Characteristics of the Diffuse Component of Solar Irradiation in Hong Kong

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ABSTRACT

The results of an analysis of diffuse irradiation measurements taken at hourly intervals throughout 1980 are presented in the form of two alternative correlations between beam irradiation and sunshine duration which exhibit certain departures from the more generally accepted correlations. If confirmed on a regional basis, they indicate the need for care in estimating diffuse irradiation for the Southeast Asia region.

INTRODUCTION

The comparative advantages of using large concentration ratios in photovoltaic arrays can only be assessed when the magnitude of the solar radiation in the direct beam is known, since this type of array does not utilise the diffuse component of radiation. If the beam component normal to the sun direction is derived from any of the various correlations published for the ratio of diffuse-to-global irradiation on a horizontal surface, it is found that the result is sensitively dependent on the estimated diffuse irradiation. Bearing in mind that most data upon which the correlations are based come from North America, or regions of high sunshine levels such as the Mediterranean region and Australia, it is doubtful if such correlations are universal enough to provide good short-term estimates of direct irradiation in regions of high humidity, high temperature and high cloudiness. The Royal Observatory in Hong Kong (HKRO) only provides data on global irradiation and so it was decided at the University of Hong Kong (HKU) to embark on a programme of measurement of diffuse irradiation.

This paper presents the results of an analysis of the measurements taken at hourly intervals throughout 1980. These are presented in the form of two alternative correlations which exhibit certain departures from the more generally accepted correlations. If confirmed on a regional basis, they indicate the need for care in estimating diffuse irradiation for the Southeast Asia region.

MEASUREMENT PROCEDURE

The chosen measurement site was the roof of the Engineering building, some 70 m above sea-level and 6 km from the Royal Observatory situated on the other side of the harbour. The diffuse component was measured by means of a Kipp and Zönen pyranometer fitted with a shadering by the manufacturer and supplied with a table of corrections to allow for the effect of the shaded portion of the sky. Periodic calibration checks showed no degradation in the performance of this pyranometer over a three-year period. The total global irradiation was measured using a photovoltaic panel in a short-circuit-current configuration, utilising a conversion factor obtained for each month by comparison with Royal Observatory measurements during clear periods at both stations. A gradual change of about 3% per month was observed throughout the year due to the build-up of ingrained dirt in the silicone rubber potting compound of the panel which reduced the short-circuit current. The essential compatibility of the two sets of measurements was confirmed by noting that in periods of high diffuse radiation under zero-sunshine conditions, the readings for diffuse and global irradiance at HKU agreed to within, typically, ±10 W/m^2 in a total of 300 W/m^2. The Royal Observatory also used a Kipp and Zönen pyranometer, and at both stations integrations of irradiance were carried out electronically and recorded at hourly intervals. In addition, a 6-channel point recorder was used as an analogue signal back-up recorder enabling short-term fluctuation to be observed at 30-second intervals. In general there was a close correlation between the global irradiation obtained at the two stations, even at the hourly level. Sunshine duration was measured at the Royal Observatory but not at Hong Kong University. Because of slight variations in the short-term cloud conditions at the two stations, the relationship between sunshine duration and the diffuse irradiation fraction shows some random fluctuation, which becomes smoothed out as the time period involved becomes longer. The reason for this is not entirely clear, since the two stations would appear to be sufficiently close together to anticipate that the diffuse component should be nominally the same within the isotropic assumption.

