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Hourly values of solar irradiation in clear skies

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Hourly values of global solar irradiation in clear skies are determined as a function of solar elevation using empirical parameters derived from the measurements of radiation in Zagreb ($\phi = 45.828^\circ$ N, $\lambda = 15.992^\circ$ E) in the period between 1960 and 1985. The estimation was performed on the 15th of every month for geographical latitudes between 41° and 46°N. By means of the well known procedure the global solar radiation is then divided into the direct and diffuse solar radiation and calculated for a south-facing surface inclined at 35°. A possibility of taking into consideration the influence of clouded sky on the decrease in the clear-sky solar irradiation is also presented.

Satne vrijednosti dozračene Sunčeve energije pri uvjetima vedrog neba

Satne vrijednosti globalne radijacije pri uvjetima vedrog neba određene su pomoću visine Sunca upotrebom empirijskih parametara izvedenih iz mjerenja zračenja u Zagrebu ($\phi = 45.828^\circ$N, $\lambda = 15.992^\circ$E) u nizu 1960–1985. Proračun je proveden za 15. dan u svakom mjesecu za geografske širine od 41 do 46°N. Poznatim postupkom globalno je zračenje zatim rastavljeno na direktno i difuzno te je preračunato na južnu plohu nagnutu pod kutom 35°. Navodi se i mogućnost uvažavanja naoblake na smanjenje dozračene energije dobivene za uvjete vedrog neba.

1. Introduction

It is well known that a realistic estimation of the efficiency of the heliotechnic system is obtained by using the hourly values rather then the daily values of solar irradiation. When measured data are not available, an alternative used in practice is a good estimation of solar flux. This estimation is based on certain astronomical, geometrical and meteorological conditions. The most simple case for the estimation is the one of clear skies with the given degree of atmospheric transparency. There are numerous methods for successful estimation in such

Table 1. Values of the parameters $g_n(n=0,1,2)$ expressed in $Jcm^{-2}h^{-1}$ according to the pyranometric measurements taken in Zagreb on clear days in the period 1960—1985.

Month	g_0	g_1	g_2
January	4.099	314.149	–13.610
February	4.063	493.286	–115.289
March	4.219	523.272	–136.655
April	3.749	514.158	–145.999
May	6.584	580.922	–196.292
June	5.914	515.456	–153.346
July	6.249	532.651	–181.751
August	4.949	508.308	–166.735
September	4.497	522.128	–159.368
October	3.267	495.745	–142.022
November	3.620	418.818	–82.152
December	4.029	340.943	–25.710

Table 2. Efficiency R of the estimation (3).

Month	R	Month	R
January	0.797	July	0.979
February	0.930	August	0.973
March	0.960	September	0.967
April	0.958	October	0.955
May	0.982	November	0.893
June	0.976	December	0.794

conditions. They are based on pyranometric measurements and on mathematical models in which coefficients are derived from empirical data. The derived analytical relations are then primarily valid for the area where the measurements of solar radiation have been taken. However, they might also be applied to the adjacent areas with similar meteorological conditions.

2. Data

The sources of data used were:

– measurements by solarimeter Moll-Gorczynski (Kipp und Zonen) for global radiation, and by Campbell-Stokes recorder for sunshine duration, both at Zagreb, Grič Observatory, in the period 1960–1985;

– measurements by pyranometer with shadow ring and solarimeter Moll-Gorczynski (Kipp und Zonen) at Zagreb, Horvatovac between 1988–1990, for simultaneous values of diffuse and global radiation.

Grič and Horvatovac are situated on the 2 km distant hills, at the same absolute height and about 40 m above the city of Zagreb.

