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THE RELATION
BETWEEN THE
DURATION OF BRIGHT SUNSHINE
REGISTERED BY A CAMPBELL-STOKES SUNSHINE RECORDER
AND THE ESTIMATED
AMOUNT OF CLOUD

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THE RELATION BETWEEN THE DURATION OF BRIGHT SUNSHINE REGISTERED BY A CAMPBELL-STOKES SUNSHINE RECORDER AND THE ESTIMATED AMOUNT OF CLOUD

By C. E. P. Brooks, D.Sc.

One of the desiderata of climatology is a set of charts showing the duration of bright sunshine in different parts of the globe. Unfortunately it is not yet possible to prepare such charts directly, for there are still large areas of the globe, including the whole of the oceans, without a single sunshine recorder of any type, while to complicate the matter further, even where recorders are in use they are of various patterns, some registering by burns and others by the chemical action of light, and the results of these different recorders are not easily comparable. On the other hand, observations of cloud amount are available for almost all the land areas, and for a considerable part of the oceans, and if a satisfactory conversion formula can be found, these cloud observations can be used to supplement the instrumental measurements of sunshine. This paper is a preliminary study directed towards the construction of such a conversion formula.

A comparison of measurements of bright sunshine* expressed as percentages of the " possible " duration, as the time between sunrise and sunset is somewhat optimistically termed, with estimates of cloud amount, quickly brings out two interesting features, which are illustrated by the following data for Valentia (Table I).

TABLE I—SUNSHINE (S) AND CLOUDINESS (C) AT VALENTIA, 1881–1915

	Jan.	Feb.	March	April	May	June	July	August	Sep.	Oct.	Nov.	Dec.	Year
S per cent. ..	19	25	33	39	41	38	32	34	35	30	24	17	31
C per cent. ..	77	76	72	68	68	71	77	73	70	72	74	78	73
$S + C$ ..	96	101	105	107	109	109	109	107	105	102	98	95	104

In the first place, the sum of the percentages of sunshine and cloudiness, on the mean for the year, is 104. If a sunshine recorder were also a perfect inverse recorder of cloud, if it were able to burn the card from the instant of sunrise to the instant of sunset, and if there were no diurnal variation of cloudiness, the total should equal 100. Evidently there is a certain amount of cloud too thin to prevent the sun from burning the card. Secondly, the sum $S + C$ is greatest in summer and least in winter, falling below 100 in the three months of shortest days. It is known that when the sun is very low it fails to burn the card, and the proportion of this time of low sun to total daylight is greatest in these three months. From these two facts we can derive a

* In this paper " bright sunshine " is defined as sun which burns a Campbell-Stokes card.

tentative formula for the relation between cloudiness and sunshine. First, however, it is necessary to consider more closely the effect of thin cloud. Most of such cloud is cirriform, and at a high level. As a first approximation we may assume that the amount of thin cloud *present* is proportional to the amount of low cloud, so that we can write for the amount of thin cloud $t' c'$, where c' is the amount of low cloud and t' is a constant*. Of this thin cloud, however, only $t' c' (1 - c')$ will be actually *visible*, the remainder being hidden by the low cloud. This expression is inconvenient, because average figures of cloudiness rarely distinguish between low and high cloud, and for experimental purposes we may write for the amount of thin cloud visible simply $t\, c\, (1 - c)$.

For the duration of the time during which the sun fails to burn the card I took as a first approximation the time during which the sun is less than five degrees above the horizon. This figure, divided by the duration of possible sunshine, gives w, the fractional duration of low sun. The subsequent results showed that at the majority of stations this angle is too low, and that in fact the sun may not begin to burn the card until it is ten degrees above the horizon. Except in high latitudes, however, the time when the sun is less than ten degrees above the horizon is approximately double the time when it is less than five degrees above, and it was considered sufficiently accurate to use the values of w for sun below five degrees, multiplied by an appropriate constant a, as giving a measure of the fraction of the time during which the sun is too low to burn the card. The true limit of sunshine registered by a Campbell-Stokes recorder therefore is not L, the length of day from sunrise to sunset, but approximately $L\,(1 - a\,w)$, where a is a constant. a is in general greater than one, but in practice it was found convenient to express the values of w as percentages W of the total time from sunrise to sunset, and to divide the calculated values of a by 100. Similarly cloud amounts were employed in the form of percentages, and the values of the coefficient t were divided by 100. Values of W for different latitudes for all months are given in Table II. Values of the time from sunrise to sunset are given for convenience in Table III.

