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Measurements of Diffuse Solar Radiation at Blue Hill Observatory

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MEASUREMENTS OF DIFFUSE SOLAR RADIATION AT BLUE HILL OBSERVATORY

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ABSTRACT

Records of diffuse radiation have been obtained at Blue Hill Observatory continuously since October 28, 1945, by means of a pyrheliometer equipped with an occulting ring which shades the receiving surface from the sun but permits practically all of the diffuse radiation to impinge upon the instrument. The results of the first four years of record are summarized in tabular and graphical form. The difficulties of obtaining precise measurements and the limitations of the instrumental equipment are described.

A selected bibliography on diffuse radiation is included.

INTRODUCTION

Diffuse radiation is the scattered solar radiation received by the earth from the atmosphere. This scattering is caused by the gas molecules, water vapor, dust particles, and clouds in the atmosphere, which also account for a certain loss in the incoming solar radiation by absorption and reflection back to space.

Landsberg [1] estimates that, for a whole year, 58 percent of the total solar and sky radiation received from the sun on the whole earth's surface is direct, with the remaining 42 percent scattered (diffuse) radiation. At Blue Hill Observatory, Milton, Mass., 4 years of measured data to be presented in this paper show the diffuse to be 38 percent of the total radiation received on a horizontal surface. Ratios of diffuse to total radiation are dependent upon the latitude and elevation of an observing station and vary daily with the amount of cloudiness and the amount of atmospheric pollution. On high mountains, as for example Mount Evans, Colo., at an elevation of 14,259 feet, the diffuse radiation from cloudless skies amounts to only 4 to 5 percent of the total solar and sky radiation received on a horizontal surface at noon in midsummer.[1] Comparison of the Mount Evans data with the data from a station such as Blue Hill shows that values of diffuse radiation during cloudless conditions are much smaller at high elevations than at sea level or at comparatively low altitudes. Cloudiness is the predominate factor in causing daily variations in the ratio of the diffuse to total radiation; the cloudiness itself is dependent upon such factors as time of year, time of day, local orography, nearness to large bodies of water, and the synoptic weather situation. Over large industrial cities, the diffuse component of the total radiation is a high percentage of the total radiation, even with skies nearly free of water vapor, due to the atmospheric pollution from industries [2]. Such pollution is often so severe that the sun may be viewed with the naked eye throughout the day, and appears as a distorted red disk. Volcanoes [3], dust storms [4], and forest fires [5] are other occasional causes of increased percentages of the diffuse component of the total radiation.

[1] Unpublished results obtained by the senior author on Mount Evans, Colo., in 1938.

PURPOSE OF THE MEASUREMENTS

Knowledge of the distribution of solar radiation is essential in the study of the heat balance of the atmosphere and in many other researches conducted by meteorologists. Illuminating engineers and architects who calculate the minimum requirements of light received on desks, work benches, and walls may plan the dimensions and arrangements of their windows with great accuracy through the use of data of diffuse radiation. The use of these data in conjunction with values of the amount of Illumination from the sky [6, 7, 8] should avoid the necessity of planning window surfaces many times too large, since, for example, the amount of diffuse radiation received through north windows when certain types of clouds are present is often many times that received with cloudless skies. The increasing attention being given to the possibility of house-heating by solar radiation has also initiated an interest in the amount of diffuse radiation received, as well as in the total amount of radiation received on various vertical and inclined surfaces. Photographers, artists, plant physiologists, paint manufacturers, and many others are also interested in these data.

The purpose of this paper is to present the results of measurements of diffuse radiation received on a horizontal surface at Blue Hill Observatory from October 29, 1945, through October 28, 1949.[2] Following the summary of the four year's data, a description of the method and equipment for measurement and an investigation of problems encountered in measurement are briefly presented to aid users of the data in understanding limitations in the accuracy of the records.

SUMMARY OF FOUR YEARS' DATA

Table 1, summarizing the measurements made from October 29, 1945, through October 28, 1949, at Blue Hill Observatory, includes the following data:

For each day during the 4-year period:

1. Daily value of diffuse radiation $= D$
2. Daily value of total solar and sky radiation $= T$

For each week during the 4-year period:

3. Weekly mean daily value of diffuse radiation $= \overline{D} = (1/n)\Sigma D$
4. Weekly mean daily value of total solar and sky radiation $= \overline{T} = (1/n)\Sigma\, T$
5. Weekly ratio of diffuse to total solar and sky radiation $= (\overline{D}/\overline{T}) \times 100\% = (\Sigma D/\Sigma T) \times 100\%$ where the summations in items 3, 4, and 5 are over the n daily values during the week (i. e., $n = 7$ or 8).

For weekly periods (last column of table):

6. Weekly mean ratio of diffuse to total solar and sky radiation $= (\Sigma\overline{D}/\Sigma\overline{T}) \times 100\%$ where the summations are over the four values of $\overline{D}$ and $\overline{T}$ for a given weekly period for the four years of record.

For each year (summary rows at end of table):

7. Yearly total diffuse radiation $= \Sigma D$
8. Yearly total solar and sky radiation $= \Sigma T$
9. Yearly mean daily diffuse radiation $= (1/n)\Sigma D$
10. Yearly mean daily total solar and sky radiation $= (1/n)\Sigma T$
11. Yearly ratio of diffuse to total solar and sky radiation $= (\Sigma D/\Sigma T) \times 100\%$.
12. Yearly mean weekly ratio of diffuse radiation to total solar and sky radiation $= (1/m)\Sigma(\overline{D}/\overline{T}) \times 100\%$ where the summations in items 7, 8, 9, 10, and 11 are over the n daily values during the year (i. e., $n \leq 365$), and the summations in item 12 are over the m weekly values of $\overline{D}/\overline{T}$ as defined in item 5 (i. e., $m \leq 52$).

For the entire period of record (last entry in table):

13. Four-year mean daily ratio of diffuse to total solar and sky radiation $= (\Sigma D/\Sigma T) \times 100\%$ where the summations are over the n daily values for the entire 4-yr. record (i. e., $n \leq (4 \times 365)$).

Table 1 shows that diffuse radiation at Blue Hill Observatory constituted 38 percent of the total solar and sky radiation received on a horizontal surface for the 4-year period. For the last 2 months of 1945, the diffuse was 43 percent of the total; for the whole year of 1946, 38 percent; for 1947, 38 percent; for 1948, 40 percent; and for the first 10 months of 1949, 36 percent. These percentages indicate a remarkable consistency from year to year.

The annual march (4-year average) of the weekly mean ratio of diffuse to total solar and sky radiation is shown in figure 1. (This is a plot of the data in the last column of table 1.) As is to be expected with so few years of data, the curve in figure 1 is very irregular, and because of the variability in the amount of cloudiness, the relationship between the ratio and the time of year is not clearly defined. However, there appears to be a tendency for the ratio to be slightly higher in winter than in summer, probably due to the greater amount of cloudiness usually occurring in winter at Blue Hill. The maximum and

[2] Diffuse radiation data for 1950 were published in *Climatological Data National Summary*, vol. 1, No. 13, 1950. Subsequent diffuse data are being published monthly on a current basis in *Climatological Data, National Summary*.

TABLE 1.—*Total solar and sky radiation and diffuse radiation received on a horizontal surface (expressed in langleys per day),* and ratios of the diffuse to the total (in percentages). (See p. 2 for explanation of computations of means.)*

