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SOLAR RADIATION TABLES FOR THAILAND

R.H.B. EXELL and K. SARICALI*

Division of Community and Regional Development, Asian Institute of Technology, P.O. Box 2754, Bangkok.

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Summary

A survey has been made of the geographical, seasonal, and diurnal variations of global solar radiation in Thailand. Seasonal variations of radiation were determined from separate studies for eight 1½ month periods of the year defined by standard solar declination values. The geographical distribution was found from data on the duration of sunshine at 18 *stations and from the relation between sunshine and radiation at Chiang Mai and Bangkok. Fluctuations in the daily solar radiation were examined in an unbroken five-year sequence of radiation measurements at Bangkok. The distribution of radiation levels in the sequence and the transition probabilities between the levels were determined. The distributions of radiation levels elsewhere in Thailand were estimated from daily sunshine measurements. Finally, morning and afternoon radiation amounts at Chiang Mai and Bangkok throughout the year were compared.*

Introduction

Prior to the present study the most recent survey of solar radiation covering Thailand was that of Lof, Duffie and Smith[1]. It contained world maps of the monthly means of daily totals of global solar radiation. The data for Thailand consisted of radiation measurements at four stations over periods of one to three years.

The present study was undertaken to provide a more detailed survey of solar radiation in Thailand. A selection of the results, together with an account of the methods used, have been reported elsewhere[2]. The purpose of the present paper is to make the full results readily accessible to workers in Thailand. It is hoped to publish a comprehensive AIT research report in due course.

*Present address: Uludag Sokak 4A–6, Maltepe, Ankara, Turkey.

Seasonal periods and solar radiation in the absence of cloud

Although calendar months are usually employed in the presentation of climatic data, they are not related to the position of the sun on the celestial sphere in a simple way. An improved subdivision of the year into eight periods, each approximately 1½ months in length has been used in the present study. These periods, which are based on the analysis by Heywood[3], are defined by standard solar declination values, and are shown in Table I.

The table also shows the mean daily total global solar radiation in the absence of cloud Q_m at various latitudes in each period. These values of Q_m were obtained from those calculated by Schuepp[4] for the standard atmospheric conditions: 2 cm for precipitable water, pressure 1000 mb, ozone content 0.34 cm NTP, and zero turbidity.

Relations between solar radiation and sunshine duration

Chiang Mai and Bangkok are the only locations in Thailand from which solar radiation data are currently available. At these stations the global solar radiation is measured by the Meteorological Department with thermopile pyranometers. The duration of sunshine is measured with Campbell-Stokes sunshine recorders at 18 stations throughout the Kingdom.

In order to use the sunshine records to estimate solar radiation amounts a linear relation of the Angstrom type[5] was established for the observations[6] at Chiang Mai and Bangkok in the five-year period 1968–1972. Table II gives data for the regression equations $Q/Q_m = a + bS/S_m$. Here Q is the daily total global solar radiation. Q_m is the daily total global solar radiation in the absence of cloud as defined earlier. S is the daily duration of sunshine measured with a sunshine recorder. S_m is the maximum daily duration of sunshine recordable, and is put equal to the time between sunrise and sunset minus 0.4 hr, during which time the sun is too low to burn the recorder paper. The numbers a and b are dimensionless parameters, and s is the dimensionless standard error of estimate of Q/Q_m on S/S_m. The results for Chiang Mai have been reduced to mean sea level.

Estimates of solar radiation from sunshine duration

The regression equations were used to estimate the mean daily totals of global solar radiation reduced to mean sea level from the mean daily durations of sunshine in each 1½ month period at the 18 stations with sunshine recorders. The values of S used were from averages[6] over the period from the mid-1950's to 1968. Table III gives the results. It si estimated that the tabulated values are accurate to within 50 cal cm^{-2} cay^{-1}.

The results are consistent with the general trends on the world maps of Lof, Duffie and Smith[1], but depart from their values by as much as 50 cal cm^{-2} day^{-1} in some cases. The data for Chiang Mai and Bangkok used in the present study showed fluctuations in the mean values of Q of the order 50 cal cm^{-2} day^{-1} from year to year during the period 1968 to 1972. Such fluctuations might explain the differences between the present results based on sunshine averages over 15 to 20 years and the results of Lóf, Duffie and Smith based on radiation averages over one to three years.