The formula adopted in calculating values of W was given by Elias Loomis † :—

$$\sin \tfrac{1}{2} P = \frac{\sin \dfrac{(z + \phi - \delta)}{2} \sin \dfrac{(z - \phi + \delta)}{2}}{\cos \phi \cos \delta}$$

where P = hour angle
ϕ = latitude of the place
δ = declination
z = true zenith distance, in this case 85°.

* Throughout the paper percentage values are given as S, C, W, and fractional values as s, c, w.

† An introduction to practical astronomy. 7 ed., New York, 1870, p. 347.

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The duration of the time during which the sun is above 5° was calculated by this formula and subtracted from the total duration of daylight.

With these assumptions we can write for s, the duration of the record of bright sunshine expressed as a fraction of the length of day, the expression :—

$$s = [(1 - c) + tc(1 - c)](1 - aw) \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Whence

$$\frac{s}{1 - c} = (1 + tc, (1 - aw) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

TABLE II—VALUES OF W, THE PERCENTAGE TIME DURING WHICH THE SUN IS WITHIN FIVE DEGREES OF THE HORIZON

Lat.	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
°N.												
60 ..	40	21	14	13	11	12	12	11	12	18	31	50
58	33	18	13	12	11	11	11	11	11	17	26	39
56	27	16	13	11	10	10	10	10	11	16	23	33
54	23	15	12	11	9	10	10	10	11	15	20	27
52	20	14	11	10	9	9	9	10	10	14	18	23
50	18	13	11	10	9	9	9	9	10	13	16	20
45	14	11	10	9	8	8	8	9	9	11	14	15
40	12	10	9	8	8	8	8	8	8	10	12	13
35	11	9	8	8	7	7	7	7	8	9	10	11
30	10	9	8	7	7	7	7	7	7	8	9	10
25	9	8	7	7	7	7	7	7	7	8	9	9
20	8	7	7	7	7	7	7	7	7	7	8	8
15	8	7	7	7	7	7	7	7	7	7	7	8
10	8	7	7	7	7	7	7	7	7	7	7	8
5	7	7	7	6	7	7	7	6	7	7	7	7
0	7	7	7	6	7	7	7	7	6	7	7	7
°S.												
5	7	7	6	7	7	7	7	7	6	7	7	7
10	7	7	7	7	7	7	7	7	7	7	7	7
15	7	7	7	7	8	8	8	7	7	7	7	7
20	7	7	7	7	8	8	8	8	7	7	7	7
25	7	7	7	7	9	9	9	8	7	7	7	7
30	7	7	7	8	9	10	9	8	8	7	7	7
35	7	7	7	8	10	11	10	9	8	7	7	7
40	8	8	8	9	12	13	12	10	9	8	8	8
45	8	8	9	10	14	15	15	11	9	8	8	8
50	9	9	9	11	17	19	17	13	10	9	9	9
52	9	9	10	12	19	22	19	14	11	9	9	9
54	10	9	10	13	21	26	21	15	11	9	10	10
56	10	10	11	14	24	32	25	17	12	10	10	11
58	11	10	12	15	28	40	31	19	13	10	11	12
60	12	11	12	16	32	50	38	21	14	11	11	13