HONG KONG CLIMATE

Hong Kong lies just inside the tropical zone at latitude 22.3°N and has several distinct seasonal weather patterns.[1] The monthly mean normals of relative humidity taken at 1400 hours re-

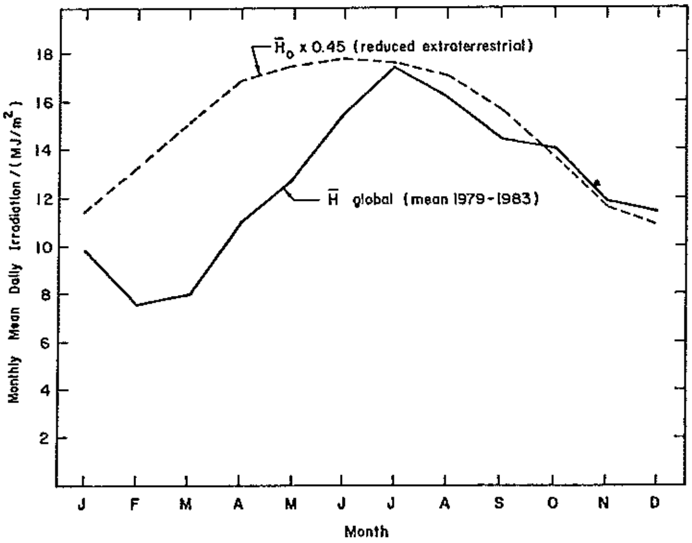

Fig. 1 Monthly mean daily irradiation against the month of the year; global irradiation averaged for the period 1979-1983 (data from the Royal Observatory Hong Kong), showing the enhanced effect of cloudiness in February to May.

main high throughout the year, having a broad minimum from October to January (60-65%) and a broad maximum from March to August (74-78%). The percentage cloud cover also remains high during most of the year with a minimum from October to December (52%) and a maximum from March to June (73-76%). The bright-sunshine fraction shows and approximately inverse relationship to cloud cover, having a minimum from February to April (28-34%) and a maximum from July to December (51-58%). The monthly mean daily global solar irradiation on a horizontal surface exhibits a smooth variation, peaking in July and falling to a minimum of about 50% of this value in February. The elevation angle of the sun at solar noon is 44.7° in December (when the maximum possible sunshine duration is 10.8 hours), and 90° in June (when the maximum possible sunshine duration is 13.4 hours). The extra-terrestrial mean daily irradiation on a horizontal surface is a maximum in June (39.58 MJ/m^2) and a minimum in December (24.09 MJ/m^2): the December minimum is 61% of the June peak, hence the low sunshine fraction and high cloud cover in the period February to May results in an enhanced reduction in the global irradiation at ground level, as depicted in Fig. 1.

THE CLEARNESS INDEX K_T

The diffuse irradiation H_d on a horizontal surface is not often measured directly, whereas the corresponding global irradiation H (direct + diffuse) is readily available for many locations. The clearness index K_T, defined as H/H_o where H_o is the extra-terrestrial irradiation on a horizontal surface, has often been used as a means of determining H_d through the correlation of K_T and the diffuse fraction K_d, defined as H_d/H.

A number of workers, notably Liu & Jordan,[2] Ruth & Chant,[3] Page,[4] Collares-Pereira & Rabl[5] and Orgill & Hollands[6] have studied this form of correlation.

It is important here to distinguish between the various correlations that have been studied. With data from integration periods of one hour it is possible to develop correlations based on hourly values, on daily values, and one monthly mean daily values, each of which will produce a different relationship.

RESULTS OF CORRELATION WITH CLEARNESS INDEX

Monthly Mean Daily Values

Here we define $\bar{K}_d$ as:

$$\bar{K}_d = \frac{1}{n} \sum_{j=1}^{n} H_d(j) / \frac{1}{n} \sum_{j=1}^{n} H(j)$$

where $H_d(j)$ and $H(j)$ are daily values and the summation is over the n days j in the month. A similar definition is used for $\bar{K}_T$.

Fig. 2 shows the results for the HKU data, with the correlations due to Liu & Jordan, Page, and Collares-Pereira & Rabl included for comparison. It can be seen that our $\bar{K}_d$ is generally lower at the high values of $\bar{K}_T$ than for the other curves. This result is observed for both daily-value and hourly-value correlations.

