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SOLAR RADIATION AT WAGENINGEN

by

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1. INTRODUCTION

Measurements of solar radiation intensity have been made at Wageningen since 1926. The results up to 1946 were reported in a number of papers published in the 'Mededelingen van de Landbouwhogeschool'. From the beginning of 1951 the daily totals of solar radiation intensity have been included in the monthly meteorological reports[2]) (the so-called 'Maandgrafieken') issued by the Physico-Technical Service for Agriculture. The present paper contains the data up to the end of 1953.

2. INSTRUMENTATION AND ELABORATION OF THE RECORDS

The intensity of the total short wave radiation from sun and sky at Wageningen (51°58′N, 5°39′E) is measured by a horizontal MOLL-thermopile, connected to a thread-recorder. The pile is on a steel tower at a height of about 11 m above ground (about 20 m above sea level). The properties of the KIPP solarimeter were recently investigated in great detail by BENER (1951) and the reader is referred to his paper for a full discussion of it. The instruments at Wageningen were described earlier by VAN GULIK (1927) and by ZUIDHOF and DE VRIES (1940).

The solarimeter has been calibrated regularly against an ÅNGSTRÖM compensation pyrheliometer (cf. K. ÅNGSTRÖM (1899)). During the period of observations the constant of the pyrheliometer was redetermined twice at Utrecht. The first redetermination yielded the same value as that obtained originally at Upsala and the second gave a value which was 0.6 % lower.

Daily totals of radiation from sun and sky on a unit horizontal surface, called the total global radiation, *I*, were obtained from the traces of the thread recorder (Fig. 1) by planimetering their surface. Hourly values were also read from the diagrams by means of a transparent scale[3]).

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[1]) Now: C.S.I.R.O., Division of Plant Industry, Regional Pastoral Laboratory, Deniliquin, N.S.W. Australia.

[2]) For a description of these reports see PRINS (1940). Up to September 1951 they were issued by the Laboratory of Physics and Meteorology, and since then by the Physico-Technical Service for Agriculture (L.P.T.D.) located in the same laboratory. Further information can be obtained by writing to the L.P.T.D., Duivendaal 2, Wageningen.

[3]) During the years 1926 to 1930 an electrolytic integrator, manufactured by KIPP, and a mechanical integrator, constructed by VAN GULIK, were in use for obtaining daily totals. These instruments were afterwards abandoned, however, since they gave less reliable results.

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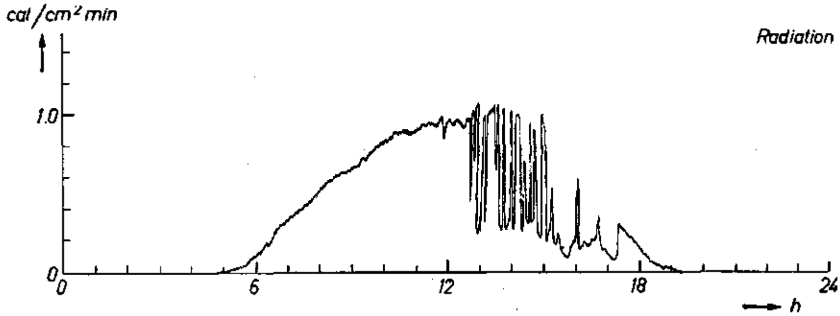

FIGURE 1. Example of a solarimeter – recording on a fine day with some fair weather cumuli in the afternoon.

A second instrument has been in use in which the hemispherical glass cover of the pile was surrounded by a water layer of 10 cm thickness contained in a concentric glass hemisphere (see ZUIDHOF and DE VRIES (1940)). This water layer absorbs most of the radiation with wave-length above 0.85 μ, the part of the spectrum inactive in photosynthesis. The daily total of the water-filtered radiation is denoted by I_w. Up to 1931 only I_w was measured, from 1931 to 1940 I and I_w were measured, and after 1940 only I was measured.

From 1938 onwards the duration of bright sunshine, n, has been recorded by a CAMPBELL-STOKES sunshine recorder on the steel tower next to the thermopile. The method prescribed by the 'Preussische Meteorologische Institut' (see MAURER (1914)) was used for counting the duration of sunshine from the traces.

Units

The thermopile gives a measure of the incident radiant energy flux. The measured radiation is expressed as cal $cm^{-2}h^{-1}$ for the hourly values of intensity and as cal cm^{-2} for the daily totals. For conversion into the MKS-system the following factors must be applied:

$$1 \text{ cal cm}^{-2}\text{h}^{-1} = 1.163 \times 10^{-3}\text{W cm}^{-2}$$
$$1 \text{ cal cm}^{-2} = 4.1855 \text{ J cm}^{-2}.$$

It is sometimes desirable to know the photometric illumination instead of the energy flux density. The lux-equivalent per cal $cm^{-2}h^{-1}$ depends on the spectral distribution of the radiation and therefore changes with the state of the atmosphere and with solar altitude. REESINCK and DE VRIES (1940) stated on theoretical grounds that the following conversion factor holds for average conditions at Wageningen:

$$1 \text{ cal cm}^{-2}\text{h}^{-1} = 1.26 \times 10^{3} \text{ lux}.$$

This factor is in good agreement with the experimental determinations of KIMBALL at Washington (cf. Smithsonian Meteorological Tables, 1951, Table 153) and of REESINCK at Wageningen. The latter gave extreme values of 1.40 during rain and of 1.15 with a clear sky.

3. THE DAILY TOTALS AND THEIR ANNUAL VARIATION

Prior to 1938 measurements were carried out only during the growing season, i.e. from the 21 March to 10 October, but from the beginning of 1938 onwards

TABLE 1 Daily totals (in cal/cm^2) of total global radiation at *Wageningen*

1946	J	F	M	A	M	J	J	A	S	O	N	D
1	113	24	68	341	332	314	330	307	318	88	(38)	71
2	60	72	90	360	421	221	502	152	211	129	28	40
3	46	39	207	346	468	255	569	169	343	117	17	30
4	69	22	83	335	508	320	540	303	270	112	30	55
5	21	99	102	273	245	319	224	318	136	44	130	44
6	30	39	86	303	435	350	322	173	340	195	(38)	21
7	47	19	141	388	495	569	495	260	283	155	(38)	42
8	50	16	62	379	505	(515)	288	203	99	123	(38)	31
9	44	78	88	428	540	314	329	277	241	103	61	27
10	69	25	53	256	532	286	526	187	214	255	90	32
D	54.9	43.3	98.0	340.9	448.1	346.3	412.5	234.9	245.5	132.1	50.8	39.3
11	11	43	91	265	482	335	436	406	(172)	252	100	28
12	61	132	133	205	394	(500)	463	193	247	214	(38)	12
13	79	181	76	337	270	424	506	129	232	81	64	25
14	87	32	73	158	116	464	208	149	194	88	38	40
15	69	47	108	432	439	355	244	212	319	59	70	77
16	71	29	281	368	353	233	144	372	357	107	49	78
17	91	111	310	112	519	308	237	125	59	78	74	80
18	32	93	128	252	396	227	279	187	106	(191)	29	83
19	46	22	261	403	230	257	271	435	122	187	77	55
20	44	122	276	385	(290)	413	258	239	67	137	77	70
D	59.1	81.2	173.7	291.7	348.9	351.6	304.6	244.7	187.5	139.4	61.6	54.8
21	44	101	158	287	350	518	273	129	237	41	75	45
22	41	66	25	415	(187)	381	125	255	192	52	37	12
23	24	45	245	468	219	442	(348)	165	59	59	91	71
24	40	125	193	194	(491)	175	519	376	130	188	60	15
25	31	251	315	337	405	247	279	279	124	142	49	32
26	104	85	181	398	(360)	275	492	281	266	(146)	65	(28)
27	76	191	263	406	201	350	374	(330)	239	17	(60)	(79)
28	36	207	304	336	576	265	408	143	263	50	72	(28)
29	93		337	283	468	491	256	290	251	(171)	56	27
30	49		312	400	257	522	170	271	57	(119)	46	35
31	81		302		258		220	320		(79)		25
D	56.3	133.9	239.5	352.4	342.9	366.6	314.9	258.1	181.8	96.7	61.1	36.1
M	1759	2316	5352	9850	11742	10645	10635	7635	6148	3779	1735	1338

D = average per decade *M* = monthly total

TABLE 1 *(continued)* Daily totals (in cal/cm²) of total global radiation at *Wageningen*

1947	J	F	M	A	M	J	J	A	S	O	N	D
1	57	109	191	(150)	153	(480)	(312)	558	376	225	26	17
2	15	112	(230)	114	(166)	573	(348)	488	363	212	71	24
3	53	66	179	80	300	530	(510)	460	272	301	72	(65)
4	88	83	183	50	112	311	(529)	456	(300)	261	80	12
5	83	83	113	140	146	(286)	(321)	163	413	284	81	26
6	81	135	(96)	77	486	(376)	(321)	169	301	230	52	81
7	87	69	184	139	507	(312)	(348)	223	307	161	38	27
8	39	108	(222)	66	471	(312)	(221)	254	132	190	23	20
9	39	152	(275)	150	471	(327)	(368)	271	325	161	24	26
10	23	114	(96)	(363)	469	642	(348)	502	262	171	41	30
D	56.5	103.1	176.9	132.9	328.1	(414.9)	(362.6)	354.4	305.1	219.6	50.8	32.8
11	21	114	(96)	(473)	409	361	(237)	472	386	101	11	19
12	35	74	(96)	440	304	433	(510)	362	362	193	7	8
13	61	59	(96)	438	436	613	(585)	493	(331)	209	55	26
14	44	99	62	321	504	212	(256)	489	227	110	30	36
15	61	150	203	252	233	294	(580)	(472)	356	200	33	25
16	99	121	169	193	408	555	(582)	496	362	70	56	20
17	34	180	167	255	185	507	(570)	508	268	92	34	19
18	76	202	91	496	126	613	(572)	460	231	198	39	36
19	90	92	106	332	324	(286)	(494)	(441)	242	204	45	5
20	(38)	67	15	380	406	(409)	(580)	435	333	219	23	16
D	55.9	115.8	110.1	358.0	333.5	428.3	(496.6)	462.8	309.8	159.6	33.3	21.0
21	48	91	44	252	412	251	(476)	494	147	190	15	7
22	61	83	79	289	545	324	(556)	499	309	158	9	9
23	81	167	106	306	240	346	(539)	417	151	87	20	9
24	99	103	117	303	(472)	562	(460)	399	323	62	52	10
25	99	121	158	482	424	602	(539)	380	153	197	37	9
26	94	134	226	459	480	561	(560)	412	221	223	41	24
27	121	(143)	147	454	485	559	(551)	470	61	185	17	4
28	111	(58)	98	202	582	499	(556)	464	196	89	42	21
29	118		58	279	(571)	424	(529)	408	143	153	12	41
30	130		(212)	100	514	493	(560)	459	314	70	22	46
31	120		(230)		563		(572)	308		129		24
D	98.4	112.5	134.1	312.6	480.7	462.1	(536.2)	428.2	201.8	140.3	26.7	28.5
M	2206	3089	4345	8035	11904	(13053)	(14490)	12883	8167	5335	1108	742

