CHAPTER 4

RESULTS AND DISCUSSIONS

This chapter presents the first statistical results from the analysis of variations of daylight efficacy in the tropics. The analysis was performed for three components of solar radiation: global, diffuse horizontal and beam normal. The annual average values of the global, diffuse horizontal and beam normal efficacy are respectively 111.0, 132.5 and 89.5 lm/W. Influences of climate conditions on the variations of the efficacies can be observed clearly. To investigate such influences, the tropical efficacy data were plotted against various insolation parameters and were evaluated with many efficacy models described in Chapter 2. At the end of the chapter, a new efficacy model for the tropics was proposed. The accuracy of the existing models to predict tropical daylight efficacy were compared with the new model.

4.1 Characteristics of Daylight Efficacy in the Tropics

This section presents statistical results of the hourly mean values and standard deviations of the daylight efficacy in tropical climate. The radiation database employed for the analysis is the five-minute average records of measurements from the AIT station during 1999-2004. At each measurement time step, the daylight efficacy was derived by dividing the daylight illuminance with its corresponding solar irradiance.

4.1.1 Global Luminous Efficacy

Table 4.1 exhibits the hourly mean values of the global daylight efficacy presented for *local standard time*. The results show that the values of the global efficacy change with time in a day. The values are generally higher in early morning (6:00-8:00) and in late evening (17:00-19:00) or in another sense during low sun position. At these periods, value of the global efficacy can reach 120 lm/W. The mean values of the global efficacy vary in a range of 100-125 lm/W. The yearly average value of the global efficacy is estimated at 111.0 lm/W.

Table 4.1: The hourly mean values of global efficacy (lm/W) by calendar month

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6-7			110.31	114.27	120.70	112.51	112.45	118.18	109.15	111.20	122.46	
7-8	110.58	101.11	110.58	114.98	117.63	114.87	114.08	116.70	113.74	113.41	118.72	123.71
8-9	112.44	104.03	110.35	111.56	114.13	114.25	112.63	113.89	112.53	113.26	112.20	114.68
9-10	109.69	103.33	109.30	108.30	111.01	111.41	110.84	110.73	110.12	111.04	109.00	110.29
10-11	106.90	103.21	106.76	105.46	108.14	109.54	109.25	107.71	109.31	108.49	106.98	107.51
11-12	105.99	101.41	104.74	104.52	107.94	107.19	108.18	106.13	107.57	107.22	106.07	105.92
12-13	105.57	101.62	104.21	104.73	107.51	108.25	108.25	106.40	107.30	107.32	105.52	105.55
13-14	105.20	101.93	106.64	105.20	108.26	109.93	109.84	106.97	107.57	108.95	106.56	106.57
14-15	106.93	101.38	106.59	106.84	110.13	110.13	110.02	108.95	110.01	112.08	108.73	108.27
14-16	109.16	102.26	108.59	107.81	112.05	112.80	111.66	112.21	113.31	115.87	112.24	111.33
16-17	112.45	103.89	111.07	110.71	115.96	116.28	114.21	115.10	116.72	117.92	118.91	117.09
17-18	121.89	109.39	115.73	116.38	119.74	118.65	119.19	117.59	119.18	126.25	130.17	129.71
18-19			121.26	125.73	121.87	121.52	119.58	120.04	105.47			

The results in the table also explore the seasonal dependency of the global efficacy. The values of the global efficacy are comparatively low during the dry season in November, December, January and February, when the majority of global illuminance and irradiance is the beam component. In Thailand, the sky is explicitly clear during this period. Values of the global efficacy become larger during the rainy season from July to October. The Appearance of the sun over the sky is less frequent in this season. The average values of the global efficacy in dry and wet seasons are approximately 109.74 and 112.07 lm/W, respectively.

Table 4.2 exhibits the standard deviations of the hourly mean values of the tropical global efficacy. It can be observed that large variations occur in the early morning and in the late afternoon, but less at noon. The variation is also comparatively high during the rainy season (July-October).

Table 4.2: Standard deviations of the hourly mean values of global efficacy

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6-7			9.29	6.82	9.85	6.17	8.13	13.30	9.95	9.75	12.37	
7-8	8.10	4.54	8.98	2.23	2.98	2.53	4.06	4.70	5.35	6.12	5.54	6.88
8-9	4.36	3.36	5.55	1.42	1.29	1.68	1.55	2.33	2.52	2.16	2.30	2.65
9-10	2.32	3.10	7.94	1.94	1.64	1.89	1.65	2.75	2.97	1.78	2.69	1.47
10-11	2.05	2.73	7.19	1.68	2.69	2.73	2.88	3.63	4.27	2.20	3.56	1.94
11-12	2.32	2.82	5.62	3.21	5.50	3.45	4.00	4.88	4.77	2.36	4.93	2.04
12-13	4.19	3.63	6.39	4.88	5.18	4.08	5.72	5.34	4.42	3.23	4.42	2.57
13-14	3.80	3.55	8.24	4.21	5.15	5.47	9.19	4.65	3.80	4.55	3.83	2.59
14-15	4.34	4.35	5.84	5.52	5.72	3.55	6.21	4.78	4.85	4.33	3.25	2.48
14-16	4.21	4.51	6.17	3.62	3.03	2.99	3.85	4.58	6.68	9.17	3.02	4.65
16-17	4.64	4.75	6.93	2.93	3.95	3.42	2.00	3.82	6.73	3.96	3.18	4.84
17-18	10.92	8.74	8.57	5.35	6.13	4.69	9.62	4.39	7.87	11.02	10.74	11.30
18-19			.	13.54	12.30	11.41	8.54	9.03	5.79			

4.1.2 Diffuse Luminous Efficacy

Similarly to Table 4.1, Table 4.3 exhibits the hourly mean values of the tropical diffuse luminous efficacy for 12 calendar months. Normally, the diffuse efficacy is larger or comparable to the global efficacy.

Table 4.3: The hourly mean values of diffuse efficacy (lm/W) by calendar month

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6-7			122.96	134.05	133.25	125.04	122.52	127.25	120.39	120.87	143.10	
7-8	129.66	123.62	130.28	145.15	132.44	130.87	127.01	133.15	128.67	129.45	143.59	151.01
8-9	139.75	142.68	138.41	142.67	130.85	126.50	126.84	132.18	131.10	133.02	141.21	147.73
9-10	139.11	143.37	137.53	137.29	127.19	129.46	126.15	127.90	130.35	131.24	139.86	143.46
10-11	138.93	142.19	134.57	134.69	124.75	122.75	123.74	127.20	126.84	128.22	139.28	142.41
11-12	135.38	139.11	131.59	131.97	122.79	120.93	121.89	124.89	124.83	128.11	137.10	140.57
12-13	134.22	138.24	131.53	131.08	126.42	132.36	121.90	124.62	124.17	126.58	136.28	137.49
13-14	134.31	137.42	132.04	133.35	124.28	125.56	124.53	124.05	126.49	126.56	135.67	136.36
14-15	137.80	139.41	136.17	136.24	126.90	132.56	127.50	126.78	127.56	128.13	137.56	137.84
14-16	141.04	142.14	139.42	138.49	128.99	128.93	129.20	129.32	130.93	130.36	143.17	142.72
16-17	144.56	140.31	138.82	142.33	131.17	127.96	131.29	132.53	132.26	132.41	147.00	145.89
17-18	144.71	133.53	136.17	143.58	129.17	127.47	131.23	128.95	131.03	133.91	148.36	142.49
18-19			138.34	139.91	128.54	127.15	128.34	125.92	116.81			

It can be observed that the values of the efficacy of the diffuse component are relatively high during the dry season (November-January) when the sky is dominant. The opposite is true during the wet season from July to October. The average values of the diffuse efficacy in dry and wet seasons are approximately 140.03 and 127.59 lm/W, respectively. Again, the diffuse efficacy is time-dependent (with respect to solar position). These values tend to be lower at noon. The yearly average value of the tropical diffuse efficacy is measured at 132.8 lm/W.

Table 4.4 exhibits standard deviations of the hourly mean values of diffuse efficacy by calendar months. The variation of the diffuse efficacy is large compared with that of the global efficacy. The standard deviation is high in the early morning and the late afternoon and throughout the course of the day in the dry period. The yearly standard deviation of the hourly mean values of the tropical diffuse efficacy is measured at 13.9 lm/W.

Table 4.4: Standard deviations of the hourly mean values of diffuse efficacy

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6-7			14.75	13.79	18.59	22.17	8.31	14.17	12.05	14.16	20.36	
7-8	17.95	15.59	16.59	9.92	11.26	17.82	9.57	12.17	11.43	13.75	19.97	17.51
8-9	16.83	14.52	14.96	8.60	8.38	5.49	8.10	8.56	10.43	13.48	19.74	15.52
9-10	12.85	14.08	10.79	8.13	6.94	16.29	6.25	5.24	10.59	9.32	16.49	15.46
10-11	13.57	13.66	10.58	7.80	6.22	7.25	4.93	5.54	9.01	6.18	14.20	13.38
11-12	13.55	13.01	10.70	8.42	4.94	5.29	4.75	5.35	7.78	14.08	13.36	11.84
12-13	12.81	13.40	9.29	9.32	13.15	23.27	4.78	13.60	7.62	5.85	12.31	12.17
13-14	12.37	14.07	9.13	8.69	6.20	12.04	7.31	6.00	7.59	5.39	12.48	13.28
14-15	13.44	13.47	9.37	9.08	6.35	16.44	7.15	5.03	7.03	5.74	13.00	13.12
14-16	15.48	12.88	11.75	9.39	6.99	10.80	5.87	5.91	8.46	7.94	15.27	14.81
16-17	18.55	13.65	12.00	12.20	9.48	7.86	8.70	14.11	10.92	12.02	17.60	16.77
17-18	24.21	14.39	13.98	16.25	10.53	9.75	9.00	6.07	11.87	14.61	24.11	17.69
18-19				20.18	13.06	14.01	8.86	6.98	0.70			

The relatively high variance of both global and diffuse efficacies throughout the year would result from the dynamic transverse of scattered clouds over the sky vault. This is a distinguishing characteristic of the tropical sky and daylight climate.