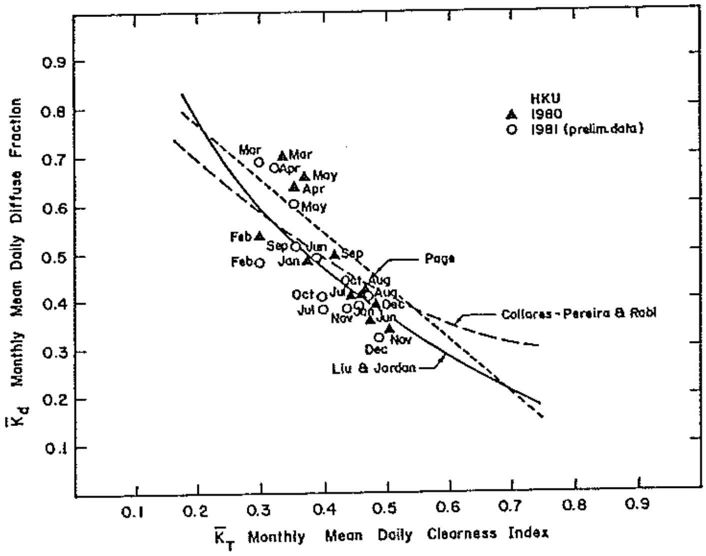

Fig. 2 Monthly means of diffuse fraction $\bar{H}_d/\bar{H}$ against the clearness index $\bar{H}/\bar{H}_o$: experimental points for Hong Kong 1980-81, compared with the correlations of Liu & Jordan, Page, and Collares-Pereira & Rabl.

Daily Values

Fig. 3 shows a curve based on the daily values of H_d/H. This curve has been obtained by drawing a smooth curve through the points $K_d{}'$ resulting from an unweighted averaging of the K_d values within each bin of width 0.05 in K_T. In this case:

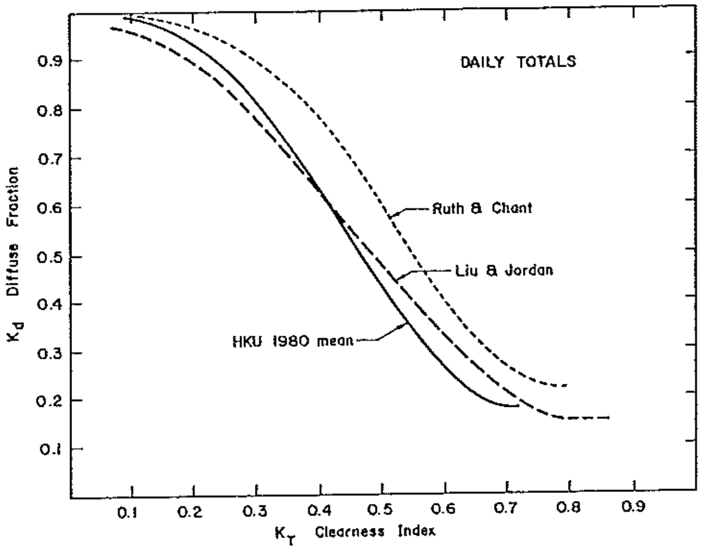

Fig. 3 Mean curves of daily diffuse fraction H_d/H against the clearness index H/H_o, showing the correlations of Liu & Jordan and Ruth & Chant for comparison.

$$K_d' = \frac{1}{n}\sum_{j=1}^{n} K_d(j)$$

where n is the number of values of K_d for the whole year in the range K_T to $K_T + 0.05$. This procedure is repeated for K_T from zero to the maximum value observed. Again, we include other correlations for comparison.

Hourly Values

Fig. 4 illustrates the result of applying the same procedure to hourly values as to daily values. Also shown is a curve derived from data for the period February to May illustrating the seasonal effect for the period of highest cloud cover and lowest sunshine duration in Hong Kong.