D = average per decade *M* = monthly total

TABLE 1 *(continued)* Daily totals (in cal/cm²) of total global radiation at *Wageningen*

1948	J	F	M	A	M	J	J	A	S	O	N	D
1	9	113	160	251	(317)	372	160	530	326	106	41	89
2	23	35	151	216	315	320	239	445	294	288	24	91
3	20	30	189	299	(396)	603	503	305	151	(170)	47	87
4	26	87	170	290	526	318	411	156	354	105	41	15
5	11	75	216	200	295	255	220	336	244	132	(85)	32
6	43	68	246	316	516	400	250	456	102	109	128	62
7	26	22	189	203	564	395	158	388	379	243	36	88
8	16	20	107	177	538	634	371	229	192	230	134	35
9	41	22	136	125	564	556	648	308	394	210	135	28
10	22	67	307	473	(439)	589	318	272	362	254	89	83
D	23.7	53.9	187.1	255.0	447.0	444.2	327.8	342.5	279.8	184.7	76.0	61.0
11	7	22	138	494	431	575	168	356	206	187	115	48
12	22	102	319	427	258	567	149	246	367	64	54	21
13	7	78	277	430	144	(584)	327	391	304	160	85	32
14	36	38	295	168	594	632	380	513	67	193	65	12
15	44	63	209	299	630	125	363	279	194	216	96	45
16	48	200	157	442	641	336	223	369	222	195	74	50
17	40	158	147	441	672	367	303	312	196	89	(38)	73
18	69	160	115	477	661	340	174	469	209	132	24	44
19	20	153	70	426	681	371	283	189	151	123	28	50
20	25	152	104	315	517	484	379	354	245	123	(109)	13
D	31.8	112.6	183.1	391.9	522.9	438.1	274.9	347.8	216.1	148.2	68.8	38.8
21	12	195	94	449	606	332	513	373	310	33	80	31
22	14	158	272	304	638	236	513	308	162	56	76	22
23	32	73	391	131	365	493	522	349	251	135	33	77
24	29	252	366	481	427	599	249	412	173	73	46	46
25	40	255	316	449	265	600	552	137	310	66	104	91
26	65	242	370	399	274	193	584	171	181	124	108	121
27	67	216	416	512	545	201	547	515	280	207	104	75
28	48	210	410	477	223	296	627	242	(300)	148	71	59
29	48	152	323	134	390	308	603	499	137	79	63	85
30	58		300	174	327	352	544	455	202	35	(38)	65
31	12		235		272		373	439		22		16
D	38.6	194.8	318.0	350.3	393.8	361.0	511.6	354.5	230.6	88.9	72.3	62.5
M	980	3418	7195	9972	14031	12433	11654	10803	7265	4307	2171	1686

D = average per decade *M* = monthly total

TABLE 1 *(continued)* Daily totals (in cal/cm²) of total global radiation at *Wageningen*

1949	J	F	M	A	M	J	J	A	S	O	N	D
1	(33)	107	218	277	602	(413)	(500)	279	339	292	163	24
2	(93)	156	253	344	555	(320)	(582)	117	230	184	157	30
3	40	169	(304)	86	580	(409)	(576)	224	324	95	148	(28)
4	33	157	220	272	478	(493)	(582)	570	352	151	151	36
5	25	68	216	309	71	(270)	(373)	523	383	223	144	33
6	(33)	53	226	126	285	(510)	(300)	487	209	193	154	39
7	29	142	210	90	219	(560)	(285)	478	258	208	77	27
8	35	50	290	265	358	(528)	(256)	181	228	183	63	9
9	74	21	281	406	402	(311)	(500)	(400)	281	164	89	37
10	77	106	104	378	340	(473)	(367)	450	254	(90)	124	79
D	47.2	102.9	223.2	255.3	389.0	(428.7)	(432.1)	370.9	285.8	178.3	127.0	34.2
11	12	58	230	387	170	(290)	(547)	154	343	213	114	67
12	91	99	215	48	541	(381)	(590)	369	321	201	74	88
13	57	112	(104)	93	577	(244)	(496)	385	320	206	67	23
14	19	39	(120)	386	176	(462)	(439)	(386)	(236)	159	72	57
15	76	29	336	443	299	(409)	(330)	409	227	178	122	21
16	48	148	36	490	216	(357)	(429)	(423)	127	187	66	63
17	29	181	119	434	204	(270)	286	379	185	127	34	30
18	91	164	225	441	(396)	(225)	275	429	225	88	98	9
19	29	66	271	452	(396)	(290)	227	61	277	139	66	45
20	74	80	259	508	(520)	(576)	443	205	201	139	26	46
D	52.6	97.6	191.5	368.2	349.5	(350.4)	(406.2)	320.0	246.2	163.7	73.9	44.9
21	92	181	75	428	335	(557)	302	443	264	58	25	43
22	90	206	279	506	304	(432)	262	425	146	176	52	21
23	112	52	228	487	279	(327)	515	401	284	77	72	16
24	78	91	379	484	109	(510)	515	166	274	72	18	16
25	74	127	349	151	138	(551)	541	346	257	56	39	15
26	106	102	299	218	112	(380)	503	340	225	73	53	(28)
27	114	139	240	579	166	(567)	453	(396)	157	166	15	25
28	119	137	272	132	290	(485)	327	(233)	90	163	55	(28)
29	128		367	230	107	(352)	412	(313)	90	121	46	20
30	130		363	375	267	(510)	459	(297)	72	163	23	33
31	62		364		(390)		301	(360)		157		41
D	100.5	129.4	292.3	359.0	227.0	(467.1)	417.3	338.2	185.9	117.5	39.8	26.0
M	2104	3040	7362	9825	9882	(12462)	(12973)	10629	7179	4908	2407	1077

D = average per decade *M* = monthly total

TABLE 1 *(continued)* Daily totals (in cal/cm^2) of total global radiation at *Wageningen*

1950	J	F	M	A	M	J	J	A	S	O	N	D
1	82	97	217	121	471	572	523	216	313	195	107	9
2	11	14	220	207	411	563	557	203	81	134	33	55
3	44	75	146	196	244	491	303	150	270	227	16	41
4	23	71	207	269	236	484	279	(356)	160	110	40	42
5	13	117	158	309	59	473	174	(393)	142	199	57	38
6	43	72	76	177	356	476	256	(437)	338	219	52	63
7	37	102	183	363	(376)	479	386	(393)	204	145	85	13
8	52	31	184	272	(166)	453	483	445	267	104	26	52
9	63	55	86	255	326	466	560	420	142	169	35	17
10	16	24	71	216	546	388	401	300	103	121	25	39
D	38.4	65.8	134.1	238.5	319.1	484.5	392.2	331.3	202.0	162.3	47.6	36.9
11	22	51	55	199	540	540	232	269	248	213	86	52
12	90	89	297	211	490	611	524	458	181	148	32	23
13	56	74	166	263	516	560	438	183	306	200	61	46
14	20	131	98	282	558	231	125	399	167	113	40	23
15	26	33	207	300	400	276	420	430	60	160	74	30
16	78	48	217	406	316	575	304	157	202	131	38	43
17	41	183	38	400	459	544	388	323	232	36	40	66
18	80	162	302	318	51	322	311	327	127	177	48	43
19	85	139	76	267	337	509	103	391	210	86	24	48
20	104	43	227	453	362	364	289	395	139	50	36	52
D	60.2	95.3	168.3	309.9	402.9	453.2	313.4	333.2	187.2	131.4	47.9	42.6
21	69	71	81	451	383	378	359	367	263	96	21	20
22	27	140	120	192	334	394	429	96	192	133	80	18
23	(92)	142	101	371	476	158	274	213	217	136	11	34
24	104	24	208	145	55	516	274	168	53	148	39	26
25	87	110	49	290	313	350	299	466	79	163	49	83
26	80	160	281	159	367	353	315	298	172	142	30	38
27	53	209	314	186	250	183	439	378	118	131	51	45
28	(92)	142	334	326	(410)	254	377	243	65	85	15	65
29	(91)		186	392	403	(524)	445	284	49	21	25	45
30	111		204	370	412	(270)	414	321	129	90	35	45
31	26		122		457		(209)	202		77		55
D	75.5	124.8	181.8	288.2	350.9	338.0	348.5	276.0	133.7	111.1	35.6	43.1
M	1818	2609	5024	8366	11080	12757	10890	9681	5229	4159	1311	1269

D = average per decade, *M* = monthly total

TABLE 1 *(continued)* Daily totals (in cal/cm²) of total global radiation at *Wageningen*