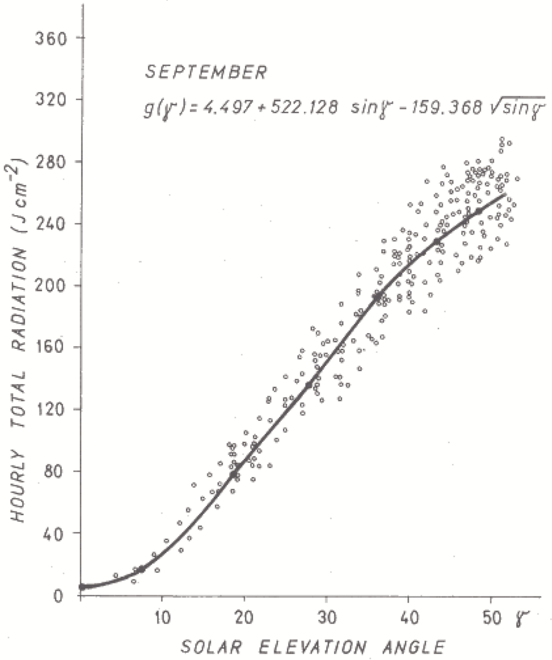

Figure 1. Measured (o) and estimated (—) hourly total radiation values on clear days in September.

3. Description of the model

The hourly global solar radiation $g(\gamma)$ in $\mathrm{mWh\,cm^{-2}}$ in clear skies can be expressed as a function of solar elevation γ. According to Paltridge and Platt (1976) this correlation for the Aspendale (Victoria, Australia) for the period 1967–1972 reads as follows:

$$g(\gamma) = 1.0 + 141.1\sin\gamma - 31.0(\sin\gamma)^{1/2} \tag{1}$$

For Zagreb, Grič Observatory (Croatia) the analogous expression based on the measurements in the period 1960–1985 is obtained as:

$$g(\gamma) = 1.6 + 130.6\sin\gamma - 32.2(\sin\gamma)^{1/2} \tag{2}$$

Since the atmospheric transparency and the Sun elevation at noon slightly vary from month to month, in the above relation (2) special coefficient values for every month have been derived from empirical data. Thus, we can write the general equation for $g(\gamma)$ as:

$$g(\gamma) = g_o + g_1\sin\gamma + g_2(\sin\gamma)^{1/2} \tag{3}$$

Table 3. Hourly global radiation on a clear day upon a horizontal surface (J/cm^2)