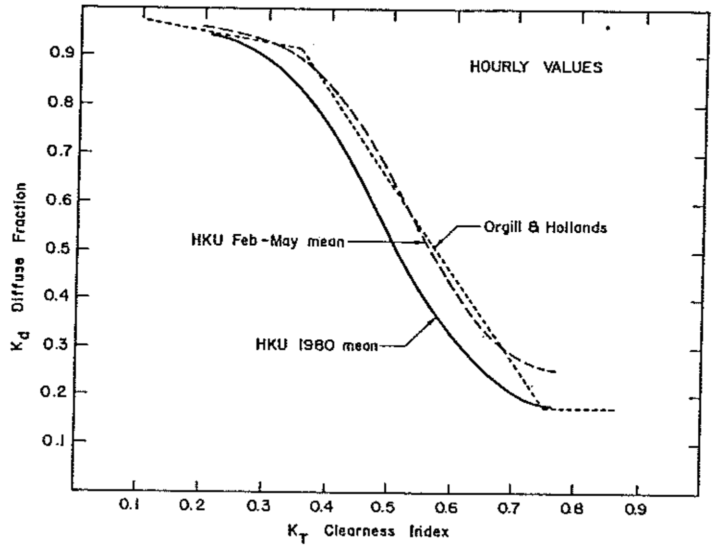

Fig. 4 Mean curves of hourly diffuse fraction H_d/H against the clearness index H/H_0, showing the extent of the seasonal effect in Hong Kong, compared with the correlation of Orgill & Hollands.

The correlation developed by Orgill & Hollands is plotted for comparison. It is notable that on clear days K_T exceeded 0.70 on only 230 occasions during the year, and 0.75 on only 24 occasions out of a total of some 4300 hours. Only for one hour did K_T exceed 0.80. This is in contrast to data from the other locations used in the correlations cited where values in excess of 0.80, even on a daily basis, are recorded on many occasions. Figs. 5a and 5b show the scatter diagrams for the months February to May, and for the whole year, respectively.

Data for early morning (before 8 a.m.) and late afternoon (after 5 p.m.) where the sun elevation is below about 20° have not been plotted. These data increase the concentration of points towards the bottom left-hand corner of the diagram and largely reflect errors in instrumentation at low levels of irradiation. In obtaining the mean curves no additional attempt has been made to weight the significance of the points according to the absolute irradiation values.