Percentage distribution of solar radiation amounts at Bangkok

Fluctuations in the solar radiation at Bangkok were examined in an unbroken five-year sequence (1968–1972) of daily totals of global solar radiation measured at the old AIT site in Bangkok. The solar radiation amounts were divided into classes of width 50 cal cm^{-2} day^{-1} and the frequencies of occurrence of the classes during each $1\frac{1}{2}$ month period were counted. The results, expressed as percentage frequencies, are shown in Table IV.

Day to day sequence of solar radiation amounts at Bangkok

To study the day to day sequence of solar radiation amounts as a random process the measured values were divided into three classes. Class A contains values greater than 500 cal cm^{-2} day^{-1}, class B contains values from 500 to 300 cal cm^{-2} day^{-1}, and class C contains values less than 300 cal cm^{-2} day^{-1}.

A complete statistical description of the random sequence would contain the first order probabilities $p_1(A)$, p_1 (B), and p_1 (C) of the radiation classes A, B, and C respectively, the second order (Markov) probabilities p_2 (A, A), p_2 (A, B), ... of the transitions of successive days from A to A, from A to B, ... respectively, the third order probabilities such as p_3 (C, A, B) that after the transition from C to A the next transition is from A to B, and so on. The use of probailities of higher order than the first is made necessary by the persistence of meteorological phenomena.

In the present study the first and second order probabilities were determined for each $1\frac{1}{2}$ month period by a simple counting of events in the data. It was not possible to determine the third order probabilities because the occurrences of many of the transitions were too few to obtain meaningful results. Tables V and VI show the probabilities found.

The probabilities in Table VI differ significantly from those for a system in which the solar radiation class on each day is independent of the solar radiation class on the preceding day.

Periods of low solar radiation

The probability of a specified number of dull days in succession in each $1\frac{1}{2}$ month period may be estimated from the results in Tables V and VI. Let p_1 (A), p_1 (B), p_1 (C) be the probabilities in Table V, and let p_2 (A, A), p_2 (A, B), etc., be the probabilities in Table VI. Then the probability that a particular day is the first of a sequence of exactly n class C days preceded and followed by days of class A or B is

$$(p_1 (A)\, p_2 (A, C)+p_1 (B) p_2 (B,C))\, p_2 (C, C)^{n-1} (p_2 (C, A)+p_2\, C, B)).$$

Analogous formulae may be used to estimate the probabilities of other kinds of sequences.

Table I.
Seasonal periods and mean values of Q_m at various latitudces

	Mean solar declination	Q_m (cal cm^{-2} day^{-1}) 5°N	10°N	15°N	20°N
Jan 14 – Feb 26	–15°50'	643	608	568	523
Feb 27 – Apr 12	0°	680	672	658	638
Apr 13 – May 28	15°50'	668	686	702	710
May 29 – Jul 15	22°47'	644	675	700	720
Jul 16 – Aug 31	15°50'	662	680	692	700
Sep 1 – Oct 15	0°	670	662	648	628
Oct 16 – Nov 29	–15°50'	637	604	564	518
Nov 30 – Jan 13	–22°47'	606	564	516	462

