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AMOUNT OF SOLAR RADIATION THAT REACHES THE SURFACE OF THE EARTH ON THE LAND AND ON THE SEA, AND METHODS BY WHICH IT IS MEASURED[1]

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The time available for presenting this paper will not permit a detailed discussion of all the points involved. Therefore, for a description of pyrheliometers employed in radiation measurements I would refer you to a paper by Professor Marvin and myself on Solar Radiation and Weather Forecasting, in the Journal of the Franklin Institute, volume 202, page 273, September, 1926.

It may be added that since the above paper was written there has been published a description of important improvements which have been made in the Smithsonian silver disk pyrheliometer and which greatly decrease the sky area to which the thermal element is exposed. Also, thermo-electric pyrheliometers are finding increased favor for use in obtaining continuous records of the total solar radiation (direct + diffuse) received on a horizontal surface.

The Smithsonian pyrheliometric scale of 1913 is the accepted standard in most countries, although the Ångström standard still has adherents. Recently a radiogram from Prague, picked up by an amateur in this country, informs me that an absolute ice pyrheliometer has been constructed by Professor Volŏsin of the Karlova University in that city. Details have not yet been received.

In the MONTHLY WEATHER REVIEW for April, 1927, volume 55, page 155, I have given a summary of pyrheliometric measurements made at about 100 different points, nearly all of which are inland, and frequently at considerable altitudes above sea level. In response to a recent circular I have learned of several additions and some corrections to be made to this summary.

Having thus disposed of the beginning and ending of my subject I will devote the remainder of my time to a discussion of the amount of radiation that reaches the surface of the sea.

Very few pyrheliometric measurements have been made at strictly marine stations. The list includes measurements by Thomson, at Apia, Samoa (**1**); Linke at sea between Hamburg, Germany, and Buenos Aires, Argentina (**2**); Gorczyński, at sea between Antwerp and Bangkok (**3**); Westman, at Treurenberg, Spitzbergen (**4**); at Cape Horn, Chile, during the International Polar Expedition of 1882–83 (**5**); and an important measurement at Flint Island, by Abbot, during a solar eclipse expedition in 1907 (**6**).

These observations by no means cover the seven seas, so I have sought to determine if our knowledge of meteorological conditions over the oceans, and of the relation between meteorological conditions and solar radiation intensities at the surface of the earth, is not sufficient to enable us to compute mean solar radiation intensities for different latitudes with reasonable accuracy.

Figure 1 is a chart for computing the transmission for solar radiation of dust-free air when its water vapor content is known. Using an equation developed by King (**7**) from Rayleigh's classical work (**8**) we may compute the atmospheric transmission, a_λ, for different wave lengths of light through pure dry air of any desired barometric pressure. I have made these computations for the 38 different wave lengths for which Abbot has given what he consideres the most reliable relative energy intensities, $I_{0\lambda}$, outside the atmosphere (**9**). Then by Lambert's formula, $a_{\lambda m} = a_\lambda^m$ we may determine what will be the form of the solar spectrum energy curve after the solar rays have passed through pure dry air of a given pressure. I have made the computations for pressures of 40.0 and 76.0 cm. of mercury. Considering passage through the latter when the sun is in the zenith to represent unit air mass, I have extended the computations to air masses 2.0, 3.0, and 4.0, which represent solar zenith distances of 60°.0, 70°.7, and 75°.7.

Effecting a graphical integration by finding the area under these various curves, and applying Abbot's (**10**) latest published corrections for energy beyond the limits of his measurements, the pure dry air transmission, a'_m, for the total radiation through the different air masses, is given by the ratio of the respective areas to that for $I_0\lambda$. A smooth curve through these transmissions, which are plotted on their logarithmic scale as ordinates against their air masses as abscissas, gives curve (1).

Similarly, using Fowle's (**11**) values of the transmission of water vapor for solar radiation, $a_{w\lambda}$, and disregarding selective absorption, we obtain the transmissions represented by curves (2) to (8), inclusive, Or, stated in another way, the difference between 1.00 and the transmissions given by curves (1) to (8), gives the depletion of solar radiation by scattering in passing through dust-free air having a water-vapor content indicated by w, and a length of path through the atmosphere given by m. At sea level $w = 2.3e$, where e is the water-vapor pressure expressed in cm.[2]

To compute the depleton of solar radiation represented by the great water-vapor bands in the solar spectrum I have made use of curves given by Fowle [(**12**) Fig. 4], and my computed values of $I_{0\lambda}(a_{a\lambda}a_{w\lambda})$ for the values

[1] This paper by H. H. Kimball and the following paper by G. F. McEwen were presented before the joint meeting of the sections of meteorology and oceanography during the ninth annual assembly of the American Geophysical Union held at Washington, D. C., Apr. 26, 1928, in the building of the National Academy of Sciences. The joint meeting was devoted to a symposium and discussion on interrelations between the sea and the atmosphere, and the effect of these relations on weather and climate. The communications presented were on problems related to (a) solar radiation, (b) surface-water temperatures, and (c) atmospheric circulation. The two papers here printed were under (a); the other complete papers under this subhead, or references to where they have been published, appear in Bulletin No. 68 of the National Research Council which contains also references to the communications presented under (b) and (c).