1951	J	F	M	A	M	J	J	A	S	O	N	D
1	61	24	69	168	523	673	720	377	328	174	81	91
2	32	89	119	166	442	480	584	419	333	151	98	76
3	44	38	168	290	490	396	330	476	409	297	131	99
4	26	124	250	148	468	576	201	233	166	279	165	23
5	20	93	238	369	420	650	440	389	408	282	108	28
6	34	49	176	117	437	664	310	428	367	303	45	6
7	41	56	182	153	365	601	494	404	198	282	54	71
8	23	30	70	213	62	682	409	303	340	243	73	39
9	44	115	72	140	127	664	382	123	369	253	84	78
10	61	81	58	69	354	437	258	253	317	259	75	29
D	38.6	69.9	140.2	183.3	368.8	582.3	412.8	340.5	323.5	252.3	91.4	54.0
11	11	36	135	242	535	593	249	241	130	247	121	82
12	48	150	106	260	586	280	428	247	330	229	37	52
13	23	75	256	132	303	282	467	344	239	224	46	79
14	40	28	78	217	266	678	271	220	331	225	37	70
15	46	82	211	447	119	267	217	235	354	217	38	19
16	75	89	240	313	463	654	655	293	301	241	46	10
17	13	27	73	402	495	544	565	223	186	208	58	18
18	21	54	153	439	535	396	146	431	119	61	58	15
19	44	79	42	392	530	544	590	231	154	105	20	26
20	18	95	106	412	546	612	193	323	196	190	39	72
D	33.9	71.5	140.0	325.6	437.8	485.0	378.1	278.8	234.0	194.7	50.0	44.3
21	27	102	371	461	115	558	495	419	232	87	70	23
22	14	137	31	529	339	275	585	347	323	201	40	63
23	31	83	59	486	403	242	350	239	108	200	23	19
24	86	148	211	513	421	232	130	351	280	227	16	53
25	16	193	287	527	89	431	86	339	263	189	48	13
26	38	114	227	413	431	255	404	303	181	50	96	68
27	16	128	208	121	298	101	461	342	161	175	68	10
28	48	122	278	119	236	209	541	87	134	147	30	15
29	16		290	386	533	339	392	282	226	106	67	60
30	25		310	472	691	331	550	260	157	63	39	31
31	25		193		685		355	263		62		43
D	31.1	128.4	224.1	402.7	385.5	297.3	395.4	293.8	178.5	137.0	49.7	36.2
M	1067	2441	5267	9116	12307	13646	12258	9425	7360	5977	1911	1381

D = average per decade *M* = monthly total

TABLE 1 *(continued)* Daily totals (in cal/cm²) of total global radiation at *Wageningen*

1952	J	F	M	A	M	J	J	A	S	O	N	D
1	26	49	100	408	470	407	628	401	322	23	20	93
2	31	96	197	399	466	455	558	436	403	69	96	109
3	75	31	135	235	367	576	248	420	143	128	74	46
4	55	118	208	356	251	684	343	437	232	247	88	106
5	11	155	154	323	321	609	635	535	269	153	64	28
6	39	31	232	340	519	217	554	181	325	88	110	48
7	13	79	235	78	463	412	464	200	385	177	131	14
8	26	99	45	244	587	556	482	335	240	208	144	40
9	40	145	233	363	204	318	140	176	329	142	133	9
10	18	58	94	410	568	647	496	344	335	197	71	51
D	33.4	86.1	163.3	315.6	421.6	488.1	454.8	346.5	298.3	143.2	93.1	54.4
11	58	78	175	447	424	414	542	209	321	188	117	9
12	64	158	124	236	298	286	408	485	283	252	124	41
13	103	99	93	395	314	544	408	529	254	71	105	26
14	84	137	358	494	493	242	256	331	262	60	101	25
15	11	172	344	453	304	88	380	308	364	119	52	38
16	49	139	254	412	560	514	330	365	386	194	19	63
17	28	77	282	466	386	587	235	298	285	221	79	33
18	51	60	201	472	541	347	330	305	240	164	54	59
19	46	63	269	454	593	365	144	156	228	197	31	22
20	35	94	92	168	660	317	439	92	150	108	111	47
D	52.9	107.7	219.2	399.7	457.3	370.4	347.2	307.8	277.3	157.4	79.3	36.3
21	35	51	339	(133)	635	232	631	333	58	57	22	34
22	43	39	92	231	571	90	438	219	197	95	32	25
23	28	73	240	463	287	336	382	472	130	59	64	23
24	39	106	39	399	340	300	371	287	112	53	47	8
25	120	69	50	558	259	186	328	248	95	193	128	43
26	61	223	92	251	194	587	481	426	193	127	87	50
27	95	247	440	220	196	624	273	222	148	150	19	27
28	114	43	283	289	371	618	266	337	287	63	14	33
29	82	19	65	502	367	552	421	442	150	116	32	18
30	24		97	564	456	641	238	297	94	141	36	51
31	19		146		279		313	200		133		15
D	60.0	96.7	171.2	361.0	359.5	416.6	376.5	316.6	146.4	107.9	48.1	29.7
M	1523	2808	5708	10763	12744	12751	12162	10026	7220	4193	2205	1234

D = average per decade *M* = monthly total

TABLE 1 *(concluded)* Daily totals (in cal/cm²) of total global radiation at *Wageningen*

1953	J	F	M	A	M	J	J	A	S	O	N	D
1	63	22	307	128	464	330	497	353	443	220	122	68
2	34	67	295	168	532	231	314	512	370	146	88	90
3	30	22	106	66	556	366	394	360	214	104	95	41
4	23	67	87	55	458	354	469	472	206	119	34	74
5	52	112	69	320	408	503	426	274	377	160	41	78
6	74	62	104	281	208	641	274	395	470	83	91	19
7	72	184	219	296	299	621	446	534	438	149	119	53
8	109	69	230	410	487	460	467	595	418	220	32	59
9	9	103	220	225	151	377	392	621	185	97	59	26
10	84	47	245	498	510	62	421	481	364	253	135	16
D	55.0	75.5	188.2	244.7	407.3	394.5	410.0	459.7	348.5	155.1	81.6	52.4
11	111	27	204	449	549	200	471	562	206	268	56	22
12	21	44	122	354	470	517	458	471	230	235	67	8
13	15	92	267	480	352	262	237	464	342	143	25	59
14	11	136	231	273	449	366	418	536	356	96	33	47
15	19	88	392	306	320	490	338	400	380	42	50	21
16	15	213	334	256	463	461	348	537	165	54	42	23
17	27	20	317	245	456	422	444	492	346	39	64	14
18	16	35	230	440	271	278	372	366	331	184	26	51
19	18	49	188	541	498	429	423	399	279	55	27	4
20	47	88	293	528	572	494	150	216	151	42	45	22
D	30.0	79.2	257.8	387.2	440.0	391.9	365.9	444.3	278.6	115.8	43.5	27.1
21	41	38	89	533	431	633	587	152	127	40	16	44
22	26	65	84	541	517	319	329	288	63	50	27	16
23	36	48	262	542	447	159	423	381	160	128	42	17
24	30	88	330	514	619	345	485	124	349	145	103	13
25	34	233	385	415	631	385	610	195	334	187	36	30
26	25	244	323	501	345	235	509	384	318	64	33	74
27	8	216	307	296	276	299	292	369	207	204	28	77
28	50	219	150	361	299	696	387	291	173	84	90	56
29	34		103	327	277	672	455	76	305	144	66	85
30	22		190	415	385	611	320	108	97	61	24	67
31	36		206		229		154	371		138		30
D	31.9	143.9	220.8	444.5	405.1	435.4	413.7	249.0	213.3	113.2	46.5	46.3
M	1192	2698	6889	10764	12929	12218	12310	11779	8404	3954	1716	1304

D = average per decade *M* = monthly total

the measurements have been made throughout the year. The daily totals of total global radiation, I, were published for the years 1931 to 1940 and for the growing season by ZUIDHOF and DE VRIES (1940). Daily totals for the whole year were reported by REESINCK and DE VRIES (1942) for the period 1938 to 1941 and by PRINS and REESINCK (1946) for the years 1942 to 1945.

Values of I for the period 1946 to 1953 are given in Table 1[1]).

When the solarimeter was out of order or the results obtained with it were considered as less reliable, values were deduced from the duration of sunshine, using the empirical equation 7.2 (see section 7). These values are indicated in brackets in Table 1.

Average random errors in the individual values of I are estimated at 5%. BENER (1951) has shown that in addition there are some systematic errors which in total also amount to a few percent (see section 6).

Average values of total global radiation intensity, $\bar{I}$, were computed for the months April to September over the period 1931 to 1953 and for the remaining months over the period 1938 to 1953. Some small systematic corrections discussed in section 6, have been applied. The corrected values are shown in Figure 2. From this figure values of $\bar{I}$ for each day were read. These are given in Table 2.

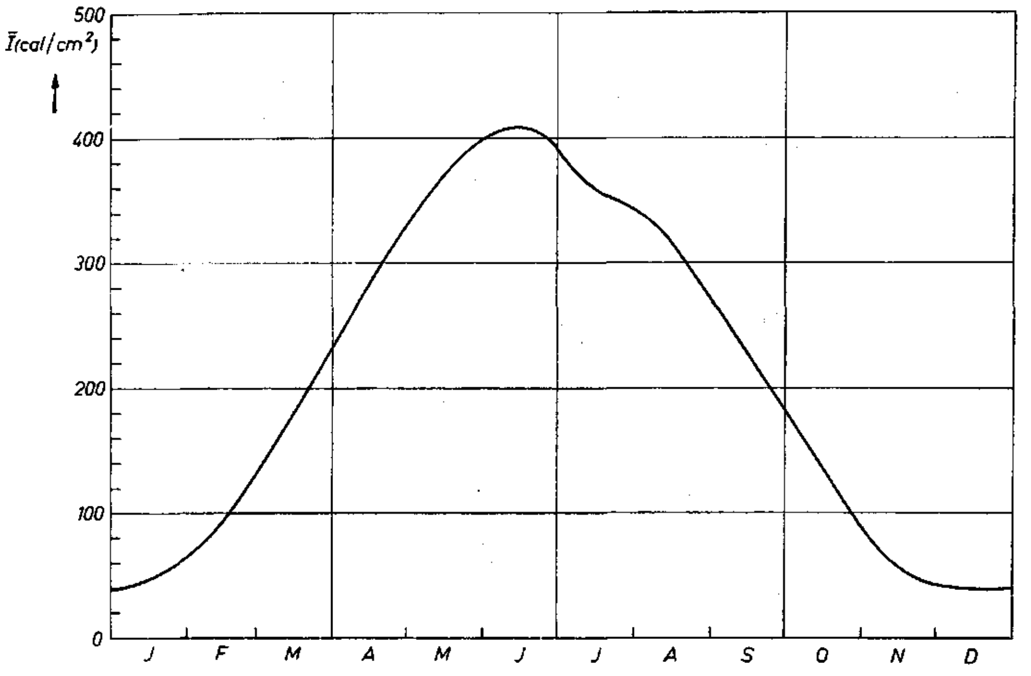

FIGURE 2. Annual variation of the average daily total global radiation intensity, $\bar{I}$, at Wageningen.