Table II.
Data for the regression equation $Q/Q_m = a + bS/S_m$

	Mean Q_m cal cm^{-2} day^{-1}	Mean S_m h day^{-1}	a	b	s
Chiang Mai					
Jan 14 – Feb 26	534	10.99	.272	.575	.055
Feb 27 – Apr 12	642	11.70	.271	.560	.071
Apr 13 – May 28	708	12.45	.340	.508	.060
May 29 – Jul 15	715	12.82	.351	.536	.059
Jul 16 – Aug 31	698	12.45	.346	.533	.076
Sep 1 – Oct 15	634	11.70	.319	.605	.071
Oct 16 – Nov 29	529	10.99	.329	.581	.064
Nov 30 – Jan 13	476	10.66	.323	.559	.058
Bangkok					
Jan 14 – Feb 26	578	11.20	.294	.503	.088
Feb 27 – Apr 12	661	11.70	.272	.566	.074
Apr 13 – May 28	698	12.24	.286	.526	.074
May 29 – Jul 15	694	12.52	.332	.488	.065
Jul 16 – Aug 31	690	12.24	.333	.479	.066
Sep 1 – Oct 15	652	11.70	.307	.538	.102
Oct 16 – Nov 29	574	11.20	.314	.507	.097
Nov 30 – Jan 13	528	10.96	.322	.519	.090

Table III.
Mean daily totals of global solar radiation (cal cm^{-2} day^{-1}) estimated from mean daily durations of sunshine

	Jan 14 to Feb 26	Feb 27 to Apr 12	Apr 13 to May 28	May 29 to Jul 15	Jul 16 to Aug 31	Sep 1 to Oct 15	Oct 16 to Nov 29	Nov 30 to Jan 13
Chiang Rai	394	430	470	406	385	399	369	324
Chiang Mai	400	460	481	412	376	402	406	372
Loei	383	418	443	399	381	355	354	344
Nakhon Phanom	369	396	426	370	360	374	395	366
Sakhon Nakhon	386	429	442	389	382	405	406	392
Phitsanulok	394	451	483	419	390	375	402	386
Khon Kaen	403	431	463	418	393	381	418	394
Roi Et	376	441	461	433	408	389	403	376
Nakhon Sawan	398	442	456	403	378	369	400	388
Ubon	404	450	447	423	393	379	407	393
Korat	397	435	445	421	402	379	401	388
Surin	405	454	439	415	407	397	409	396
Bangkok	401	465	425	397	370	356	391	398
Chantaburi	406	438	397	360	337	328	396	410
Hua Hin	409	448	415	370	345	349	391	398
Ban Don	417	457	402	384	399	362	341	350
Phuket Airport	440	474	388	378	373	354	380	398
Songkhla	427	462	417	399	406	380	350	354

Table IV.
Percentage distributions of daily totals of global solar radiation at Bangkok

Radiation class cal cm^{-2} day^{-1}	Jan 14 to Feb 26	Feb 27 to Apr 12	Apr 13 to May 28	May 29 to Jul 31	Jul 16 to Aug 31	Sep 1 to Oct 15	Oct 16 to Nov 29	Nov 30 to Jan 13
0 – 50	0	0	0	1	0	2	0	0
50 – 100	1	1	0	0	0	1	1	1
100 – 150	1	2	1	2	2	2	2	1
150 – 200	1	1	2	3	4	6	2	4
200 – 250	5	3	4	9	6	9	7	4
250 – 300	4	5	6	7	14	15	9	7
300 – 350	9	4	10	11	23	15	13	11
350 – 400	20	8	8	17	20	14	13	16
400 – 450	29	14	14	23	14	15	18	30
450 – 500	18	26	14	11	8	10	22	25
500 – 550	9	27	17	12	7	6	11	1
550 – 600	2	9	20	3	2	4	1	0
600 – 650	1	0	3	1	0	1	1	0
650 – 700	0	0	1	0	0	0	0	0

Table V.
Probabilities of solar radiation classes at Bangkok

Radiation class cal cm^{-2} day^{-1}	Jan 14 to Feb 26	Feb 27 to Apr 12	Apr 13 to May 28	May 29 to Jul 15	Jul 16 to Aug 31	Sep 1 to Oct 15	Oct 16 to Nov 29	Nov 30 to Jan 13
A (over 500)	.12	.36	.41	.16	.09	.11	.13	.01
B (300 to 500)	.76	.52	.46	.62	.65	.54	.66	.82
C (under 300)	.12	.12	.13	.22	.26	.35	.21	.17

Table VI.
Probabilities of transitions between solar radiation classes on successive days at Bangkok