TABLE III—VALUES OF POSSIBLE DURATION OF BRIGHT SUNSHINE IN HOURS

Lat.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
°N. 60 ..	6·71	9·02	11·69	14·46	17·03	18·59	17·88	15·56	12·87	10·12	7·52	5·93
58 ..	7·19	9·27	11·72	14·27	16·59	17·94	17·34	15·27	12·80	10·27	7·91	6·50
56 ..	7·60	9·48	11·74	14·10	16·21	17·41	16·88	15·02	12·74	10·41	8·24	6·98
54 ..	7·95	9·67	11·76	13·95	15·88	16·96	16·48	14·79	12·69	10·53	8·54	7·40
52 ..	8·27	9·84	11·78	13·81	15·59	16·57	16·14	14·59	12·65	10·64	8·80	7·77
50 ..	8·55	10·00	11·80	13·68	15·33	16·21	15·83	14·41	12·61	10·73	9·04	8·09
45 ..	9·14	10·33	11·84	13·42	14·78	15·49	15·18	14·02	12·52	10·95	9·54	8·78
40 ..	9·63	10·62	11·88	13·20	14·32	14·91	14·65	13·70	12·44	11·13	9·96	9·33
35 ..	10·04	10·85	11·91	13·01	13·94	14·43	14·22	13·42	12·38	11·28	10·31	9·80
30 ..	10·41	11·07	11·94	12·84	13·60	13·99	13·83	13·18	12·32	11·42	10·63	10·21
25 ..	10·74	11·27	11·97	12·70	13·31	13·62	13·49	12·98	12·28	11·55	10·93	10·58
20 ..	11·05	11·45	12·00	12·57	13·05	13·29	13·18	12·80	12·25	11·68	11·19	10·92
15 ..	11·33	11·63	12·03	12·45	12·81	12·99	12·90	12·61	12·22	11·79	11·44	11·23
10 ..	11·61	11·80	12·07	12·34	12·58	12·69	12·63	12·45	12·19	11·90	11·67	11·53
N. 5 ..	11·87	11·97	12·09	12·23	12·35	12·41	12·38	12·28	12·15	12·01	11 90	11·83
0 ..	12·12	12·12	12·12	12·12	12·12	12·12	12·12	12·12	12·12	12·12	12·12	12·12
°S. 5 ..	12·38	12·27	12·14	12·00	11·89	11·84	11·86	11·95	12·08	12·22	12·33	12·41
10 ..	12·63	12·42	12·17	11·88	11·65	11·53	11·58	11·78	12·04	12·31	12·56	12·69
15 ..	12·89	12·57	12·18	11·75	11·41	11·23	11·31	11·61	12·00	12·41	12·78	12·98
20 ..	13·17	12·73	12·20	11·62	11·16	10·92	11·02	11·42	11·95	12·51	13·02	13·29
25 ..	13·46	12·91	12·22	11·49	10·89	10·58	10·70	11·21	11·90	12·63	13·28	13·62
30 ..	13·79	13·10	12·24	11·34	10·59	10·21	10·36	11·00	11·85	12·75	13·56	13·98
35 ..	14·16	13·32	12·28	11·19	10·29	9·80	10·00	10·77	11·81	12·90	13·88	14·41
40 ..	14·60	13·60	12·33	11·03	9·91	9·32	9·58	10·50	11·76	13·08	14·25	14·89
45 ..	15·11	13·90	12·38	10·82	9·48	8·79	9·07	10·20	11·69	13·25	14·69	15 48
50 ..	15·78	14·27	12·44	10·57	8·96	8·08	8·45	9·84	11·62	13·49	15·22	16·19
52 ..	16·08	14·44	12·47	10·47	8·71	7·76	8·16	9·66	11·59	13·61	15·46	16·54
54 ..	16·41	14·63	12·51	10·35	8·44	7·39	7·83	9·47	11·55	13·72	15·75	16·92
56 ..	16·80	14·85	12·55	10·21	8·15	6·96	7·47	9·26	11·50	13·86	16·06	17·38
58 ..	17·24	15·08	12·59	10·06	7·80	6·48	7·04	9·04	11·47	14·00	16·43	17·90
S. 60 ..	17·78	15·34	12·62	9·89	7·39	5·90	6·55	8·79	11·43	14·18	16·86	18·56

This is a quadratic which would be possible of solution, but inconvenient. Since both tc and aw are probably small, we can simplify into—

$$\frac{s}{(1-c)} = 1 + tc - a'w \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where $a' = a\ (1 + tc)$.

A somewhat closer approximation is given if we assume that the mean annual cloudiness $\bar{c}$ prevails in each of the individual months. We can then write in place of equation (3)—

$$\frac{s}{(1-c)} = 1 + tc - a\ (1 + t\bar{c})\ w \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Experience shows that this form is an improvement at stations where the annual variation of cloudiness is small, but where the annual variation is large it gives little improvement on (3). Before evaluating the coefficient a it is necessary to calculate t and a' by means of equation (3).