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[1]) Users of the "Maandgrafieken" will find some discrepancies between the present values and those given previously, The values given in this paper should be considered as the most reliable ones in those cases.

TABLE 2
Daily totals of the average total global radiation at *Wageningen*

Date	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
1	39	65	132	232	329	400	392	342	271	182	90	43
2	39	66	135	236	332	401	389	341	268	179	87	42
3	40	68	138	239	335	402	386	340	265	176	85	42
4	40	70	141	242	338	403	384	339	262	173	82	41
5	40	72	144	246	341	404	381	337	259	170	79	41
6	40	74	147	249	344	405	379	335	256	167	76	40
7	40	76	150	252	347	406	377	334	253	164	74	40
8	41	78	153	255	350	407	375	332	250	161	71	40
9	41	80	156	258	353	407	372	330	247	158	69	40
10	42	82	160	261	356	408	370	328	244	155	67	39
11	42	84	164	265	359	408	368	326	241	151	65	39
12	43	86	167	268	362	408	366	324	238	148	63	39
13	44	88	170	271	365	409	365	322	235	145	61	39
14	45	90	174	274	367	409	364	320	232	142	59	38
15	46	92	177	278	369	409	362	318	229	139	58	38
16	47	94	181	281	372	410	360	316	226	136	57	38
17	48	97	184	285	374	410	359	313	223	133	55	38
18	49	100	187	288	376	410	358	310	220	130	54	38
19	50	103	190	292	379	409	357	308	217	127	52	38
20	51	106	194	295	381	409	356	305	214	124	51	38
21	52	109	197	298	383	408	355	302	211	121	50	38
22	53	112	200	301	385	408	354	299	208	119	49	38
23	54	115	203	304	387	407	353	296	205	116	48	38
24	55	118	206	307	389	405	351	293	202	113	47	38
25	56	120	209	310	390	404	350	290	200	110	46	38
26	57	123	212	313	392	402	349	287	197	107	45	38
27	58	126	216	316	394	400	348	284	194	104	45	38
28	60	129	219	319	395	398	347	282	191	101	44	38
29	61	130	222	322	396	396	346	279	188	99	44	39
30	62		225	325	398	394	345	276	185	96	43	39
31	64		229		399		344	274		93		39

The variation of $\bar{I}$ throughout the year shows the expected minimum in December and maximum in June. The summer dip in the curve is a consequence of the relatively strong development of convective clouds during July. May does not show this feature owing to lower temperatures and humidities in this month.

The frequency distributions of the values of $I/\bar{I}$ (Figure 3) show that with a few exceptions the individual I values lie within the range 0.1 $\bar{I}$ to 2.5 $\bar{I}$. During the summer months the maximum values are reduced to less than 2.0 $\bar{I}$.

4. THE RATIO BETWEEN FILTERED AND UNFILTERED RADIATION

Values of the daily sums of water-filtered radiation, I_w, for the growing season were published by VAN GULIK (1929) for the period 1926 to 1929 and by ZUIDHOF and DE VRIES (1940) for the years 1928 to 1940.

The ratio I_w/I proved to be remarkably constant, the average value being 0.69 (ZUIDHOF and DE VRIES (1940)). For the single days the standard deviation of this ratio was 0.04 (number of observations = 1940) and for 10 day periods, 0.03 (number of observations = 195). The extreme values were 0.60 and 0.78

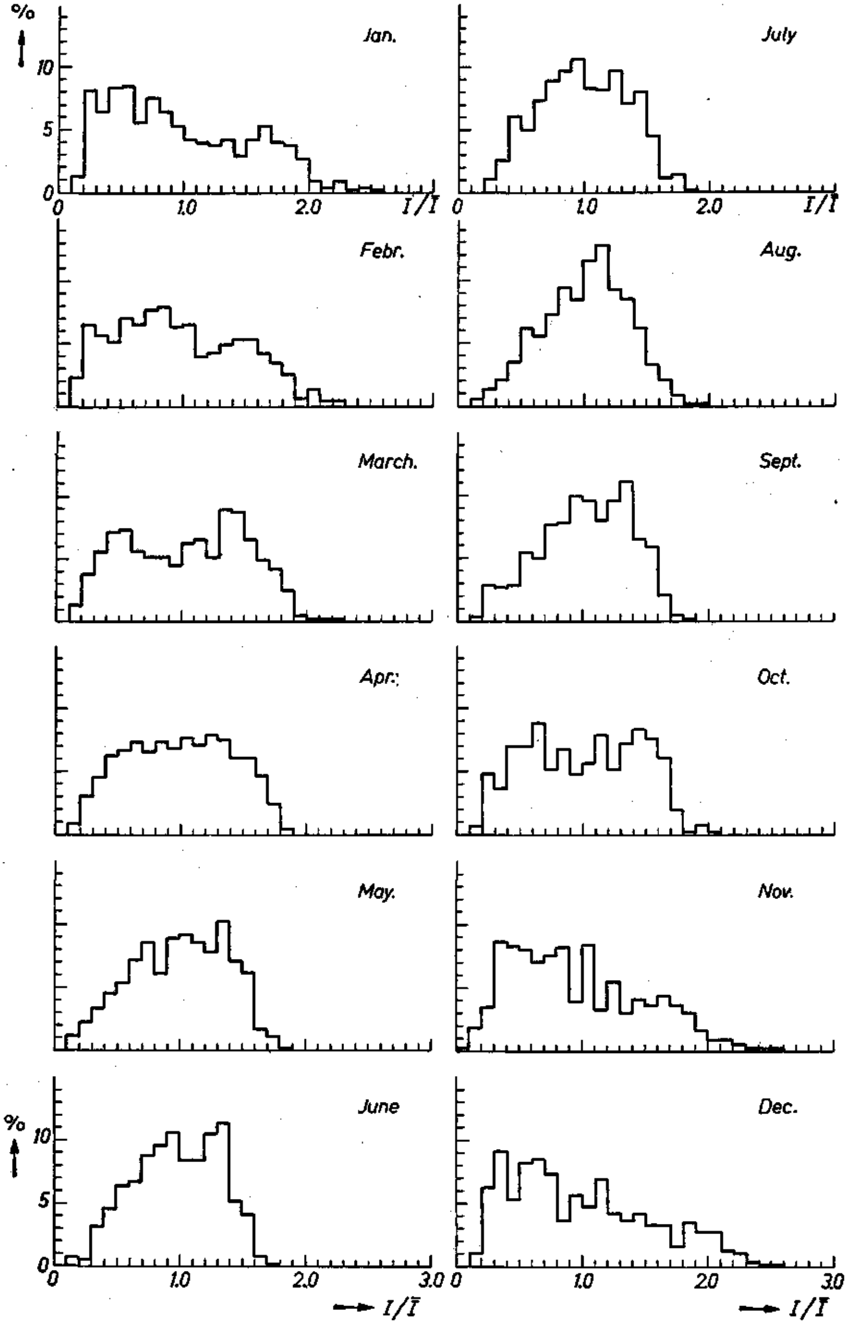


FIGURE 3. Frequency distributions of $I/\bar{I}$. The ordinate gives the percentage of occurrence of a value of $I/\bar{I}$ represented by the corresponding abscis for an interval of 0.1 on the abscis-scale.

in the latter case. Hence for periods of ten days or longer during the growing season the fraction of the incoming radiation that is active in photosynthesis is virtually constant.

5. THE DIURNAL VARIATION

Hourly values were averaged for each month and the systematic corrections (section 6) were applied. The resulting diurnal variation of the total global radiation intensity is shown in Figure 4. Unfortunately the records for the years 1941 to 1945 were lost as a consequence of war so that these averages refer to the years 1938 to 1940 and 1946 to 1953 for the months October to March and to the years 1931 to 1940 and 1946 to 1953 for the remaining months.

REESINCK and DE VRIES (1942) have already noted the similarity of the curves for the different months. Reduced curves for each month were obtained by plotting $H_r = \bar{L}\bar{H}/\bar{I}$ against $t/\bar{L}$, where $\bar{H}$ represents the average hourly value of the total global radiation, t the time (in hours) counted from true noon as zero, and $\bar{L}$ the average day-length for the month under consideration. The reduced curves differ very little from each other, with a tendency for a somewhat flatter shape during the winter months. An average reduced curve for the months March to October and a second for November to February are shown in Figure 5. The reduced curves for the individual months differ by less than 4 % from the corresponding average curves for $|t/\bar{L}|<0.4$. For larger values of $|t/\bar{L}|$ the relative differences are of the order of 10 %, but absolute differences are small, since the value of H_r decreases rapidly with increasing $t/\bar{L}$. In addition it should be noted that the degree of accuracy of the $\bar{H}$ values is rather low in this region, as will be discussed in section 6.

The reduced curves of Figure 5 are almost identical with those given previously by REESINCK and DE VRIES (1942) for a much shorter period of observation. They are almost symmetrical with respect to true noon; the total for the first half of the day, being slightly greater than that for the second half probably because cloudiness and atmospheric turbidity are on the average slightly greater in the afternoon than in the morning.