[2] This relation between w and e is true only for mean values of e for a considerable period. In dealing with individual observations it may give results seriously in error.

of λ covered by the bands (**12**) [p. 408]. The plotted results give curve (16), Figure 1.

Subtracting from the values given by curves (2) to (8), inclusive, the water vapor absorption for corresponding values of *wm* given by curve (16) increased by 0.005 to take account of the selective absorption by the permanent gases of the atmosphere (**12**), we obtain the atmospheric transmission: a''_m, represented by curves (9) to (15). These curves give atmoshperic transmissions for dust-free air containing the amounts of precipitable water, *w*, indicated.

Finally, Linke (**13**) has defined atmospheric turbidity as the number of clear dry atmospheres, which together bring about the same extinction of radiation as the actual turbid moist atmosphere. He expresses it by the equation

$$T=\frac{1}{-m \log a'_m} \log \frac{I_o}{I_m} \qquad (5)$$

where a'_m is the atmospheric transmission for pure dry air through air mass *m*, and I_o and I_m are the solar radiation intensities at air masses 0 and *m*, respectively.

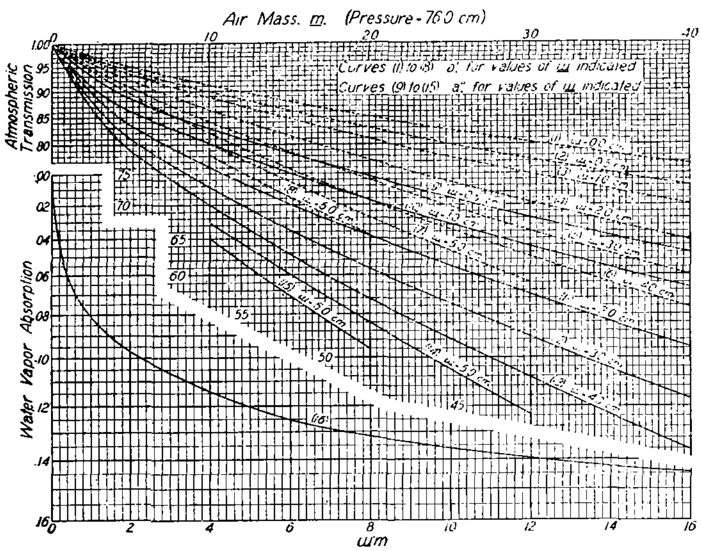

FIG. 1.—Atmospheric transmission of solar radiation through dust-free air: Curves (1) to (8) after scattering by dust-free air containing the quantities of water-vapor indicated by *w*; curves (9) to (15) after scattering and absorption by dust-free moist air containing the quantities of water-vapor indicated by *w*; curve (16) absorption by water-vapor for different values of the product *wm*

I have sought to compute the atmospheric turbidity due to dust alone, T_d, by substituting for a'_m in equation (5) the atmospheric transmission for dust-free moist air, a''_m, as given by curves (9) to (15), Figure 1.

A concrete example of the use of Figure 1 follows:

At Apia, Samoa, Thomson (**1**) divides the year into three seasons, as follows:

Dry season, May to August, inclusive.

Equinoctial season, March, April, September, October.

Wet season, November to February, inclusive.

Table 1 gives seasonal means of the meteorological elements with which we are particularly concerned.

TABLE 1.—*Seasonal means for Apia, Samoa*

Seasons	Barometer B (cm.)	Vapor pressure e (cm.)	$B-e$ (cm.)	w	Ratio, $\frac{B-e}{76.0}$	$\frac{I_{m=1}}{I_o}$	$\frac{I_{m=2}}{I_o}$	$\frac{I_{m=3}}{I_o}$
Dry	75.9	1.97	73.9	4.53	0.972	0.653	0.534	0.424
Equinoctial	75.8	2.07	73.7	4.76	.970	.637	.520	.441
Wet	75.6	2.10	73.5	4.83	.967	.674	.570	.475

From Table 1, Figure 1, and equation (5) the values of a'' and T_d given in Table 2 have been computed.

TABLE 2.—*Seasonal values of a'' and T_d for Apia, Samoa*

Seasons	$a''_{m=1}$	$a''_{m=2}$	$a''_{m=3}$	$T_{d(m=1)}$	$T_{d(m=2)}$	$T_{d(m=3)}$
Dry	0.686	0.554	0.460	1.14	1.06	1.11
Equinoctial	.680	.547	.451	1.18	1.08	1.03
Wet	.678	.545	.448	1.02	.926	.927

For extreme accuracy we should take for unit air mass the ratios $B-e/76.0$ given in Table 1. In the above example the value a'' is thereby increased about 0.002, which is inconsequential.