Date	1945			1946			1947			1948			1949			1945–49
	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	Weekly mean ratio ($\Sigma\overline{D}/\Sigma\overline{T}$)
	ly	*ly*	%	*ly*	*ly*	%	*ly*	*ly*	%	*ly*	*ly*	%	*ly*	*ly*	%	%
Jan. 1				47	202		103	103		86	90		26	--		
2				34	233		42	42		35	36		66	73		
3				44	209		17	17		91	91		55	175		
4				57	197		86	169		61	62		53	155		
5				63	190		83	208		70	92		13	13		
6				88	88		85	176		87	87		33	112		
7				17	17		72	84		65	68		56	172		
Means				50	162	31	70	114	61	71	75	95	46	117	39	51
8				88	172		51	208		76	196		46	185		
9				50	50		37	245		57	66		76	88		
10				52	197		70	193		76	195		54	63		
11				53	208		84	87		46	238		79	158		
12				32	32		76	189		86	90		96	104		
13				33	211		55	228		21	23		53	210		
14				72	193		41	41		62	87		68	176		
Means				54	152	36	59	170	35	61	128	48	68	141	48	41
15				70	70		81	81		50	258		42	251		
16				37	259		45	45		128	155		67	182		
17				129	129		96	211		50	55		24	29		
18				95	95		59	210		74	130		27	36		
19				51	251		84	206		73	257		40	51		
20				117	20		24	24		57	229		41	297		
21				41	21		50	194		36	36		92	116		
Means				77	145	53	63	139	45	67	160	42	48	137	35	44
22				107	113		50	255		60	62		--	256		
23				39	277		95	178		98	111		--	251		
24				148	148		89	150		71	78		34	49		
25				81	154		77	188		133	140		24	32		
26				105	112		109	212		58	281		50	70		
27				96	277		59	63		146	169		84	122		
28				145	209		62	229		51	286		25	27		
Means				103	184	56	77	182	42	88	161	55	43	60	72	53
Jan. 29				70	290		94	100		138	174		54	286		
30				55	55		49	49		55	296		48	300		
31				27	27		91	230		50	311		19	19		
Feb. 1				86	222		41	288		99	232		74	281		
2				78	204		--	238		105	239		46	321		
3				59	295		50	294		63	314		71	297		
4				45	336		84	84		64	64		49	49		
Means				60	204	29	68	174	39	82	233	35	51	222	23	31
5				69	303		118	224		154	285		106	202		
6				49	49		90	230		152	205		124	275		
7				103	195		96	168		80	290		37	40		
8				109	328		69	88		103	281		61	338		
9				83	83		--	262		56	337		101	269		
10				78	318		142	229		168	278		124	188		
11				46	297		52	317		186	250		96	291		
Means				77	225	34	94	209	45	128	275	47	93	229	41	42
12				37	338		44	357		111	234		79	348		
13				98	98		69	347		145	176		122	164		
14				36	36		104	282		77	107		156	209		
15				92	180		109	122		83	367		92	99		
16				126	272		90	116		146	253		116	116		
17				120	258		150	161		77	192		61	400		
18				81	330		44	358		47	350		61	386		
Means				84	216	39	87	248	35	98	240	41	98	246	40	39
19				--	230		39	396		144	236		103	301		
20				133	133		108	274		158	222		102	104		
21				42	423		108	108		60	349		107	343		
22				--	276		--	320		53	54		79	80		
23				43	375		--	366		88	350		--	349		
24				95	95		75	389		112	365		80	379		
25				43	389		135	209		92	113		46	46		
Means				71	283	25	93	275	34	101	241	42	86	209	41	35
26				142	142		101	410		104	109		64	64		
27				47	47		201	323		161	306		56	429		
28				183	240		---	348		39	39		66	66		
Mar. 1				66	416		---	363		137	149		108	114		
2				136	172		35	35		94	460		66	458		
3				71	406		147	156		99	101		121	429		
4				91	363		185	302		175	190		79	457		
Means				105	255	41	134	245	55	116	193	60	80	288	28	44

*The term "langley" is used in place of the more cumbersome phrase "gram calories per square centimeter." This substitution has been recommended by a group of officials directly concerned with the use of this value and the term already has received recognition among workers in the study of solar radiation and related fields.

TABLE 1.—*Total solar and sky radiation and diffuse radiation received on a horizontal surface (expressed in langleys per day), and ratios of the diffuse to the total (in percentages). (See p. 2 for explanation of computations of means.)*—Con.

Date	1945			1946			1947			1948			1949			1945–49
	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	Weekly mean ratio ($\Sigma\overline{D}/\Sigma\overline{T}$)
	ly	*ly*	%	*ly*	*ly*	%	*ly*	*ly*	%	*ly*	*ly*	%	*ly*	*ly*	%	%
Mar. 5				160	307		204	337		114	114		136	351		
6				112	350		218	341		63	508		134	206		
7				148	253		119	321		70	466		94	176		
8				176	270		217	217		74	74		171	228		
9				111	204		111	334		164	269		59	480		
10				60	477		155	163		134	374		87	89		
11				160	211		190	225		48	48		34	36		
Means				132	297	44	173	277	62	95	265	36	102	224	46	47
12				78	465		66	453		73	103		227	369		
13				94	414		78	457		89	458		172	407		
14				101	401		56	57		76	466		59	526		
15				115	115		100	452		138	430		187	385		
16				74	458		78	474		137	307		57	552		
17				174	260		150	296		107	110		70	532		
18				72	486		174	385		112	222		49	49		
Means				101	372	27	100	368	27	105	300	35	117	403	29	29
19				142	490		62	510		95	463		83	605		
20				77	472		96	430		151	245		63	599		
21				72	490		185	334		80	497		210	434		
22				67	525		158	430		178	280		239	352		
23				68	544		158	491		236	280		75	82		
24				72	535		101	101		91	91		116	537		
25				89	106		172	229		104	380		175	395		
Means				84	452	19	133	361	37	134	320	42	137	429	32	31
26				173	440		250	340		67	558		214	373		
27				78	538		166	514		87	456		152	177		
28				90	513		171	474		33	33		154	458		
29				124	504		218	228		101	183		83	568		
30				236	346		130	509		63	575		189	255		
31				108	576		57	598		119	490		150	175		
Apr. 1				213	412		177	474		110	509		220	415		
Means				146	476	31	168	448	38	83	400	21	166	346	48	34
Apr. 2				149	359		62	62		37	37		102	567		
3				161	174		72	593		84	86		173	451		
4				174	174		90	571		180	374		99	105		
5				200	244		52	52		68	608		108	572		
6				176	287		154	276		189	455		64	70		
7				221	545		176	481		112	286		210	450		
8				200	438		127	591		100	596		171	229		
Means				183	317	58	105	375	28	110	349	32	132	349	38	38
9				118	135		144	159		152	157		235	304		
10				288	500		104	612		166	501		113	631		
11				198	352		126	564		68	655		189	584		
12				240	469		208	263		177	360		89	627		
13				218	233		226	531		115	123		219	464		
14				196	543		85	85		157	198		158	200		
15				216	226		82	616		62	73		162	167		
Means				211	351	60	140	404	35	128	295	43	266	425	53	50
16				130	620		179	190		218	271		239	296		
17				119	638		155	579		235	548		154	163		
18				127	592		153	436		72	694		211	250		
19				106	622		174	370		76	686		132	438		
20				170	442		39	39		251	539		198	630		
21				96	662		75	75		229	310		141	605		
22				212	334		192	528		150	178		164	566		
Means				137	559	25	138	317	44	176	461	38	177	422	42	36
23				110	599		222	613		85	682		128	526		
24				136	261		234	449		226	574		216	463		
25				289	438		174	174		---	575		137	690		
26				62	62		230	369		---	703		238	378		
27				79	79		184	472		75	692		134	558		
28				283	428		82	716		64	713		157	670		
29				157	157		271	481		266	530		170	617		
Means				159	289	55	200	468	43	143	638	22	169	557	30	34
30				161	519		194	356		232	369		169	644		
May 1				100	653		83	83		232	355		182	635		
2				---	642		126	126		222	529		238	377		
3				92	717		98	98		80	725		150	206		
4				276	467		118	156		188	678		177	639		
5				145	145		302	368		104	730		189	612		
6				184	511		211	298		244	407		263	334		
Means				160	502	32	162	212	76	186	542	34	195	492	40	40
7				253	390		156	182		137	677		256	376		
8				191	240		204	472		102	122		152	730		
9				119	623		269	410		183	217		182	662		
10				214	596		80	744		199	661		262	325		
11				149	149		121	696		220	306		310	563		
12				182	182		182	594		296	547		111	114		
13				116	693		193	400		212	424		162	669		
Means				175	411	43	172	231	74	193	422	46	205	491	42	48

TABLE 1.—*Total solar and sky radiation and diffuse radiation received on a horizontal surface (expressed in langleys per day), and ratios of the diffuse to the total (in percentages). (See p. 2 for explanation of computations of means.)*—Con.