hours g.l.	4–5 19–20	5–6 18–19	6–7 17–18	7–8 16–17	8–9 15–16	9–10 14–15	10–11 13–14	11–12 12–13	total
January									
41				11.5	57.9	97.0	124.8	139.2	860.9
42				9.1	54.6	93.0	120.3	134.5	823.0
43				6.8	51.2	88.9	115.8	129.8	785.0
44				4.6	47.8	84.9	111.3	125.0	747.3
45					44.4	80.8	106.7	120.2	704.3
46					41.0	76.7	102.2	115.4	670.5
February									
41				28.0	89.1	143.1	182.5	203.1	1291.5
42				25.6	85.3	138.3	176.9	197.3	1246.6
43				23.2	81.5	133.4	171.4	191.3	1201.5
44				20.8	77.6	128.5	165.7	185.3	1156.1
45				18.5	73.8	123.6	160.1	179.3	1110.4
46				16.2	70.0	118.7	154.4	173.1	1064.6
March									
41			5.0	71.1	140.3	199.7	242.7	265.1	1847.7
42			4.4	69.1	137.2	195.5	237.7	259.8	1807.5
43			4.2	67.2	133.9	191.2	232.7	254.4	1767.4
44			4.2	65.2	130.7	186.9	227.6	248.9	1727.1
45			4.2	63.2	127.4	182.5	222.5	243.4	1686.2
46			4.2	61.2	124.0	178.1	217.2	237.7	1644.8
April									
41		3.7	43.5	114.7	183.3	241.3	283.1	304.9	2349.0
42		3.7	43.7	113.8	181.3	238.4	279.5	300.9	2322.8
43		3.7	44.0	112.9	179.3	235.4	275.7	296.8	2295.6
44		3.7	44.2	111.9	177.2	232.3	271.9	292.6	2267.7
45		3.7	44.3	110.9	175.0	229.1	268.0	288.4	2238.9
46		3.7	44.5	109.8	172.7	225.8	264.0	284.0	2209.2
May									
41		7.6	75.0	151.3	224.0	285.3	329.4	352.5	2850.3
42		9.2	76.1	151.3	222.9	283.2	326.6	349.3	2837.4
43		10.9	77.2	151.3	221.7	281.0	323.7	346.0	2823.5
44		12.7	78.2	151.1	220.4	278.7	320.6	342.5	2808.5
45		14.4	79.3	151.0	219.0	276.2	317.4	338.9	2792.5
46		16.2	80.2	150.7	217.5	273.7	314.1	335.3	2775.4
June									
41		30.0	95.6	165.3	230.6	285.2	324.3	344.7	2951.4
42	5.9	32.2	97.1	165.8	230.0	283.8	322.3	342.4	2958.8
43	5.9	34.3	98.5	166.2	229.4	282.3	320.2	339.9	2953.2
44	5.9	36.5	99.9	166.5	228.7	280.7	317.9	337.3	2946.7
45	5.9	38.7	101.2	166.7	227.9	278.9	315.5	334.6	2939.0
46	5.9	40.9	102.5	166.9	227.0	277.1	313.1	331.8	2930.3
July									
41		16.2	79.3	148.6	214.2	269.4	309.1	329.8	2733.1
42		18.0	80.6	148.9	213.5	267.8	306.9	327.3	2725.9
43		19.9	81.8	149.1	212.7	266.1	304.6	324.6	2717.7
44	6.2	21.8	83.0	149.3	211.8	264.3	302.1	321.8	2720.9
45	6.2	23.8	84.2	149.4	210.8	262.4	299.5	318.9	2710.6
46	6.2	25.7	85.4	149.4	209.8	260.4	296.9	315.9	2699.3
August									
41		4.9	51.3	118.8	183.7	238.6	278.2	298.9	2348.8
42		4.9	51.9	118.4	182.3	236.3	275.2	295.6	2329.2
43		4.9	52.5	117.9	180.8	233.9	272.1	292.1	2308.6
44		4.9	53.0	117.4	179.2	231.4	269.0	288.6	2287.1
45		4.9	53.5	116.9	177.5	228.8	265.7	285.0	2264.7
46		4.9	54.1	116.2	175.8	226.1	262.3	281.3	2241.5
September									
41			16.8	83.9	151.5	209.4	251.2	273.2	1972.0
42			16.6	82.5	149.0	205.8	247.0	268.6	1938.8
43			16.4	81.0	146.3	202.2	242.7	263.8	1904.9
44			16.1	79.6	143.7	198.5	238.2	259.0	1870.3
45			15.9	78.0	140.9	194.8	233.7	254.1	1834.9
46			15.6	76.5	138.1	190.9	229.1	249.2	1798.9
October									
41			3.3	35.5	96.0	149.3	188.2	208.7	1362.1
42				33.4	92.7	145.0	183.2	203.3	1315.2
43				31.3	89.3	140.6	178.1	197.8	1274.4
44				29.2	85.9	136.2	173.0	192.3	1233.3
45				27.2	82.5	131.7	167.8	186.7	1191.8
46				25.1	79.1	127.2	162.5	181.1	1150.0
November									
41				10.3	60.0	105.3	138.5	155.8	940.0
42				8.2	56.5	100.8	133.4	150.4	898.6
43				6.2	52.9	96.3	128.2	145.0	857.2
44				4.3	49.3	91.8	123.1	139.5	815.9
45				3.6	45.7	87.3	117.9	134.0	776.9
46				3.6	42.2	82.7	112.7	128.4	739.1
December									
41				4.1	49.1	89.3	118.1	133.1	787.3
42					45.5	84.9	113.3	128.1	743.7
43					41.9	80.6	108.5	123.0	708.1
44					38.4	76.3	103.6	117.9	672.3
45					34.8	71.9	98.8	112.8	636.4
46					31.2	67.6	93.9	107.6	600.4

Table 4. Values of the parameter $k(\gamma) \cdot 10^2$ in the relation (5) according to the measurements taken in Zagreb on clear days.