TABLE 3.—*Daily totals of solar radiation (direct+diffuse) received on a horizontal surface in the absence of clouds. Gr. cal. per cm².*

Latitude	Longitude	Jan. 21	Feb. 21	Mar. 21	Apr. 21	May 21	June 21	July 22	Aug. 22	Sept. 22	Oct. 20	Nov. 21	Dec. 21
90° N	----	----	----	----	----	818	896	745	----	----	----	----	----
60° N	7° E.–56° W	----	204	376	582	735	771	692	556	361	193	----	----
	135–170° W	----	229	413	629	793	704	726	564	368	208	----	----
56° N	7° W	113	240	415	620	750	799	724	578	388	228	105	----
	135–170° W	120	252	437	639	773	824	736	584	390	235	115	----
52° N	10° W	171	307	460	641	763	795	735	589	415	287	164	119
	129° W	174	314	472	656	782	827	754	650	460	304	171	123
48° N	60° W	226	409	536	686	790	842	736	634	495	329	214	179
	4° W. and 124° W	211	335	514	656	770	805	721	622	474	313	202	160
42° N	66–70° W	298	444	592	727	802	811	743	639	514	390	285	256
	124° W	278	404	582	723	807	830	770	674	522	391	270	233
36° N	6° W; 131–140° E	365	459	612	716	732	743	716	653	546	433	341	317
30° N	65–77° W; 128–130° E	404	466	629	722	768	732	692	633	516	424	386	360
	15° W and 117° W	436	519	630	739	772	772	755	692	593	479	420	392
20° N	61–77° W.; 158° W	492	610	692	736	751	790	736	706	663	587	487	466
10° N	61–69° W.; 17° W.–3° E.; 116° E.–80° W.	581	655	726	722	702	696	701	712	704	645	574	553
0°	7–12° E.; 48° W. and 170° E.; 55° E. and 159° W.	658	688	683	670	626	609	623	667	687	685	657	650
10° S	14° E.; 36°–38° W.; 72°–171° E.	723	738	681	605	538	513	555	630	695	712	718	720
20° S	46° W.; 47° E.–150° W	742	708	646	548	473	442	473	563	661	721	787	788
	70° W.; 14° E.; 114°–122° E.	750	721	675	586	496	497	506	603	680	732	816	766
30° S	17° E.; 116° E.; 110° W	858	751	626	505	386	354	396	514	642	712	850	893
36° S	62° W.; 18° E.; 115° E.; 78° W.	818	710	577	440	327	282	334	454	591	731	830	867
42° S	73° W.; 147° E	806	704	537	383	260	219	263	387	575	735	848	888
48° S	70° E.; 168° E	807	655	507	322	202	161	203	376	510	684	829	900
52° S	58° W	830	652	452	293	160	113	162	299	462	663	830	898
56° S	37–70° W	807	637	411	234	110	----	113	238	427	652	808	919
60° S	45° W	838	631	386	203	----	----	----	219	407	647	846	891

The values of T_d less than unity during the wet season, while partly due to the fact that frequent showers keep the air nearly free from dust (**1**), are no doubt principally due to the shallowness of the southeast trades at this season (**1**), and, in consequence, an overestimate of the value of *w*.

Determinations of T_d from observations on individual days at sea give great variations in its value. From all the observations available I have been led to use the value 1.15 except near the west coast of Africa, where Linke's observations indicate a very considerable increase in the atmospheric dustiness, and during the wet season in the tropics, when the value ±0.0 was employed. It is to be noted that T_d usually decreases in value with increase in air mass.

Atmospheric transmissions have been computed from Figure 1 for the latitudes indicated in Table 3 and corrected by T_d. Estimates of the water vapor content of the atmosphere have been based on monthly means of temperature and relative humidity for about 140 stations, obtained principally from the various volumes of the Pilot, published by the hydrographic department, British Admiralty, and from meteorological summaries prepared by Reed (**14**). Vapor pressure values thus obtained are undoubtedly more accurate for island than for continental stations, on account of the relatively small temperature variations at sea.

The stations selected are distributed in latitude from Treurenberg, Spitzbergen, 79° 55′ N., to Laurie Island, South Orkneys, 60° 44′ S. They have been grouped so as to give the vapor pressures at the latitudes indicated in Table 3. In the Tropics there is little variation in vapor pressure with longitude. In temperate regions the west shores of oceans usually show higher humidities than east shores, especially in north latitudes, probably on account of the warm west-shore ocean currents. The vapor pressures have been grouped so as to bring out these differences, which are reflected in the radiation intensities.