The diurnal variation of total global radiation depends largely on the variation in solar altitude. For a transparent atmosphere it can be represented by:

$$H_0 \sin h = H_0 (\sin d \sin \varphi + \cos d \cos \varphi \cos \pi t/12), \qquad (5.1)$$

where H_0 is the solar constant ($= 116.4$ cal cm^{-2}h^{-1}), d the solar declination and φ the latitude. Reduced curves of this quantity for maximum and minimum solar declinations (23.4° and -23.4° respectively) are represented in Figure 6, together with the curves of Figure 5. The ordinate is here

$$\frac{L' H_0 \sin h}{\int_{-\frac{1}{2}L'}^{\frac{1}{2}L'} H_0 \sin h \, dt}$$

and the abscissa t/L', where L' is found from the equation:

$$\sin d \sin \varphi + \cos d \cos \varphi \cos \pi L'/24 = 0,$$

$$\text{i.e.} \quad \sin h = 0 \quad \text{for } t = \pm \tfrac{1}{2} L'.$$

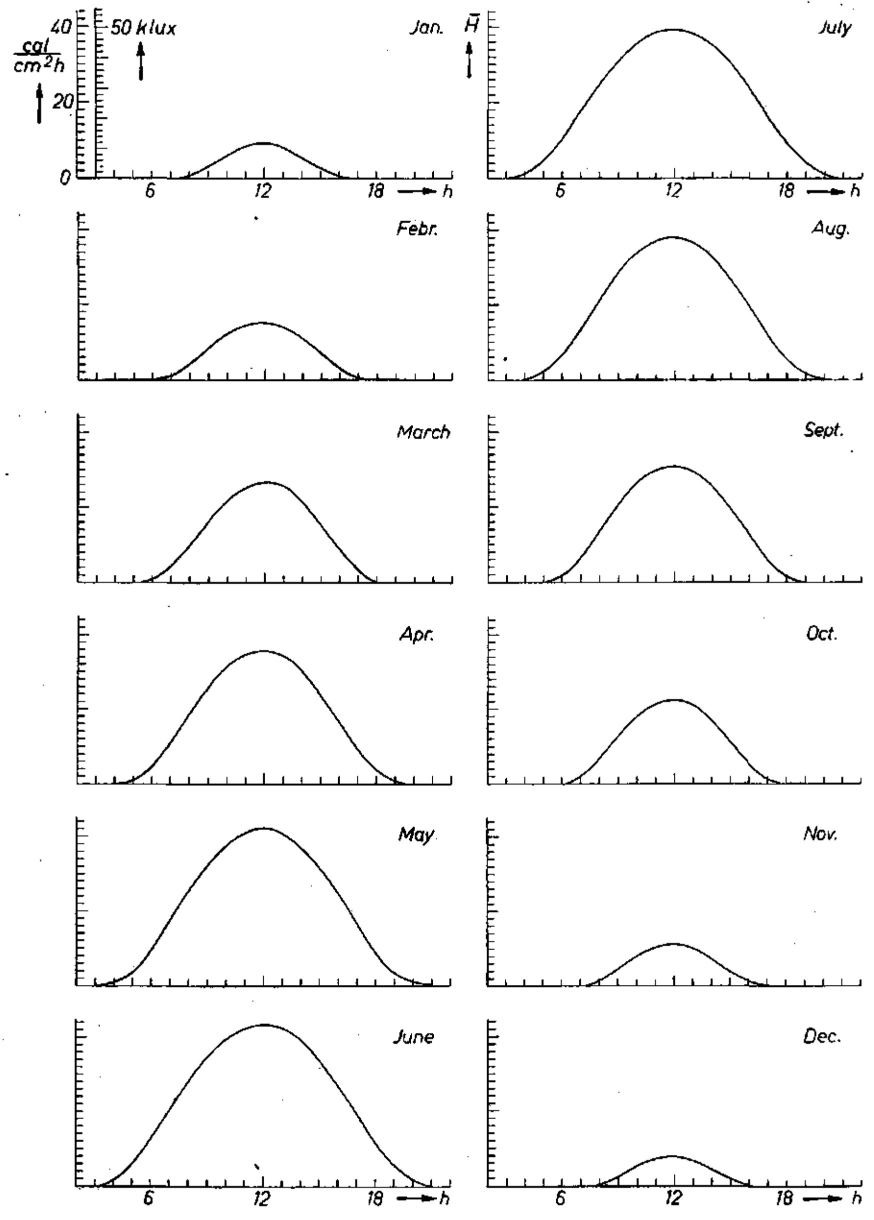


FIGURE 4. Diurnal variation of the average hourly total global radiation intensity, $\bar{H}$. The horizontal scale gives true solar time. The lux scale holds under average conditions.

The frequency distribution of the values of $H/\bar{H}$, where H is the observed hourly total global radiation intensity, is shown in Figure 7. The curves for the individual hours of the day in a given month do not show much difference, so that only one curve is given for each month.

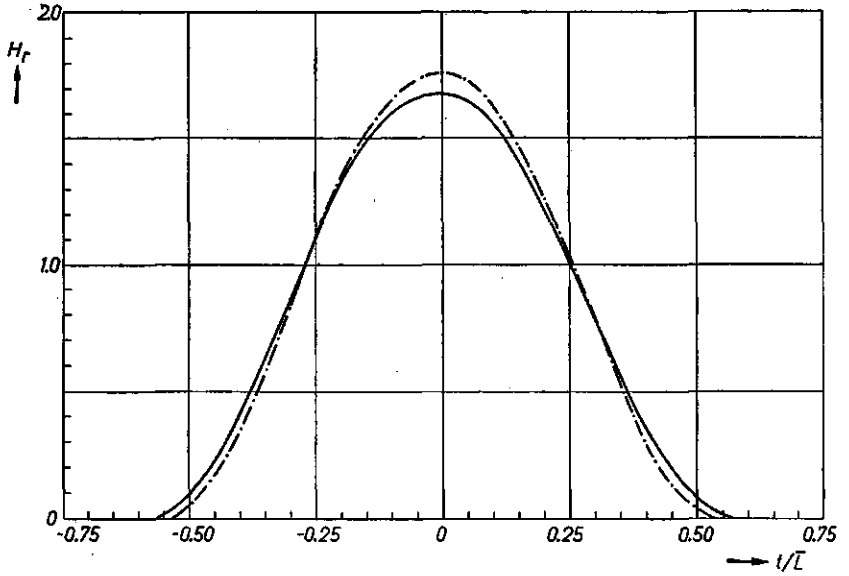


FIGURE 5. Reduced diurnal variation of total global radiation ($Hr = \bar{L}\bar{H}/\bar{I}$ plotted against $t/\bar{L}$)
——— November to February, -·-·-·-·-·- March to October.

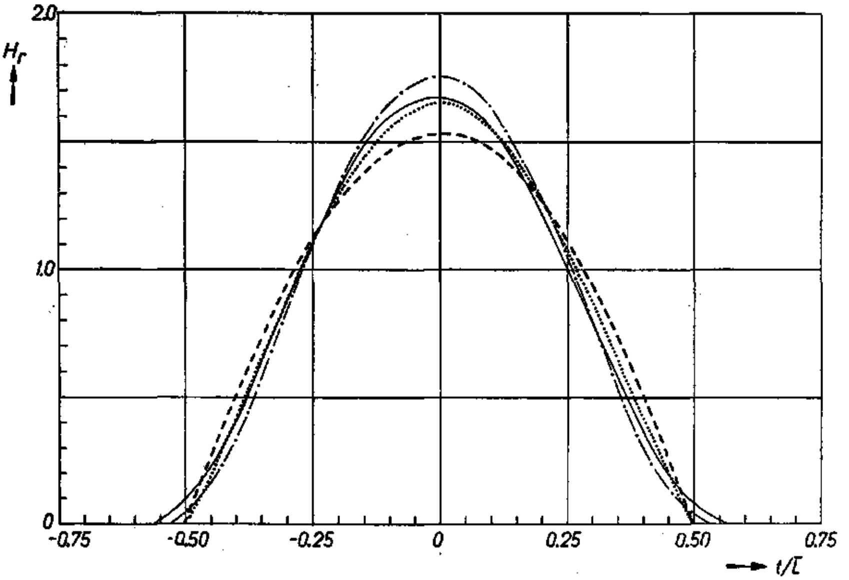


FIGURE 6. Reduced diurnal variation of total global radiation (——— November to February, -·-·- March to October) compared with the variation of solar altitude (cf. eq. (5.1)) in a reduced form.
(..... solar declination = $d = +23.4°$, ---- $d = -23.4°$).

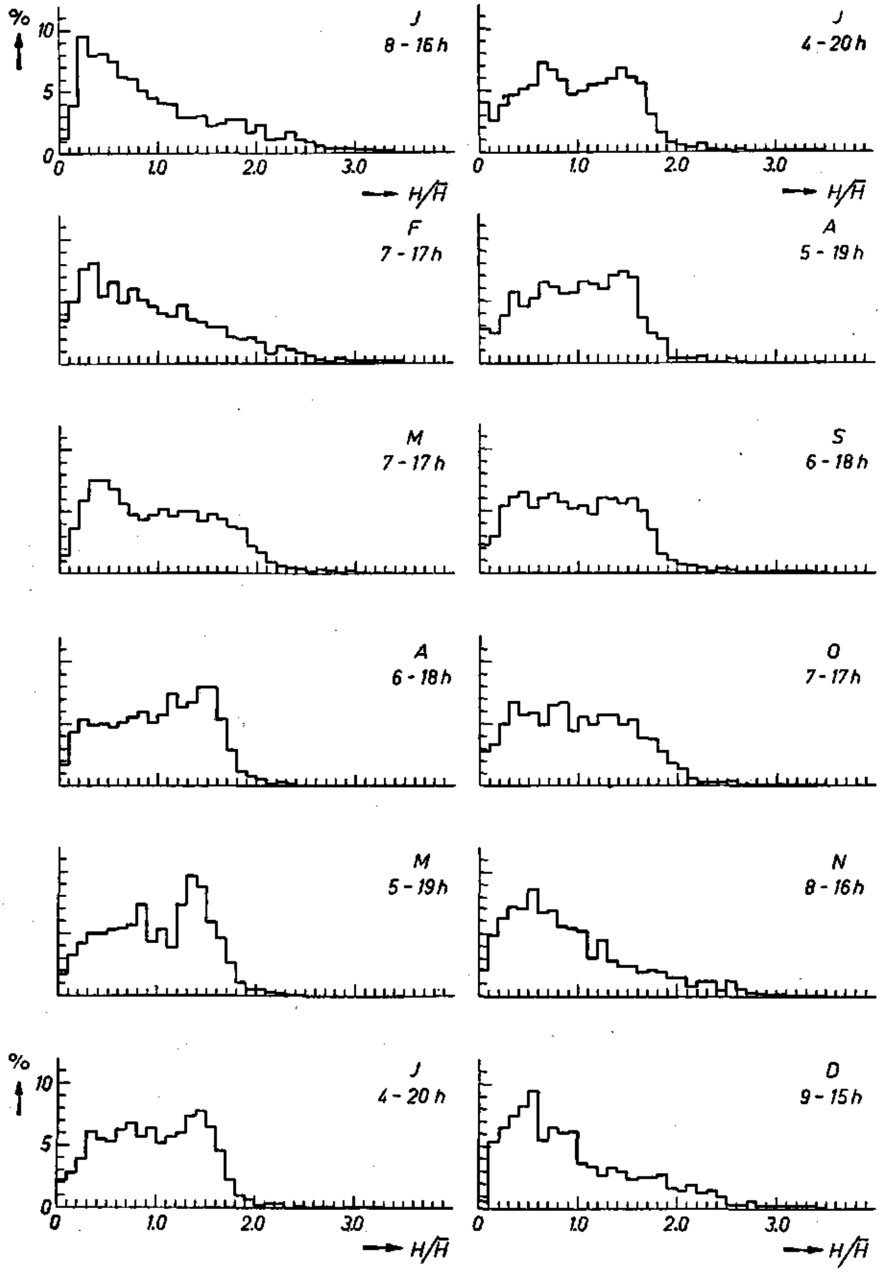


FIGURE 7. Frequency distribution of $H/\bar{H}$. The ordinate gives the percentage of occurrence of a value of $H/\bar{H}$ represented by the corresponding abscis for an interval of 0.1 on the abscis-scale.