Date	1945			1946			1947			1948			1949			1945–49
	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	Weekly mean ratio ($\Sigma\overline{D}/\Sigma\overline{T}$)
	ly	*ly*	%	*ly*	*ly*	%	*ly*	*ly*	%	*ly*	*ly*	%	*ly*	*ly*	%	%
May 14				312	530		171	230		72	82		186	586		
15				112	112		79	759		96	103		218	677		
16				313	359		175	649		326	257		301	592		
17				203	203		201	661		182	290		239	623		
18				124	124		84	84		100	164		237	627		
19				235	460		---	514		184	295		269	579		
20				279	541		230	361		107	645		46	46		
Means				225	333	68	157	457	34	138	262	53	214	533	40	46
21				190	210		164	176		181	212		96	787		
22				163	777		106	106		64	66		204	222		
23				78	745		177	270		---	142		275	478		
24				135	724		154	622		---	659		233	608		
25				185	671		243	396		146	695		167	606		
26				228	366		227	682		292	415		201	623		
27				129	129		130	721		180	205		37	37		
Means				158	509	31	172	425	40	172	319	54	173	480	36	39
28				98	98		251	568		318	380		324	409		
29				298	391		230	628		244	667		259	540		
30				189	678		156	484		294	573		236	503		
31				220	601		176	649		76	90		144	769		
June 1				135	135		206	652		95	106		161	712		
2				80	80		327	453		278	297		146	730		
3				137	683		112	136		308	555		121	763		
Means				165	381	43	208	510	41	230	382	60	199	624	32	42
June 4				156	216		99	791		288	547		99	774		
5				208	387		224	---		248	578		242	608		
6				162	704		263	606		94	105		78	793		
7				195	533		202	222		80	122		191	682		
8				235	571		45	60		75	86		181	728		
9				---	---		255	360		154	150		177	723		
10				---	772		168	707		98	100		285	688		
Means				191	482	40	179	457	39	148	334	44	179	714	25	35
11				222	488		228	640		200	222		208	701		
12				178	274		132	712		309	374		207	547		
13				205	242		136	746		161	169		151	722		
14				148	702		245	315		71	74		312	520		
15				114	720		206	636		170	687		207	632		
16				131	705		255	577		296	447		154	695		
17				175	642		177	639		292	526		255	590		
Means				167	539	31	197	609	32	214	356	60	214	630	34	37
18				145	145		247	322		185	646		207	572		
19				81	768		252	508		176	687		242	508		
20				136	694		258	508		85	93		228	577		
21				298	319		126	770		141	707		223	599		
22				---	423		92	780		198	694		119	387		
23				121	714		147	771		344	494		107	775		
24				163	677		139	161		132	144		197	682		
Means				157	553	28	180	546	33	180	495	36	189	686	32	32
25				130	681		237	434		210	480		231	577		
26				162	560		211	647		154	726		108	764		
27				180	630		189	691		243	652		234	376		
28				214	593		160	664		241	299		218	603		
29				163	660		230	666		246	552		188	745		
30				273	395		170	671		223	537		356	600		
July 1				262	300		241	624		142	642		185	650		
										178	238					
Means				198	545	36	205	628	33	204*	516*	40	217	616	35	36
2				203	359		86	727		120	724		126	707		
3				111	736		301	675		158	710		264	606		
4				137	737		272	496		164	670		220	597		
5				182	662		258	686		276	464		149	745		
6				285	478		283	591		254	566		230	617		
7				---	664		203	670		106	642		124	775		
8				130	710		231	271		105	735		99	765		
Means				175	614	29	234	588	40	169	636	27	173	687	25	30
9				184	184		210	349		186	681		172	730		
10				297	335		242	546		197	637		168	248		
11				306	408		284	408		---	682		256	662		
12				248	538		268	517		194	618		314	580		
13				115	721		264	622		215	283		211	230		
14				175	657		271	557		162	300		239	655		
15				209	506		231	631		86	719		217	243		
Means				219	428	51	253	519	49	173	539	32	225	478	47	44

*8-day mean.

TABLE 1.—*Total solar and sky radiation and diffuse radiation received on a horizontal surface (expressed in langleys per day), and ratios of the diffuse to the total (in percentages). (See p. 2 for explanation of computations of means.)*—Con.

Date	1945			1946			1947			1948			1949			1945–49
	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	Weekly mean ratio ($\Sigma\overline{D}/\Sigma\overline{T}$)
	ly	*ly*	%	*ly*	*ly*	%	*ly*	*ly*	%	*ly*	*ly*	%	*ly*	*ly*	%	%
July 16				90	761		278	399		104	680		300	424		
17				96	746		204	474		214	642		209	232		
18				94	705		250	516		246	560		263	498		
19				---	650		170	181		283	472		284	526		
20				---	502		284	338		200	611		199	466		
21				122	122		293	439		254	454		146	684		
22				198	198		160	178		103	674		296	398		
Means				120	506	24	234	361	65	200	585	34	242	461	52	42
23				288	321		251	373		191	282		96	733		
24				---	598		96	654		302	573		103	741		
25				257	348		---	568		141	649		129	138		
26				155	568		198	602		281	499		176	671		
27				---	515		212	581		198	290		189	656		
28				---	682		227	368		218	383		233	474		
29				166	618		188	590		120	659		148	639		
Means				217	464	47	195	528	37	207	477	43	154	579	27	38
July 30				269	444		140	639		139	646		191	405		
31				287	382		242	406		136	615		216	223		
Aug. 1				28	28		139	699		191	203		266	488		
2				119	119		120	695		208	489		286	351		
3				---	606		262	572		277	428		193	198		
4				259	476		175	630		264	316		128	136		
5				214	428		213	597		274	408		341	449		
Means				196	313	63	184	606	30	213	414	48	232	322	72	49
6				228	529		139	654		175	204		341	---		
7				31	31		214	445		190	577		171	577		
8				185	495		249	394		134	640		173	621		
9				145	594		130	161		132	583		168	593		
10				200	271		212	501		140	585		138	620		
11				214	544		---	519		164	555		205	495		
12				232	354		152	625		157	162		119	135		
Means				176	402	44	183	463	40	156	472	33	164	507	32	37
13				149	189		173	576		173	203		144	156		
14				81	81		205	518		206	574		166	673		
15				211	622		214	497		88	624		220	541		
16				284	375		70	83		153	562		173	544		
17				286	393		230	289		207	474		217	606		
18				137	596		226	383		194	516		228	297		
19				54	54		241	475		258	368		167	549		
Means				172	330	52	194	403	48	183	474	39	188	481	39	44
20				232	499		65	72		279	377		141	656		
21				284	446		242	278		206	540		114	667		
22				238	394		110	586		233	465		113	636		
23				62	62		141	554		232	372		226	514		
24				164	567		116	569		258	474		204	316		
25				129	585		136	541		200	469		100	616		
26				250	500		132	252		130	501		149	579		
Means				194	436	44	135	408	33	220	457	48	150	569	26	37
27				28	28		134	356		157	401		163	532		
28				112	540		201	242		217	380		209	471		
29				193	230		178	494		156	468		137	154		
30				301	366		203	476		202	413		254	466		
31				181	536		142	442		157	116		219	322		
Sept. 1				144	531		91	526		74	576		201	354		
2				188	380		41	40		93	423		63	618		
Means				164	373	44	141	368	38	148	420	35	178	417	43	40
3				94	513		109	544		---	422		119	531		
4				75	569		79	560		214	295		106	568		
5				193	445		179	275		184	473		191	473		
6				108	544		194	326		179	429		223	435		
7				124	475		170	311		113	496		256	333		
8				165	191		221	338		120	506		253	394		
9				128	128		97	528		152	456		123	176		
Means				127	409	31	150	412	36	160	442	36	182	416	44	37
10				151	198		106	524		186	331		---	597		
11				209	318		174	476		219	335		84	539		
12				182	211		114	501		101	464		120	562		
13				162	464		132	303		108	436		149	160		
14				239	302		110	130		96	463		196	273		
15				128	472		153	328		107	494		156	174		
16				53	507		180	271		69	508		101	514		
Means				161	354	45	139	362	38	126	433	29	134	370	36	38
17				103	470		50	532		182	400		92	511		
18				135	441		68	504		169	346		174	397		
19				94	480		108	136		144	279		129	382		
20				89	463		84	548		46	49		124	422		
21				147	377		156	169		94	471		123	470		
22				187	236		58	58		58	492		166	194		
23				128	128		45	502		122	321		70	82		
Means				126	371	34	81	350	23	117	337	35	126	351	36	32

TABLE 1.—*Total solar and sky radiation and diffuse radiation received on a horizontal surface (expressed in langleys per day), and ratios of the diffuse to the total (in percentages).* (*See p. 2 for explanation of computations of means.*)—Con.

