	AVG	(1)	(2)	K_{max2}	K_{max3}
Jan	58	72	78	77	25	14	17	79	70
Feb	57	73	79	79	25	8	10	78	70
Mar	58	75	82	81	25	6	12	79	70
Apr	60	76	80	79	25	12	13	79	72
May	61	76	84	82	39	12	14	81	76
Jun	68	77	84	83	47	18	24	81	76
Jul	61	77	85	81	41	23	28	81	76
Aug	64	74	81	80	39	14	18	80	74
Sep	60	76	80	79	27	7	12	79	72
Oct	59	71	82	82	24	8	9	79	71
Nov	57	75	82	78	22	10	13	78	70
Dec	58	74	80	80	21	12	12	79	70
Column: 1	2	3	4	5	6	7	8	9	10

Column 1: month
Column 2: the observed monthly values of K_{avg}
Column 3: the average of the monthly K_{max}
Column 4 and 5: the two highest values of K_{max} for the month
Column 6 the average of the monthly K_{min}
Column 7 and 8: the two lowest values of K_{min} for the month
Column 9 and 10: the calculated values of K_{max} using equations (2) and (3)

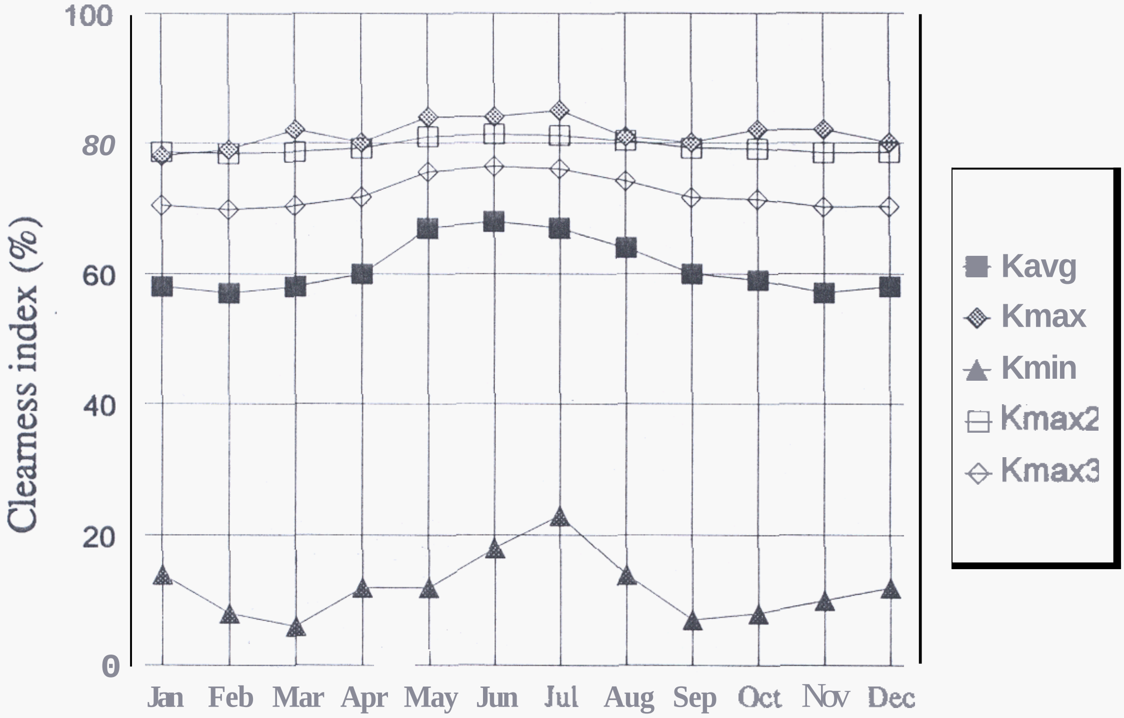

Fig. 1. Monthly values of the cleamess index (K_{min}, K_{max} and K_{AVG}) for Sebele in Botswana K_{max2} and K_{max3} are the values as calculated using two different equations, (2) and (3).