As a basis for investigating the values of the constants t, a' and a, monthly averages of sunshine data obtained with recorders of the Campbell-Stokes type, with corresponding estimates of cloudiness, were collected or tabulated from various sources, the most fruitful being a paper by J. Friedmann*. The constants were calculated from the twelve monthly values of $S/(100 - C)$ by the method of least squares, using one of three variants, according to the nature of the material. It is more convenient to employ percentage values of C and W instead of fractional values c and w, hence the coefficients as calculated are equal to $\frac{t}{100}$ and $\frac{a'}{100}$. In the subsequent text, and in Tables IV, V, and VI, where numerical values of these constants are given, they are to be understood in this sense. If C and W both showed a considerable variation, and did not run either closely parallel or nearly opposite, the coefficients t and a' were calculated directly. If, as happens near the equator, W is practically constant throughout the year, the expression (3) was given the form—

$$s/(1 - c) = 1 + tc - A \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

and the value of a' was taken as A/w. On the other hand, if the mean cloudiness showed a very slight annual variation, the expression was written—

$$s/(1 - c) = 1 + B - a'w \quad . \quad . \quad . \quad . \quad . \quad (6)$$

whence $t = B/c$.

The same expression was employed for a few stations, especially in the Mediterranean region, where the annual variations of cloudiness and of low sun were so closely similar that the complete solution could not separate them.

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* *Hamburg, Aus. d. Archiv D. Seewarte*, 35, 1912, No. 2. Bewolkung und Sonnenschein des Mittelmeergebietes.

The calculated values of t, a', and a are shown in Table IV, their numerical values, as previously explained, being directly applicable to percentage values of C and W. For the great majority of the stations the results agree very well—remarkably well considering the rather summary method of analysis. The stations are arranged in ten-degree zones of latitude from the poles to the equator, irrespective of hemisphere. The highest latitude is represented by Cape Evans, which called for special treatment, both because the sun is only visible for nine months of the year, and because the duration of daylight changes rapidly from day to day. The duration of daylight, the value of W and the average cloudiness as nearly as possible for the daylight hours, were tabulated for each day for which sunshine records were available, and the monthly means were taken from these days only. The equations were then compiled directly from these eighteen sets of monthly figures (representing two years), instead of taking the average of the two years. This station was especially valuable, for the cloudiness ranged from 47 to 85 per cent., and the values of W from 0 to 100. The value of t, the cloudiness coefficient, came out as ·006, identical with the average of all the other stations which have fairly normal conditions. On the other hand, the values of $a'$and a are unusually low, similar to those for high-level stations—a natural result considering the abnormal clearness and dryness of the atmosphere. Under average conditions at this Antarctic station the sun burns the card when it is within four degrees of the horizon.

Abisko in northern Sweden possesses many of the characteristics of Cape Evans, and the value of a, ·011, is well below that found at most stations in lower latitudes, though higher than that at Cape Evans. Normally the sun does not burn the card until it is more than five degrees above the horizon.

Valentia and Aberdeen call for no remark, but Greenwich presents abnormally high values of a' and a, evidently due to the smoke of London. It is well known that the sunshine records of London are reduced by this cause, and it is interesting to find the result reflected in these calculations. Owing to this local influence, the values for Greenwich have been omitted from the means used in the subsequent generalisations.

The remaining stations in this zone call for no remark, except that at Pavlovsk two separate periods were analysed. The cloudiness during the second period was appreciably greater than that during the first, and the second period also shows a greater value of t, probably indicating that in estimating the amount of cloud, thin clouds were included to a rather greater extent during the second period than during the first. The two values of a are practically identical.

The zone from 50° to 40° is remarkable for some abnormally high values of a among the Mediterranean stations, many exceeding ·025. These include Perpignan, Gorizia, Sulina, Sarajevo, and Sinaia. The country surrounding these stations is generally