Date	1945			1946			1947			1948			1949			1945–49
	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	Weekly mean ratio ($\Sigma\overline{D}/\Sigma\overline{T}$)
	ly	*ly*	%	*ly*	*ly*	%	*ly*	*ly*	%	*ly*	*ly*	%	*ly*	*ly*	%	%
Sept. 24				137	151		197	277		114	342		168	359		
25				181	226		82	99		65	433		76	508		
26				77	431		---	498		76	436		75	469		
27				77	445		---	504		74	423		138	364		
28				116	370		---	482		82	417		50	50		
29				150	370		---	484		98	419		93	93		
30				64	64		93	202		186	262		154	255		
Means				114	294	39	124	193	64	99	390	25	108	300	36	38
Oct. 1				146	298		55	495		144	292		47	499		
2				129	216		182	230		95	315		80	412		
3				53	446		118	404		204	322		54	473		
4				55	409		86	412		84	414		192	287		
5				50	404		114	364		195	223		135	218		
6				55	396		110	392		198	258		84	431		
7				51	405		74	392		159	227		175	333		
Means				120	367	33	106	384	28	154	293	53	110	379	29	34
8				120	293		176	310		59	59		126	145		
9				130	388		104	394		70	345		114	116		
10				181	233		101	380		100	319		106	341		
11				52	397		60	401		128	131		118	236		
12				146	175		---	408		164	204		63	392		
13				44	400		---	330		90	310		68	384		
14				50	384		49	412		125	133		40	410		
Means				103	324	32	98	379	26	105	214	49	91	289	31	33
15				91	330		50	387		101	299		97	117		
16				85	310		61	368		70	362		39	413		
17				113	307		57	369		82	311		89	356		
18				56	56		126	252		21	21		152	244		
19				49	389		118	156		67	359		95	358		
20				125	288		82	341		---	151		82	330		
21				55	359		52	375		123	149		45	346		
Means				82	291	28	78	321	24	78	250	31	86	309	28	28
22				53	345		43	388		70	289		73	82		
23				46	338		72	312		122	123		42	354		
24				88	281		105	340		3	3		56	67		
25				81	302		132	336		19	19		158	220		
26				120	143		130	250		71	74		97	139		
27				110	300		---	302		58	292		35	362		
28				122	136		102	274		57	270		52	331		
Means				89	264	34	98	317	31	57	153	37	73	222	33	33
29	116	194		117	153		67	72		102	262					
30	82	233		112	181		42	44		55	295					
31	106	243		67	231		48	52		63	270					
Nov. 1	50	317		72	304		58	94		118	253					
2	132	199		64	64		31	312		48	305					
3	80	208		76	76		100	235		109	216					
4	9	9		108	165		59	62		16	16					
Means	82	200	41	88	168	52	58	124	47	73	231	32				42
5	104	208		37	313		89	94		96	131					
6	44	287		48	296		47	54		78	80					
7	89	182		74	272		86	147		49	119					
8	64	246		45	45		49	57		51	252					
9	125	158		97	131		51	236		109	222					
10	37	37		90	208		36	288		53	53					
11	50	50		40	40		102	183		35	266					
Means	72	167	43	62	186	33	66	151	44	67	160	42				40
12	53	53		49	248		8	11		98	104					
13	52	52		40	270		39	266		26	26					
14	27	27		67	175		49	274		69	259					
15	84	177		86	219		90	257		113	145					
16	69	163		37	270		105	174		59	212					
17	107	128		63	63		46	262		28	28					
18	52	61		83	202		38	270		40	236					
Means	64	94	68	61	207	29	54	216	25	62	144	43				36
19	80	164		51	250		45	259		47	205					
20	61	80		100	220		115	159		12	12					
21	46	235		109	156		47	250		71	175					
22	25	25		24	24		115	156		46	46					
23	76	187		44	186		70	91		7	7					
24	46	214		111	172		77	107		14	14					
25	53	188		92	102		95	174		12	12					
Means	55	156	35	76	159	48	80	171	47	30	67	45				44
26	51	202		59	98		69	196		60	188					
27	58	190		26	218		41	229		21	49					
28	89	89		79	176		35	57		87	144					
29	23	23		95	150		72	149		9	9					
30	38	38		87	112		38	210		47	211					
Dec. 1	76	76		68	81		22	226		85	91					
2	71	176		82	128		68	136		32	213					
Means	58	113	51	71	138	51	49	172	28	49	129	38				41

TABLE 1.—*Total solar and sky radiation and diffuse radiation received on a horizontal surface (expressed in langleys per day), and ratios of the diffuse to the total (in percentages). (See p. 2 for explanation of computations of means.)*—Con.

Date	1945			1946			1947			1948			1949			1945–49
	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	D	T	$\overline{D}/\overline{T}$	Weekly mean ratio ($\Sigma\overline{D}/\Sigma\overline{T}$)
	ly	*ly*	%	*ly*	*ly*	%	*ly*	*ly*	%	*ly*	*ly*	%	*ly*	*ly*	%	%
Dec. 3	74	74		76	180		67	158		66	80					
4	57	57		60	170		33	213		80	84					
5	96	126		70	111		24	31		78	160					
6	23	23		36	36		40	210		9	9					
7	17	17		77	158		66	204		37	196					
8	31	204		75	134		14	22		54	132					
9	54	151		43	43		69	173		79	123					
Means	50	93	43	62	119	52	45	145	31	58	112	52				46
10	38	38		68	128		31	204		76	101					
11	34	224		25	199		46	181		71	156					
12	31	235		58	83		37	197		47	55					
13	76	193		39	172		27	201		30	197					
14	74	74		38	201		40	205		24	220					
15	101	131		78	151		57	164		70	86					
16	66	130		28	217		53	140		27	27					
Means	60	146	41	48	164	29	42	185	23	49	120	41				32
17	42	204		24	24		40	195		66	146					
18	40	199		53	53		51	113		28	197					
19	20	20		66	182		37	200		30	31					
20	50	198		62	62		42	201		64	181					
21	44	216		17	17		59	147		78	133					
22	71	184		78	147		46	211		31	186					
23	37	226		---	158		29	32		32	192					
Means	43	178	24	50	81	62	43	157	27	47	152	31				32
24	32	220		---	136		51	218		23	221					
25	130	130		---	151		40	227		91	129					
26	78	78		74	136		27	28		27	231					
27	54	94		111	183		64	65		90	151					
28	38	203		16	16		98	107		69	132					
29	18	18		33	33		46	233		43	57					
30	96	159		66	206		38	226		36	39					
31	29	29		126	126		84	118		13	13					
Means	59	116	51	71	117	61	56	153	37	49	121	40				46
Yearly total	3,876	8,974		43,502	113,617		44,453	117,850		44,838	113,047		42,721	118,479		
Number of days	64	64		349	349		348	348		359	359		295	295		
Yearly mean daily	60.6	140.2		124.6	325.6		127.7	338.6		124.9	314.9		144.8	401.6		
Yearly ratio $\left(\frac{\Sigma D}{\Sigma T}\right)\times 100\%$			43.2			38.3			37.7			39.7			36.1	
Yearly mean weekly ratio—$\Sigma\left(\frac{\overline{D}}{\overline{T}}\right)\times 100\%$			43.0			38.5			38.5			39.1			36.7	
4-year mean daily ratio																38.0

minimum values of the ratio occur in the weeks beginning January 22 and October 15, respectively, or at approximately the periods of maximum and minimum average cloudiness. Percentage of bright sunshine data recorded at Blue Hill Observatory show slightly less sunshine during the winter months.

Table 2 shows the monthly and the mean monthly distribution of the daily ratios of diffuse total solar and sky radiation received on a horizontal surface for various categories of possible sunshine. Each ratio is a mean value of the daily ratios for cases falling in the given category, and is computed by the formula $(1/n)\ \Sigma\ (D/T)\times 100\%$, where the summation is over the n daily ratios D/T falling in each category. The percentages of bright sunshine were obtained from the Campbell-Stokes sunshine recorder [9] at Blue Hill Observatory. Owing to the variability in the amount of cloudiness and the uneven number of cases in each category, the distribution of ratios is somewhat irregular.

Figure 2 is a plot of the mean monthly ratios (from bottom of table 2) against the percentage of possible sunshine. In spite of having only 4 years of data for the comparison, the figure shows a fairly smooth curve. In general, greater discrepancies appear with percentages of bright sunshine ranging from 20 to 70 percent than with meager or abundant sunshine. This probably is due to the greater accuracy with which the record of the Campbell-Stokes sunshine recorder may be evaluated when the sky is either cloudless or completely obscured. As expected, the value of