During the winter months (May - August) the values of K_{AVG} are slightly higher than during the other months. The values of the observed K_{max} are in close agreement with those calculated using equation (2) although slightly higher. Equation (3), on the other hand, gives values which are much lower than the observed values of K_{max}. The monthly averages of the daily values of K_T, K_{AVG}, vary from a low of 44% to a high of 75%. The daily values of K_T have a much wider range of course, the extreme values being 6% and 85% (Table 1). Figure 2 shows the frequency distribution of the all monthly values of K_{AVG} (44%-75%). In Fig. 1 it can be seen that for all months K_{avg} is much closer to K_{max} than to K_{min}, suggesting a skewed distribution (shown in Fig. 2).

Figure 3 shows the daily clearness index values presented in a frequency distribution. The skewed distribution of K_T is obvious. The mean value of the daily clearness index is 61%, the mode 68% and the median is 64%. These values are also presented in a cumulative frequency distribution in Fig. 4. It is obvious that there are not many cloudy days in Sebele.

Let us now consider months with different degrees of overcast conditions. For this purpose the months are grouped into three classes with relative low, moderate and high values of K_{AVG}. For Botswana a representative choice for the class values was made with K_{AVG} about 50% (Kclass = 50), about 60% (Kclass = 60) and about 70% (Kclass = 70). In Table 2 the various characteristics of these classes are given. The Kclass = 50 contain values for K_{AVG} from 47.5% to 52.5%, these ranges are shown in Table 2. As there were no months with observed K_{AVG} below 45% or above 75% there are no classes for about 40% nor for about 80%. This stresses the sunny conditions of Botswana but hinders

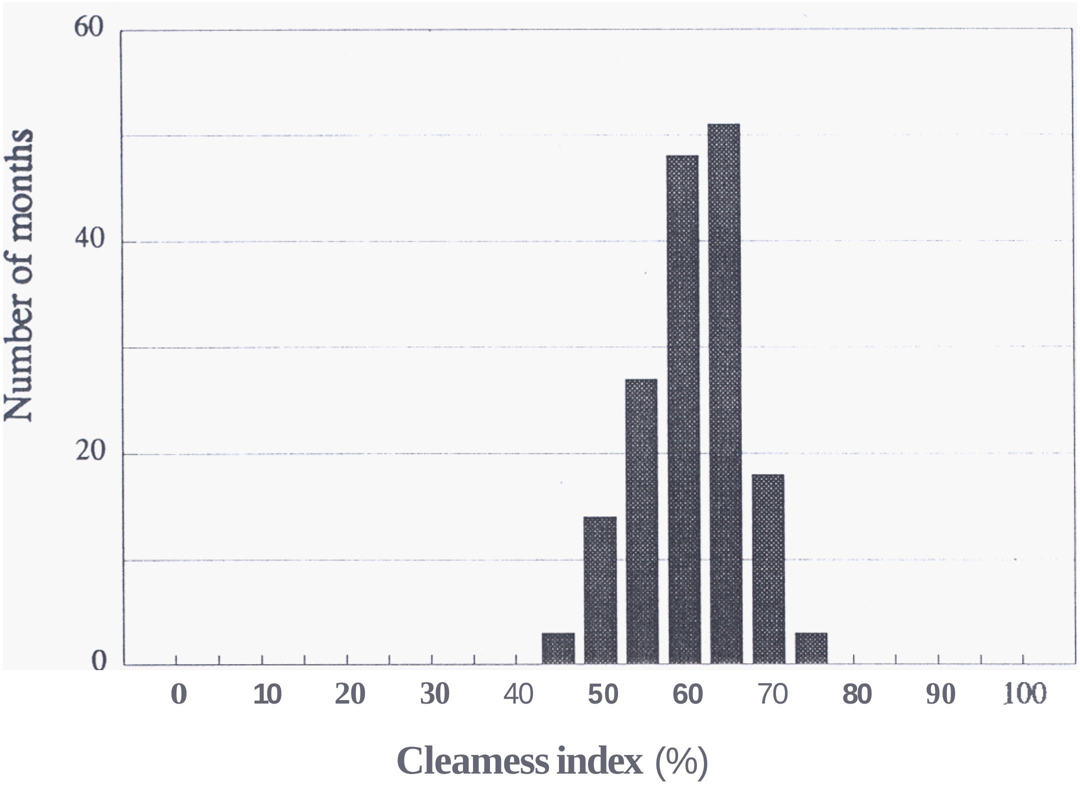

Fig. 2. The frequency of the months with monthly cleamess index K, in multiples of 5; there are for example 48 months which have a value of K, between 57.5% and 62.5%.