TABLE IV—VALUES OF t, a', AND a FOR VARIOUS STATIONS ARRANGED ACCORDING TO LATITUDE

Zone.	Station.	Lat.	Long.	Height.	Period.	C	t	a'	a
		° ′	° ′	metres					
80°–70°	Cape Evans	S. 77 38	E. 166 24	18	1911–1912	67	·006	·011	·008
70°–60°	Abisko	N. 68 20	E. 18 49	388	1913–1925	68	·004	·014	·011
	Valentia	N. 51 56	W. 10 15	14	1881–1920	73	·006	·025	·018
60°–50°	Aberdeen	57 10	2 6	27	1886–1920	65	·003	·021	·018
Coast	Greenwich *	51 28	0 0	46	1881–1915	66	·009	·056	·035
	Tylstrup	57 12	E. 9 57	12	1916–1925	67	·010	·036	·021
	Tystofte	55 15	11 21	13	1916–1925	65	·008	·032	·021
	Copenhagen	55 41	12 36	5	1914–1925	66	·002	·017	·015
	Bornholm	55 4	14 56	88	1918–1923	62	·005	·030	·023
Inland	Donnersberge	N. 50 33	E. 13 56	853	1905–1918	67	·002	·016	·014
	Potsdam	52 23	13 4	85	1893–1902	68	·004	·015	·012
	Pavlovsk	59 41	30 29	40	1881–1894	69	·005	·018	·013
					1895–1905	74	·007	·021	·014
	Ekaterinburg	56 50	60 38	281	1895–1905	61	·004	·017	·014
50°–40°									
Coast.	Perpignan	N. 42 42	E. 2 53	32	1881–1907	51	·008	·037	·026
	Rome	41 54	12 29	63	1887–1904	43	·003	·023	·020
	Triest	45 39	13 46	26	1886–1905	51	·006	·032	·024
	Pola	44 52	13 51	32	1882–1908	44	·003	·018	·016
	Gorizia	45 57	13 37	94	1891–1907	51	·005	·039	·031
	Lussinpiccolo	44 32	14 28	3	1888–1907	40	·004	·027	·024
	Lecce	40 22	18 12	72	1887–1895	39	·002	·021	·020
	Sulina	45 9	29 40	2	1890–1907	47	·004	·030	·025
	Vladivostok	43 7	131 34	128	1912–1921	52	·010	·027	·018
	Hobart	S. 42 53	E. 147 22	54	1920–1924	64	·012	·040	·023
	Wellington	41 16	174 46	2	1919–1927	64	·008	·029	·019
Inland.	Paris*	N. 48 49	E. 2 29	50	1881–1903	63	·008	·045	·030
	Besancon	47 15	5 59	311	1891–1920	67	·004	·015	·012
	Lugano	46 0	8 57	276	1886–1910	47	·006	·021	·016
	Bjelasnica*	43 42	18 15	2,067	1896–1907	65	·001	·005	·005

	Sarajevo*	43 52	18 26	637	1894–1907	58	·007	·059	·041
	Sinaia*	45 21	25 34	860	1887–1907	57	·003	·040	·034
	Bucharest	44 25	26 6	82	1885–1907	54	·003	·014	·012
	Tiflis	41 43	44 48	404	1891–1894	54	·010	·037	·024
40°–30° *Coast.*	San Fernando	N. 36 28	W. 6 12	28	1881–1908	43	·008	·033	·024
	Malta	35 31	E. 4 30	56	1924–1927	41	·007	·019	·015
	Athens	37 58	23 43	107	1894–1903	42	·005	·021	·017
	Alexandria*	31 12	29 54	32	1902–1909	30	·000	·002	·002
	Aboukir*	31 18	30 6	11	1924–1927	35	·007	·001	·001
	Abu Sueir	30 35	32 9	16	1924–1927	27	·009	·018	·014
	Perth W.A.	S. 31 57	E. 115 51	60	1921–1924	45	·009	·037	·026
	Adelaide	34 56	138 35	43	1921–1924	49	·007	·030	·022
	Sydney, N.S.W...	33 51	151 13	45	1921–1924	47	·006	·029	·023
Inland.	Amman*	N. 31 57	E. 35 57	796	1926–1928	25	·007	·006	·005
	Hinaidi	33 17	44 29	49	1924–1927	26	·007	·012	·010
	Shaibah	30 26	47 41	20	1924–1927	24	·008	·018	·015
	Cordoba	S. 31 25	W. 64 12	423	1889–1922	50	·010	·033	·022
30°–20° *Coast.*	Rio de Janeiro	S. 22 54	W. 43 10	61	1898–1920	64	·010	·031	·019
	Mauritius	20 6	E. 57 33	55	Unknown.	53	·010	·022	·014
Inland.	Helwan	N. 29 52	E. 31 20	116	1906–1920	23	·006	·007	·006
	Johannesburg	S. 26 11	E. 28 4	1,806	1919–1927	34	·005	·010	·008
20°–10° *Coast.*	Berbera	N. 10 22	E. 45 2	10	1926–1928	28	·005	·007	·006
	Madras	13 4	80 14	7	1917–1921	46	·001	·012	·012
	Manila	14 35	120 59	14	1903–1927	64	·012	·063	·035
	Apia, Samoa	S. 13 48	W. 171 46	2	1905–6, 16–19	52	·004	·030	·025
Inland.	Khartum	N. 15 37	E. 32 33	390	1912–1921	19	·003	·027	·025
	Kodaikanal	10 14	77 28	2,343	1917–1921	59	·008	·019	·013
	Livingstone	S. 17 51	E. 25 51	960	1924–1928	35	·008	·013	·010
	Salisbury	17 48	31 5	1,481	1925–1927	37	·009	·027	·020
10°–Eq.	Entebbe	N. 0 5	E. 32 29	1,171	1923–1927	64	·003	·017	·014