Atmospheric transmissions give solar radiation intensities on the assumption that the value of the solar constant is 1.0. They have been computed for each hour angle of the sun from noon for the dates indicated in Table 3, which have been selected so as to include the dates of greatest north and south declination of the sun, dates when its declination is ±0, and dates in July, August, October, and November, which have the same solar declination as the 21st of May, April, February, and January, respectively. They have been multiplied by the sine of the sun's altitude at each hour from noon, apparent time, to obtain the relative intensity of the solar radiation on a horizontal surface, and increased by a proportional part, depending upon the water-vapor content of the atmosphere and the solar altitude, so as to include in the total the diffuse solar radiation from the sky (15). These final values have then been plotted against intensities as ordinates and hour angles as abscissas and a smooth curve drawn through them from the value at noon to 0 at the time of sunrise or sunset. A graphical integration is effected by finding the area under this curve. The area is then multiplied by twice the solar constant divided by the square of the earth's relative solar distance on the dates indicated for each month. The result given in Table 3 is the average radiation to be expected on the dates indicated with cloudless sky conditions, expressed in gram-calories per cm.² per day. It is to be noted that in both hemispheres the daily totals average higher in the spring months than in the fall.

Figure 2 shows graphically the variations with latitude in the total solar radiation received over the oceans on the 21st of June. No radiation is then received south of the Antarctic Circle. There is in general a gradual increase in the daily total until latitude 48° N. is reached, although the changes are slight from latitude 42° N. to the pole. Increasing length of day and decreasing water-vapor content of the atmosphere unite to give maximum values at high north latitudes, in spite of the low altitude of the sun even at midday. The higher values on the east shores of oceans than on the west is well brought out in the daily totals for latitude 20° S. and 30° N. At latitude 48° N. the conditions are reversed over the Atlantic Ocean on account of the cold Labrador current on the west shore. On December 21 (fig. 3) daily maxima are reached at about latitude 48° S. with little change to latitude 60° S. In general, there is less variation in the daily totals with longitude in the southern hemisphere than in the northern.

From the same sources as for temperature and humidity, and for about the same number of stations, monthly means of cloudiness have been obtained. Ångström (16) and others have determined an approximate relation between daily totals of solar radiation and both the duration of sunshine and the average cloudiness. The latter relation is not so well determined as the former, since the relation with cloudiness seems to vary with the percentage of cloudiness (17) and perhaps also with solar altitude (16). I have determined average daily totals of solar radiation, Q, from the totals with a cloudless sky, Q_o, by the equation

$$Q = Q_o(0.29 + 0.71[1.0 - C]) \qquad (6)$$

where C is the proportion of the sky covered by clouds, and Q_o is taken from Table 3. The results are given in Table 4, "Average daily totals of solar radiation received on a horizontal surface."

TABLE 4.—*Average daily totals of solar radiation received on a horizontal surface (direct+diffuse), gr. cal. per cm.²*

Latitude	Longitude	Jan. 21	Feb. 21	Mar. 21	Apr. 21	May 21	June 21	July 22	Aug. 22	Sept. 22	Oct. 20	Nov. 21	Dec. 21
90° N		----	----	----	----	356	387	322	----	----	----	----	----
60° N	7° E.–56° W	----	101	200	318	406	421	372	287	189	92	----	----
	135–170° W	----	141	240	316	399	365	345	244	167	102	----	----
56° N	7° W	50	109	206	308	372	389	328	229	182	107	49	----
	135–170° W	66	127	235	321	389	356	318	231	183	110	54	----
52° N	10° W	74	146	228	331	378	383	354	288	212	140	80	54
	129° W	81	147	204	283	366	357	326	304	199	131	74	53
48° N	60° W	114	206	270	345	397	424	422	364	284	165	108	78
	4° W. and 124° W	94	157	259	339	414	405	388	335	255	153	90	71
42° N	66–70° W	139	223	327	402	449	477	421	376	317	235	153	120
	124° W	148	246	313	435	486	524	442	382	318	233	151	129
36° N	6° W	225	280	378	472	498	522	538	496	371	285	225	196
	131–140° E	215	260	334	380	389	321	360	375	275	242	208	196
30° N	65–77° W	212	247	365	420	462	441	432	399	326	259	244	197
	15° W. and 117° W	306	364	415	482	476	482	449	437	420	340	301	281
	128–130° E	206	225	303	353	376	332	378	372	296	249	216	189
20° N	61–77° W.; 158° W	335	420	466	475	452	493	464	450	428	379	324	307
10° N	61–69° W	371	404	437	440	383	404	412	424	409	384	350	345
	17° W.–3° E	424	483	556	527	477	414	422	439	444	453	403	392
	116° E.–80° W	329	385	427	394	363	340	348	348	359	338	321	314
0°	7–12° E	345	361	348	328	297	280	269	283	326	349	344	336
	48° W. and 170° E	373	385	411	432	448	428	433	511	531	520	480	382
	55° E. and 159° W	340	395	402	403	355	337	366	397	419	408	363	355
10° S	14° E; 36–38° W	476	471	421	356	309	294	350	411	458	469	453	464
	72–171° E	415	455	454	406	381	360	397	451	483	444	432	439
20° S	46° W; 47° E. and 150° W	453	426	389	353	305	285	308	363	417	465	508	486
	70° W	564	567	508	441	337	321	326	367	415	447	555	548
	14° E	345	332	335	295	278	285	269	303	323	348	399	342
	114–122° E	575	526	536	486	408	405	427	533	613	649	712	614
30° S	17° E. and 116° E	657	553	475	343	254	208	255	324	423	535	585	627
	110° W	541	454	359	290	222	183	222	288	360	477	488	576
36° S	62° W.; 18° E	597	528	421	306	209	170	208	286	385	477	559	621
	115° E.; 78° W	510	422	335	243	174	140	173	238	323	404	471	529
42° S	73° W.; 147° E	492	404	308	206	140	118	141	208	289	395	456	510
48° S	70° E.; 168° E	423	358	291	185	116	92	117	216	293	368	429	464
52° S	58° W	412	319	227	151	80	52	78	155	232	333	406	439
56° S	37–70° W	395	320	198	113	55	----	58	128	233	319	401	449
60° S	45° W	303	228	139	73	----	----	----	95	176	234	305	322