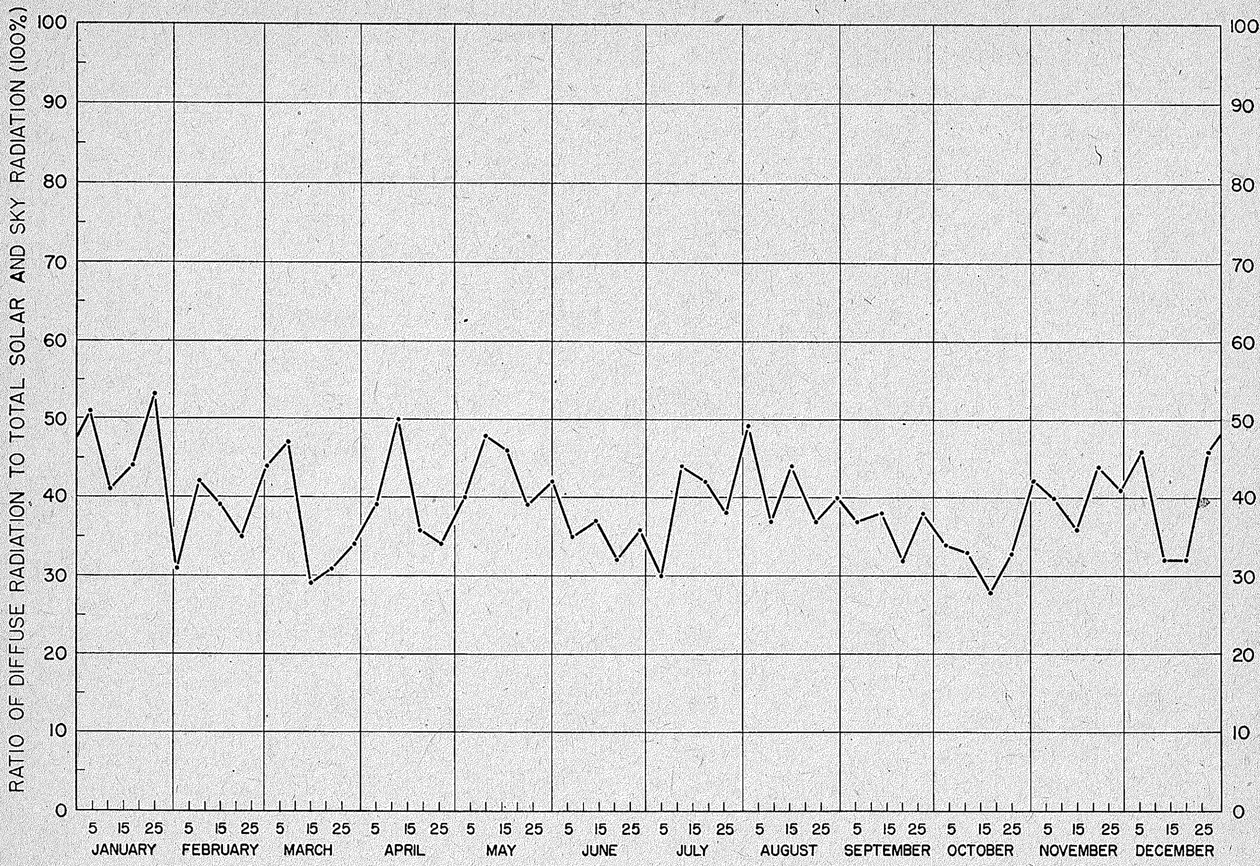

FIGURE 1.—Annual march of the ratio of diffuse radiation to total solar and sky radiation received on a horizontal surface at Blue Hill Observatory, Milton, Mass. The plotted values are weekly means of the ratio, computed from daily measurements from November 1945 through October 1949 by the formula $(\Sigma\overline{D}/\Sigma\overline{T}) \times 100\%$, where $\overline{D}$ and $\overline{T}$ are weekly means of the daily values of diffuse and total radiation and the summations are over the four values for a given weekly period for the 4 years of record.

the ratio of diffuse radiation to total solar and sky radiation shows a rather steady decrease in the ratios as the percentage of sunshine increases. (See table 2 and fig. 2.)

METHOD OF MEASUREMENT

INSTRUMENTAL EQUIPMENT

The equipment in use at Blue Hill Observatory for measuring diffuse radiation consists of a pyrheliometer [10] of the same type used for total solar and sky radiation measurements and an occulting ring positioned so that it shades the pyrheliometer from the direct solar radiation at all times and permits the pyrheliometer to measure only the scattered radiation received from the sky.

The occulting ring in use at Blue Hill Observatory was designed by the Instrument Division of the U. S. Weather Bureau (see fig. 3). It is constructed of pipe having an outside diameter of two inches formed into a circular ring with a 20-inch radius. This ring is mounted so that its plane is in the plane of the apparent path of the sun's diurnal march across the sky. The ring is moved up or down on its two parallel supporting pipes, without changing the position of its plane in space, to allow for the seasonal change in declination of the sun. The angle of the two supporting pipes depends upon the latitude of the station, and, once established, needs no further adjustment. The ring is checked at least once daily to make certain that it is shading properly, although, on the average, adjustments are necessary only once every 4 or 5 days. Close to the summer and winter solstices, when the sun's maximum altitude is changing very little from day to day, adjustment is required only once every 7 or 8 days; near the spring and fall equinoxes when the sun's maximum altitude shows most daily change, adjustment is required at least once every 2 days.

The pyrheliometer is mounted at the center of the occulting ring so that throughout the year its average distance from the ring is 20 inches. Com-

TABLE 2.—*Monthly distribution of the daily ratios of diffuse to total solar and sky radiation received on a horizontal surface with percentage of sunshine, during 4-year period, November 1945 through October 1949, at Blue Hill Observatory, Milton, Mass. The mean value of the ratio shown in each category was computed as explained on p. 8.*

Month		PERCENT SUNSHINE											
		0	1–9	10–19	20–29	30–39	40–49	50–59	60–69	70–79	80–89	90–99	100
Jan	Mean ratio, %	100	92	92	70	61	49	41	37	37	30	18	17
	Cases	40	9	7	4	3	5	6	8	4	15	12	7
Feb	Mean ratio, %	100	86	72	68	56	49	52	43	39	22	19	14
	Cases	19	9	3	4	7	1	3	9	4	11	22	5
Mar	Mean ratio, %	100	90	70	71	61	61	38	40	29	28	18	12
	Cases	13	9	4	9	6	8	5	7	9	12	27	12
Apr	Mean ratio, %	100	86	84	73	58	46	44	36	34	28	18	11
	Cases	18	6	6	7	7	11	8	7	11	15	19	3
May	Mean ratio, %	100	88	81	68	56	48	55	40	34	30	22	11
	Cases	21	12	5	13	2	5	9	8	14	12	13	5
June	Mean ratio, %	100	88	73	52	58	50	48	41	31	31	22	10
	Cases	12	4	5	4	6	7	5	16	10	20	24	1
July	Mean ratio, %	100	82	82	75	63	54	52	45	32	26	20	-------
	Cases	3	9	5	8	9	10	9	13	10	20	21	0
Aug	Mean ratio, %	100	86	81	77	67	57	52	45	41	29	24	19
	Cases	13	7	8	2	9	6	9	13	9	25	17	2
Sept	Mean ratio, %	100	85	70	73	58	54	41	32	32	26	19	14
	Cases	9	7	7	6	7	10	8	7	8	7	31	9
Oct	Mean ratio, %	100	91	81	79	70	55	54	43	44	29	17	15
	Cases	6	9	5	7	4	7	3	8	12	11	24	18
Nov	Mean ratio, %	100	89	85	68	54	54	45	49	30	20	20	14
	Cases	29	6	4	11	5	5	9	7	10	7	18	8
Dec	Mean ratio, %	100	88	80	73	69	45	44	44	29	19	18	13
	Cases	32	3	5	7	4	9	8	7	11	10	21	4
Mean monthly ratio, %		100	88	79	71	61	52	47	41	34	26	20	14
Total cases		215	90	64	82	69	84	82	110	112	165	249	74

bined with the 2-inch diameter of the pipe forming the occulting ring, this gives a 10 to 1 ratio for the distance of the shade from the target to the diameter of the shade. This corresponds to the distance/diameter ratio generally used in previous diffuse radiation measurements. It is perhaps worth noting in passing that the same ratio of 10 to 1 has been adopted as standard in the instruments used in this country for measuring direct solar radiation at normal incidence [11, 12].

The receiver employed for these measurements is a 50-junction Eppley 180° pyrheliometer of the same general type as the 10-junction pyrheliometers [10] used for obtaining measurements of total solar and sky radiation at all stations in the Weather Bureau network. A 50-junction pyrheliometer was chosen for this work since quantities of diffuse radiation received are generally small, necessitating a sensitive instrument. Except for two short periods during experimenting and standardizing procedures, the same Eppley pyrheliometer (No. 516) has been in continuous service from October 1945 to the present time.

A Leeds and Northrup micromax potentiometer with two scales serves as a recorder. The use of this dual scale is necessary owing to the great range of diffuse radiation received with different amounts of cloudiness and the relatively high response of the pyrheliometer (7.58 millivolts per langley per minute). The potentiometer has a switching device whereby the full-scale deflection may be changed from 3 to 15 millivolts as needed. The 3-millivolt scale is used whenever possible in order to record the more minute variations of the radiation and to make fuller use of the record paper; the 15-millivolt scale is used when the trace approaches the top of the chart. For example, on overcast days when all the radiation received is diffuse, but with the overcast thin enough to transmit a large amount of radiation, the voltage generated exceeds 3 millivolts, necessitating a change to the 15-millivolt scale. Nearly all the measurements have been obtained on the potentiometer described above, except during a few short periods when the record was switched to other potentiometers for comparative purposes.

One factor producing improper exposure that cannot be ignored when evaluating the diffuse record is the icing sometimes experienced at Blue Hill in winter. At this latitude and elevation (42°13′ N., 635 feet MSL), the pyrheliometer and occulting ring are occasionally coated with glaze, rime, or both. The ice is removed immediately after formation has ceased and the record made during icing conditions is corrected by interpolating as accurately as possible. If icing continues for a number of hours, interpolation can be per-

3. Response and accuracy of the potentiometers.
4. Comparison of records obtained with similar and with dissimilar equipment.
5. Amount of diffuse radiation lost or gained because of excess or incomplete shading by the occulting ring.
6. Accuracy obtainable in the analysis of the records.