* Not included in means.

mountainous, and as the high values of a are not offset by correspondingly high values of t—in other words, as the percentages of bright sunshine are generally low compared with what would be expected from the amounts of cloud—it seems probable that the exposures of the sunshine recorders are at fault. The more extreme of these figures have accordingly been omitted from the subsequent calculations. The high value of a at Paris, ·030, is evidently due to the same cause as that which operates at Greenwich, the smoke of a great city. This value has also been ignored.

At the other extreme is Bjelasnica, at a height of over 2,000 metres, with a figure for a of only ·0045. This is no doubt in part due to the abnormal clearness of the atmosphere at a great height, but the extremely low value of t, ·001, suggests that the analytical method adopted has in this case not given an accurate result.

In the zone $40° - 30°$ the remarkably low values of a at Alexandria and Aboukir appear inexplicable. The value of t is zero at Alexandria, but is nearly normal at Aboukir. No doubt the air is very clear, but it does not seem reasonable to believe that the sun can burn the card when its centre is within half a degree of the horizon. On the other hand, the low value of a at Amman, ·0054, is quite in accordance with expectations, as this desert station at a relatively high level must have air of remarkable clearness.

In the zone from 30° to 20° both Helwan and Johannesburg give low values of a, the former no doubt because of its dry clear air, the latter also because of its altitude. Clearness of the air would also account for the low value of a at Berbera, Somaliland, but Khartum presents an abnormally high value of a, presumably owing to the presence of dust haze. It appears that the effects of a desert situation on the records of bright sunshine are rather incalculable. It should be remarked that the Khartum figures for March and September had to be omitted because of a remark by L. J. Sutton that near the equinoxes the sunshine recorder does not function correctly near sunrise and sunset. Attention should also be called to the abnormally high values of both t and a at Manila. This appears to be a case where the method is at fault. During the rainy season the cloudiness is very great, but the records of sunshine do not show a corresponding diminution. There must be an abnormally large amount of thin cloud, and it appears probable that in this case the thin cloud is not high cloud but is largely low cloud not dense enough to prevent the nearly vertical sun from burning the card. If so, the correct measure of thin cloud would be, instead of $t\,C\,(1 - C)$, something between this value and $t\,C$. Two short series at Colombo and Hongkong, where conditions are rather similar to those at Manila, were examined and gave a similar result. At Colombo the mean cloudiness and mean sunshine percentage during the months of

May to August 1923 to 1925 were as follows :—

	May	June	July	August
Cloudiness, per cent.	80	92	88	87
Sunshine, per cent.	60	39	50	51
$S + C$	140	131	138	138

Thus it appears that the hypothesis embodied in equation (1), and therefore the method, are not applicable to tropical stations with a monsoon climate.

The average values for the different belts of latitude, omitting doubtful values and those obtained under exceptional conditions, are shown in Table V. The values of t show no systematic variations, and differ very little at coast and inland stations, and it seems reasonably safe to adopt ·006 as the general value of this coefficient. The values of a' and a are more variable, but there seems no reason to believe that the variations are systematic, except the decrease in high latitudes and the systematically smaller values inland than near the coast.