	Hour							
Month	4–5 19–20	5–6 18–19	6–7 17–18	7–8 16–17	8–9 15–16	9–10 14–15	10–11 13–14	11–12 12–13
January			100	67	46	28	24	23
February		100	62	56	29	27	23	22
March		100	59	30	23	20	19	18
April	100	61	31	25	19	18	18	17
May	80	40	25	23	18	17	17	16
June	66	39	24	22	17	16	15	15
July	66	39	23	21	16	15	15	15
August	76	40	25	23	19	18	17	16
September	85	58	29	29	23	20	19	18
October	100	63	50	34	29	23	22	21
November		100	62	53	29	24	23	22
December			100	75	45	29	24	23

The parameters g_n in Table 1 are derived from hourly values of global radiation and solar elevation angles at each corresponding hour. It turned out that the first term has explicit annual course, whereas the coefficients in the second and third term have lower absolute values in winter than in summer.

Goodness of fit of the estimation (3) to the measured data is described by:

$$R = 1 - \frac{\sum (g_{\mathrm{m}} - g_{\mathrm{e}})^2}{\sum (g_{\mathrm{m}} - \bar{g}_{\mathrm{m}})^2} \tag{4}$$

where m and e indicate measured and estimated values, respectively, and $\bar{g}_{\mathrm{m}}$ is the mean measured value. As can be seen from Table 2, the fit proved to be very good, even in winter months, when the atmospheric transparency is often more or less reduced by the mist. An example of the relation between $g(\gamma)_{\mathrm{e}}$ and $g(\gamma)_{\mathrm{m}}$ is illustrated in Figure 1.

4. Application of the model

The described model (3) with the coefficient values from Table 1 has been applied to the geographical zone between 41 and 46°N. The estimation has been performed on the 15th of every month. The Sun's elevation has been determined at each full hour from sunrise till noon. The constant atmospheric transparency during the day is presumed, so that the afternoon values of $g(\gamma)$ are symmetrical to the morning values. If at low Sun elevations (γ amounts to approximately 6°) the estimation predicts $g(\gamma) < g_{\mathrm{o}}$, $g(\gamma) = g_{\mathrm{o}}$ is assumed, where g_{o} is the numerical

Table 5. Hourly direct — normal radiation on a clear day (J/cm^2)