4.1.3 Beam Luminous Efficacy

Table 4.5 presents the hourly mean values of beam normal efficacy for the tropics. It is obvious that values of the beam normal efficacy are the lowest among them.

Table 4.5: The hourly mean values of beam normal efficacy (lm/W) by calendar months

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6-7			25.30	30.99	66.57	27.29	62.67	94.52	52.78	67.60	57.52	
7-8	40.76	9.41	54.05	77.65	101.67	35.97	84.93	103.48	74.85	85.01	92.51	81.49
8-9	72.77	34.54	74.59	90.87	105.49	96.61	106.74	106.50	95.20	98.99	105.10	98.16
9-10	85.89	60.64	83.82	92.13	108.00	61.42	92.36	111.46	97.23	101.98	106.02	104.13
10-11	91.38	73.41	93.94	94.19	105.87	95.05	107.31	110.43	100.51	104.45	108.36	106.50
11-12	94.77	74.94	95.24	94.54	109.62	103.12	109.64	111.49	103.41	104.44	108.69	107.12
12-13	93.75	74.62	92.95	89.08	89.12	80.12	110.47	106.93	101.14	105.52	108.31	105.81
13-14	91.68	73.26	87.59	92.49	100.83	81.48	109.86	107.58	102.43	105.26	106.75	104.94
14-15	90.30	65.60	82.48	90.76	107.89	88.75	109.97	107.16	99.40	103.71	104.72	102.04
14-16	81.58	56.67	75.44	82.21	110.55	98.47	110.80	110.07	95.50	102.24	101.06	97.03
16-17	71.18	40.48	60.51	79.24	109.33	99.01	109.32	102.09	85.27	93.17	87.80	83.73
17-18	48.05	17.73	40.88	59.65	100.27	102.54	103.13	95.71	72.55	61.75	57.91	50.80
18-19				10.21	69.39	74.21	82.43	62.11				

Examining the values in Table 4.5, the beam efficacy is comparatively high during the dry season when the sky is generally clear. The results also show that the values of beam efficacy tend to be high during noon. Throughout the year, the values of beam luminous efficacy are in a range of 60-110 lm/W with an average of 90.7 lm/W. The trend for beam normal efficacy is inversely proportional to global and diffuse efficacies. The highest values occurred between 9:00 to 15:00. Table 4.6 exhibits standard deviations of the hourly mean values of the diffuse efficacy by calendar months. The deviation of the beam efficacy is quite large.

Table 4.6: Standard deviations of the hourly mean values of beam normal efficacy

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6-7			26.05	26.11	35.84	32.46	38.76	14.73	39.35	24.16	19.58	
7-8	19.94	11.70	39.71	16.09	12.81	37.66	31.96	25.72	32.08	22.99	10.66	17.65
8-9	16.21	22.22	29.73	10.91	15.24	13.99	10.33	20.47	19.86	13.40	5.88	13.67
9-10	12.79	19.69	27.47	8.98	8.20	32.34	29.33	6.67	14.94	13.97	7.92	10.00
10-11	11.53	15.80	16.34	9.87	6.80	34.41	5.18	10.15	11.48	10.68	5.03	4.56
11-12	9.11	14.57	15.58	10.77	5.79	20.53	4.71	5.82	10.09	10.87	3.90	3.41
12-13	11.46	14.86	16.50	15.12	27.65	33.21	4.15	13.77	11.38	5.86	3.85	4.60
13-14	13.36	15.68	25.24	9.50	23.71	34.47	4.54	13.96	12.01	6.36	4.34	5.55
14-15	13.77	20.88	30.06	13.94	12.78	32.15	4.65	14.44	16.37	8.19	5.81	7.34
14-16	20.77	24.44	31.96	23.14	6.58	31.15	4.68	10.53	24.51	9.20	8.36	9.22
16-17	24.77	24.90	24.58	14.78	4.83	31.58	6.70	28.66	30.54	10.15	11.70	13.86
17-18	26.61	17.80	27.68	16.56	8.49	14.02	9.35	28.18	39.62	19.65	15.92	23.29
18-19			.	12.39	11.89	21.90	16.43	43.47				

4.2 Correlations of the Daylight Efficacy with Insolation Parameters

The results from the statistical analysis show that the variations of the daylight efficacy are influenced by, or dependent. On the climate conditions (clear, intermediate or overcast skies) and position of the sun in the sky (time of a day). This section aims to investigate in deeper details on correlations between the daylight efficacy and sky conditions in tropical climate. The parameters adopted here for classification or description of sky conditions are Perez's clearness index and brightness index. Another crucial parameter is solar zenith angle, which is used to describe the solar geometry or the sun position. The values of each of the parameters were derived from the radiation records with its corresponding time of measurements. The definitions of each parameter are provided mathematically in Chapter 2. Regarding the definition of Perez's Clearness Index, the higher the value of the index, the clearer the condition of the sky. Values of Perez's clearness index are categorized into 8 bins where Bin no.1 represents overcast sky and Bin no.8 represents clear sky condition. The bins in between (Bins 2-8) represent the transition of intermediate skies from overcast sky to clear sky.

Table 4.7 shows the mean values and the standard deviations of global, diffuse horizontal and beam normal efficacies for different ranges of Perez's clearness index. Each of the values in the table was computed from its corresponding five-minute data sorted into each index bin.

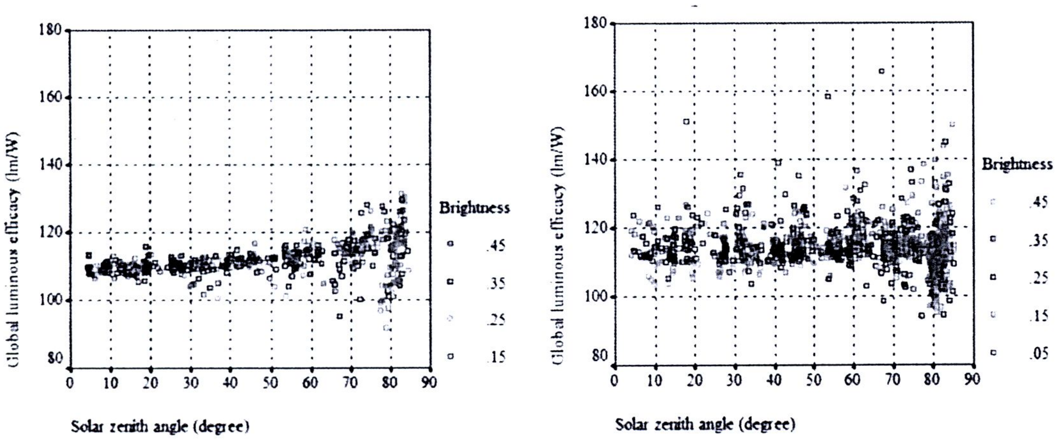
From Table 4.7, the mean values of the global efficacy decrease when the sky becomes clearer. This phenomenon is opposed to that of the efficacies of diffuse horizontal and beam normal components. The results warrant primarily the inter-dependency of the efficacy with sky conditions. Through a number of scatter plots, the next sections illustrate in more detail the dependency of the daylight efficacy on the insolation parameters and the sun's position using sets of scatter plots.

Table 4.7: The mean values and the standard deviations of global, diffuse horizontal and beam normal efficacies for different sky conditions.

Clearness bin no.	Statistical parameter	Efficacy (lm/W)			Irradiance (W/m²)			Illuminace (klux)		
		Global	**Diffuse**	**Beam**	**Global**	**Diffuse**	**Beam**	**Global**	**Diffuse**	**Beam**
1.Overcast	Mean	114.33	121.99	82.80	196.22	166.17	6.66	22.16	20.18	1.94
	Deviation	6.69	8.36	30.11	167.72	129.84	8.92	18.47	15.69	8.00
2	Mean	111.92	123.24	83.73	343.93	268.51	68.97	38.04	32.71	6.06
	Deviation	5.00	5.54	33.11	205.12	158.01	32.71	22.23	18.77	4.12
3	Mean	110.99	129.08	77.56	370.17	242.82	159.10	40.33	30.68	13.44
	Deviation	7.76	8.26	36.18	228.88	144.71	58.70	24.40	17.53	8.57
4	Mean	110.41	135.33	82.50	441.40	235.60	283.90	47.54	31.09	24.59
	Deviation	8.12	10.92	28.77	237.44	122.04	81.18	24.62	15.13	11.71
5	Mean	110.00	140.68	91.46	541.62	220.94	441.42	57.87	30.18	41.44
	Deviation	8.75	12.68	20.10	257.00	102.01	106.24	26.02	12.94	14.51
6	Mean	110.27	146.08	100.15	611.81	173.60	627.51	65.26	24.58	63.69
	Deviation	9.71	13.85	12.20	261.36	75.84	116.60	25.73	9.68	15.62
7	Mean	108.27	145.95	105.99	696.96	138.59	776.62	74.12	19.86	82.54
	Deviation	6.94	11.59	9.75	221.92	44.93	85.24	21.27	5.66	12.09
8. Clear	Mean	105.31	145.45	109.72	814.76	111.59	901.74	85.29	16.13	98.92
	Deviation	3.88	9.86	3.86	154.69	22.10	55.99	14.34	2.86	6.70
Overall	**Mean**	**111.25**	**132.75**	**89.50**	**423.39**	**203.17**	**288.57**	**45.74**	**26.35**	**28.60**
	Deviation	**7.83**	**13.92**	**27.65**	**281.06**	**127.62**	**281.74**	**29.04**	**15.57**	**30.46**

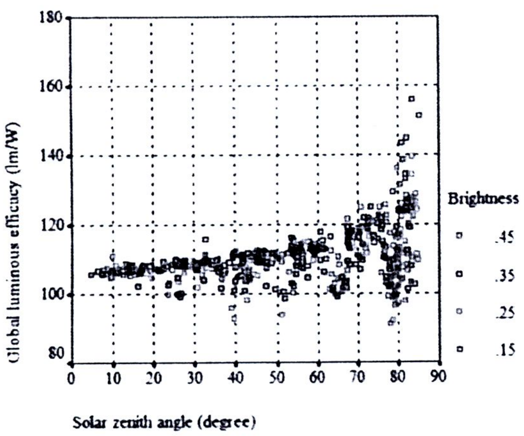
4.2.1 Global Luminous Efficacy

This section investigates particular correlations of the global efficacy with the insolation parameters. Figure 4.1 shows a set of plots correlating the dependencies of the global efficacy with Perez's clearness, brightness and solar zenith angle. Figure 4.1(a) describes the case of overcast sky (Perez's clearness bin no.1). Under this condition, the value of global efficacy increases gradually with solar zenith angle starting from about 110 to 120 lm/W. Very large scatter of the global efficacy can be observed for high solar zenith or low solar altitude.