Some data pertaining to the variation of solar altitude are collected in Table 3.

TABLE 3

Solar declination (d), equation of time (Δt = true solar time minus local mean time) and day length (L, at 52° latitude).

	d	Δt (min)	L (h)		d	Δt (min)	L (h)
Jan. 1	-23.1	- 3	7.8	July 1	23.2	-4	16.6
11	-21.9	- 7	8.1	11	22.2	-5	16.4
21	-20.1	-11	8.5	21	20.6	-6	16.0
Febr. 1	-17.3	-14	9.1	Aug. 1	18.2	-6	15.5
11	-14.3	-14	9.7	11	15.5	-5	14.9
21	-10.9	-14	10.3	21	12.4	-3	14.3
March 1	- 7.9	-13	10.9	Sept. 1	8.6	0	13.6
11	- 4.0	-10	11.6	11	4.9	3	12.9
21	- 0.1	- 8	12.2	21	1.0	7	12.3
April 1	4.2	- 4	12.9	Oct. 1	- 2.9	10	11.6
11	8.0	- 1	13.5	11	- 6.7	13	11.0
21	11.6	1	14.1	21	-10.4	15	10.3
May 1	14.8	3	14.9	Nov. 1	-14.2	16	9.6
11	17.7	4	15.5	11	-17.2	16	9.1
21	20.0	4	16.0	21	-19.8	14	8.5
June 1	22.0	2	16.4	Dec. 1	-21.7	11	8.1
11	23.0	1	16.6	11	-23.0	7	7.8
21	23.4	- 1	16.7	21	-23.4	2	7.7

6. ACCURACY. SYSTEMATIC CORRECTIONS

The accuracy with which the hourly or the daily totals of global radiation can be determined from the charts depends on the shape of the recorded curve. It is estimated to be about 3% on the average. Random errors in a determination of the calibration factor of the solarimeter amount to about 2%. Thus the degree of accuracy of the individual values of I and H is about 5% as far as it is determined by random errors.

In a critical study of the MOLL-GORCZYNSKI solarimeter BENER (1951) has shown the existence of some systematic errors, which were not taken into account previously. The influence of these errors and the corrections made will now be discussed.

A first correction arises from the geometry of the recording instrument. The deflection of the galvanometer is proportional to the current if it is measured along the arc of the circle swept out by the end of the pointer. In fact the points are recorded along a chord of this circle. If the deflection measured along this chord is a cm, a correction of k cm must be applied such that $a + k$ is proportional to the galvanometer current. It was shown by BENER that this correction is given by:

$$k = \frac{a_M}{2}\left\{1 - \frac{\operatorname{arctg}\,(\frac{1}{2}\,a_M - a)/l}{\operatorname{arctg}\,a_M/2l}\right\} - a, \tag{6.1}$$

where a_M is the maximum deflection and l the distance of the thread from the axis of rotation of the pointer. Values of k and of k/a for the instrument in use

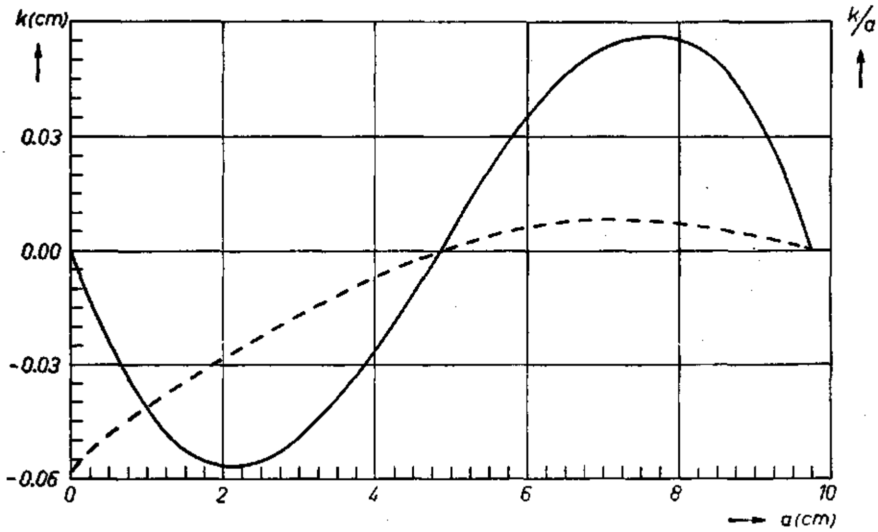


FIGURE 8. Values of the correction k (cf. eq. (6.1); full line) and of k/a (dotted line).

at Wageningen are shown in Figure 8. It can be seen that the fractional error in a is largest for small deflections and therefore the influence of this correction on the values of I is small.

The effect of the zero-point depression discussed by BENER is negligible for our instrument because the points recorded during the night form the zero line of the diagrams.

No correction for variations of resistance in the galvanometer circuit with air temperature is needed, because a large temperature-independent resistance is used in series with the recorder.

An unavoidable systematic error arises because the calibration factor is not independent of radiation intensity or of ambient air temperature. Its effect is small, so small indeed that it has escaped attention in previous work. A consideration of a number of calibration results showed, however, that small variations of the calibration constant, previously ascribed to random errors, could be explained by BENER'S formulae. Unfortunately most of the calibration results prior to 1946 were lost through war circumstances, so that a correction of individual values of H and I had become impossible. It was decided therefore to apply the systematic corrections to the averages only.

According to BENER'S theory the relation between the calibration factor (F) the temperature (ϑ) and the instantaneous radiation intensity (i) can be represented by:

$$F = F_0 (1 + \alpha\vartheta + \beta i),$$

where $F = i/a$, while α and β are constants. The value of α was determined experimentally by BENER as 0.0024 °C^{-1}. The value of β has not yet been measured; an estimated value of 0.026 cal^{-1} cm^2 min, based on data given by BENER, proved to be in good agreement with calibration results obtained at Wageningen.

A calibration factor $\bar{F}$, which is the average of a number of individual calibration results, has been used so far. Therefore the correction factor that must be applied to the value of i becomes:

$$\frac{F_0\,(1 + 0.0024\vartheta + 0.026i)\,(a + k)}{\bar{F}a} \approx \frac{F_0}{\bar{F}}\left(1 + 0.0024\vartheta + 0.026i + \frac{k}{a}\right).$$

Further $\bar{F} = F_0\,(1 + 0.0024\bar{\vartheta}_c + 0.026\bar{i}_c)$, where $\bar{\vartheta}_c$ and $\bar{i}_c$ are averages of ϑ and i for the calibration experiments. Since calibrations were always performed around noon with clear skies and mostly during the growing season these averages are not the same as the general averages of ϑ and i over a whole year. They were estimated at $\bar{\vartheta}_c = 15\,°C$ and $\bar{i}_c = 0.8$ cal $cm^{-2}min^{-1}$. Thus the correction factor for the instantaneous values of total global radiation becomes:

$$1 + 0.0024\,(\vartheta - \bar{\vartheta}_c) + 0.026\,(i - \bar{i}_c) + k/a.$$

The corrections for the average values of H were obtained for each month separately by introducing the appropriate averages of ϑ, i and a ($= i/F$) in this expression. Though the distribution of the individual i-values around their averages should be taken into account in obtaining an average correction factor, this effect is negligibly small.

The correction factors for $\bar{I}$ can now be found as follows:

$$f = \frac{\bar{I}}{\bar{I}'} = \frac{\int_{-\frac{1}{2}L}^{\frac{1}{2}L} \bar{H}\,dt}{\int_{-\frac{1}{2}L}^{\frac{1}{2}L} \bar{H}'\,dt}$$

where the non-corrected averages are denoted by a dash. These correction factors are represented in Table 4.

TABLE 4. Correction factors according to BENER for average total daily radiation intensity

Month	f	Month	f
January	0.92	July	0.99
February	0.94	August	0.98
March	0.97	September	0.97
April	0.96	October	0.97
May	0.98	November	0.93
June	0.99	December	0.92

Finally a systematic error can be due to deviations from the cosine-law. This error is negligibly small for sky radiation measurements and – with a well leveled instrument – also for direct solar radiation at solar altitudes of more than 15°. At solar altitudes below 15° it may be of the order of 10% for direct radiation measurements according to REITZ (quoted by BENER). The error will be different for different instruments, however.

Summarizing, the results of this section lead to the following estimates of the degree of accuracy of the results reported:

a. Individual values of daily total global radiation intensity (I): random errors 5%, systematic errors 1 to 10%. The systematic errors can be reduced to 1 to 5% by multiplication of the I-values by the appropiate f-factor from Table 4.

b. Average values, $\bar{I}$: random errors 1%, systematic errors 2%, total 3%.

c. Average values of the ratio between water-filtered and unfiltered radiation ($\bar{I}_w/\bar{I}$): random errors 1 %, systematic errors 1 %, total 2 %.
d. Average hourly values of total global radiation intensity ($\bar{H}$): random errors 1 %, systematic errors 2 % (except at solar altitudes below 15° where systematic errors are estimated to be about 5 %), total 3 % (6 %).
e. Reduced diurnal variation of total global radiation (H_r): random errors 1 %, systematic errors 2 %, except for small values of H_r, say $H_r < 0.5$, where these errors are estimated at 5 %, total 3 % (6 %).

7. THE CORRELATION BETWEEN RADIATION INTENSITY AND SUNSHINE PERCENTAGE. ÅNGSTRÖM'S FORMULA

In continuation of the work of REESINCK (1940) and PRINS and REESINCK (1946) the statistical relation between the daily total global radiation intensity and the daily percentage of bright sunshine, as measured with the CAMPBELL-STOKES recorder, was evaluated for the period 1938 to 1953. The fraction of bright sunshine, R, is defined as the ratio of the recorded duration of bright sunshine, n, and the day length, L.