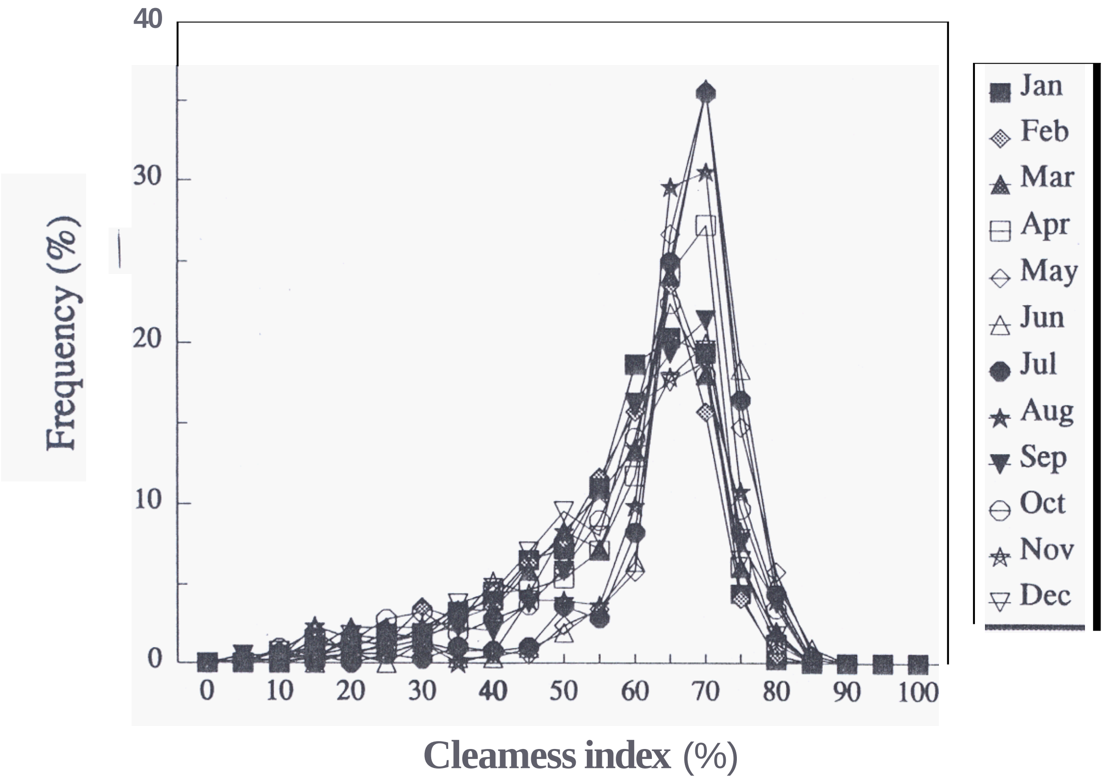

Fig. 3. The frequency distribution of the daily cleamess index $K_{,,}$ for every month in the period 1977-1992, Sebele. Botswana.