Transition	Jan 14 to Feb 26	Feb 27 to Apr 12	Apr 13 to May 28	May 29 to Jul 15	Jul 16 to Aug 31	Sep 1 to Oct 15	Oct 16 to Nov 29	Nov 30 to Jan 13
A to A	.27	.58	.60	.29	.12	.28	.21	.13
A to B	.54	.35	.35	.60	.80	.48	.72	.73
A to C	.19	.07	.05	.11	.08	.24	.07	.14
B to A	.12	.24	.29	.11	.11	.10	.13	.01
B to B	.78	.63	.51	.68	.68	.58	.69	.87
B to C	.10	.13	.20	.21	.21	.32	.18	.12
C to A	.07	.19	.19	.20	.03	.07	.08	.05
C to B	.71	.62	.62	.51	.53	.53	.51	.62
C to C	.22	.19	.19	.29	.44	.40	.41	.33

Table VII.

Percentage distributions of daily totals of global solar radiation estimated from duration of sunshine

Radiation class cal cm^{-2} day^{-1}	Jan 14 to Feb 26	Feb 27 to Apr 12	Apr 13 to May 28	May 29 to Jul 15	Jul 16 to Aug 31	Sep 1 to Oct 15	Oct 16 to Nov 29	Nov 30 to Jan 13
Chiang Mai								
0 – 100	0	0	0	0	0	0	0	0
100 – 200	1	1	1	1	4	2	5	6
200 – 300	3	4	4	14	25	12	14	8
300 – 400	19	11	9	26	31	23	20	45
400 – 500	75	52	31	33	26	35	52	41
500 – 600	2	31	47	23	12	26	9	0
600 – 700	0	1	8	3	2	2	0	0
Khon Kaen								
0 – 100	0	0	0	0	0	0	0	0
100 – 200	3	2	0	1	3	5	3	3
200 – 300	7	6	4	13	22	15	8	8
300 – 400	28	17	15	28	29	22	23	37
400 – 500	58	53	38	36	39	33	55	51
500 – 600	4	21	38	20	15	22	11	1
600 – 700	0	1	5	2	2	3	0	0
Bangkok								
0 – 100	0	0	0	0	0	0	0	0
100 – 200	2	2	2	1	2	6	5	4
200 – 300	7	4	9	15	18	19	12	11
300 – 400	29	13	19	31	36	31	33	38
400 – 500	53	46	33	36	34	31	41	44
500 – 600	9	33	32	16	10	12	9	3
600 – 700	0	2	5	1	0	1	0	0
Songkhla								
0 – 100	0	0	0	0	0	0	1	0
100 – 200	1	1	1	2	1	3	11	7
200 – 300	4	3	5	14	12	15	25	19
300 – 400	19	9	18	32	26	30	27	31
400 – 500	57	45	47	39	42	34	27	36
500 – 600	19	39	27	13	18	16	9	7
600 – 700	0	3	2	0	1	2	0	0

Table VIII.

Mean morning and afternoon totals of global solar radiation (cal cm^{-2})

	Apparent solar time	
	7h to 12h	12h to 17h
Chiang Mai		
Jan 14 – Feb 26	219	212
Feb 27 – Apr 12	228	220
Apr 13 – May 28	260	227
May 29 – Jul 15	218	201
Jul 16 – Aug 31	198	176
Sep 1 – Oct 15	221	210
Oct 16 – Nov 29	203	202
Nov 30 – Jan 13	191	190
Bangkok		
Jan 14 – Feb 26	198	201
Feb 27 – Apr 12	225	226
Apr 13 – May 28	221	214
May 29 – Jul 15	200	179
Jul 16 – Aug 31	203	172
Sep 1 – Oct 15	197	169
Oct 16 – Nov 29	204	189
Nov 30 – Jan 13	202	194

Estimates of solar radiation statistics from sunshine duration statistics

The percentage distributions of daily totals of global solar radiation at Chiang Mai, Khon Kaen, Bangkok, and Songkhla during each $1\frac{1}{2}$ month period were estimated from the daily records of duration of sunshine[6] at these stations for the five years 1968 to 1972 with the help of the known regression relations and standard errors of estimate of the solar radiation on sunshine duration. It was assumed for the calculations that the deviations of the radiation amounts from the regression lines were norally distributed, an assumption that was confirmed by an examination of the data for Chiang Mai and Bangkok.