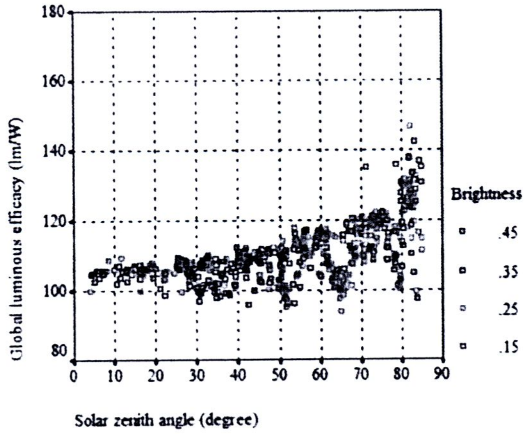


a) K_g with solar zenith for Perez's bin no.1 b) K_g with solar zenith for Perez's bin no.2

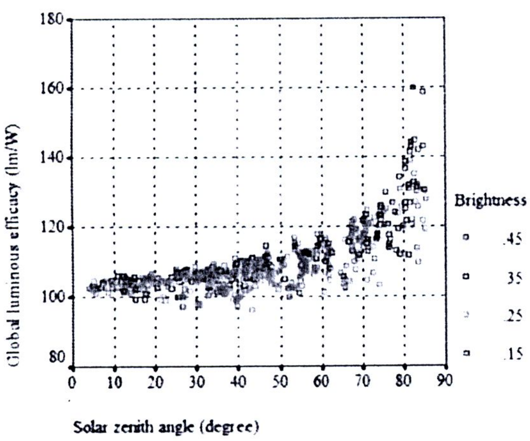
Figure 4.1: Correlations of the global efficacy (K_g) with the insolation parameters.



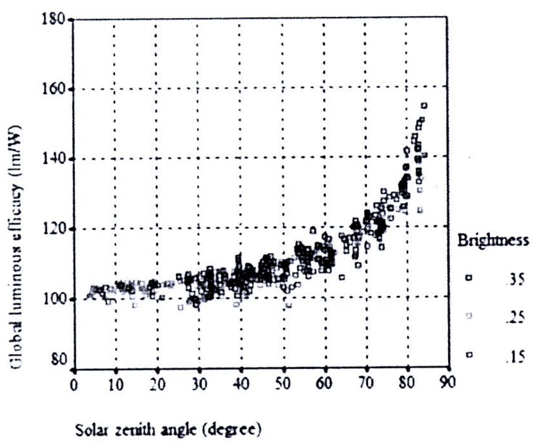
c) K_g with solar zenith for Perez's bin no.3



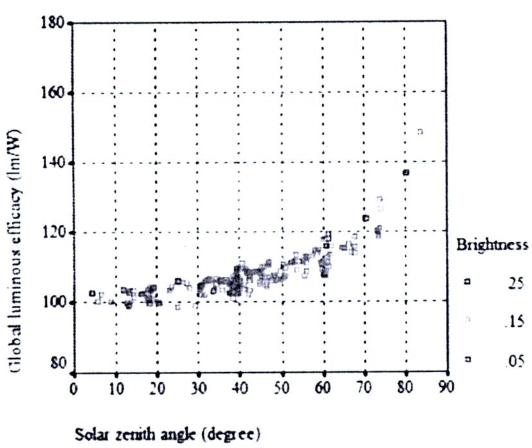
d) K_g with solar zenith for Perez's bin no.4



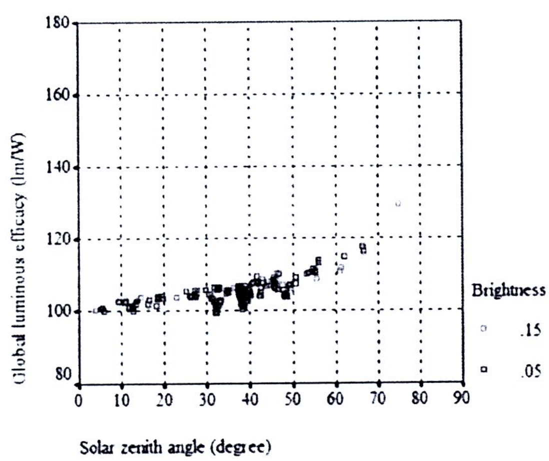
e) K_g with solar zenith for Perez's bin no.5



f) K_g with solar zenith for Perez's bin no.6



g) K_g with solar zenith for Perez's bin no.7



h) K_g with solar zenith for Perez's bin no.8

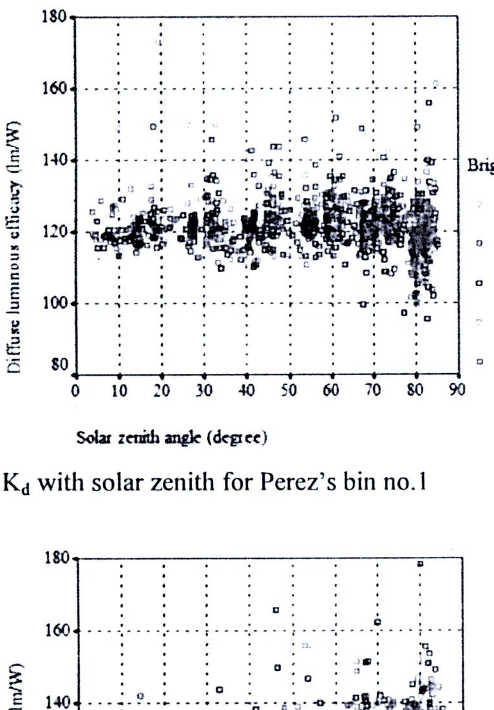
Figure 4.1: (Continued)

For clear skies and intermediate skies, there is scattering of the data. For each sky condition, the variation of global efficacy looks like an exponential curve with different degrees. At a particular solar zenith angle, the values of the global efficacy decrease as the sky becomes clearer. From the plots, the brightness index seems not be able to differentiate the variations of global efficacy.

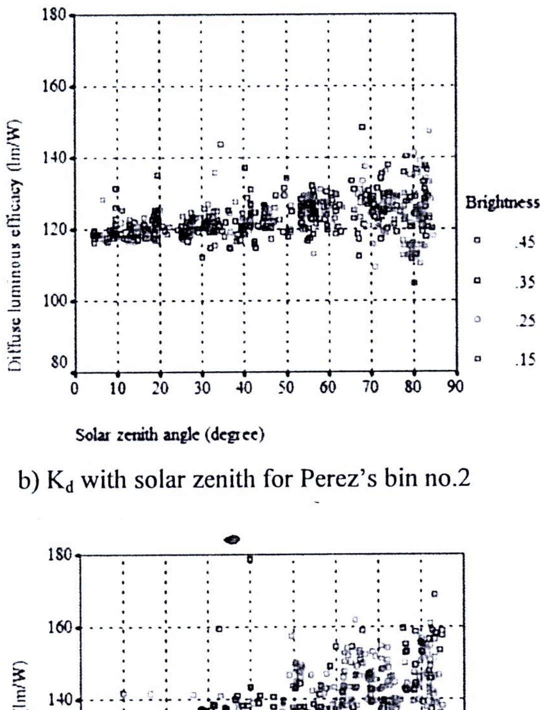
4.2.2 Diffuse Luminous Efficacy

The scatter plots in Fig. 4.2 illustrate the variations of diffuse efficacy with the independent climate variables i.e. Perez's clearness index, brightness index and solar zenith angle. Figure 4.2(a) demonstrates a plot for dark overcast condition (Perez's clearness bin no.1). It was observed that the diffuse efficacy seems to be invariant with solar zenith angle. The average value was measured about 122 lm/W. Larger scattering of the diffuse efficacy appears at high solar zenith angle.

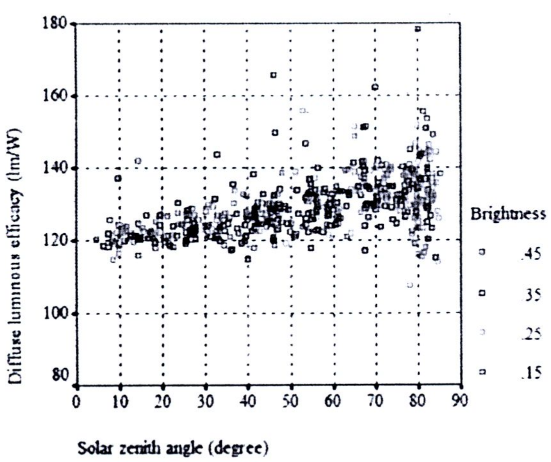
A plot in Fig. 4.2(b) is also present for the overcast sky case but brighter. The dependence of the diffuse efficacy on solar zenith can be observed. The values seem to increase linearly with solar zenith angle. This phenomenon is prominent when the sky becomes clearer. The values of the diffuse efficacy can be high upto 180 lm/W when the sky is clear and the sun stays high (Fig. 4.2(h)). Compared to the global efficacy, the diffuse efficacy is more dispersed in nature. From the plots, it seems again that brightness index cannot be used to differentiate the variations of the efficacy of skylight.