hours g.l.	4–5 19–20	5–6 18–19	6–7 17–18	7–8 16–17	8–9 15–16	9–10 14–15	10–11 13–14	11–12 12–13	daily total
January									
41				108.9	164.4	218.1	230.2	233.3	1909.9
42				86.1	164.6	218.1	230.2	233.3	1864.6
43				64.0	164.9	218.2	230.2	233.3	1821.0
44				43.9	165.2	218.2	230.2	233.2	1781.4
45					165.6	218.3	230.2	233.2	1694.5
46					166.1	218.4	230.2	233.2	1695.7
February									
41				91.9	210.5	239.5	264.0	272.3	2156.3
42				88.7	208.3	237.9	262.6	271.0	2137.1
43				85.3	206.0	236.2	261.1	269.6	2116.6
44				81.6	203.6	234.5	259.6	268.2	2094.7
45				77.5	201.0	232.6	258.0	266.6	2071.3
46				72.9	198.2	230.7	256.2	265.0	2046.2
March									
41			28.7	190.4	250.3	279.8	293.7	301.8	2689.6
42			26.3	188.8	249.0	278.7	292.6	300.8	2672.6
43			25.8	187.2	247.7	277.5	291.5	299.7	2658.8
44			26.7	185.5	246.3	276.3	290.3	298.6	2647.2
45			27.6	183.6	244.8	275.0	289.1	297.4	2635.0
46			28.5	181.8	243.2	273.6	287.9	296.2	2622.4
April									
41		41.9	145.5	218.3	264.1	282.9	291.3	298.8	3085.6
42		41.9	145.8	217.9	263.5	282.2	290.7	298.1	3080.1
43		41.9	146.1	217.4	262.9	281.5	290.0	297.4	3074.2
44		41.9	146.4	216.9	262.2	280.8	289.2	296.6	3068.0
45		41.9	146.6	216.3	261.5	280.0	288.5	295.9	3061.4
46		41.9	146.8	215.8	260.7	279.2	287.7	295.1	3054.4
May									
41		38.6	185.0	240.6	284.4	304.5	313.9	322.0	3378.0
42		45.0	186.0	240.6	284.1	304.0	313.3	321.4	3389.0
43		51.0	187.0	240.6	283.7	303.4	312.7	320.8	3398.7
44		56.6	188.0	240.5	283.3	302.9	312.1	320.2	3407.2
45		61.8	188.9	240.4	282.8	302.3	311.5	319.5	3414.6
46		66.8	189.8	240.3	282.4	301.7	310.8	318.8	3421.0
June									
41		108.2	207.6	245.7	280.9	295.9	306.3	309.5	3508.3
42	57.6	111.7	208.5	245.9	280.7	295.7	306.0	309.1	3630.6
43	57.6	115.0	209.4	246.0	280.6	295.4	305.6	308.8	3636.8
44	57.6	118.1	210.2	246.1	280.4	295.1	305.3	308.4	3642.4
45	57.6	121.1	211.0	246.2	280.2	294.8	304.9	308.0	3647.4
46	49.8	123.8	211.8	246.3	280.0	294.4	304.5	307.5	3636.1
July									
41		65.1	182.5	229.6	268.7	286.6	295.0	298.9	3252.9
42		69.8	183.6	229.8	268.5	286.2	294.6	298.4	3261.8
43		74.2	184.6	229.9	268.2	285.8	294.1	298.0	3269.7
44	60.9	78.4	185.6	229.9	268.0	285.4	293.6	297.4	3398.5
45	60.9	82.3	186.6	230.0	267.7	284.9	293.1	296.9	3404.7
46	60.9	86.0	187.5	230.0	267.3	284.5	292.6	296.3	3410.1
August									
41		44.5	149.3	206.9	245.0	263.6	275.6	283.0	2935.8
42		41.6	150.0	206.7	244.6	263.0	275.0	282.3	2926.4
43		39.0	150.7	206.5	244.1	262.4	274.4	281.7	2917.5
44		36.8	151.4	206.2	243.5	261.8	273.7	281.0	2908.8
45		34.8	152.0	205.9	243.0	261.1	273.0	280.3	2900.2
46		33.0	152.6	205.6	242.4	260.5	272.3	279.5	2891.7
September									
41			87.7	182.4	234.9	263.5	277.2	285.3	2662.1
42			87.0	181.4	233.9	262.5	276.3	284.4	2650.8
43			86.2	180.4	232.8	261.4	275.3	283.4	2639.0
44			85.4	179.3	231.7	260.4	274.2	282.4	2626.7
45			84.6	178.1	230.5	259.2	273.1	281.3	2613.8
46			83.7	176.9	229.3	258.1	272.0	280.2	2600.3
October									
41			46.8	123.4	190.1	231.6	247.2	255.9	2190.0
42				120.2	188.1	230.0	245.8	254.5	2077.0
43				116.7	186.1	228.2	244.3	253.1	2056.6
44				113.0	183.9	226.5	242.7	251.5	2035.2
45				109.1	181.6	224.6	241.0	250.0	2012.6
46				104.9	179.2	222.6	239.3	248.3	1988.7
November									
41				72.8	186.6	222.0	234.8	241.9	1916.0
42				66.1	184.2	220.3	233.4	240.7	1889.5
43				58.1	181.5	218.6	232.1	239.4	1859.5
44				48.4	178.7	216.8	230.6	238.1	1825.1
45				48.8	175.6	214.8	229.0	236.6	1809.7
46				48.8	172.2	212.7	227.4	235.1	1792.5
December									
41				29.2	166.1	218.1	235.5	239.5	1776.6
42					165.8	217.7	235.2	239.2	1715.9
43					165.5	217.4	234.9	238.9	1713.3
44					165.3	217.0	234.5	238.6	1710.8
45					165.1	216.6	234.2	238.2	1708.2
46					165.0	216.2	233.8	237.9	1705.7