The variations in cloudiness with longitude cause much greater variations in the daily totals of radiation than do the variations in absolute humidity. For this reason an increased number of groupings along the different parallels of latitude becomes necessary. These variations become clearly apparent when the daily radiation totals are charted as in Figures 4 to 7, inclusive, for December 21, June 21, March 21, and September 22.

The monthly mean cloudiness on the Gilbert Islands is so much less than at other islands near the equator that one may well ask if topographic features on islands may not in some cases markedly modify the cloudiness, so that it is not representative of the general cloudiness of its locality. Sufficient data was not at hand while this paper was in preparation to make a study of the topography of the different islands. It therefore seemed best to base the computations on the data as published.

A few solar radiation records are available for checking the computed daily totals of solar radiation of Tables 3 and 4. Reference has already been made to measurements of the intensity of direct solar radiation at certain marine stations, and their use in computations of the value of T_d. It has also been found that atmospheric

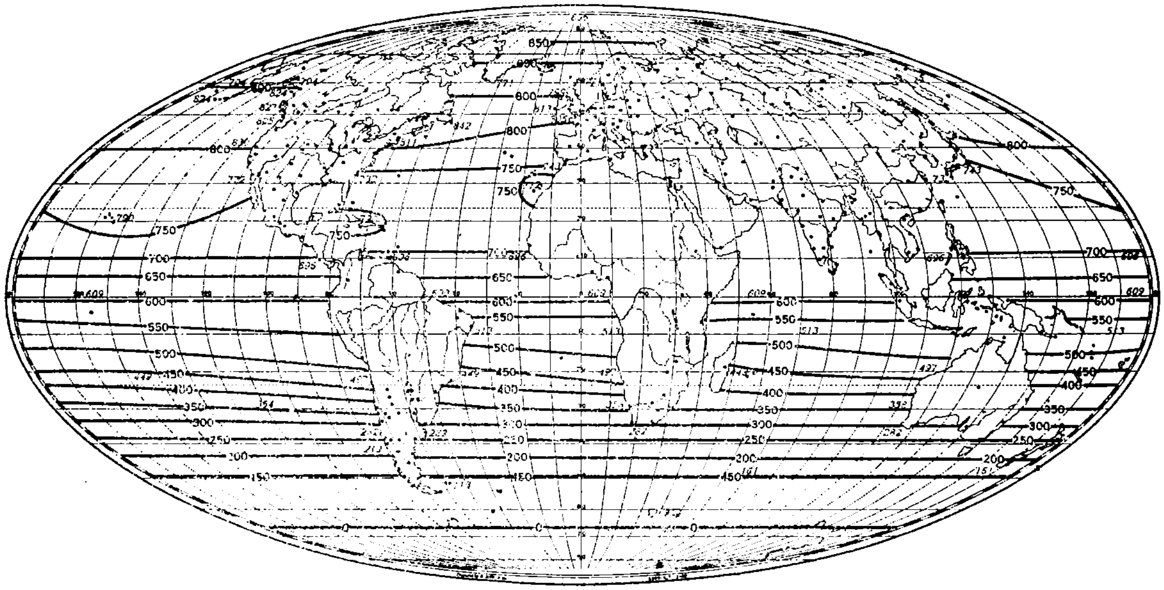

FIG. 2.—Isopleths of total solar radiation (direct plus diffuse) on June 21 with cloudless sky (Gram-calories per day per cm.² of horizontal surface)