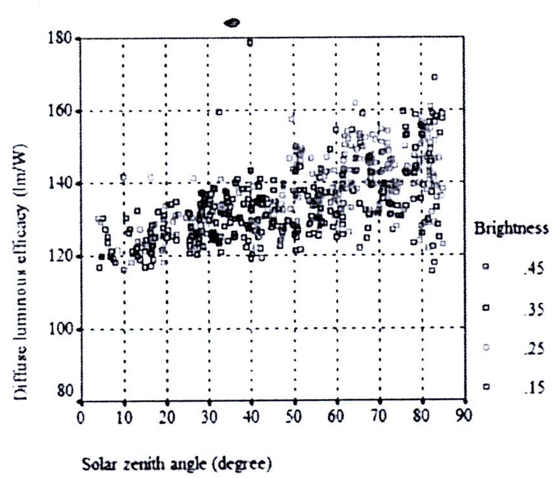
a) K_d with solar zenith for Perez's bin no.1



b) K_d with solar zenith for Perez's bin no.2

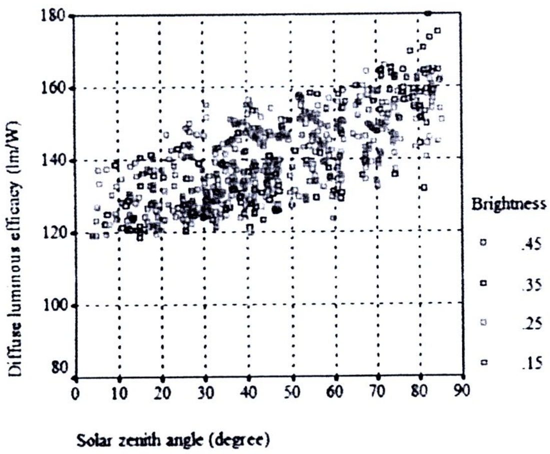


c) K_d with solar zenith for Perez's bin no.3

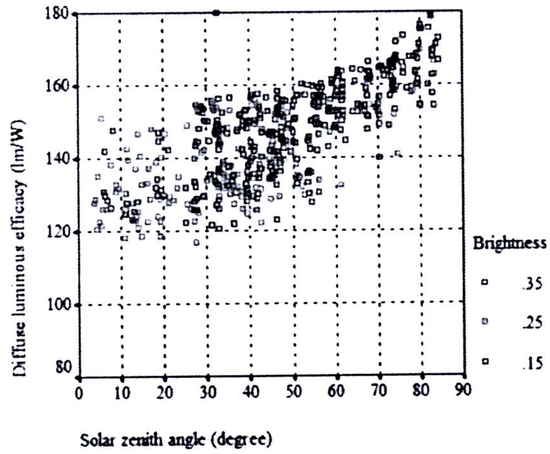


d) K_d with solar zenith for Perez's bin no.4

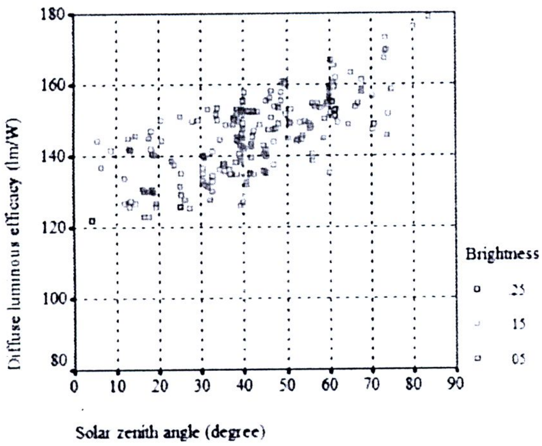
Figure 4.2: Correlations of the diffuse efficacy (K_d) with the insolation parameters.



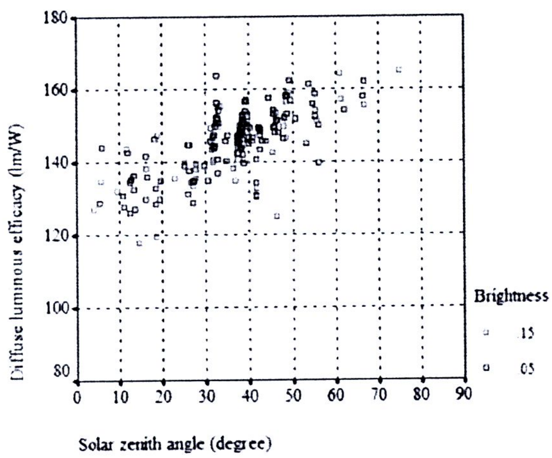
e) K_d with solar zenith for Perez's bin no.5



f) K_d with solar zenith for Perez's bin no.6



g) K_d with solar zenith for Perez's bin no.7



h) K_d with solar zenith for Perez's bin no.8

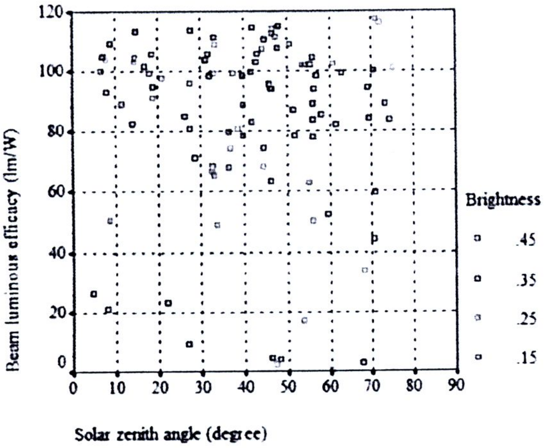
Figure 4.2: (Continued)

4.2.3 Beam Luminous Efficacy

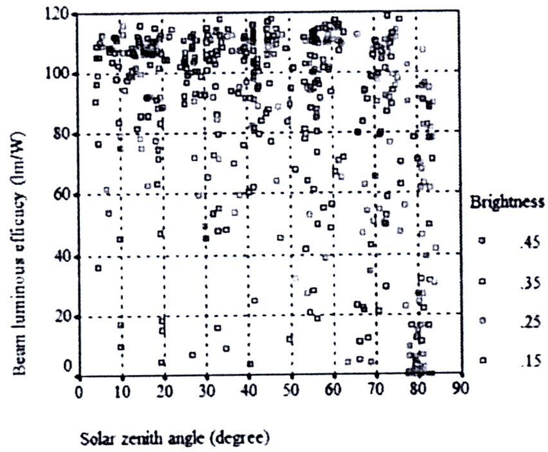
Similar to Fig 4.1 and 4.2, Figure 4.3 illustrates a set of scatter plots of variations of beam normal efficacy against the insolation parameters. Different from the previous plots, a very large dispersion of the variation of the beam efficacy is evident. However, particular trends can still be observed.

From Fig. 4.3(a), the variation of beam efficacy during overcast sky shows much scattering with no discernible trend or correlation. Actually, beam radiation is quite small under this condition. Figure 4.3(b) presents the beam efficacy for brighter overcast sky condition. It seems that values of the beam efficacy are relatively higher at low solar zenith angle (the sun stays close to the zenith of the sky). The average value of beam efficacy is approximately 83 lm/W for an overcast sky.

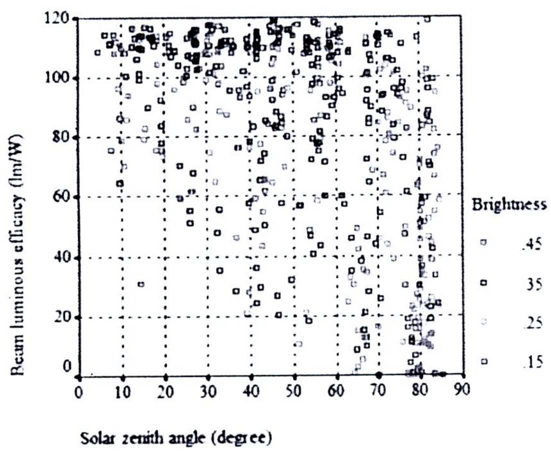
Figure 4.3(c) and 4.3(d) illustrate the beam efficacy for intermediate sky conditions. Large scattering can still be observed. The average value of beam efficacy is about 80 lm/W, slightly lower than that of overcast sky conditions.



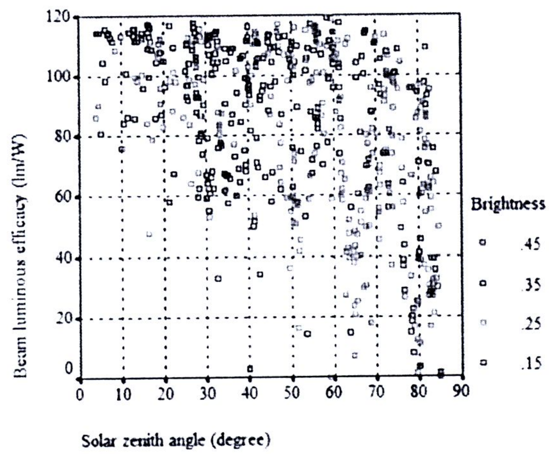
a) K_b with solar zenith for Perez's bin no.1



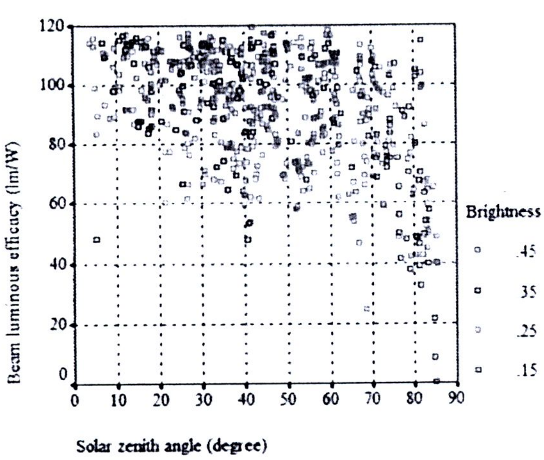
b) K_b with solar zenith for Perez's bin no.2