Table 6. Hourly total radiation on a clear day on a south-facing collector inclined at 35° (J/cm^2)

hours	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12	daily
g.l.	19–20	18–19	17–18	16–17	15–16	14–15	13–14	12–13	total
January									
41				45.7	111.6	178.1	217.3	236.6	1578.5
42				47.2	109.0	175.4	214.4	233.6	1559.2
43				54.1	106.4	172.6	211.5	230.6	1550.4
44				99.5	103.9	169.7	208.5	227.5	1618.1
45					101.3	166.9	205.4	224.3	1395.8
46					98.7	164.0	202.3	221.1	1372.2
February									
41				46.6	143.9	215.6	270.8	298.7	1951.2
42				43.8	140.6	211.9	266.9	294.6	1915.5
43				41.0	137.2	208.0	262.8	290.4	1878.8
44				38.1	133.7	204.1	258.6	286.1	1841.1
45				35.1	130.0	200.1	254.3	281.6	1802.2
46				32.0	126.3	195.9	249.9	277.0	1762.2
March									
41			6.3	91.9	181.6	258.4	313.5	343.1	2389.7
42			5.7	90.5	179.6	256.1	310.9	340.3	2366.2
43			5.5	89.0	177.6	253.6	308.1	337.4	2342.4
44			5.6	87.5	175.4	251.0	305.2	334.3	2318.2
45			5.7	85.9	173.2	248.3	302.2	331.2	2293.0
46			5.7	84.3	170.9	245.5	299.0	327.8	2266.7
April									
41		2.1	34.0	113.3	196.5	267.8	319.2	346.9	2559.7
42		2.1	34.5	113.4	196.1	267.1	318.3	345.9	2555.0
43		2.1	35.0	113.5	195.8	266.3	317.2	344.7	2549.1
44		2.1	35.5	113.4	195.3	265.4	316.0	343.4	2542.2
45		2.1	35.9	113.4	194.7	264.4	314.7	341.9	2534.3
46		2.1	36.4	113.2	194.1	263.3	313.2	340.3	2525.3
May									
41		2.9	47.0	128.5	212.3	285.7	339.0	367.6	2766.1
42		3.5	48.4	129.7	213.2	286.2	339.3	367.7	2775.9
43		4.1	49.9	130.8	213.9	286.6	339.4	367.7	2784.7
44		4.8	51.3	131.8	214.6	286.8	339.3	367.5	2792.3
45		5.4	52.6	132.8	215.2	287.0	339.1	367.2	2798.8
46		6.1	54.0	133.8	215.7	287.0	338.8	366.7	2804.1
June									
41		11.0	55.5	131.4	206.6	272.1	319.8	344.8	2682.3
42	3.6	11.8	57.4	133.1	208.0	273.2	320.8	345.7	2707.2
43	3.6	12.6	59.2	134.7	209.4	274.3	321.7	346.4	2723.8
44	3.6	13.4	61.1	136.2	210.7	275.3	322.4	347.0	2739.5
45	3.6	14.2	62.9	137.8	211.8	276.1	323.0	347.5	2754.1
46	3.6	15.0	64.7	139.2	213.0	276.9	323.5	347.8	2767.6
July									
41		6.0	46.7	120.5	195.6	261.5	309.6	334.8	2549.4
42		6.6	48.3	121.9	196.8	262.4	310.3	335.4	2563.4
43		7.3	49.9	123.3	197.9	263.2	310.8	335.8	2576.4
44	3.8	8.0	51.5	124.6	198.9	263.9	311.2	336.1	2596.1
45	3.8	8.7	53.0	125.9	199.8	264.5	311.5	336.2	2607.0
46	3.8	9.5	54.6	127.1	200.7	264.9	311.7	336.2	2616.9
August									
41		1.9	35.0	108.1	184.3	250.6	299.3	325.2	2408.8
42		1.9	35.9	108.7	184.5	250.5	298.9	324.8	2410.2
43		1.9	36.7	109.2	184.6	250.3	298.4	324.2	2410.5
44		1.9	37.5	109.6	184.7	249.9	297.8	323.4	2409.8
45		1.9	38.4	110.1	184.7	249.5	297.1	322.6	2408.1
46		1.9	39.2	110.4	184.5	248.9	296.2	321.6	2405.4
September									
41			16.6	93.7	177.1	250.0	302.8	331.0	2342.5
42			16.5	92.9	175.9	248.4	300.9	329.0	2327.3
43			16.4	92.2	174.6	246.7	298.9	326.8	2311.0
44			16.2	91.3	173.2	244.8	296.7	324.5	2293.6
45			16.1	90.5	171.7	242.9	294.4	322.1	2275.2
46			15.9	89.5	170.1	240.8	292.0	319.5	2255.7
October									
41			1.6	56.0	137.6	210.5	261.2	288.4	1910.6
42				53.8	134.8	207.3	257.7	284.8	1876.9
43				51.5	131.9	204.1	254.2	281.1	1845.6
44				49.1	129.0	200.7	250.5	277.3	1813.2
45				46.7	126.0	197.2	246.7	273.3	1779.7
46				44.2	122.9	193.6	242.7	269.2	1745.2
November									
41				29.0	117.7	183.2	227.7	251.6	1618.4
42				25.3	114.1	179.5	223.8	247.6	1580.7
43				21.4	110.5	175.7	219.8	243.5	1541.6
44				17.1	106.8	171.7	215.6	239.2	1500.9
45				17.3	102.9	167.7	211.4	234.8	1468.3
46				22.1	99.0	163.5	207.0	230.4	1443.9
December									
41				55.7	106.3	173.8	216.4	236.7	1577.7
42					103.3	170.5	213.0	233.2	1440.2
43					100.3	167.3	209.6	229.7	1413.7
44					97.3	163.9	206.1	226.1	1386.8
45					94.3	160.5	202.5	222.4	1359.5
46					91.3	157.1	198.9	218.7	1331.9