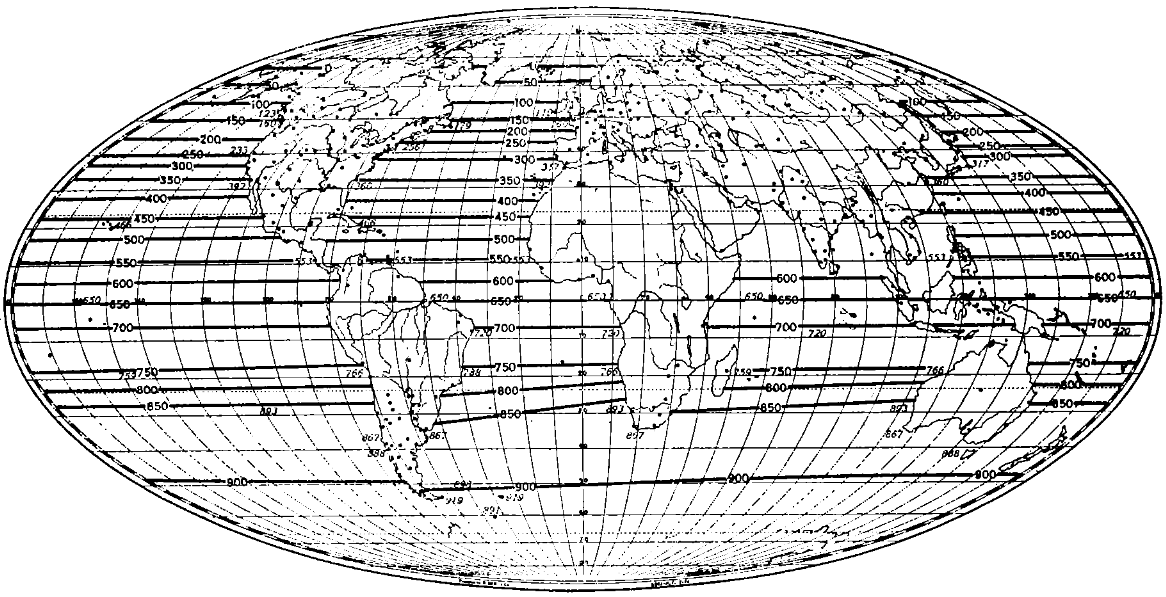

FIG. 3.—Isopleths of total solar radiation (direct plus diffuse) on December 21 with cloudless sky (Gram-calories per day per cm.² of horizontal surface)

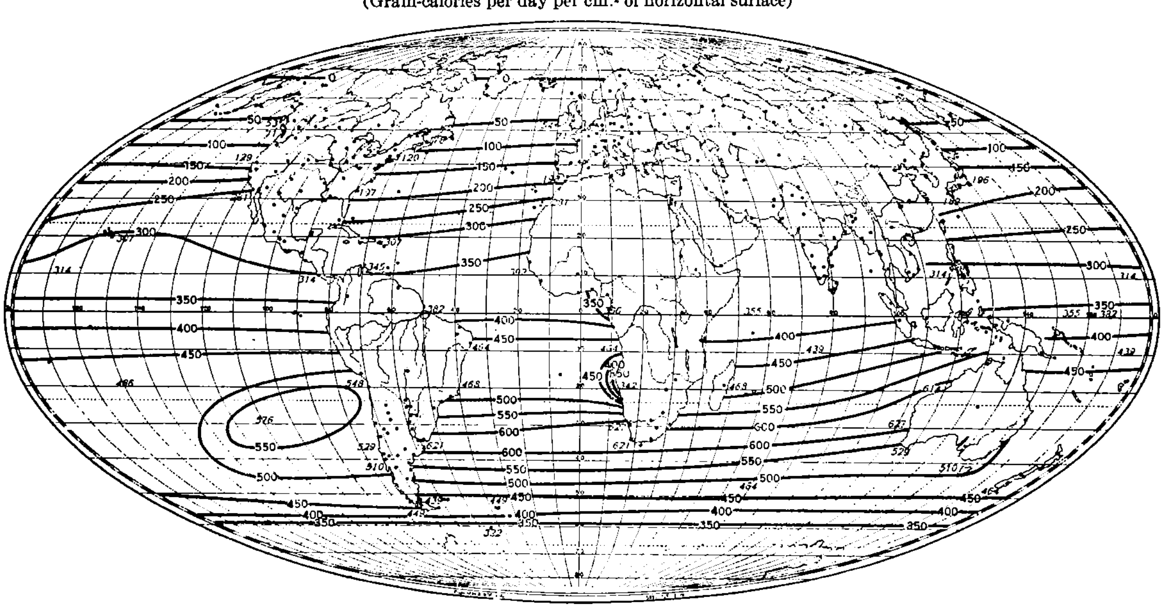

FIG. 4.—Isopleths of total solar radiation (direct plus diffuse) on December 21 with average cloudiness (Gram-calories per day per cm.² of horizontal surface)