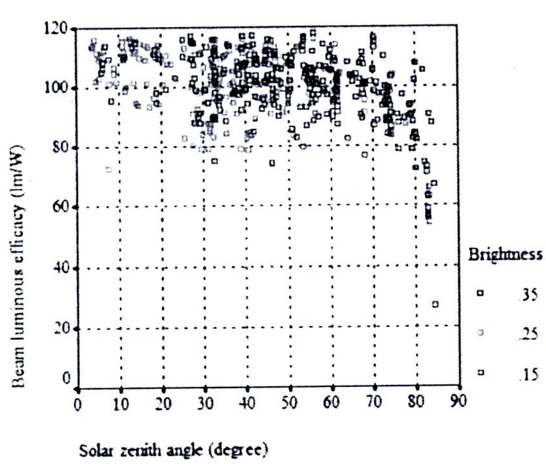
c) K_b with solar zenith for Perez's bin no.3



d) K_b with solar zenith for Perez's bin no.4

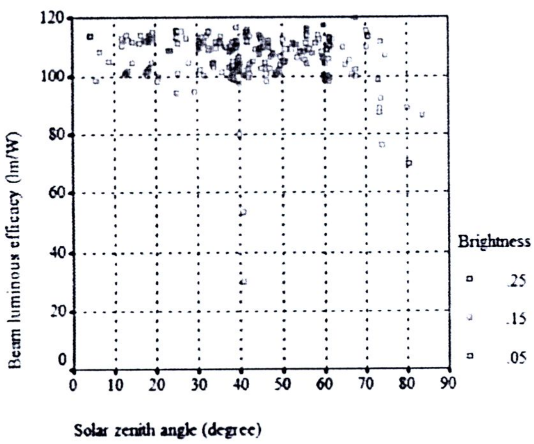


e) K_b with solar zenith for Perez's bin no.5

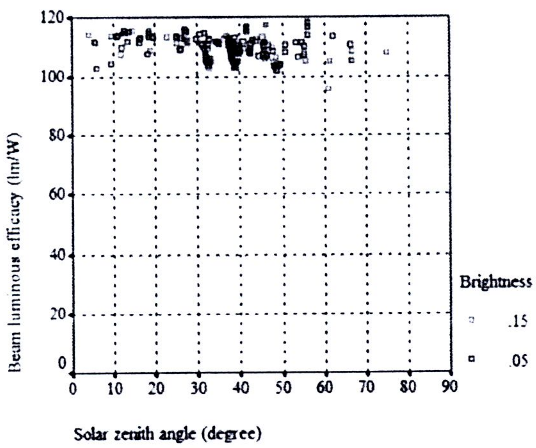


f) K_b with solar zenith for Perez's bin no.6

Figure 4.3: Correlations of the beam normal efficacy (K_b) with the insolation parameters.



g) K_b with solar zenith for Perez's bin no.7



h) K_b with solar zenith for Perez's bin no.8

Figure 4.3: (Continued)

Figure 4.3(e)-4.3(h) exhibit the variations of beam normal efficacy for clear sky conditions. The dispersion of its variations decreases as the sky becomes clearer. The beam efficacy seems invariant with the sun's position for very clear sky (Perez's clearness bin no. 7 and 8). The average value of beam efficacy is approximately 110 lm/W.

4.3 Modeling of Tropical Daylight Efficacy

In the first part of modeling the daylight efficacy for the tropics, the existing models proposed by various authors were evaluated against the tropical efficacy data. The functional forms of the proposed models by various authors were also adopted to regress with the tropical efficacy data in order to obtain the new sets of local coefficients of the models. The results explore the prediction performance of the models and suitability of the model functional forms to account for the variations of the efficacy with daylight climate. The models selected for the evaluation are summarized in Chapter 2.

4.3.1 Global Luminous Efficacy

Table 4.8 presents the evaluation results for the selected global efficacy models with its original coefficients. Table 4.9 presents similar results but for the models with new set of the coefficients obtained from regression with Thailand's efficacy data. The statistical parameters MBD and RMSD were employed for evaluation of model performance.

Table 4.8: Evaluation of the global luminous efficacy model with original coefficients

Sky condition	Littlefair		Muneer and Kinghorn		Ruiz E and Robledo L		Roblodo L and Soler A		Chung	
	MBD	RMSD	MBD	RMSD	MBD	RMSD	MBD	RMSD	MBD	RMSD
All	-	-	4.83	8.63	11.07	15.97	-	-	-	-
Clear	2.04	8.09	6.77	8.17	4.37	5.98	17.18	19.86	-	-
Overcast	-19.9	22.59	9.33	12.03	34.18	35.97	21.14	23.99	-	-
Intermediate	-	-	1.93	9.28	6.74	12.17	-	-	-8.36	12.35

As mentioned in Chapter 2, Littlefair proposed two separate models: one for clear sky and the other one for overcast sky. The testing results show that Littlefair's models overestimate the global efficacy by about 2.04 lm/W for clear sky and underestimate by a significant 19.9 lm/W for overcast sky. The RMSD values obtained from the models are also rather high, 8.09 and 22.59 lm/W, respectively for clear sky and overcast sky. Littlefair's models did not be tested with intermediate sky data and all sky data.

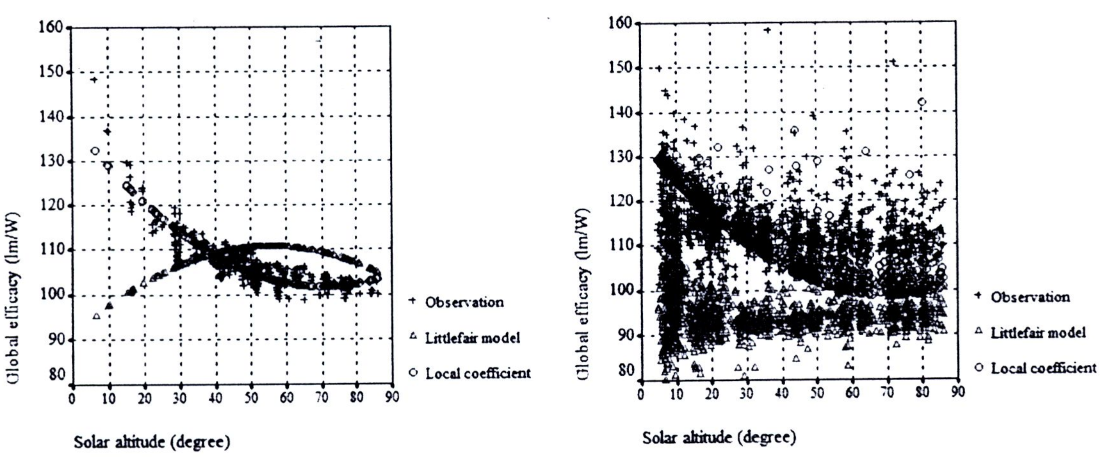
Littlefair's model was next regressed with the tropical efficacy data to produce its local coefficients. As could be observed from Table 4.9, performance has greatly improved.

Table 4.9: The global luminous efficacy model with calculated local coefficients

	Models with local coefficients
Littlefair	$K_{gcl} = 138.46 - 59.04\alpha_s + 24.04\alpha_s^2$
	$K_{gov} = K_{gcl}\left(1.05 - 0.71\Delta + 1.48\Delta^2\right)$
Muneer and Kinghorn	$K_g = 120.82 - 19.52k_t - 1.08k_t^2$
Ruiz E and Robledo L	$K_g = 108 \cdot sin\alpha_s^{-0.004} \cdot k_t^{-0.05}$
Roblodo L and Soler A	$K_{gcl} = 98.40 \cdot sin\alpha_s^{-0.18} \cdot e^{0.024\alpha}$
	$K_{gov} = K_{gcl(Ro)}(1.022 - 0.76\Delta + 1.74\Delta^2)$
Chung	$K_{gm} = (84.51 + 34.24k) \cdot k + (159.98 - 95.41\alpha_s + 42.45\alpha_s^2) \cdot (1-k)$

Sky condition	Littlefair		Muneer and Kinghorn		Ruiz E and Robledo L		Roblodo L and Soler A		Chung	
	MBD	RMSD	MBD	RMSD	MBD	RMSD	MBD	RMSD	MBD	RMSD
All	-	-	-0.0002	6.84	1.74	7.03	-	-	-	-
Clear	-0.38	2.63	- 0.30	3.75	3.64	5.42	-0.09	2.24	-	-
Overcast	-0.62	11.19	0.13	8.18	2.03	7.90	-1.15	13.74	-	-
Intermediate	-	-	- 1.38	9.28	- 0.07	9.09	-	-	8.36	10.91

Shown in Fig. 4.4 (a), the values of the global efficacy produced from Littlefair's models with both original coefficients and local coefficients were plotted against the tropical efficacy data. The plot is presented particularly for clear sky condition. It exhibits clearly that the original Littlefair model is not applicable for predicting global efficacy for Thailand's clear sky.



a) Clear sky condition

b) Overcast sky condition

Figure 4.4: Evaluation of Litterfair's models for prediction of the tropical global efficacy

Figure 4.4(b) illustrates a similar plot with that in Fig. 4.4(a) but for overcast sky. The original Littlefair model underestimates the global efficacy under this sky condition.

Muneer and Kinghorn proposed a global efficacy model for all sky conditions. Overall, the models overestimate the tropical global efficacy 4.83 lm/W (Table 4.8). It however performs better than the Littlefair model. Figure 4.5 shows a plot of the values of global efficacy predicted from the original Muneer and Kinghorn model. It is observed that the predicted values are higher than that of measurement under overcast and clear skies. Prediction performance of the model seems better under intermediate sky.

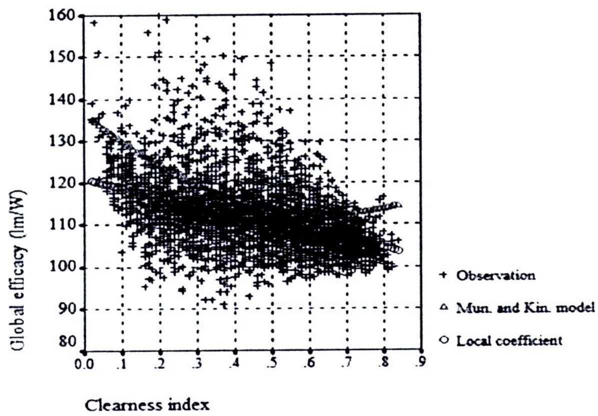


Figure 4.5: Evaluation of Muneer and Kinghorn's models for prediction of the tropical global efficacy (all sky conditions).