According to ÅNGSTRÖM a linear statistical relation holds between the quantities I and R, which may be expressed as follows:

$$I = a + bR = Q\{\alpha + (1 - \alpha) R\}. \qquad (7.1)$$

The best estimates of a and b in the linear regression of I on R were determined by the method of least squares for each month separately, using the non-corrected values of I. The correction factors of Table 4 were applied afterwards. The values of Q and α are then obtained from the equations: $Q = a + b$ and $\alpha = a/(a + b)$. The results are shown in Table 5 together with N, the number of observed pairs of I and R, and the estimate of the standard deviation, σ, given by

$$\left\{\frac{\sum_i (I_i - I_{R_i})^2}{N-2}\right\}^{\frac{1}{2}},$$

where I_i is the observed radiation intensity at a sunshine percentage R_i, and I_{R_i} is the value of I obtained by substitution of R_i in equation (7.1).

TABLE 5. Constants in the linear regression of total global radiation on sunshine fraction (cf. eq. (7.1); a, b, Q, Q_1 and σ are expressed as cal cm^{-2}day^{-1})

Month	a	b	Q	α	σ	N	Q_1
January . . .	33	79	112	0.29	19	427	112
February . . .	55	165	220	0.25	29	391	207
March	103	263	366	0.28	50	421	364
April	135	416	551	0.25	61	385	519
May	182	483	665	0.27	62	428	653
June	223	461	684	0.33	73	407	715
July	210	450	660	0.32	65	447	683
August . . .	184	352	536	0.34	64	480	571
September . .	120	306	426	0.28	46	445	422
October . . .	75	191	266	0.28	36	441	264
November . .	38	105	143	0.27	22	426	136
December . .	27	66	93	0.29	15	458	93

The values of α do not show a pronounced annual variation, although there is a tendency for a maximum in summer and a minimum in winter. The average value of α is 0.29, which is in good agreement with the value 0.30 found by REESINCK for the years 1938 to 1940. If lines are drawn for this average value of α through the points $(\bar{I}, \bar{R})$ for each month, slightly different values of Q are obtained, which are denoted by Q_1 in Table 5. These values were plotted against time and from the graph drawn through these points Q_1-values for each day were obtained. These are represented in Table 6, the equivalent to Table II of REESINCK and DE VRIES (1942).

TABLE 6
Values of Q_1, in the formula $I = Q_1\,(0.29 + 0.71\,R)$

Date	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
1	92	151	280	442	592	698	715	635	496	345	192	105
2	93	154	286	447	596	700	714	631	491	340	188	104
3	94	158	292	453	601	702	713	627	486	334	184	103
4	95	162	298	458	605	704	712	623	480	329	180	102
5	96	166	303	464	610	705	710	619	474	324	176	101
6	97	170	308	469	614	706	708	615	469	318	172	100
7	98	174	313	475	618	707	706	611	464	313	168	99
8	99	178	318	480	622	708	704	607	459	307	164	98
9	100	182	324	486	626	709	702	603	454	302	160	97
10	101	186	330	491	630	710	700	599	449	294	156	96
11	102	190	336	496	634	711	698	595	444	289	152	95
12	104	194	342	502	638	712	695	591	439	284	148	94
13	106	198	348	507	642	713	692	586	434	279	144	94
14	108	202	352	512	646	714	689	581	429	274	140	93
15	110	206	358	517	650	715	686	576	424	269	137	93
16	112	210	364	523	653	716	683	571	419	264	134	93
17	114	214	366	529	657	717	681	566	414	259	132	92
18	116	218	371	534	661	718	678	561	409	254	130	92
19	118	223	376	539	664	718	675	556	404	249	128	92
20	120	228	382	544	667	719	673	552	399	244	126	91
21	122	233	387	549	670	719	670	548	394	239	124	91
22	124	238	392	554	673	719	668	543	389	234	122	91
23	126	244	397	559	676	719	665	539	384	229	120	90
24	128	250	402	564	679	719	662	535	379	224	118	90
25	130	256	407	568	682	718	659	530	374	220	116	90
26	133	262	412	572	685	718	656	525	369	216	114	90
27	136	268	417	576	688	718	653	520	364	212	112	90
28	139	274	422	580	690	717	650	515	359	208	110	91
29	142		427	584	692	717	647	510	354	204	108	91
30	145		432	588	694	717	643	505	350	200	107	91
31	148		437		696	716	639	500		196	106	91

REESINCK has already noted a slight systematic deviation from the linear relation, eq. (7.1), the curve representing the statistical relation between I and R being concave towards the R-axis REESINCK remarked that this is probably because low values of R are usually associated with heavy clouds, while at values of R around 0.5 the reflection by the sides of clouds causes an increase in radiation intensity.

To investigate this question further the best estimates of the coefficients in the quadratic regression equation:

$$I = p + qR + rR^2 \qquad (7.2)$$

were evaluated by the method of least squares. The results, corrected from Table 4, are shown in Table 7, together with the estimate of the standard deviation,

$$\sigma = \left\{\frac{\sum_i (I_i - I_{R_i})^2}{N-3}\right\}^{\frac{1}{2}},$$

where I_{R_i} is now found from equation (7.2).

TABLE 7. Constants in the quadratic regression of total global radiation on sunshine fraction (cf. eq. (7.2) p, q, r and σ are expressed as cal cm^{-2}day^{-1})

Month	p	q	r	σ
January	31	132	− 78	19
February	55	212	− 86	28
March	93	398	−179	49
April	130	459	− 65	61
May	163	649	−203	61
June	223	510	− 60	73
July	207	475	− 34	65
August	175	423	− 90	64
September	109	411	−135	46
October	68	282	−120	35
November	35	176	−113	21
December	26	106	− 61	14

As r is negative in every month the deviation of the linear relation is in the sense indicated above. It is most pronounced during the winter months. The estimates of the standard deviation are nearly the same as those obtained for the linear regression and thus the usefulness of equation (7.2) for predicting I from an observed R is little better than that of equation (7.1).

This conclusion is supported by a consideration of the confidence limits of the regression equations (7.1) and (7.2) as shown in Figure 9.

The limits of the interval which will contain an expected value of I following from a linear or a quadratic regression on R in 95 out of 100 cases (95% confidence interval) have been calculated for a number of months. A typical result is represented in figure 9. Here the curves representing equations (7.1) and 7.2) for August are shown together with these intervals. Besides the figure contains the limits of the prediction interval of I at a given R with 95% confidence, i.e. the interval that will contain a single predicted value of I at a given R in 95 out of 100 cases, under the assumptions that a linear or a quadratic statistical relationship between both quantities holds. It can be seen that the corresponding areas for the linear and the quadratic regressions overlap to a large extent.

The shifted linear relation with $\alpha = 0.29$ is also included in figure 9 for comparison. From Table 5 it can be seen that of all months the value of α differs most from the average value for August. Thus for other months the relative differences between the shifted and the original lines will be smaller than in the case shown here.

The degree of uncertainty of a predicted value of I at a given R for a single day is large, as follows directly from the comparatively large values of σ. It will be interesting to investigate the usefulness of a linear or a quadratic regression if average values of I and R for periods of more than one day are considered.

8. THE CORRELATION BETWEEN RADIATION INTENSITY AND CLOUDINESS

REESINCK has also investigated the statistical relation between the total global radiation and the part of the sky covered by clouds C, for the period 1938 to 1940. C was taken by REESINCK – and also in the present investigation – as the arithmetic mean between the values observed visually at the climatological observation times of 8h and 14h local mean time, as it was expected that this mean would provide a reasonably representative estimate of the cloudiness during daylight hours.

A linear regression of I on C may be expressed as follows:

$$I = a' + b'C = Q' \{1 - (1 - \alpha') C\}. \tag{8.1}$$

The best estimates of a' and b' were evaluated by the method of least squares for the period 1938 to 1953. The results, corrected with the factors of Table 4, are shown in Table 8 together with the number of observations N' and the estimate of the standard deviation, σ, given by

$$\left\{\frac{\sum_i (I_i - I_{c_i})^2}{N-2}\right\}^{\frac{1}{2}},$$

where I_{c_i} is found from equation (8.1).

TABLE 8. Constants in the linear regression of total global radiation on cloudiness (cf. eq. (8.1); a', b', Q', Q_1' and σ' are expressed as cal cm^{-2}day^{-1}).

Month	$a' = Q'$	$-b'$	α'	σ'	N'	Q_1'	Q_1'/Q_1
January	94	64	0.32	19	427	90	0.80
February	194	136	0.30	34	418	177	0.85
March	318	200	0.37	61	452	322	0.88
April	478	303	0.37	76	446	481	0.93
May	589	352	0.40	66	437	612	0.94
June	635	362	0.43	87	407	680	0.95
July	612	357	0.42	81	447	649	0.95
August	505	294	0.42	69	480	536	0.94
September	390	244	0.37	57	445	394	0.93
October	235	152	0.35	43	458	230	0.87
November	124	87	0.30	22	441	112	0.82
December	74	52	0.30	16	459	68	0.73

The values of α' are somewhat lower in winter than in summer, just as the values of α. The average value is 0.36 whereas REESINCK found 0.38. Shifted values of Q', denoted by Q_1', in Table 6, were found by passing lines with $\alpha' = 0.36$ through the points $(\bar{I}, \bar{C})$ for each month. Daily values of Q_1' are given in Table 9. The ratio Q_1'/Q_1 is also included in Table 8; it is not constant here, as found by REESINCK, but it shows an annual variation with a maximum in June and a minimum in December.

Estimates of the coefficients in a quadratic regression of I on C were evaluated for four months. The I, C-curve was concave towards the C-axis in all cases and the curvature was somewhat more pronounced than in the corresponding cases of section 7. The estimates of the standard deviations obtained for the quadratic regressions were only about 4% lower than those obtained for the linear regressions. The results for August are shown as an example in Figure 10, which is similar to figure 9. The shifted linear relation, the 95 % confidence intervals and the limits of the prediction intervals with 95 % confidence are included.