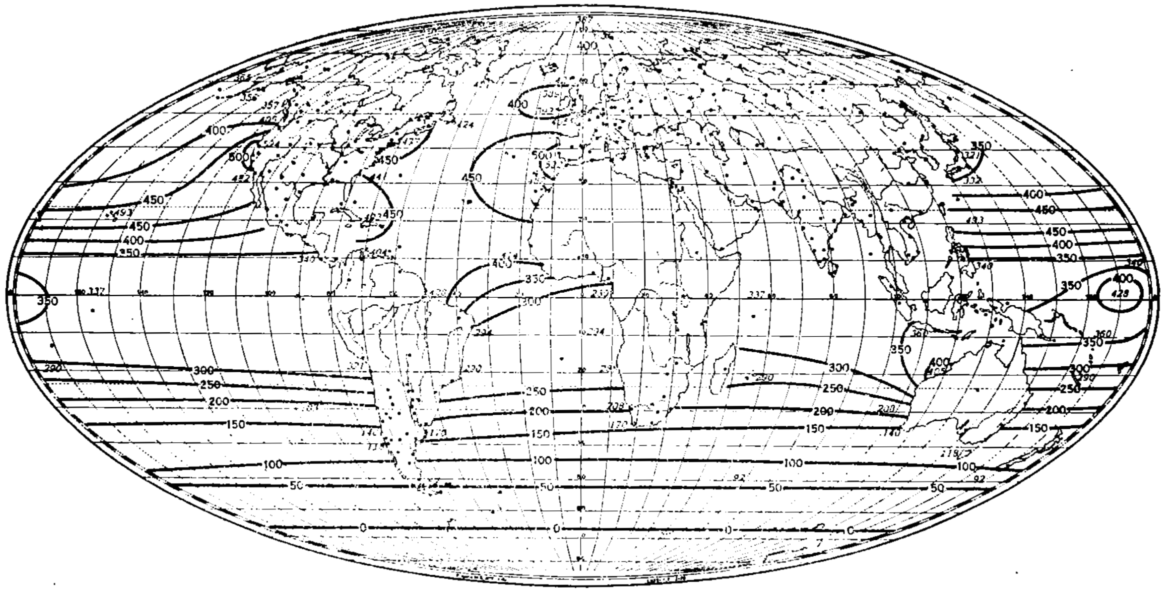

FIG. 5.—Isopleths of total solar radiation (direct plus diffuse) on June 21 with average cloudiness (Gram-calories per day per cm.² of horizontal surface)

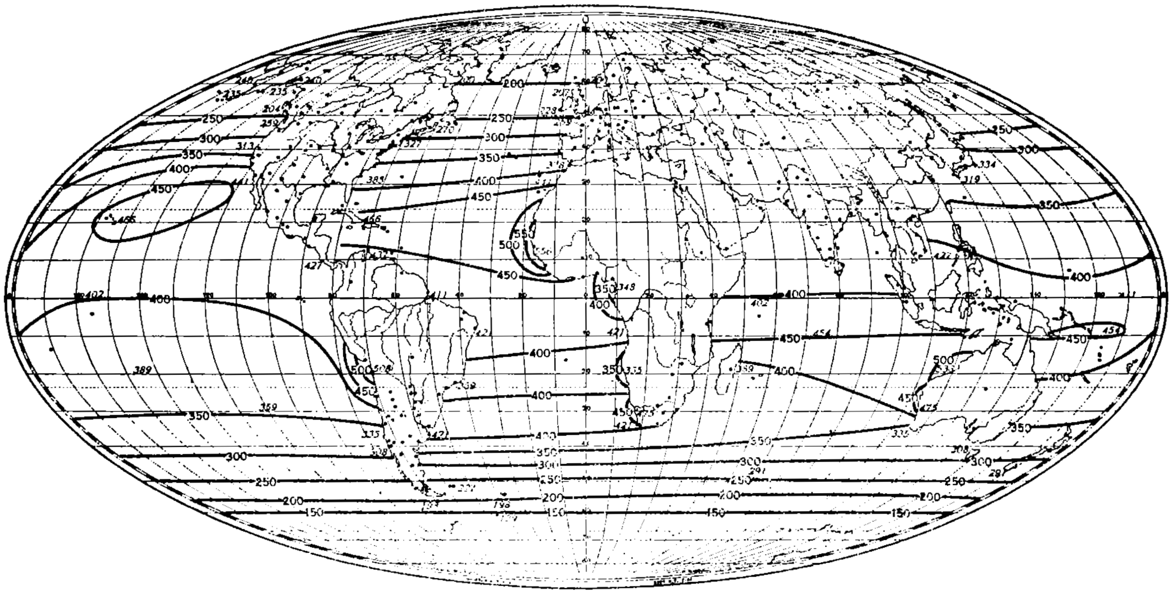

FIG. 6.—Isopleths of total solar radiation (direct plus diffuse) on March 21 with average cloudiness (Gram-calories per day per cm.² of horizontal surface)