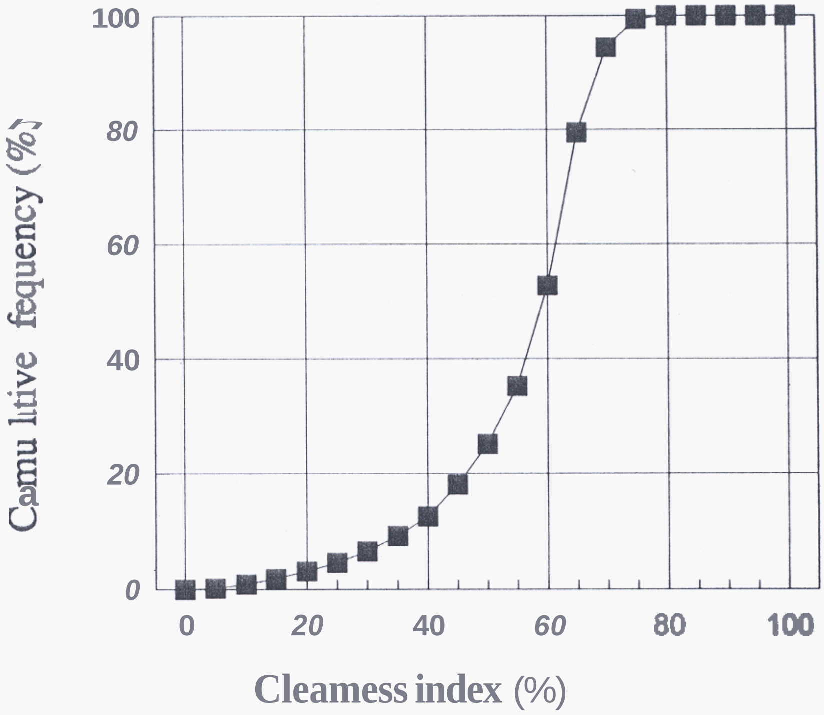

Fig. 4. The cumulative frequency distribution of the daily clearness index K_T for Sebele, 1977-1992.

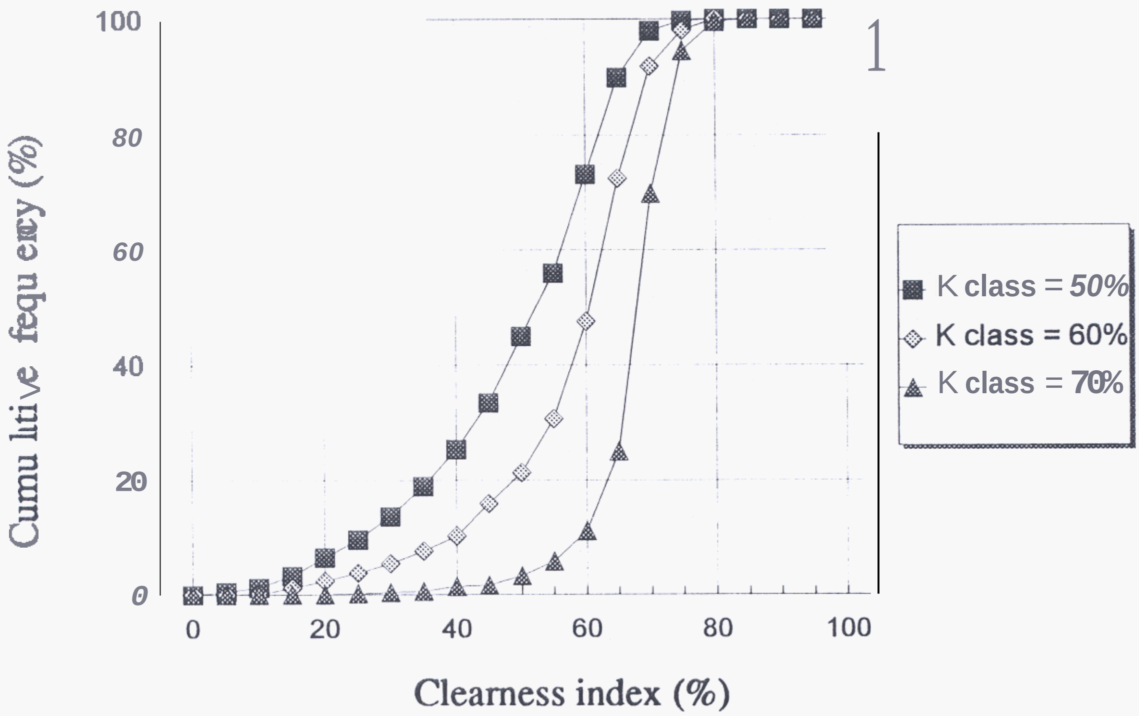

Fig. 5. The cumulative frequency distribution of the daily clearness index for Sebele separated into *three* groups. with K_{AVG} about 50%, 60% and 70%.respectively.