TABLE V—AVERAGE VALUES OF t, a' AND a IN DIFFERENT LATITUDES

Zone	Coast				Inland			
	No. of Stations	t	a'	a	No. of Stations	t	a'	a
° 80–60	1	·006	·011	·008	1	·004	·014	·011
60–50	6	·006	·027	·019	4	·004	·017	·013
50–40	11	·006	·029	·022	4	·006	·022	·016
40–30	7	·007	·027	·020	3	·008	·021	·016
30–20	2	·010	·026	·017	2	·005	·008	·007
20–10	4	·005	·028	·019	4	·007	·021	·017
10– 0	—	—	—	—	1	·003	·017	·014
Mean, 60–10	30	·006	·028	·021	18	·006	·020	·015

Average values of t, a', and a corresponding with different values of mean cloudiness are shown in Table VI. There is again no appreciable variation of t. This uniformity bears out very well the initial assumption that the amount of thin cloud visible is generally proportional to $C\ (1 - C)$, and not directly to C (except at tropical monsoon stations as already noted). The same result follows from some work by M. D. Marchori,* who for each month investigated the relationship between $S/(1 - C)$ and C, using 31 years' observations at Madrid with a Jordan recorder.

* La relacion entre la nubosidad y las horas de sol despejado. *Madrid, Ann. Soc. Espanola Meteor.*, 1, 1927, p. 79.

TABLE VI—AVERAGE VALUES OF t, a' AND a WITH DIFFERENT AMOUNTS OF CLOUD

Cloud amount	t	a'	a	a' Coast	a' Inland
Above 70.. ..	·0065	·0231	·0157	·025	·021
61–70	·0062	·0260	·0178	·029	·016
51–60	·0063	·0272	·0204	·031	·023
41–50	·0056	·0256	·0202	·025	·027
31–40	·0060	·0175	·0145	·024	·016
Below 31	·0063	·0148	·0129	·012	·014

He obtained a linear relationship, the correlation being as high as + ·83 in September and + ·85 in February. The average coefficient, equivalent to our t, is ·0065.

A similar result was obtained in a different way by J. R. Sutton,* who observed that the higher the percentage of cloud and the lower the percentage of sunshine, the higher the sum of the two. From Sutton's data, obtained with a Jordan recorder, it also appears that the coefficient is linear, and has a value of about ·007.

The values of a' and a, on the other hand, show a distinct relationship to the cloud amount, being greatest with an average cloudiness of 50 per cent. It is easy to see that the values should diminish with small values of cloudiness, which go with desert air, but it is difficult to see why they should also diminish with high values of cloudiness, but the figures appear to be sufficiently definite to show that the effect is real. It is shown by both coastal and inland stations, though at the former the maximum of a' occurs with a cloudiness of 51–60 per cent., and at the latter with a cloudiness of 41–50 per cent. A weighted graphical smoothing gave the values for a' shown in Table VII, those for a being calculated by the relationship :—

$$a = a' / (1 + \cdot 006\,\bar{C})$$

$\bar{C}$ being the mean annual cloudiness expressed as a percentage.

TABLE VII — VALUES OF a' AND a CORRESPONDING WITH DIFFERENT AMOUNTS OF CLOUD

Cloudiness, per cent.	75	65	55	45	35	25
Coast.						
a'	·024	·029	·031	·028	·023	·017
a	·017	·021	·023	·022	·019	·015
Inland.						
a'	·012	·018	·024	·026	·021	·014
a	·008	·013	·018	·020	·017	·012

* A note on the relationship between cloud and sunshine. *Cape Town, Trans. R.Soc. S.Africa,* 9, 1921, p. 137.

It appears reasonable to use the figures in Table VII, together with the value of ·006 for t, to calculate the percentage duration of bright sunshine at stations without recorders, but for which observations of cloudiness at three or more hours a day are available, supposing that the stations in question are not in the vicinity of large towns, at high altitudes or in a tropical monsoon climate.

For large towns it would seem necessary to use larger values of both t and a, say ·008 and ·030, but the results are naturally uncertain, depending largely on local circumstances. For stations in very high latitudes, at high levels and in dry situations where the air is known to be clear, a value of a of about ·010 would probably give reasonably accurate results, t being left at the normal figure of ·006.

Over the oceans I would also use ·006 for t, but the coefficient a is more doubtful. The air is free from dust, but there is generally a certain amount of haze on the horizon in the mornings and evenings. Probably it would be most reasonable to use the figures for coast stations, but the results must be regarded as having a higher degree of uncertainty than when applied to normal land stations.