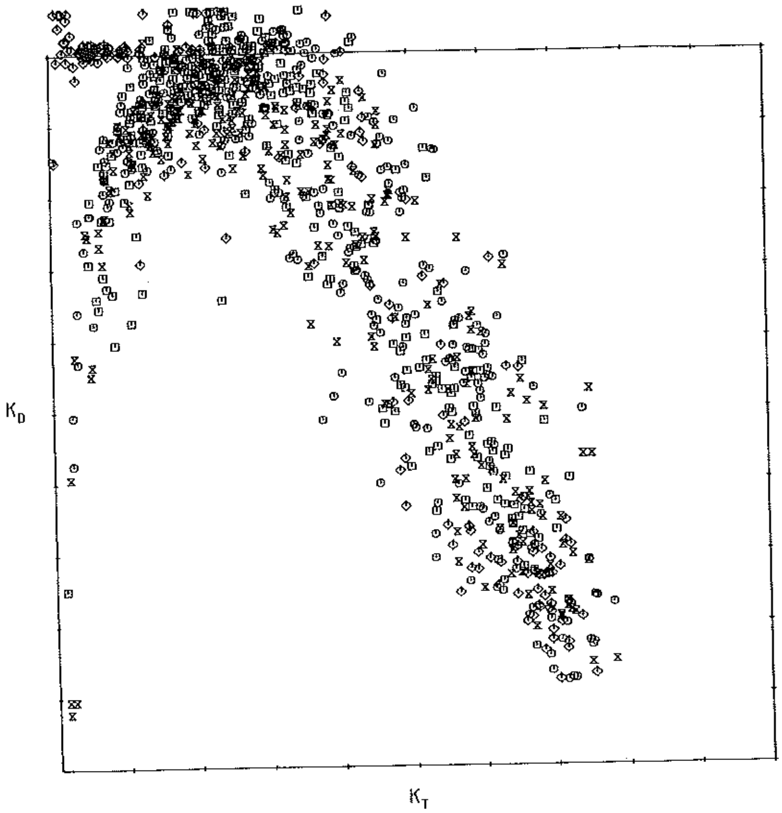

Fig. 5a Hourly values of K_d vs K_T for February to May 1980. The points shown are for the hours between, typically, 8 a.m. and 5 p.m. (airmass $\leqslant 2.6$).

THE SUNSHINE FRACTION S/S_m

There have been attempts in the past to correlate the diffuse fraction K_d with the fractional hours of sunshine S/S_m in the form

$$K_d = \mathrm{a} + \mathrm{b}\,(S/S_m) \tag{1}$$

where S/S_m is the actual sunshine duration as a fraction of the maximum possible value, and where a and **b** are empirical coefficients. When applied to monthly mean daily values of K_d and S/S_m for Canada, Iqbal[7] finds that the coefficients **a** and **b** vary widely depending on location.

In an attempt to improve the correlation we have adopted an alternative approach. We have assumed an initial relationship for the direct component of irradiation in the form

$$H_b/H_b{}' = \mathrm{a} + \mathbf{b}\,(S/S_m) \tag{2}$$

where H_b is the measured direct beam irradiation determined from the global and diffuse measurements, and $H_b{}'$ is the calculated mean clear-day beam irradiation for the atmospheric and solar

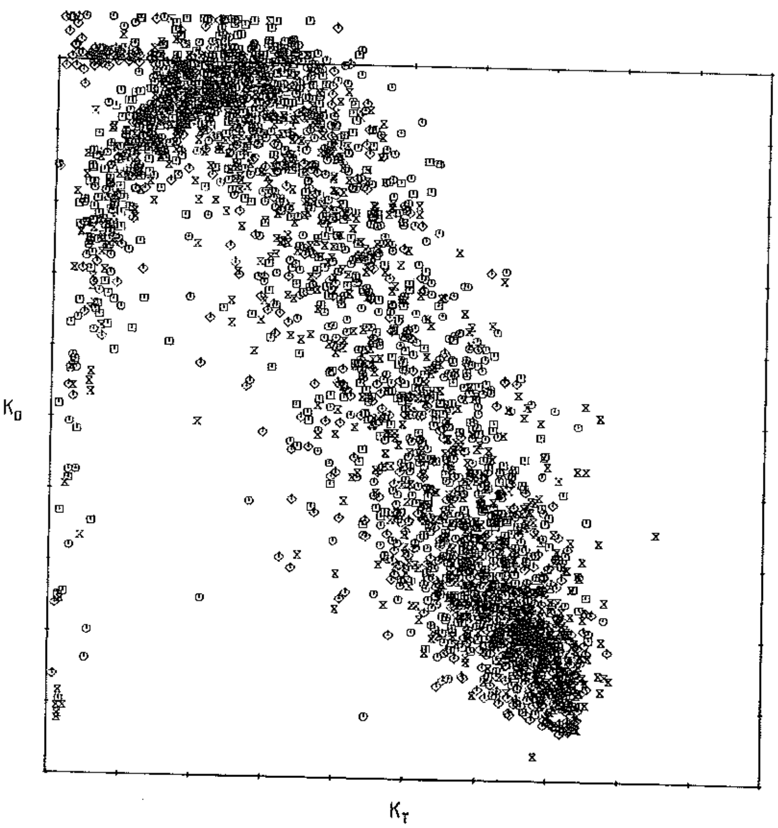

Fig. 5b Hourly values of K_d vs K_T for 1980. The points shown are for the hours between, typically, 8 a.m. and 5 p.m. (airmass $\leqslant 2.6$).

conditions prevailing at the time. We have chosen to look for such a correlation as it seems intuitively more likely that the beam fraction rather than the diffuse fraction should be closely correlated with the sunshine fraction.