COMPARISON OF RECORDS

checks against the Weather Bureau standard instruments and have, with one exception,[3] maintained a constant e. m. f. during the period of the comparisons. While we have found that this type of pyrheliometer is consistent in its behavior, its construction introduces some complications worthy of mention. There is a certain amount of disagreement among pyrheliometrists as to the error introduced by such factors as the angle of the solar rays striking the spherical glass covering around the receiving surface, the effect of reflections from the glass, and the fluctuations of the temperature of the outside air. No attempt has been made in connection with this study to investigate these factors, but such studies were made by the National Bureau of Standards [14] and by MacDonald [15].

Differences in sensitivity of the pyrheliometers produce an important effect on the potentiometers upon which the measurements are recorded. In a comparison where one pyrheliometer is approximately five times as sensitive as another, one instrument will be recording in the vicinity of five times as high a millivolt value as the other. Obviously, an error of even a fraction of a scale line, whether due to the equipment or to the analyst, will make a much greater percentage error on the less sensitive equipment.

RESPONSE AND ACCURACY OF POTENTIOMETERS

In a comparison of 50-junction and 10-junction pyrheliometers, all differences are not necessarily due to the pyrheliometers themselves, but may also be due to the potentiometers upon which they are recorded. Tests made by introducing a known potential from a portable potentiometer show that it requires approximately 0.05 millivolt to start most continuously recording potentiometers operating after they have been registering zero radiation.[4] With the 50-junction pyrheliometer recording diffuse radiation, the 0.05 millivolt represents only 0.0066 langley of incoming radiation, while with the 10-junction instrument recording total radiation it represents 0.0302 langley. This initial lag of the potentiometer has little effect on the total langley received in a day, but has a considerable effect in any hourly comparisons near sunrise. Some potentiometers also show a reluctance to return to zero at sunset, maintaining a slightly off-zero position for an hour or more after sunset. The point at which the instrument stops in its descent appears to be where the incoming radiation falls below approximately 0.05 millivolt in voltage intensity. Under such conditions, comparisons during the sunset hour are of little value.

Inaccuracy or a difference in the sensitivity of the recording potentiometers could be a possible explanation for the lack of agreement between records, so the recorders in use were checked against two portable potentiometers and against each other. The manufacturer specifies an accuracy of ±0.06 millivolt for their continuously recording potentiometer, and our tests verify this figure. It should be pointed out, however, that with the small radiation values usually obtained in diffuse and overcast-day total radiation measurements, an error of ±0.06 millivolt can be significant, especially if combined with other unavoidable errors occurring in the recording and analysis of the records.

COMPARISONS OF EQUIPMENT

To acquire some idea of the differences to be expected between records obtained from similar potentiometer-pyrheliometer combinations measuring the same radiation, two short-period comparisons were made during April, May, and June 1948. These comparisons utilized: (1) A galvanometer-type potentiometer and a 10-junction pyrheliometer (combination A) versus an electronic potentiometer with a 10-junction pyrheliometer (combination B); (2) Combination A versus another galvanometer-type potentiometer with a third 10-junction pyrheliometer (combination C). Combination A, which was accepted as the basis for comparison in both series, was the potentiometer-pyrheliometer combination which was recording total solar and sky radiation at the time. In the first series, the daily totals for 22 days for combination A averaged 3 percent higher than for B. In the second series, the daily totals for 16 days for combination A averaged 3 percent

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[3] The pyrheliometer used for the total radiation measurements for the period October 1945 to July 1948 showed an increased e. m. f. when checked in 1945 (October); later exhaustive checks indicated an e. m. f. equivalent to the one used before October 1945, so the intervening value was discarded as too high and records from the period were corrected to agree with previous ones. The check made in 1945 was a poor one, since it was a brief comparison and was made between a 10-junction and a 50-junction pyrheliometer. The apparent impossibility of an instrument increasing its e. m. f. is sufficient cause for doubting the intermediate value.

[4] This applies to the galvanometer-type potentiometer in use in the past at the U. S. Weather Bureau solar stations. New electronic potentiometers recently installed at a great many of the stations are more sensitive in this respect.

higher than for C. A comparison of the percentage deviation and the percentage of possible bright sunshine on each of the days covered in the two series showed that the largest percentage deviations generally occurred with high percentages of cloudiness. Analysis of this difference for a longer period has been impossible at Blue Hill because all recording equipment at the station is in constant use and cannot be spared for testing purposes without interrupting some record.

In order to determine what differences to expect between records made with dissimilar equipment, comparisons were made between: (1) Two 50-junction pyrheliometers, Nos. 516 and 439, and (2) the 50-junction No. 516 and a 10-junction pyrheliometer, No. 498. (No. 516 is the pyrheliometer used to record diffuse radiation; No. 498 is the pyrheliometer used to record total radiation). These tests were made on two clear days, July 2 and 8, 1948, with the occulting ring so adjusted that the sun shone directly on the receiving surface of the diffuse pyrheliometer and both instruments were thus recording total radiation for the test period. Simultaneous readings were obtained from both records at specified moments and their ratios were computed. In the first comparison (62 readings), the ratio of No. 516 to No. 439 was 100 percent; in the second (80 readings), the ratio of No. 516 to 498 was 93 percent. Although brief, the comparisons indicate that there is much closer agreement between records made with similar equipment than with dissimilar equipment.

SHADING BY OCCULTING RING

The actual angular *area* of the sky cut off by the occulting ring is about 5 percent of the total area of the sky. The *percentage* of radiation cut out by the ring is slightly more or less than this, depending upon the sky conditions. On a cloudless day, a small part of the area obscured by the ring, being adjacent to the sun, is the brightest portion of the sky; under these conditions the radiation cut out is undoubtedly somewhat more than 5 percent. However, this 5 percent will represent a very small amount when expressed in langleys, since the diffuse radiation is smallest on cloudless days. On an overcast day, when diffuse radiation is greatest, the brightness of the sky immediately around the sun will approximate that from the rest of the sky much more than on a clear day, and the percentage of the radiation lost will be nearly equal to the area of the sky obscured. The exact amount of diffuse radiation lost because of the occulting ring would be difficult to determine because of its variation with the amount of cloudiness; since it is such a small amount under any conditions, no adjustment of factor has been made to compensate for it in the evaluation of the record. The frequency of cases when the diffuse has recorded more radiation than the total, in spite of this excess shading, indicates that other factors often more than compensate for it. Reflections from the glass cover of the pyrheliometer, the occulting ring and surrounding objects, the extra sensitivity of the 50-junction pyrheliometer recording the diffuse radiation, the lesser effect of the lag in starting of the potentiometer on the record made with the 50-junction pyrheliometer, and the greater accuracy obtainable in the analysis of the diffuse record because of its fewer sudden variations may all have such a compensating effect.

The effect of incomplete shading on the amount of diffuse radiation recorded varies in proportion to the amount of receiving surface of the pyrheliometer that is exposed to direct sunlight. Trials with deliberate exposure of varying areas of receiving surface indicate that if direct solar radiation impinges upon both the black absorbing and white reflecting rings, (see [13, 16] for description of instrument) the recorded radiation intensity shows a sudden increase, while if only the outer reflecting ring is exposed, no effect is noticeable. Due to the difficulty of determining the exact percentage of the receiving surface exposed to direct radiation, it is impracticable to attempt to obtain a quantitative correlation with the increase in radiation recorded. The fact that such incomplete shading is seldom obvious on the trace is the chief reason why daily checks are made on shading conditions, even though the diurnal change in solar declination does not necessitate a daily change in the position of the occulting ring.

ACCURACY OF ANALYSIS OF RECORDS

Since records are evaluated by determination of the area below the trace, the analyst can unconsciously influence the record to a small extent. On days of variable cloudiness, particularly those with summer cumuli, the total radiation trace appears as a series of closely spaced vertical lines and is almost impossible to evaluate with any great degree of accuracy—even with the use of a planimeter. The diffuse record, being constantly shaded from direct sunlight, has much less variation and can be evaluated more accurately than the total. Comparisons between the diffuse and the total on days when the latter shows great variation obviously are affected by the difficulty of the reduction of the total radiation record.

CONCLUSION

Results of measurements of diffuse radiation received on a horizontal surface at Blue Hill Observatory from October 29, 1945, through October 28, 1949, have been presented. For the 4-year period, the diffuse radiation was 38 percent of the total solar and sky radiation received on a horizontal surface. Year-to-year percentages showed remarkable consistency. The annual march of the ratio of diffuse to total radiation was irregular but showed a tendency to be slightly higher in winter than in summer. As expected, the ratio of diffuse to total radiation, when plotted against percentage of possible sunshine, showed a rather steady decrease with increasing sunshine, though, with only 4 years data, a completely smooth curve could not have been obtained. It is hoped that the curve may be replotted in the future when more data may be incorporated.