The formulæ can be employed in three different ways. First, we may use the form of equation (3), giving

$$S = (100 - C)\,(1 + tC - a'W) \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Secondly, we may use the slightly more accurate form of equation (4), giving

$$S = (100 - C)\,[1 + tC - aW\,(1 + tC)] \quad . \quad . \quad (8)$$

C being the mean annual cloudiness.

Thirdly, we may substitute for C in equation (8) the individual monthly means of C, giving the original theoretical form of equation (2) :—

$$S = (100 - C)\,(1 + tC)\,(1 - aW) \quad . \quad . \quad . \quad . \quad (9)$$

Calculations with each of these formulæ were carried out for the stations in the highest and lowest latitudes respectively, Cape Evans and Entebbe (Uganda), and for Valentia, selected as a typical station in middle latitudes, for which a was taken as ·010, whence a' was calculated from the value of C as ·014. For Entebbe and Valentia the values of a and a' were taken from Table VII, for Cape Evans a was taken as ·010. The results are given in Table VIII. The values of $(100 - C)$, i.e., those calculated on the assumption, which is often made, that the percentages of sunshine and cloudiness are complementary, are given for comparison.

At all three stations equations (7) to (9) all show a considerable improvement on the simple values of $(100 - C)$, though the improvement is relatively less at Cape Evans than at the other stations. Between the results of the three equations there seems to be little to choose ; (7) and (9) are best at Cape Evans, (8) and

TABLE VIII—OBSERVED AND CALCULATED VALUES OF SUNSHINE IN PERCENTAGES OF "POSSIBLE"

(1) Observed Percentages.
(2) Calculated from $(100 - C)$
(3) Calculated from equation (7) ; $(100 - C)\ (1 + tC - a'W)$
(4) ,, ,, ,, (8) ; $(100 - C)\ [1 + tC - aW\ (1 + tC)\ ]$
(5) ,, ,, ,, (9) ; $(100 - C)\ (1 + tC)\ (1 - aW)$

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Mean error
Cape Evans													
(1) ..	57	22	26	16	—	—	—	8	30	41	50	59	—
(2) ..	47	18	24	32	—	—	—	15	43	27	49	53	8·1
(3) ..	62	21	26	6	—	—	—	1	34	29	62	70	5·2
(4) ..	65	19	24	5	—	—	—	0	43	28	65	73	7·3
(5) ..	62	22	24	4	—	—	—	0	32	29	55	61	5·3
Valentia													
(1) ..	19	25	33	39	41	38	32	34	35	30	24	17	—
(2) ..	23	24	28	32	32	29	23	27	30	28	26	22	5·4
(3) ..	22	27	32	37	38	35	28	32	35	30	26	20	2·1
(4) ..	21	26	32	38	39	34	27	32	35	29	24	16	1·8
(5) ..	21	26	33	37	38	35	28	32	35	32	25	19	1·8
Entebbe													
(1) ..	40	47	51	44	47	49	43	46	49	54	48	47	—
(2) ..	41	35	35	30	35	41	34	35	41	35	35	40	10·8
(3) ..	50	44	44	39	44	50	43	44	51	44	44	49	4·1
(4) ..	50	44	44	38	44	51	43	44	52	44	44	50	4·4
(5) ..	50	44	46	38	43	50	43	43	52	43	43	50	4·5

(9) at Valentia and (7) at Entebbe. It would seem best to adopt the full equation (9) at stations in middle latitudes where the conditions appear to be normal, and to use the simpler form (7) in high or low latitudes or where for any reason conditions are not normal. It is to be noted that with equation (7) the coefficient a' is employed from Table VII, while with equation (9) the coefficient a is used from the same table.

The calculated values at Valentia appear to be as close to the observed values as could reasonably be expected. At Cape Evans and Entebbe the agreement is not nearly so good. At the former station this results both from the shortness of the record (two years) and from the great variations in the length of the day. At Entebbe the record is also comparatively short (five years), but the errors are probably due to the fact that at certain seasons there is a considerable amount of low cloud which is thin enough to be penetrated by the vertical sun—the same error in fact as invalidates the method at tropical stations with monsoon climates.

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