value of the first term in the relation (3). The calculated daily course of the global solar radiation $g(\gamma)$ is presented in Table 3.

The process of dividing the global solar radiation into the direct and diffuse component has been performed in the usual way (ASHRAE Handbook, 1977, Anderson, 1983, Kreider and Kreith, 1981, Madsen, 1985).

The diffuse radiation is calculated by using

$$d(\gamma) = k(\gamma) \cdot g(\gamma) \tag{5}$$

where values for $k(\gamma)$ are taken from Table 4. They have been derived from measured clear-sky values of the diffuse and the global solar radiation obtained in Zagreb. The hourly direct solar radiation on a horizontal surface is determined according to the relation:

$$i(\gamma) = g(\gamma) - d(\gamma) \tag{6}$$

and then applying the division by sinγ the direct solar radiation upon a surface normal to solar flux has been calculated (Table 5).

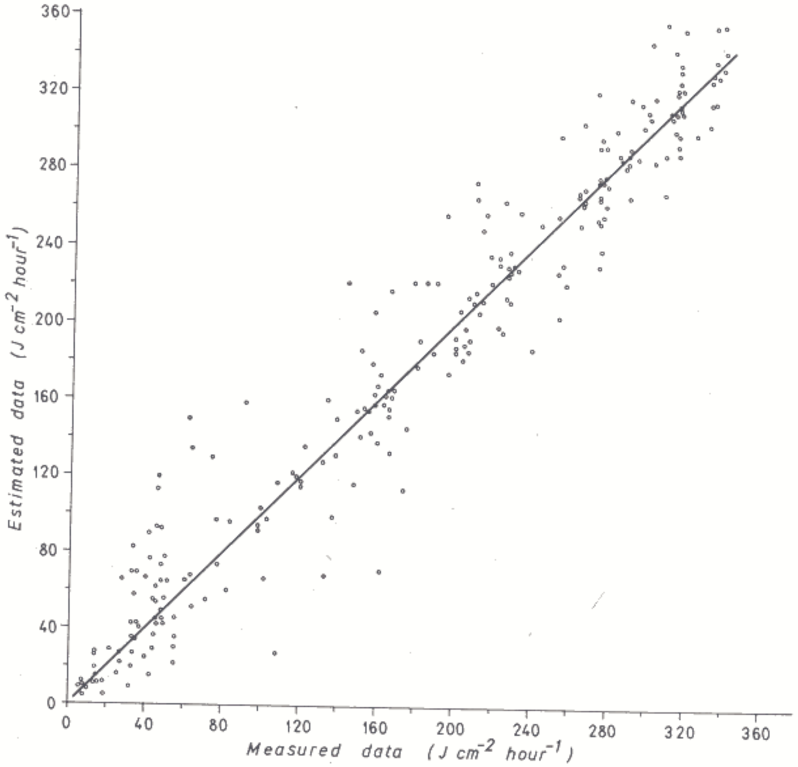

Figure 2. Comparison of measured and estimated hourly total radiation values $g_c(\gamma)$.