The instrumental equipment used in obtaining the measurements has been described and the problems encountered investigated briefly. It is concluded that the method of measurement of diffuse radiation here described gives results that are of equal accuracy with other radiation measurements being made currently. Present-day equipment to measure radiation has some important limitations, and the effect of the limitations on the radiation measurements made at Blue Hill has been discussed, along with some limiting factors that are peculiar to the diffuse radiation equipment alone. Various comparisons between different records and different equipment led to the following conclusions:

1. The variability of sky conditions will have an effect on all radiation records—with uniform sky conditions (clear or overcast) yielding a more accurate record than skies with intermittent cloudiness—both because of the sensitivity of the receiving equipment and because there is less difficulty in the graphical evaluation of the record. Higher radiation values tend to be more accurate than low for the same reasons—sensitivity of the equipment and greater ease in record evaluation.

2. The pyrheliometers themselves have some limitations that are inherent in the design of the instrument, the principal limitation being the necessity for enclosing the receiving surface in a glass sphere. Each individual pyrheliometer differs from others in its sensitivity and the 50- and 10-junction pyrheliometers differ, with the 50-junction being more sensitive and more accurate.

3. The potentiometers may introduce small errors in the record with low radiation values for two reasons: the lag in the initial response of the potentiometer, and the fact that the specified accuracy limit of ± 0.06 millivolt might have a significant effect on very low values.

4. The more similar the equipment used in any comparison of records, the finer the degree of accuracy that will be obtained. The dissimilarities in the equipment used to obtain the ratios of diffuse to total radiation in this paper are felt to be the cause of the discrepancies shown.

5. While the *angular area* of the sky cut off by the occulting ring is about 5 percent of the total area, and while the actual percentage of *radiation* cut out may be slightly more, comparisons and tests made by the authors indicate that other factors (reflections from the glass pyrheliometer cover or surrounding objects and the extra sensitivity of the diffuse equipment) almost always compensate, and very often over-compensate for the loss.

Because of the number of variables present in the procedure of measuring radiation and the seemingly impossible task of determining how the variables combine to influence the values at specific times, particularly for past records, no quantitative evaluation of possible errors has been attempted here, except for the comparisons made between the records on totally overcast days. In these comparisons the radiation measured was identical but the equipment was dissimilar and the daily ratios of diffuse to total radiation varied mostly between 85 and 110 percent, while yearly ratios varied between 88 and 100 percent. These figures should give a good estimate of the maximum magnitude of discrepancy to be expected in the comparisons in this paper and in those made under similar conditions. Although the comparisons were made under fairly uniform sky conditions, it is estimated that differences would be approximately the same under nonuniform sky conditions since they are chiefly of an instrumental nature. Individual days may show considerable deviation, but a long-term average would be expected to show a high percentage of agreement.

The relationship of diffuse radiation to the total radiation has been of interest to meteorologists and physicists for many years, principally in their determinations of the heat balance of the atmosphere. Numerous calculations have been made and a few measurements obtained, but most of the latter have been over short periods only. The difficulties of obtaining precise measurements of diffuse radiation have made it one of the least-investigated subjects in radiation studies. Experimentation with equipment for such measurements has lagged far behind similar experimentation for measurement of direct radiation and total radiation, and there is a need for more work in this field. Continuous measurements are needed in widely scattered regions in order to obtain a complete picture of this important portion of our incoming radiation. It is to be hoped that such measurements may be undertaken and that further experimentation will be made with radiation equipment.

REFERENCES

1. H. Landsberg, *Physical Climatology*, Pennsylvania State College, School of Mineral Industries, State College, Pa., 1941, pp. 91–92.
2. I. F. Hand, "Atmospheric Contamination over Boston, Massachusetts," *Bulletin of the American Meteorological Society*, vol. 30, No. 7, September 1949, pp. 252–254.
3. H. H. Kimball, "The Effect upon Atmospheric Transparency of the Eruption of Katmai Volcano," *Monthly Weather Review*, vol. 41, No. 1, January 1913, pp. 153–159.
4. H. H. Kimball and I. F. Hand, "Investigations of the Dust Content of the Atmosphere," *Monthly Weather Review*, vol. 59, No. 9, September 1931, pp. 349–352.
5. H. H. Kimball, "Measurements of Solar Radiation Intensities and Determinations of Its Depletion by the Atmosphere with Bibliography of Pyrheliometric Measurements," *Monthly Weather Review*, vol. 55, No. 4, April 1927, pp. 155–169.
6. H. H. Kimball, "Variations in the Total and Luminous Solar Radiation with Geographical Position in the United States," *Monthly Weather Review*, vol. 47, No. 11, November 1919, pp. 769–793. (See p. 785.)
7. H. H. Kimball and I. F. Hand, "Sky-Brightness and Daylight Illumination Measurements," *Monthly Weather Review*, vol. 49, No. 9, September 1921, pp. 481–488.
8. H. H. Kimball and I. F. Hand, "Daylight Illumination on Horizontal, Vertical, and Sloping Surfaces," *Monthly Weather Review*, vol. 50, No. 12, December 1922, pp. 615–628.
9. C. F. Brooks and E. S. Brooks, "Sunshine Recorders: A Comparative Study of the Burning-Glass and Thermometric Systems," *Journal of Meteorology*, vol. 4, No. 4, August 1947, pp. 105–115.
10. I. F. Hand, *Pyrheliometers and Pyrheliometric Measurements*, U. S. Weather Bureau, Washington, D. C., 1946, pp. 7–11.
11. C. G. Abbot, "The Silver Disk Pyrheliometer," *Smithsonian Miscellaneous Collections*, vol. 56, No. 19, Washington, D. C., 1911, 11 pp.
12. C. G. Abbot and L. B. Aldrich, "The Standard Scale of Radiation," *Smithsonian Miscellaneous Collections*, vol. 92, No. 13, Washington, D. C., 1934, 3 pp.
13. U. S. Weather Bureau, Multiple Address Letter to All Solar Radiation Stations, Washington, D. C., March 10, 1948, p. 1.
14. National Bureau of Standards, Report on Two Pyrheliometers, Division of Optics, Washington, D. C., May 10, 1946. (Unpublished.)
15. T. H. MacDonald, "Some Characteristics of the Eppley Pyrheliometer," *Monthly Weather Review*, vol. 79, No. 8, August 1951, pp. 153–159.
16. I. F. Hand, "Review of United States Weather Bureau Solar Radiation Investigations," *Monthly Weather Review*, vol. 65, No. 12, December 1937, pp. 415–441. (See p. 419.)

SELECTED BIBLIOGRAPHY ON DIFFUSE RADIATION

Occasional needs arise for a bibliography covering the portion of the literature on solar radiation concerned primarily with its diffuse component. Since, to the knowledge of the present authors, no such bibliography is available, it is to be hoped that a complete bibliography on the subject may be compiled at some future date. In the meantime, it is felt that the following listing of the small number of articles which have come to our attention in connection with the work reported in this paper might be of value to others interested in the subject.

1882 S. P. Langley, "Sun Light and Sky Light at High Altitudes," *American Journal of Science*, v. 24, 1882, pp. 393–398.

1908 Smithsonian Institution, *Annals of the Astrophysical Observatory*, vol. 2, pt. 2, chap. 3, "Indirect Solar Radiation," 1908, pp. 146–158.

1912 J. Patterson, "Comparison of the Ångstrom Pyrheliometer and the Calendar Sunshine Recorder, and the Determination of the Proportion of Heat Received on a Horizontal Surface from the Diffuse Radiation from the Sky to that Received from the Sun," *M. S. 50*, Canada Meteorological Service, Ottawa 1912, 21 pp.

1913 L. V. King, "On the Scattering and Absorption of Light in Gaseous Media with Application to the Intensity of Sky Radiation," *Philosophical Transactions of the Royal Society of London*, Series A, vol. 212, 1913, pp. 375–433.

1916 C. G. Abbot and L. B. Aldrich, "The Pyranometer—An Instrument for Measuring Sky Radiation," *Smithsonian Miscellaneous Collections*, vol. 66, No. 7, 1916, 9 pp.

C. G. Abbot and L. B. Aldrich, "On the Use of the Pyranometer," *Smithsonian Miscellaneous Collections*, vol. 66, No. 11, 1916, 9 pp.

1919 A. Ångström, "A New Instrument for Measuring Sky Radiation," *Monthly Weather Review*, vol. 47, No. 11, November 1919, pp. 795–797.

A. Ångström, "Some Problems Relating to the Scattered Radiation from the Sky," *Monthly Weather Review*, vol. 47, No. 11, November 1919, pp. 797–798.

1920 A. Mallock, "Diffusion of Light by Rain, Cloud, or Fog," *Proceedings of the Royal Society of London*, Series A, vol. 96, 1920, pp. 267–272.

Abstract by W. J. Humphreys, *Monthly Weather Review*, vol. 48, No. 4, April 1920, p. 220.

A. F. Moore and L. H. Abbot, "The Brightness of the Sky," *Smithsonian Miscellaneous Collections*, vol. 71, No. 4, 1920, 36 pp.