TABLE 9. Values of Q_1', in the formula $I = Q_1' (1 - 0.64\ C)$

Date	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
1	68	129	242	401	550	660	679	598	468	313	161	80
2	69	132	247	406	554	662	678	594	463	308	157	79
3	70	135	252	411	558	664	677	590	458	303	153	78
4	71	138	257	416	562	666	676	586	453	298	149	77
5	72	141	262	421	567	668	675	582	448	293	144	76
6	73	144	267	426	571	670	673	578	443	288	141	75
7	74	148	272	431	575	672	671	574	438	283	138	74
8	75	152	277	436	580	673	669	570	433	278	135	73
9	76	156	282	442	584	674	667	566	428	272	132	72
10	78	160	287	448	588	675	665	562	423	266	129	71
11	80	164	292	454	592	676	663	558	418	260	126	71
12	82	168	298	460	596	677	661	554	413	254	123	70
13	84	172	304	466	600	678	658	550	408	248	120	70
14	86	176	310	472	604	679	655	546	403	242	117	69
15	88	180	316	478	608	680	652	541	397	236	114	69
16	90	184	322	484	612	681	649	536	391	230	111	68
17	92	188	327	489	616	681	646	532	385	225	108	68
18	94	192	332	494	619	682	643	528	379	220	106	67
19	96	196	337	489	622	682	640	523	373	216	104	67
20	98	200	342	504	625	682	637	519	368	212	102	67
21	100	204	347	509	628	683	634	514	363	208	100	67
22	102	208	352	514	631	683	631	510	358	203	98	66
23	104	213	357	518	634	683	628	505	353	199	96	66
24	106	218	362	522	637	683	625	501	348	194	94	66
25	108	223	367	526	640	683	622	497	343	190	92	66
26	111	228	372	530	643	682	619	492	338	185	90	66
27	114	233	377	534	646	682	616	488	333	181	88	67
28	117	238	382	538	649	682	613	484	328	177	86	67
29	120	240	387	542	652	681	610	480	323	173	84	67
30	123		392	546	655	681	606	476	318	169	82	67
31	126		396		658	680	602	472		165		68

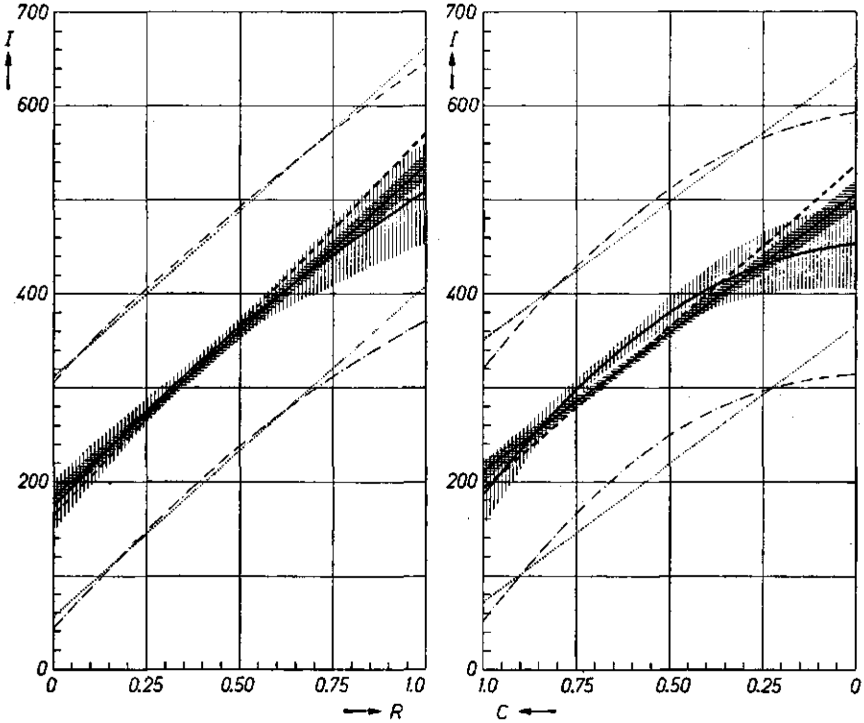
The values of σ' are somewhat larger than the values of σ for every month with the exception of January, where they are equal. The sunshine percentage is therefore slightly more valuable for estimating the radiation intensity than the cloudiness. It must be remembered, however, that C is the mean of only two observations. The degree of correlation between I and C will probably be higher if C is observed more frequently each day.

The relation between R and C:

It is often assumed that between R and C the following simple relation holds:

$$R + C = 1.$$

REESINCK (1940) has already remarked that at Wageningen this relation is not exactly fulfilled, but that $R + C$ shows an annual variation with a minimum in winter and a maximum in summer. This can be explained by the fact that the



FIGURES 9 and 10. Regressions of I on R and I on C. The linear and the quadratic regression curves are indicated by heavy full lines, the shifted linear regressions ($\alpha = 0.29$, $\alpha' = 0.36$) by heavy broken lines. The 95% confidence intervals are indicated by horizontal and by vertical hatching for the linear and quadratic regressions resp. The limits of the prediction intervals with 95% confidence are indicated by light dotted and broken lines.

screening effect of clouds on solar radiation increases with decreasing solar altitude.

By eliminating I from equation (7.1) and (8.1) the constants β and γ in the relation:

$$\beta\bar{R} + \gamma\bar{C} = 1 \tag{8.2}$$

can be easily found. Here $\bar{R}$ and $\bar{C}$ are averages over the period 1938 to 1953. The results are shown in Table 10 together with values of $\bar{R}$, $\bar{C}$ and $\bar{R} + \bar{C}$.

9. RADIATION MEASUREMENTS AT OTHER PLACES IN THE NETHERLANDS

Comparative measurements of total global radiation intensity were carried out at Den Helder (4°45′E, 52°58′N) during 1941 and 1942. The results were published by PRINS (1944). The radiation climate at Den Helder proved to be more of a maritime type than that at Wageningen, i.e. in summer the intensity at Den Helder is the greater of the two, in particular around noon, whereas in winter the reverse holds true.

Measurements were carried out at De Bilt during the period April 1943 to October 1947. The results were published by PRINS and REESINCK (1948). The differences between De Bilt and Wageningen were in the same sense as those

TABLE 10. The relation between average sunshine percentage, $\bar{R}$, and average cloudiness, $\bar{C}$ (cf. eq. (8.2))

Month	$\bar{R}$	$\bar{C}$	$\bar{R}+\bar{C}$	β	γ
January	0.19	0.72	0.91	1 29	1.05
February	0.22	0.74	0.96	1.19	0.98
March	0.32	0.65	0.97	1.22	0.93
April	0.41	0.59	1.00	1.21	0.88
May	0.42	0.58	1.00	1.19	0.86
June	0.40	0.62	1.02	1.12	0.88
July	0.35	0.68	1.03	1.12	0.89
August	0.38	0.64	1.02	1.10	0.92
September . . .	0.37	0.64	1.01	1.13	0.90
October.	0.32	0.64	0.96	1.20	0.96
November . . .	0.16	0.78	0.94	1.22	1.01
December	0.15	0.73	0.88	1.40	1.11

between Den Helder and Wageningen but they were much less pronounced in the former case. For a further discussion of these differences and for their numerical values the reader is referred to the original papers.

SUMMARY

Recording of the intensity of radiation from sun and sky with a MOLL-GORCZYNSKI solarigraph has been performed at Wageningen (51°58'N, 5°39'E) from 1931 onwards. In addition the intensity of the radiation from sun and sky filtered by a water layer of 10 cm thickness was measured up to 1941. The duration of bright sunshine has been recorded by means of a CAMPBELL-STOKES sunshine recorder from 1938 onwards.

An elaboration of the total material at hand up to 1953 inclusive is presented. Results published previously (in dutch) by various authors are included or referred to. Random and systematic errors are discussed and correction factors for the systematic errors are given. The annual and the diurnal variations of short wave radiation intensity from sun and sky are given (see table 2, figures 2 to 7). The regressions of the radiation intensity from sun and sky on sunshine percentage and on cloudiness are investigated (see tables 5 to 9, figures 9 and 10). The ratio between the daily totals of filtered and unfiltered radiation proved to show little variation from day to day and even less from decade to decade.

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REFERENCES

ÅNGSTRÖM, K., Wied. Ann. d. Phys. und Chemie **67**, 633 (1899).

BENER, P., Untersuchungen über die Wirkungsweise des Solarigraphen Moll-Gorczynski, Archiv f. Meteorologie, Geophysik und Bioklimatologie B II, 188–249 (1951).

GULIK, D. VAN, Het registreren der bestraling van het aardoppervlak, Mededelingen Landbouwhogeschool **31**, Verhandeling 6 (1927).

GULIK, D. VAN, Stralingsmetingen te Wageningen, Mededelingen Landbouwhogeschool **33**, Verhandeling 5 (1929).

MAURER, J., Der Sonnenscheinchronograph, Met. Zs. **31**, 193–196 (1914).

PRINS, J. A., Winter, lente en zomer van 1940 te Wageningen in agrometeorologische maandgrafieken, Landbouwkundig Tijdschrift **52**, 525 (1940).

PRINS, J. A., De zonneschijnintensiteit te Wageningen en Den Helder, Mededelingen Landbouwhogeschool **47**, Verhandeling 2 (1944).

PRINS, J. A. and J. J. M. REESINCK, Meteorologische waarnemingen te Wageningen tot 1 Januari 1946 en helderheidsmetingen aan de hemel te Arnhem, Mededelingen Landbouwhogeschool **48**, Verhandeling 3, 60–84 (1946).

PRINS, J. A. and J. J. M. REESINCK, De totale globale straling te Wageningen en De Bilt, Mededelingen Landbouwhogeschool **49**, Verhandeling 2, 13–16 (1948).

REESINCK, J. J. M., Het verband tussen zonneschijnduur, bewolking en stralingsintensiteit in Nederland, Mededelingen Landbouwhogeschool **44**, Verhandeling 5 (1940).

REESINCK, J. J. M. and D. A. DE VRIES, De jaarlijkse en dagelijkse gang van het daglicht in Nederland, Mededelingen Landbouwhogeschool **46**, Verhandeling 1, 1–24 (1942).

ZUIDHOF, G. and D. A. DE VRIES, Stralingsmetingen te Wageningen 1930–1940, Mededelingen Landbouwhogeschool **44**, Verhandeling 4 (1940).