Table 7. Efficiency R of the estimation (9).

Month	R	Month	R
January	0.796	July	0.962
February	0.943	August	0.929
March	0.973	September	0.872
April	0.951	October	0.918
May	0.921	November	0.948
June	0.967	December	0.913

A stationary collector placed in the observed geographical zone receives most solar energy if it is south-facing and inclined at 35°. Therefore, the obtained global solar radiation has been estimated for such surfaces.

The hourly direct solar radiation on an inclined surface as a function of the solar elevation γ, solar declination δ and observer's latitude ϕ has been determined by the formula:

$$i_{35}(\gamma) = [i(\gamma)/\sin\gamma]\,[0.81915\,\sin\gamma + 0.57358(\mathrm{tg}\varphi\,\sin\gamma - \sin\delta/\cos\varphi)] \tag{7}$$

and the diffuse solar radiation has been determined by:

$$d_{35}(\gamma)=[0.90957\,k(\gamma) + 0.01356]\,g(\gamma)\ . \tag{8}$$

By adding up the direct and diffuse solar components according to the formulas (7) and (8), the global solar radiation $g_{35}(\gamma)$ on a south-facing surface inclined at 35° was obtained (Table 6).

5. The estimation of the global solar radiation under conditions of clouded skies

The estimation of the solar irradiation under conditions of clouded skies $g_c(\gamma)$ is not simple because of the nonlinearities in cloudiness and sunshine duration processes. As a first approximation the following equation can be used:

$$g_c(\gamma) = g(\gamma)\,[a + (1 - a)r] \tag{9}$$

where r is the real, the expected, or the average sunshine duration expressed in tenths of an hour. (In the absence of heliographic measurements, visual observation of cloudiness may be applied. In that case one should have a good knowledge of the correlation between cloudiness and sunshine duration.)

Equation (9) for hourly values $g_c(\gamma)$ is analogous to the well known Angström equation for daily values of global radiation. The empirical values for the coefficient a, based upon the data used, are: $a = 0.363$ for the period November–March, and $a = 0.202$ for the warm period April–October. Strictly speaking, the coefficients are valid for Zagreb and for the period of the data set used. As already mentioned, in practice they may be applied elsewhere under similar topographical and meteorological conditions.

Differences between our measured and estimated values $g_c(\gamma)$ are relatively large (Figure 2). Efficiency R of estimation, according to (4), is shown in Table 7.

6. Conclusion

The daily course of global radiation on clear days with an average air transparency can be well estimated by means of the solar elevation. The model (3) is valid generally. In order to apply it to a particular location, the corresponding values of the parameters g_n have to be determined from pyranometric measurements.

Hourly global radiation under conditions of clouded skies may be determined approximately from relative sunshine duration and global radiation in clear skies. Though the fit for Zagreb proved to be good, in particular cases the estimated values differed considerably from the measured ones. Obviously, that occurred when the difference between real and average thickness of clouds was large.

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References

Anderson, E. E. (1983): Fundamentals of solar energy conversion, Addison-Wesley Publ. Comp., Reading, 636.

ASHRAE Handbook and Product Directory, Fundamentals Volume, Am. Soc. of Heat Refr. and Air Con. Eng., New York, 1977, 222-450.

Kreider, I. F. and F. Kreith (1981): Solar energy handbook, McGraw-Hill, New York, Chapter 2, 63-78

Madsen, H. (1985) Statistically determined dynamical models for climate processes, IMSOR, Lyngby, 143-216.

Paltridge, G. W. and C. M. R. Platt (1976): Radiative processes in meteorology and climatology, Elsevier, Amsterdam, 318.

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