Since

$$H = H_d + H_b \tag{3}$$

we obtain finally:

$$K_d = 1 - (H_b'/H)\,(\mathbf{a} + \mathbf{b}\,(S/S_m)) \tag{4}$$

Calculation of H_b

Many expressions have been published which permit calculation of H_b.'[8,9,10,11] We have chosen the one given by Rizzi *et al.*[8] for its ease in computation. The computation requires a knowledge of the air-mass, the precipitable water content and the optical thickness of the atmosphere; this latter has been taken as constant for Hong Kong ($\tau = 0.1$). It should be noted that the value used for H_b' in eq. (2) is not critical since the procedure is somewhat self-correcting through the effect on the empirical coefficients **a** and **b**.

The precipitable water content can be obtained in a variety of ways; from the dew point (King and Buckius[9]), from the vapour pressure at the surface (Exell[12]), or more directly, as in the present case, from observatory data on humidity mixing ratios in the upper air. Mean values for a month have been used in the present study and the water content is found to vary from 2.1 cm in December to 5.25 cm in July and August.

RESULTS OF CORRELATION WITH SUNSHINE FRACTION

Monthly Mean Daily Values

Linear regression analysis of the Hong Kong data using monthly mean daily values results in values for **a** = – 0.046 and **b** = 1.134, with a correlation coefficient of 0.982.

Thus we can write:

$$\bar{K}_d = 1 - (\bar{H}_b'/\bar{H})\ [-0.046 + 1.134\ (\bar{S}/\bar{S}_m)] \qquad (5)$$

Fig. 6 shows the results of applying eq. (5) to HKU data. Included in this figure are the results of applying the correlations of K_d against the clearness index K_T derived by Liu & Jordan and by Page.

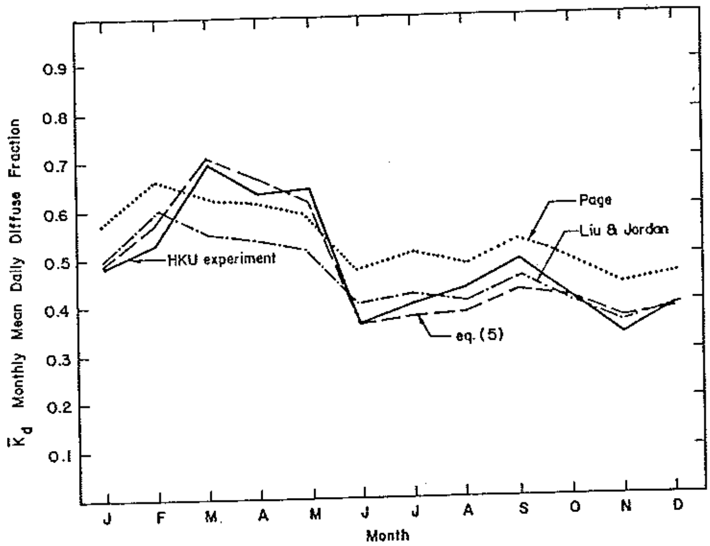

Fig. 6 Monthly mean daily diffuse fraction, $\bar{K}_d$, predicted from correlations with the clearness index (Page, and Liu & Jordan), and with the sunshine fraction (eq. (5)), compared with HKU measured values.

Daily Values

When the same procedure is adopted for daily values, with linear regression performed separately on the data for each month, the results for the correlation coefficients a and **b** shown in Table 1 are obtained. The value of H_b', used here is a mean value for the month.

Table 1. Values of the coefficients a and b in eq. (2) derived from daily HKRO sunshine data and HKU global and diffuse data for each month.