Muneer and Kinghorn's model was also used to regress with the tropical measurement data. With the new set of local coefficients, it again improves the model's performance a lot (Table 4.9). However, the plot shows the global efficacy values are producing by using the local coefficients seem to be linear with the clearness index.

Ruiz and Robledo developed a model to predict global efficacy for all skies. The results of performance evaluation of their model are presented in Table 4.8. Their model does not perform as well as worse than Muneer and Kinghorn's model (higher values of both MBD and RMSD). Next, examining the prediction performance of Ruiz and Robledo model with local coefficients, the results in Table 4.9 show that its performance can be improved but still worse than the localized Muneer and Kinghorn's model. Figure 4.6 exhibits a plot of global efficacy values from the original and localized models of Ruiz and Robledo against the measurement.

Robledo and Soler applied the same concept of Littlefair's model development. The performance evaluations for both original and local model coefficients are presented in Table 4.8 and 4.9. Figure 4.7 exhibits plots of evaluation results of Robledo and Soler's models with the tropical global efficacy data. A comparison between Figure 4.4 (a) and 4.7 (a) shows only one independent variable present for both models, which implies that for clear sky conditions, one independent variable is sufficient to predict global efficacy.

In Table 4.8 and Fig. 4.8, it was found that Chung's model underestimates the global efficacy of tropical sky. The evaluation was made only for intermediate sky conditions.

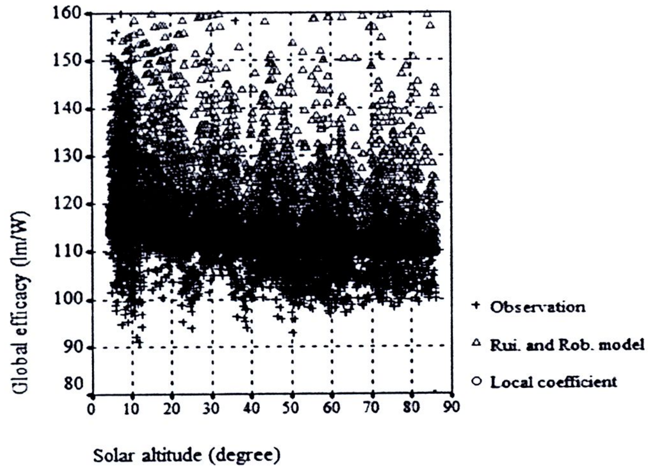


Figure 4.6: Evaluation of Ruiz E and Robledo L's models for prediction of the tropical global efficacy (all sky conditions).

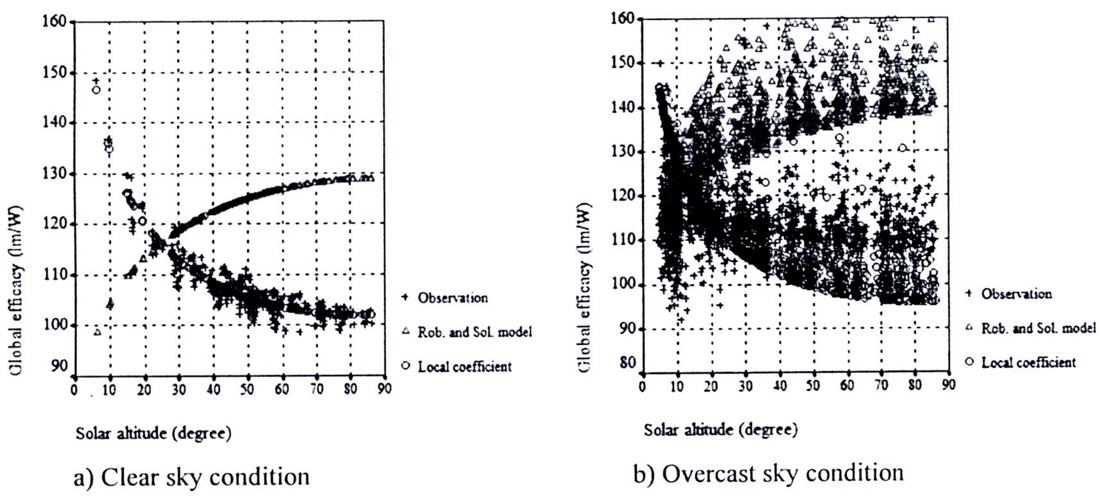


Figure 4.7: Evaluation of Robledo and Soler's models for prediction of the tropical global efficacy

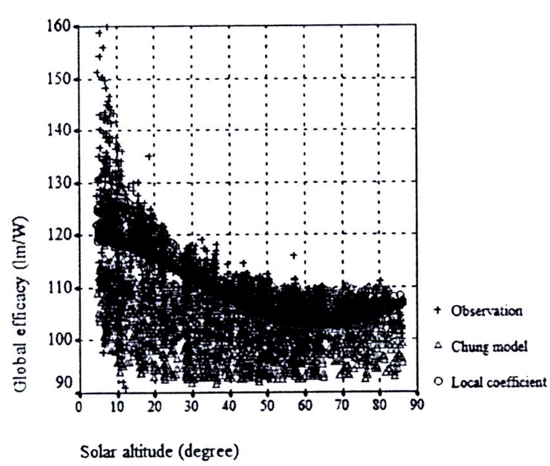


Figure 4.8: Evaluation of Chung's model for prediction of the tropical global efficacy (intermediate sky)

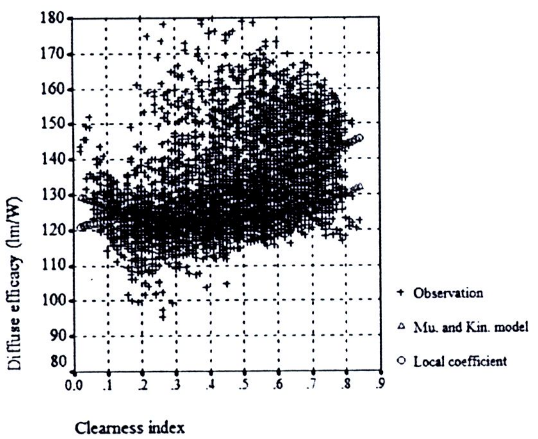
The distribution of global efficacy from Chung's model in Fig. 4.8 cites only intermediate sky conditions. Comparing predicted and observed values for this model, the values from the original model are lower than the observation.

4.3.2 Diffuse Luminous Efficacy

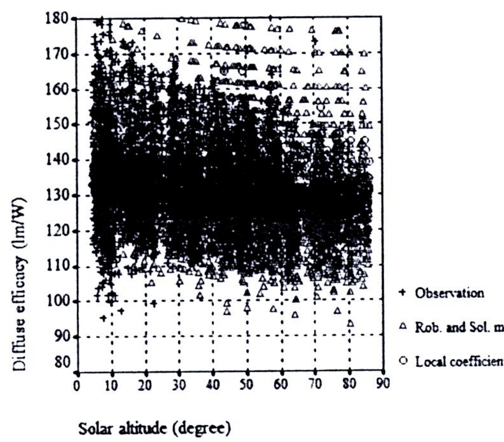
In this study, three selected models of Muneer and Kinghorn's, Roblodo L and Soler A, and Chung were evaluated against the tropical diffuse efficacy. Please note that Chung's model was proposed *only* for clear sky, whilst the other two were developed for all sky conditions. Results in Table 4.10 show that no existing model could perform well with the tropical data.

Table 4.10: Evaluation of the diffuse luminous efficacy model with original coefficients

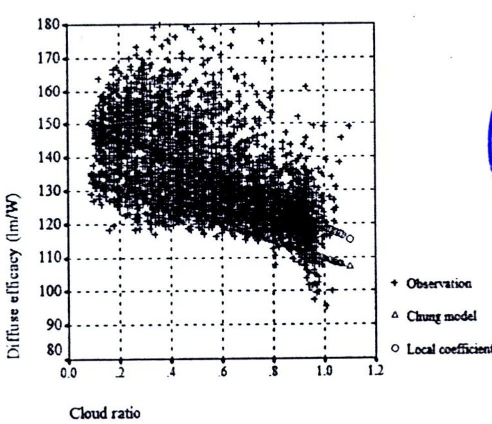
Sky condition	Muneer and Kinghorn		Roblodo L and Soler A		Chung	
	MBD	RMSD	MBD	RMSD	MBD	RMSD
All	-8.46	15.97	-2.08	16.91	-	-
Clear	-17.00	19.95	7.32	15.43	-12.86	16.88
Overcast	1.12	7.5	20.15	24.65		
Intermediate	-15.25	20.67	-18.35	21.62		



a) Muneer and Kinghorn model



b) Robledo and Soler model



c) Chung model (clear sky)

Figure 4.9: Evaluation of diffuse efficacy models for prediction of the tropical diffuse efficacy

Muneer and Kinghorn's model underestimates the tropical diffuse efficacy by 8.76 lm/W. The model uses only clearness index to account for the variations of the diffuse efficacy. From a plot in Figure 4.9(a), only an insolation index could be insufficient to model the tropical diffuse efficacy.

In the evaluation made for the model of Robledo and Soler, it can be observed that the model overestimates by up to 15 lm/W, even though if used two insolation indices to predict the diffuse efficacy, the model cannot perform well with the tropical data.

Chung's model employs a single parameter to determine the diffuse efficacy. From Table 4.10, Chung's model underestimates the tropical diffuse efficacy and cannot account well for the variations in that climate. Table 4.11 exhibits again the model's performance but for local coefficients. Overall, the performance of all the models improve. The values of both MBD and RMSD decrease.