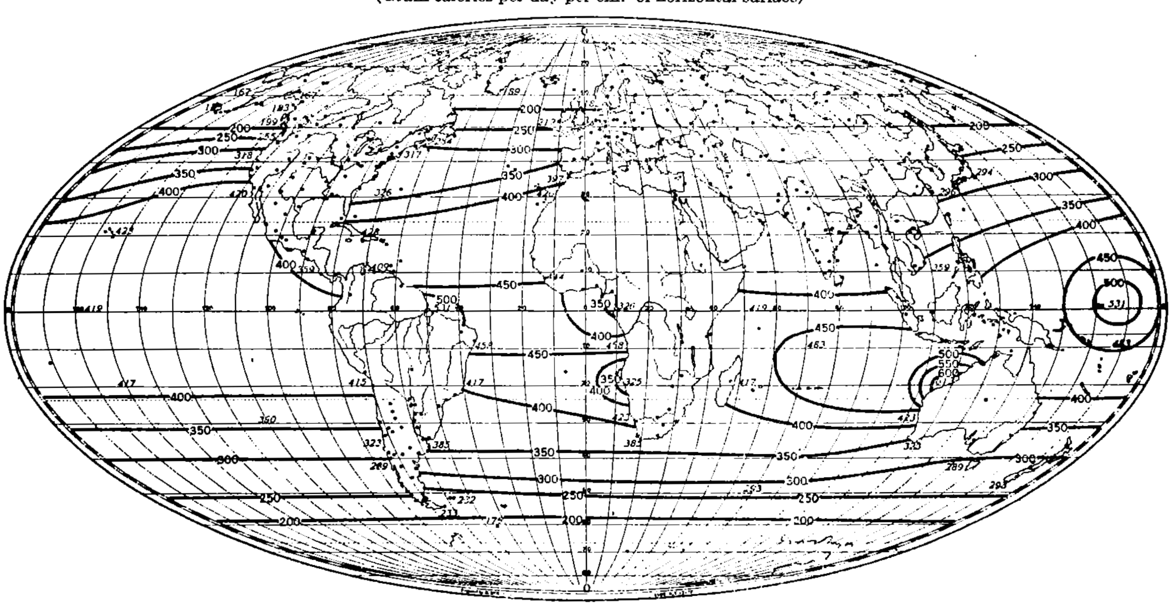

FIG. 7.—Isopleths of total solar radiation (direct plus diffuse) on September 22 with average cloudiness (Gram-calories per day per cm.² of horizontal surface)

transmission coefficients for Upsala, Sweden (**18**), latitude 59° 51′ N. are, in general, only about 0.005 less than the transmissions I have computed for latitude 60° N.

Average daily totals of the radiation received on a horizontal surface are available for Stockholm, Sweden, latitude 59° 21′ N., and for Habana, Cuba, latitude 23° 09′ N (**18**), both of which have a semimarine climate. The records for Stockholm cover a single year, those for Habana about 15 months. The Stockholm records give daily totals only a few per cent less than the computed values of Table 4 for latitude 60° N., except for May and June. The published curve of daily totals [(**18**) Figure 2], shows a decided depression for these two months. The daily totals for Habana [(**18**) Figure 1], are less than the computed values of Table 4 for latitude 20° N., for the months October to February, inclusive, and more than the computed values for March to September, inclusive. We would expect the total radiation at Habana, latitude 23° 09′ N., to be more than at latitude 20° N. in summer and less in winter.

It seems evident that with reliable climatological data the radiation intensity over the oceans may be computed with considerable accuracy; but the values here given must not be accepted as final.

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HEATING AND COOLING OF WATER SURFACES[1]

By GEORGE F. MCEWEN

(Abstract)

Under this title a brief report was read based upon a 50-page manuscript entitled: "Mathematical Theory of Vertical Temperature Distribution in Water under the Action of Radiation, Evaporation, and the Resulting Convection or Mixing." (Derivation of a general theory, and its illustration by means of numerical applications to reservoirs, lakes, and oceans.)

Since this manuscript will be ready in the summer of 1928 for publication in full as a bulletin (technical) of the Scripps Institution of Oceanography, La Jolla, Calif., by the University of California Press, only a brief abstract is presented here.

A mechanism has been devised involving the sinking of surface masses of water rendered relatively heavy, the evaporation, conduction through the air, and back radiation, and a compensating ascent of lighter, warmer masses. The mathematical theory of this mechanism of the downward diffusion of surface cooling led to a pair of simultaneous differential equations involving turbulence, rate of surface cooling, rate at which solar radiation penetrates the surface, rate of vertical distribution of temperature and salinity, and rate of vertical flow of the water.

Methods have been worked out for applying these equations to numerical data, without the need of their general solution, which has not been attempted. Three integrals appearing in these equations and depending upon the vertical variation of specific gravity have been tabulated to facilitate numerical applications.

Numerical results have been obtained by applying the theory to serial temperatures in a tank of water, to serial temperatures of Lake Mendota, Wis., and to serial temperatures and salinities in the Pacific Ocean near San Diego, Calif. From such observations the theory provided a means of estimating the rate of penetration of solar radiation through the water surface, the rate of surface cooling, and, therefore, an approximate estimate of evaporation and the rate of vertical flow of the water.

[1] The full title as given by the author is "The rate at which solar radiation penetrates the surface of lakes and oceans, and the rate at which the surface loses heat as deduced from serial temperature-observations."—*Ed.*