Month	a	b	correl. coeff.
January	− 0.045	1.152	.956
February	− 0.002	1.020	.972
March	+ 0.020	0.835	.901
April	+ 0.036	0.858	.967
May	+ 0.013	0.821	.868
June	+ 0.005	1.031	.864
July	− 0.007	1.000	.910
August	− 0.165	1.297	.890
September	− 0.083	1.106	.861
October	+ 0.015	1.008	.885
November	− 0.014	1.152	.949
December	− 0.059	1.141	.955
Annual Mean	− 0.025	1.036	

Hourly Values

The two sets of data for H and for S/S_m available on an hourly basis in Hong Kong are not for the same time interval, since the sunshine duration is measured with respect to solar noon, whereas the irradiation is measured with respect to noon local time. In this case, application of the procedure outlined will not lead to meaningful results and the necessary time correction to the data has not been attempted.

PREDICTION OF DIFFUSE IRRADIATION

Daily Values

Having obtained correlations for K_d with respect to clearness index K_T, and the sunshine fraction S/S_m, it is now possible to apply these correlations to calculate the diffuse component of irradiation from the global values, on a daily basis. We have performed these calculations using the following polynomials in K_T as approximations to the respective curves:

$$K_d = 0.946 + 0.673K_T - 5.89K_T^2 + 6.229K_T^3 - 1.875K_T^4 \text{ (Liu \& Jordan)}$$

$$K_d = 1.188 - 2.272K_T + 9.473K_T^2 - 21.856K_T^3 + 14.648K_T^4$$
(Collares-Pereira & Rabl, also Ruth & Chant)

$$K_d = 1 + 0.37K_T - 3.06K_T^2 - 2.64K_T^3 + 5.49K_T^4 \text{ (HKU)}$$

In addition, the correlation with sunshine fraction assumes the expression (4) with the coefficients as listed in Table 1.

The results of these separate calculations are shown in Tables 2 and 3.

Table 2. Summary of estimations of total monthly diffuse irradiation on a horizontal surface (MJ/m^2) 1980

Month	HKU measured	HKU[1] using S/Sm	HKU[2] using S/Sm	HKU using K_T	Ruth & Chant correlation	Liu & Jordan correlation
January	142.1	150.7	141.9	153.8	193.9	161.4
February	130.3	140.2	130.6	121.4	153.0	129.2
March	237.8	240.7	237.9	216.5	248.9	212.7
April	244.1	255.8	244.4	222.0	264.7	224.5
May	279.8	266.8	279.8	246.0	298.2	250.5
June	196.7	215.2	196.6	219.6	306.6	250.5
July	215.1	215.8	215.3	208.8	298.2	241.9
August	213.1	204.0	213.1	208.2	284.3	233.3
September	213.5	196.9	214.1	215.8	275.8	228.1
October	178.0	191.1	178.0	183.4	253.9	205.6
November	118.4	147.8	118.3	133.2	198.8	158.8
December	140.5	149.0	140.6	150.7	213.1	171.1
Annual Total	2309.1	2374.0	2310.5	2279.6	2989.0	2467.5

1 using coefficients a, b for annual mean for Table 1 in eq. (4)
2 using coefficients a, b optimised for each month from Table 1 in eq. (4)

DISCUSSION AND CONCLUSIONS

The main significant result emerging from these measurements of irradiation components for Hong Kong is the generally lower values of K_d. Of particular significance in this context is the region of K_T from about 0.4 to 0.7 where the smaller values of K_d imply a reduction in the overall diffuse irradiation totals as seen in Table 2. An additional feature of some interest is the clear-sky condition where $K_d \approx 0.10$. In Hong Kong the atmospheric transmittance (taken from K_T) rarely exceeds 0.75, a restriction which is not so generally observed elsewhere.