Table 4.11: The diffuse luminous efficacy model with calculated local coefficients

Muneer and Kinghorn	$K_d = 120.77 + 16.49k_t + 15.82k_t^2$
Roblodo L and Soler A	$K_d = 115.68 \cdot \sin\alpha_s^{-0.006} \cdot \Delta^{-0.09}$
Chung	$K_{dcl} = 153.58 - 34.73CR$

Sky condition	Muneer and Kinghorn		Roblodo L and Soler A		Chung	
	MBD	RMSD	MBD	RMSD	MBD	RMSD
All	-0.003	12.66	-0.55	12.80	-	-
Clear	-3.5	11.11	-4.42	10.87	-0.001	10.68
Overcast	-1.00	8.45	15.49	16.91		
Intermediate	-5.92	15.64	-7.25	13.87		

4.3.3 Beam Luminous Efficacy

Two models of beam luminous efficacy were evaluated against the tropical data. One model was developed by Ullah, and the other one by Chung. Both models use polynomial functional forms and proposed for clear sky condition only. Solar altitude angle is the input parameter of the models.

Evaluation results in Table 4.12 show that both of the models could not predict well for tropical beam normal efficacy. However, this is not the case of the model with local coefficients.

Table 4.12 Evaluation of the beam luminous efficacy model with original coefficients.

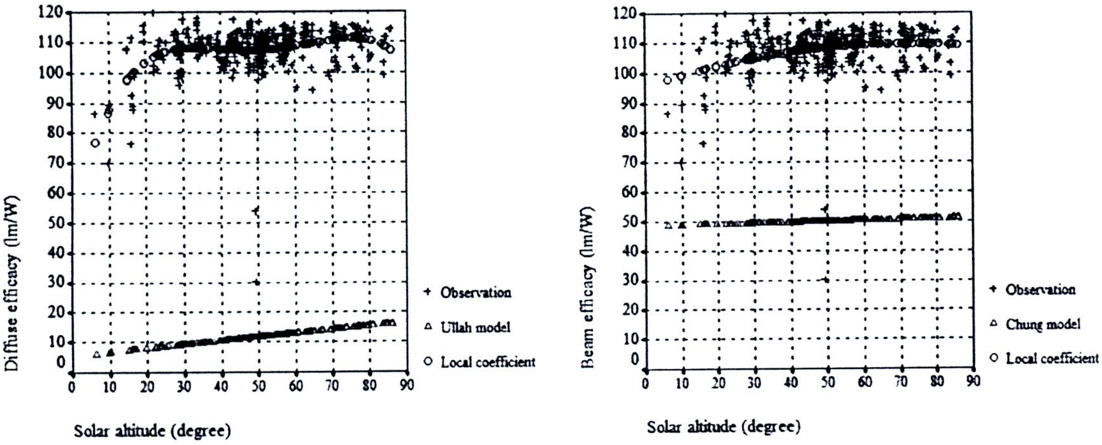
Sky condition	Ullah MB		Chung	
	MBD	RMSD	MBD	RMSD
Clear	-95.86	96.16	-57.76	58.27

Table 4.13 The beam luminous efficacy model with calculated local coefficients.

Ullah MB	$K_{bcl} = 50.78 + 292.27\alpha_s - 535.85\alpha_s^2 + 414.34\alpha_s^3 - 113.55\alpha_s^4$
Chung	$K_{bcl} = 95.32 + 22.94\alpha_s - 9.19\alpha_s^2$

Sky condition	Ullah MB		Chung	
	MBD	RMSD	MBD	RMSD
Clear	-0.008	7.24	-0.006	7.50

Figure 4.10 (a) and (b) display beam efficacy values which were generated by developing a polynomial with solar altitude as the only independent variable. From Fig. 4.10 (a) and (b) it could be inferred that one independent variable enables the modeling of the beam efficacy when clear sky occurs.



a) Ullah model

b) Chung model

Figure 4.10: Evaluation of diffuse efficacy models for prediction of the tropical beam normal efficacy.

The other point of interest is that the constant beam efficacy value may be used as well. However, in case of partly cloudy and overcast sky condition to model beam efficacy must involve more parameters due to the effect of the earth's atmosphere.

4.4 Model Development of Tropical Daylight Efficacy

In this study, two models were proposed for global efficacy and diffuse efficacy. The models are capable of determining the efficacy for all sky conditions. As observed from a number of plots of variations of the efficacy with sky conditions, the models chose Perez's clearness (ε) for the model input. The less effective brightness index (Δ) was excluded from the models. Solar zenith angle (ϕ_s) in radian is also the input of the models.

4.4.1 Global Luminous Efficacy

The relation between global luminous efficacy and the insolation parameter was made evident in Section 4.2.1. Therefore, the functional form of the proposed model of the global luminous efficacy is expressed as follows:

$$K_g = (a + b\varepsilon^c)(cos\phi_s)^{(d+e\varepsilon^f)}.$$

After regression with the efficacy data using SPSS software, the values of the model coefficients were obtained. The following equation is obtained from the regression:

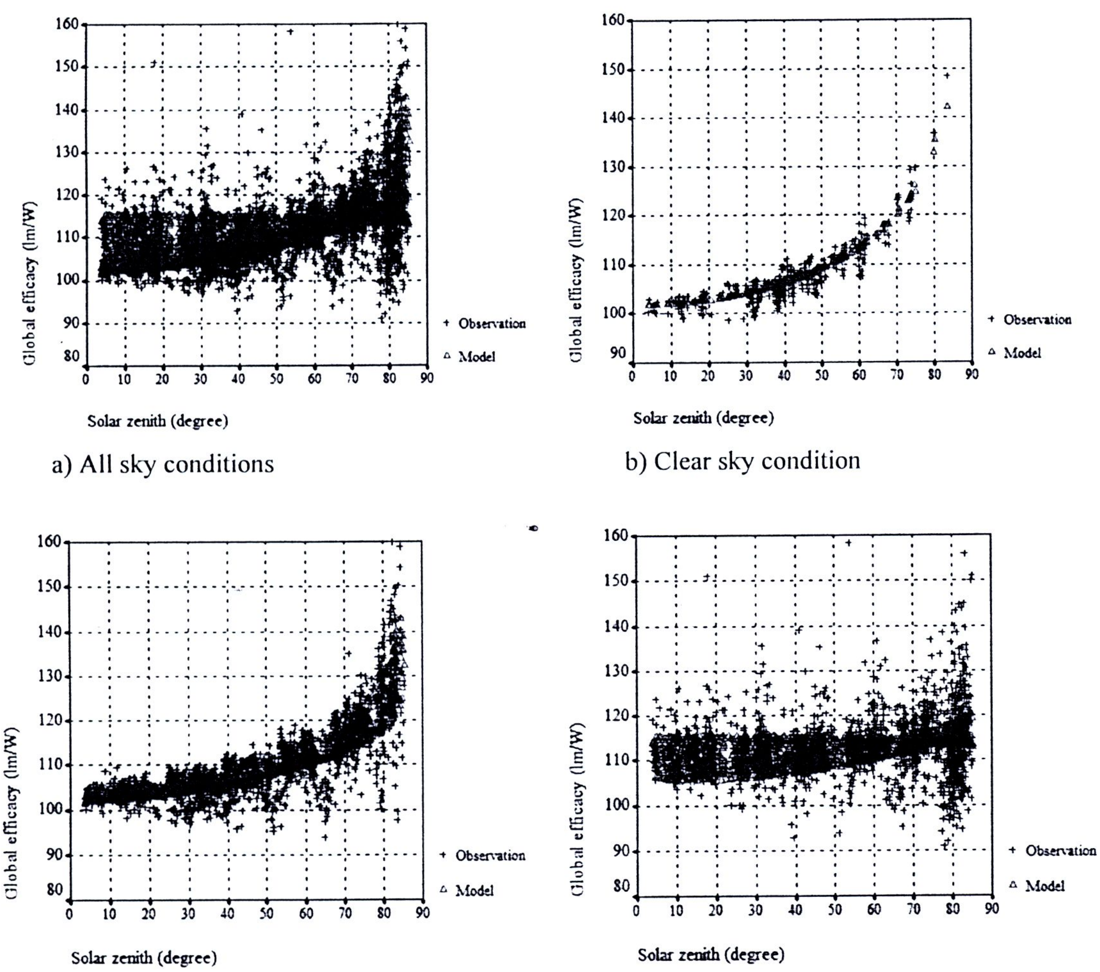
$$K_g = (101.65 + 13.92\varepsilon^{-3.49})(cos\phi_s)^{(-0.18+0.19\varepsilon^{-1.25})}.$$

Results in Table 4.14 show that the proposed model can determine well the global efficacy in tropical climate. The performance of the model is much better than those of existing authors.