R. W. Wood, "Light Scattering by Air and the Blue Color of the Sky," *London, Edinburgh, and Dublin Philosophical Magazine*, Series 6, vol. 39, No. 232, April 1920, p. 433. Author's abstract, *Monthly Weather Review*, vol. 48, No. 4, April 1920, p. 220.

A. Boutaric, "Relation between the Absorption of Solar Radiation by the Atmosphere and the Polarization of Diffuse Sky Light," *Journal de Physique*, t. 9, juillet 1920, pp. 239–256. Abstract by M. A. Giblett, *Monthly Weather Review*, vol. 49, No. 1, January 1921, p. 26. Also in *Science Abstracts*, Sect. A, vol. 23, Abstract No. 1539, December 1920.

1921 A. Ångström and C. Dorno, "Registration of the Intensity of Sun and Diffused Sky Radiation," *Monthly Weather Review*, vol. 49, No. 3, March 1921, pp. 135–138. (Translated by C. L. Meisinger.)

J. Vallot, "Comparison of Diffuse and Direct Solar Radiation," *Comptes Rendus des Séances de l'Académie des Sciences*, t. 172, 9 Mai 1921, pp. 1164–1167. Abstract by M. A. Giblett, *Monthly Weather Riview*, vol. 49, No. 9, September 1921, p. 488. Also in *Science Abstracts*, Sect. A, vol. 24, Abstracts No. 1384, August 1921.

1924 A. Ångström, "Report to the International Commission for Solar Research on Actinometric Investigations of Solar and Atmospheric Radiation," *Quarterly Journal of the Royal Meteorological Society*, vol. 50, No. 210, April 1924, pp. 121–126. (Paper presented at meeting of the International Commission, Utrecht, September 4–6, 1923.)

1927 H. H. Kimball, "Measurements of Solar Radiation Intensity and Determinations of Its Depletion by the Atmosphere, with Bibliography of Pyrheliometric Measurements," *Monthly Weather Review*, vol. 55, No. 4, April 1927, pp. 155–169. (See p. 156.)

1929 N. N. Kalitin, "A Simple Method of Measuring the Diffused Radiation of the Sky According to Zones," *Monthly Weather Review*, vol. 57, No. 2, February 1929, pp. 52–54. (With discussion by H. H. Kimball.)

H. H. Kimball, "Kalitin on Illumination of Diffused Light During the Solar Eclipse, June 29, 1927," *Monthly Weather Review*, vol. 57, No. 4, April 1929, pp. 159–160. (Review of article by N. N. Kalitin, *Geografiska Annaler*, H. 3, 1928.)

1931 L. Gorczyński, "Quelque Mesures du Rayonnement solaire diffusé par la Voûte céleste obtenues avec les Solarimètres dans les Alpes-Maritimes," *Comptes Rendus des Séances de l'Académie des Sciences*, t. 192, 4 Mai 1931, p. 1119.

1932 C. F. Brooks, "What the Atmosphere Does to Solar Radiation," *Bulletin of the American Meteorological Society*, vol. 13, No. 12, December 1932, pp. 217–220.

1933 L. Gorczyński, "Sur la Part du Rayonnement solaire diffusé par la Voûte céleste, dans les Sommes d'Insolation," *Comptes Rendus des Séances de l'Académie des Sciences*, t. 196, 13 Mars 1933, p. 801.

1935 E. Kleinschmidt, *Handbuch der Meteorologische Instrumente und ihrer Auswertung*, pp. 152–168, "Die Messgeräte der kurtzwellingen diffusen Strahlung des ganzen Himmels und der Reflexstrahlung der Erdoberfläche," J. Springer-Verlag, Berlin, 1935.

1936 N. N. Kalitin, "De la Radiation diffusé dans la Région des Ondes courtes, Observées Pendant le Ciel sans Nuage," *Journal of Geophysics*, vol. 6, Moscow, 1936, pp. 331–338. (In Russian; summary in French, p. 339.)

N. N. Kalitin, "On the Quantities of Dispersed Radiation of the Atmosphere in the Arctic," *Arctica*, No. 4, Leningrad, 1936, pp. 121–134. (In Russian; summary in English, p. 135.)

N. I. Mousalkov et A. N. Gordow, "Sur la Diffusion de l'Energie radiare dans les Brouillards," *Journal of Geophysics*, vol. 6, Moscow, 1936, pp. 419–423. (In Russian; summary in French, p. 424.)

1937 R. Failletaz, "La Radiation solaire et le Trouble atmosphérique à Tamanrasset (Hoggar)," Théses presentés à la Faculté des Sciences de l'Université de Paris, pour obtenir le tître de Docteur l'Université, Serie A, No. 345, No. d'ordre 369, juillet 1937, 73 pp. (Contains a brief description of diffuse measurements.)

T. E. Aurén, "Luminous Efficiency of Solar Radiation," *Meddelanden, Serien Uppsatser*, Nr. 16, Statens Meteorologisk-Hydrografiska Anstalt, Stockholm, 1937.

N. N. Kalitin, "Sur les Valeurs de la Radiation diffusé de l'Atmosphère," *Gerlands Beiträge zur Geophysik*, Band 50, H. 2–4, 1937, pp. 279–284.

A. Puppo e D. Bidasio, "Risultati della Campagne Solare 1936 al Col d'Olen (Instituto Angelo Mosso al Monte Rosa, 2902 m. s. m.) Pt. I Risultati della Misure di Radiazione Solare Diretta, Diffusa, Globale," *Bollettino del Comitato per la Geodesia e la Geofisica del Consiglio Nazionale della Ricerche*, Serie II, No. 7, 1937, pp. 52–82. (Abstracts in French, English, and German, pp. 83–84.)

1938 N. N. Kalitin, "La Radiation diffusé de l'Atmosphère dans les Conditions des Regions Arctiques," *Bulletin Academie des Sciences*, Moscow, 1938, pp. 129–146. (In Russian; summary in French, p. 147.)

1943 C. E. Brazier, "Etudes actinométriques d'après les Documents recueillis a l'Observatoire du Parc S. Maur," *Annales de Physique du Globe*, t. 21, pp. 118–136, 1943. (Some discussion of diffuse radiation.)

E. W. Hewson, "The Reflection, Absorption, and Transmission of Solar Radiation by Fog and

Cloud," *Quarterly Journal of the Royal Meteorological Society*, vol. 69, No. 298, January 1943, pp. 47–62. (See pp. 53–54.)
Discussion of article: *Quarterly Journal of the Royal Meteorological Society*, vol. 69, No. 301, July 1943, pp. 227–234.

1944 N. N. Kalitin, "On Scattering of Radiation by Clouds," *Comptes Rendus des Academie des Sciences, U. R. S. S.*, t. 43, 1944, pp. 289–291.

1945 B. Haurwitz, "Insolation in Relation to Cloudiness and Cloud Density," *Journal of Meteorology*, vol. 2, No. 3, September 1945, pp. 154–166.

1946 I. F. Hand, *Pyrheliometers and Pyrheliometric Measurements*, U. S. Weather Bureau, Washington, D. C., 1946, 55 pp. (See pp. 9 and 55.)
B. Haurwitz, "Insolation in Relation to Cloud Types," *Journal of Meteorology*, vol 3, No. 4, December 1946, pp. 123–124.

1947 I. F. Hand, "Preliminary Measurements of Solar Energy Received on Vertical Surfaces," *Transactions, American Geophysical Union*, vol. 28, No. 5, October 1947, pp. 705–712.
I. F. Hand, "Solar Energy for House Heating: An Application of Solar Data to Heating through Windows Facing South," *Heating and Ventilating*, Reference Section, December 1947, pp. 80–94. (See pp. 90–94.)

1948 B. Haurwitz, "Insolation in Relation to Cloud Types," *Journal of Meteorology*, vol. 5, No. 3, June 1948, pp. 110–113.
W. H. Klein, "Calculation of Solar Radiation and the Solar Heat Load on Man." *Journal of Meteorology*, vol. 5, No. 4, August 1948, pp. 119–129. (See p. 122.)
H. S. Paulsen, "Investigations Carried Through at the Station of Forest Meteorology at Os. (I) On Radiation, Sunshine, and Cloudiness," *Årbok, nr. 7*, 1948. Universitetet i Bergen, 44 pp. (Diffuse radiation discussed pp. 25–28, 30–33, 38–41.)
H. C. Peterson, "Results of the Solar Radiation Project of the Ronne Antarctic Expedition," *Technical Report No. 3*, Office of Naval Research, Washington, D. C., October 1, 1948, 17 pp. (See "Transmission of Insolation through an Overcast Sky," pp. 15–16.)

1950 I. F. Hand, "Insolation on Clear Days at the Times of the Solstices and Equinoxes for Latitude 42° N.," *Heating and Ventilating*, vol. 47, No. 1, January 1950, pp. 92–94.

U. S. GOVERNMENT PRINTING OFFICE: 1952