Table 2. Characteristics of three classes of the monthly clearness indices for Sebele.

K Class	n	Range of class (%)	K class Avg. (%)	K class St. dev. (%)	observed K_{max} (%)	observed K_{min} (%)	Calculated max_2 (%)	Calculated max_3 (%)
50	14	47.5-52.5	50.1	15.4	77	7	71	66
60	47	57.5-62.5	60.2	12.4	82	12	79	72
70	17	67.5-72.5	69.3	7.1	85	28	82	77
Column: 1	2	3	4	5	6	7	8	9

Column 1:	name of the class
Column 2:	frequency of months in the class
Column 3:	the range of the class
Column 4 and 5	the average and standard deviation of K_{m} of the class
Column 6 and 7:	the observed values of K_{max} and K_{min} of K_T in the class
Column 8 and 9	the calculated values of K_{max} using equations (2) and (3)

comparison with many other stations. For example, Akuffo [13] could make use of classes about 30, 40 and 50% for Kumasi in Ghana. For each class the average and the standard deviation of the K_{AVG} in that class was determined. The highest and the lowest value of the observed K_T in each class is given. K_{max} has been calculated from equation (2) and (3), using the class values. The cumulative frequency distributions of these classes are shown in Fig. 5. All three curves show a pronounced S-shape which is reflected in the high probability of the clearness index between 50% and 70% as shown in Fig. 3.

5. CONCLUSIONS

The line of thought is that a generalised cumulative frequency distribution could be developed so that suitable formulae can replace the observations, thereby easing the job for designers. On the other hand existing proposals to the same effect might be checked. Because of the few data presented here it is not the purpose of the authors to do so. It is only indicated that with the clear conditions of the sky in Botswana the distribution of the clearness index is markedly different from those in other zones. Data from many more stations in the area between 20" and 30" latitude (North and South) need to be looked at together to make sensible statements or formulae.

The observed maximum and minimum clearness index for Sebele was 85% and 6%, respectively. The average value of the monthly clearness index was found to be 61%, with higher values during the winter months. The monthly clearness index for Sebele ranged from 44% to 75%.

The observed monthly values for K_{max} do not correspond very well with these calculated ones using the relationship proposed by Saunier [3], but correspond better with those calculated employing the approach offered by Hollands and Huget [2]. This was confirmed for the case when the monthly averages were grouped in classes with low. moderate and high values of K_{AVG}.

The frequency of very cloudy days is very low in Sebele and the value of K_{min} for each month varies considerably. The approach to use K_{min} = 5% as suggested by Bendt et al. [1] does seem to be acceptable.

In the southern African region the climate varies from tropical to temperate conditions with a vast proportion of the subcontinent being semi arid and often experiencing thunderstorms with erratic rainfall. The present study emphasizes the point that generalisation of probability curves with their bounds neglects individual effects. Therefore it might be advantageous for designers to use various approaches for the probability of the clearness index in which a number of climatic parameters are recognised.

LIST OF ABBREVIATIONS / PARAMETERS

K_T	clearness index (daily), $K_T = G/G_0$
K_{AVG}	monthly average of the daily clearness index
K_{avg}	15-year average of the clearness index for each month
K_{min}	minimum value of K_T in a particular month
K_{max}	maximum value of K_T in a particular month
K_{max2}	is K_{max} calculated using equation (2): ($K_{max} = 0.6313 + 0.267\,K_{AVG} - 11.9\,(K_{AVG} - 0.75)^8$)
K_{max3}	is K_{max} calculated using equation (3): ($K_{max} = 0.362 + 0.597\,K_{AVG}$)
C	solar constant, taken here as 1.37 kW m^{-2}

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