Table 4.14: Performance evaluation of the proposed efficacy model for tropical climate

Sky condition	Global Efficacy		Diffuse Efficacy	
	MBD	RMSD	MBD	RMSD
All	-0.22	5.34	-0.02	8.28
Overcast	-0.16	6.18	0.12	7.47
Intermediate	-0.44	4.67	-0.32	9.21
Clear	0.43	2.35	0.54	8.14

The plots in Fig. 4.11 compare the value from the estimation and the values from the observation. The closest of both values performed better than models proposed by other authors. In particular, all predictions of global efficacy value from the new model varies with the observation values as can be seen from Fig. 4.11.



a) All sky conditions

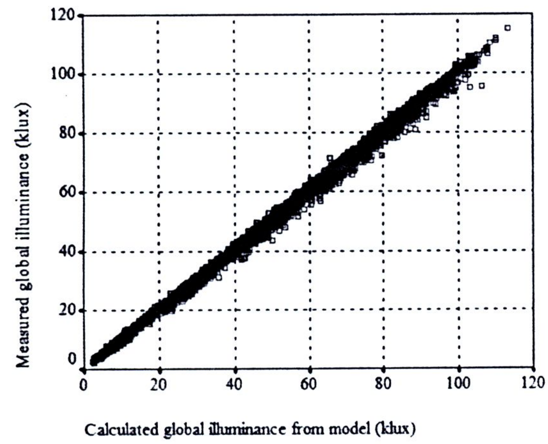
b) Clear sky condition

c) Intermediate sky condition

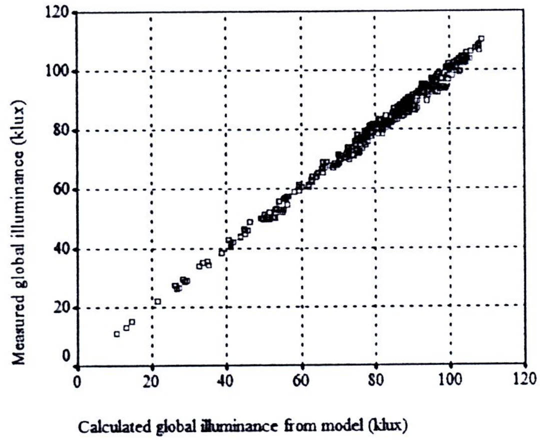
d) Overcast sky condition

Figure 4.11: Plots of tropical global efficacy from measurements and the proposed model

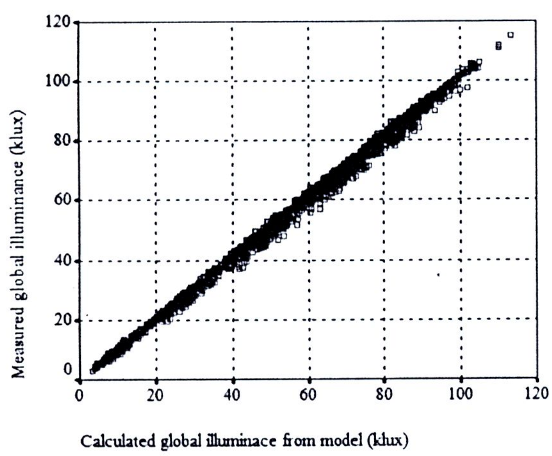
Figure 4.12 presents the plots of the measured and the modeled global illuminance. The performance shows that the new developed model provides satisfactory results.



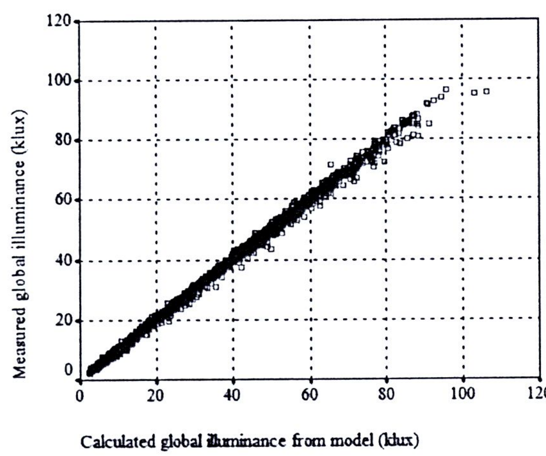
a) All sky conditions



b) Clear sky condition



c) Intermediate sky condition



d) Overcast sky condition

Figure 4.12: Plots of global illuminance from measurements and those derived from the proposed global efficacy model

4.4.2 Diffuse Luminous Efficacy

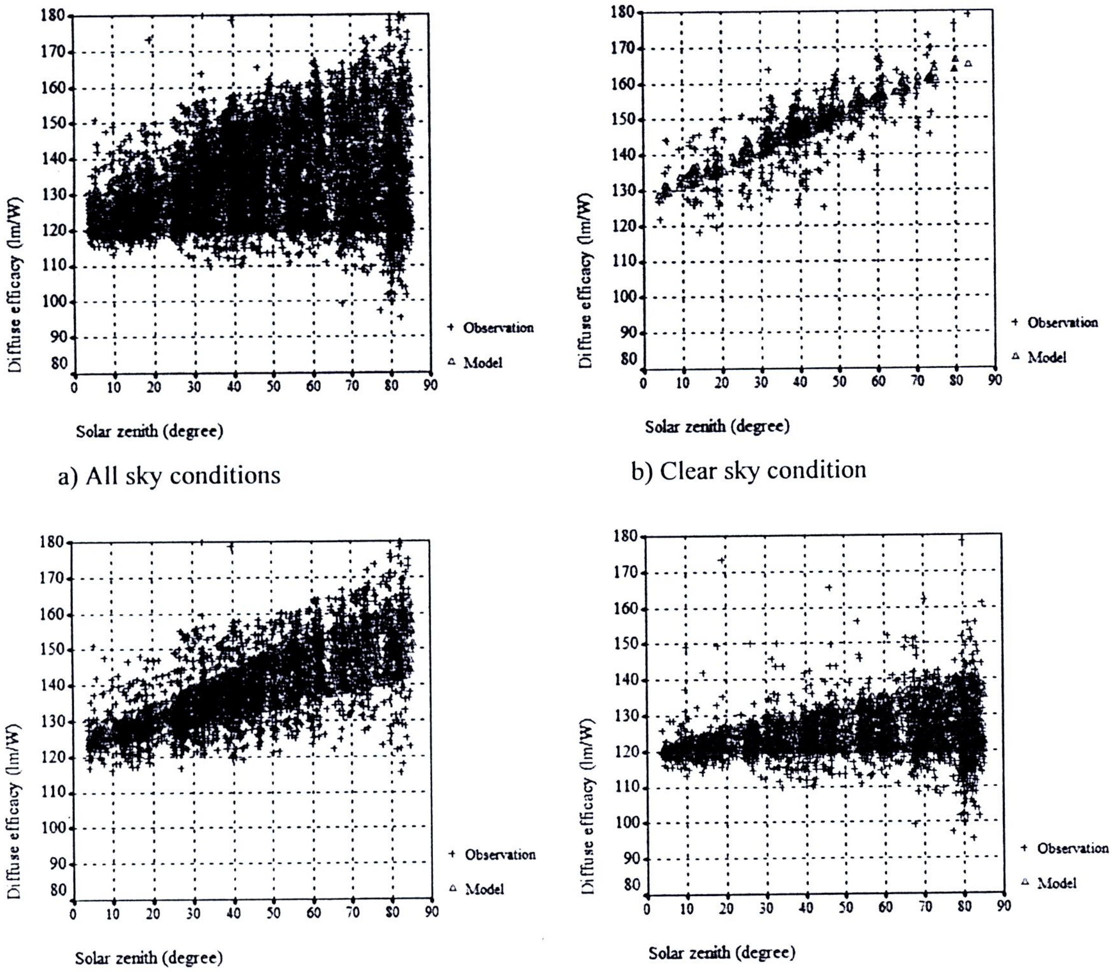
The functional form of the proposed model of the global luminous efficacy is expressed as follows:

$$K_d = (a + b\varepsilon^c) + (d + \frac{e}{\varepsilon^{1.5}})\phi_s$$

Using the local data, the curve fitting provides parameters as

$$K_d = (107.14 + 12.59\varepsilon^{0.24}) + (30.35 - \frac{30.1}{\varepsilon^{1.5}})\phi_s$$

Examining the evaluation results in Table 4.14, the proposed model can results in better predictions of tropical diffuse efficacy when compared to other models. Fig. 4.13 and 4.14 exhibits the plots of the diffuse efficacy from the observation and from the model's calculation.



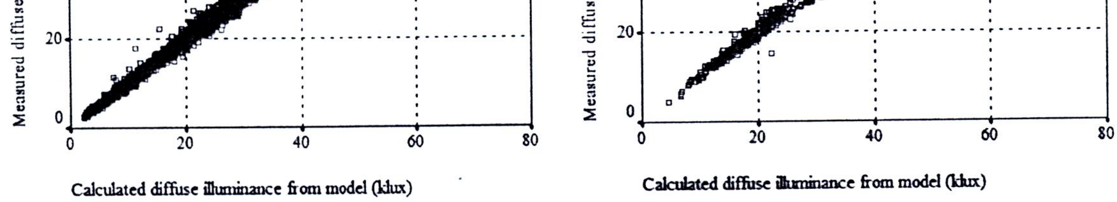
a) All sky conditions

b) Clear sky condition

c) Intermediate sky condition

d) Overcast sky condition

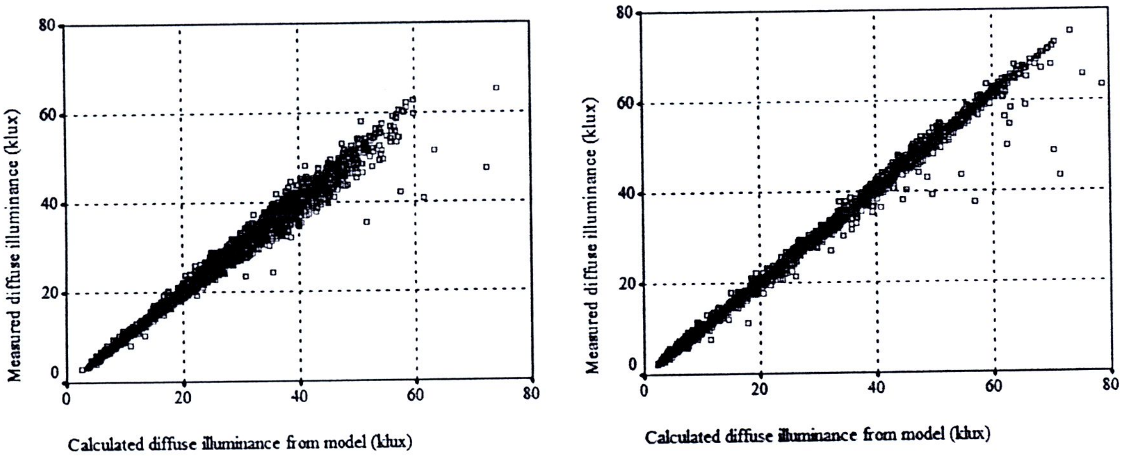
Figure 4.13: Plots of tropical diffuse efficacy from measurement and the proposed model



a) All sky conditions

b) Clear sky condition

Figure 4.14: Plots of diffuse illuminance from measurements and those derived from the proposed global efficacy model



c) Intermediate sky condition

d) Overcast sky condition

Figure 4.14: (Continued)