The results are shown in Table VII. The estimated distributions for Bangkok are in good agreement with the observed distributions given in Table IV.

Diurnal variations of solar radiation

The diurnal variations of global solar radiation at Chiang Mai and Bangkok were determined from measurements of the hourly totals of global solar radiation[6] for the years 1968 to 1972. The extent to which the mean morning and afternoon totals differ from one another is shown in Table VIII. The mean amount of solar radiation received in the afternoon is slightly less than that received in the morning.

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References

1. Lof, G.O.G., Duffie, J.A. and Smith, C.O. (1966) *World Distribution in Solar Radiation,* Report No. 21, Engineering Experiment Station. University of Wisconsin. *Solar Energy* **10,** 27–37.
2. Exell, R.H.B. and Saricali, K. (1975) Mechanical Engineering Congress on Energy, Pahlavi University, Shiraz, Iran.
3. Heywood, H. (1965) *Solar Energy* **9,** 223–225.
4. Schuepp, W. (1966) in *Solar Radiation* (Robinson, N., ed.) p. 157–158, Elsevier Publishing Co.
5. Robinson, N. (1966) in *Solar Radiation* (Robinson, N., ed. p. 279–281, Elsevier Publishing Co. Ibid. 279–281.
6. Meteorological Department, Ministry of Communications (1973) Private communication.

บทคัดย่อ

เมื่อเร็ว ๆ นี้ได้มีการสำรวจการผันแปรของพลังแสงอาทิตย์ ตามลักษณะภูมิประเทศตามฤดูกาลและตามช่วงระยะเวลาจากเช้าจดเย็นโดยเฉลี่ยขึ้นในประเทศไทย การประมาณผลของการผันแปรของพลังแสงอาทิตย์ตามฤดูกาลนั้นกระทำเป็น ๘ ระยะด้วยกัน ซึ่งแต่ระยะใช้เวลา ๑๑/๒ เดือน ทั้งนี้ได้อาศัยค่ามาตรฐานของเส้นรุ้งของดวงอาทิตย์เป็นหลัก ส่วนผลของการศึกษาการจำแนกพลังแสงอาทิตย์นั้น ได้อาศัยข้อมูลของระยะเวลาของการส่องแสงของดวงอาทิตย์จากสถานีสังเกตการณ์ ๑๘ แห่ง และจากความสัมพันธ์ระหว่างแสงอาทิตย์โดยตรงกับรังสีอาทิตย์ที่เชียงใหม่และกรุงเทพฯ การสำรวจความไม่คงที่ของพลังแสงอาทิตย์ของแต่ละวันนั้น ได้ใช้ข้อมูลของการวัดพลังแสงอาทิตย์ ซึ่งเป็นการวัดติดต่อกันเป็นระยะเวลา ๕ ปี เป็นแนวศึกษา อนึ่ง การจำแนกพลังแสงอาทิตย์ในระดับต่าง ๆ ซึ่งต่อเนื่องกันในช่วงระยะเวลาหนึ่ง ๆ และการประเมินการแปรเปลี่ยนพลังแสงอาทิตย์ในระหว่างระดับต่าง ๆ นั้น ก็ได้คำนวณกันในกรุงเทพฯ ทั้งสิ้น ส่วนการจำแนกพลังแสงอาทิตย์ ณ ที่อื่น ในประเทศไทยนอกเหนือจากเชียงใหม่ และกรุงเทพฯ ในระดับต่าง ๆ นั้น ก็ได้คำนวณจากผลการวัดการส่องแสงของดวงอาทิตย์ของแต่ละวันนั่นเอง และท้ายที่สุดก็นำเอาปริมาณต่าง ๆ ของพลังแสงอาทิตย์ทั้งในเวลาเช้าและเวลาบ่าย ที่เชียงใหม่และทั่วกรุงเทพฯ ตลอดระยะเวลาหนึ่งปีมาเปรียบเทียบกัน