There seems to be strong experimental evidence to suggest that values of $K_T \geqslant 0.8$ are related to a particular juxtaposition of sun and clouds and that these high values of K_T are accompanied by high values of K_d. Our Hong Kong experience is that these conditions rarely last for more than a few minutes at a time and that the effects are averaged out by the clouds subsequently obscuring the sun when integration periods of one hour or more are used. Factors relating to Hong Kong which are atypical of the stations providing data for the previous correlations are: high mean relative humidity, high mean solar altitude angle, a coastal rather than an inland station,

Table 3. Summary of estimated diffuse irradiation normalised to HKU measured values

Month	HKU measured	HKU[1] using S/Sm	HKU[2] using S/Sm	HKU using K_T	Ruth & Chant	Liu & Jordan
January	1.0	1.06	1.00	1.08	1.36	1.14
February	1.0	1.08	1.00	0.93	1.20	0.99
March	1.0	1.01	1.00	0.91	1.05	0.90
April	1.0	1.05	1.00	0.91	1.08	0.92
May	1.0	0.95	1.00	0.88	1.06	0.90
June	1.0	1.09	1.00	1.12	1.56	1.28
July	1.0	1.00	1.00	0.97	1.39	1.13
August	1.0	0.96	1.00	0.98	1.33	1.09
September	1.0	0.92	1.00	1.01	1.29	1.06
October	1.0	1.07	1.00	1.03	1.43	1.16
November	1.0	1.25	1.00	1.13	1.68	1.34
December	1.0	1.06	1.00	1.07	1.51	1.22
Annual Total	1.0	1.03	1.00	0.99	1.29	1.07

1 using coefficients a, b for annual mean from Table 1 in eq. (4)
2 using coefficients a, b optimised for each month from Table 1 in eq. (4)

and an urban environment. Which, if any, of these factors could account for the divergence in the measurements is unknown at present.

The shape of the K_d vs. K_T characteristics for daily totals (HKU) is almost identical to that of Ruth & Chant (and Collares-Pereira & Rabl), but with a scaling factor of 0.84 in K_T. Errors in measurement of irradiation are common and can result from a number of different causes. Because of the high slope characteristics at intermediate values of K_T, the percentage error in H_d required to account for the displacement of the curves is large (28% at $K_T = 0.5$ compared to Ruth & Chant). If it were supposed that this is due to errors in HKU measurements of H_d, it would raise a new question as to how the Royal Observatory global measurements and our own (HKU) diffuse measurements match closely on overcast days. Alternatively, errors in H would shift the curve along both the K_T axis and the K_d axis, and could hardly account for the large differences observed. The fact that the data base is small is of major concern; however, preliminary examination of the data for 1981 seems to confirm the conclusions from the 1980 measurements. The correlation with the sunshine fraction offers hope of a better means of estimating diffuse irradiation, but it requires more input data in its present form. Iqbal[7] suggests the more direct correlation (eq. (1)) for monthly mean daily values, but does not provide an equivalent set of coefficients for daily or hourly values.

Table 3 demonstrates that the sunshine fraction correlation developed at HKU (eq. (4)) gives remarkably good predictions of diffuse irradiation when optimised on a month by month basis, and is generally within 10% in a month (except November, 25%) when using the annual mean coefficients. The HKU clearness index correlation provides diffuse irradiation to within 13% in any month and with 1% for the annual total. By contrast, the Liu & Jordan and Ruth & Chant correlations overestimate the diffuse irradiation by as much as 34% and 68% in a month and by 7% and 29% in the annual total respectively.

The HKU measurements show that care is needed in applying correlations which have been developed for other locations to determine diffuse and beam irradiation: these well-known correlations have been derived from data predominantly from the temperate zone and have not been shown conclusively to apply to the tropical region of Southeast Asia. We suggest, tentatively, that the methods and correlation with the sunshine fraction demonstrated here may give improved results for this region. Further data are being processed to confirm these conclusions.

Once the diffuse and global irradiation values are available, it is a relatively straightforward matter to derive the direct beam component of irradition on a surface normal to the beam direction, which is what is required to assess the economic viability of highly-concentrating photovoltaic arrays.

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