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# SOLAR RADIATION AT KEW OBSERVATORY

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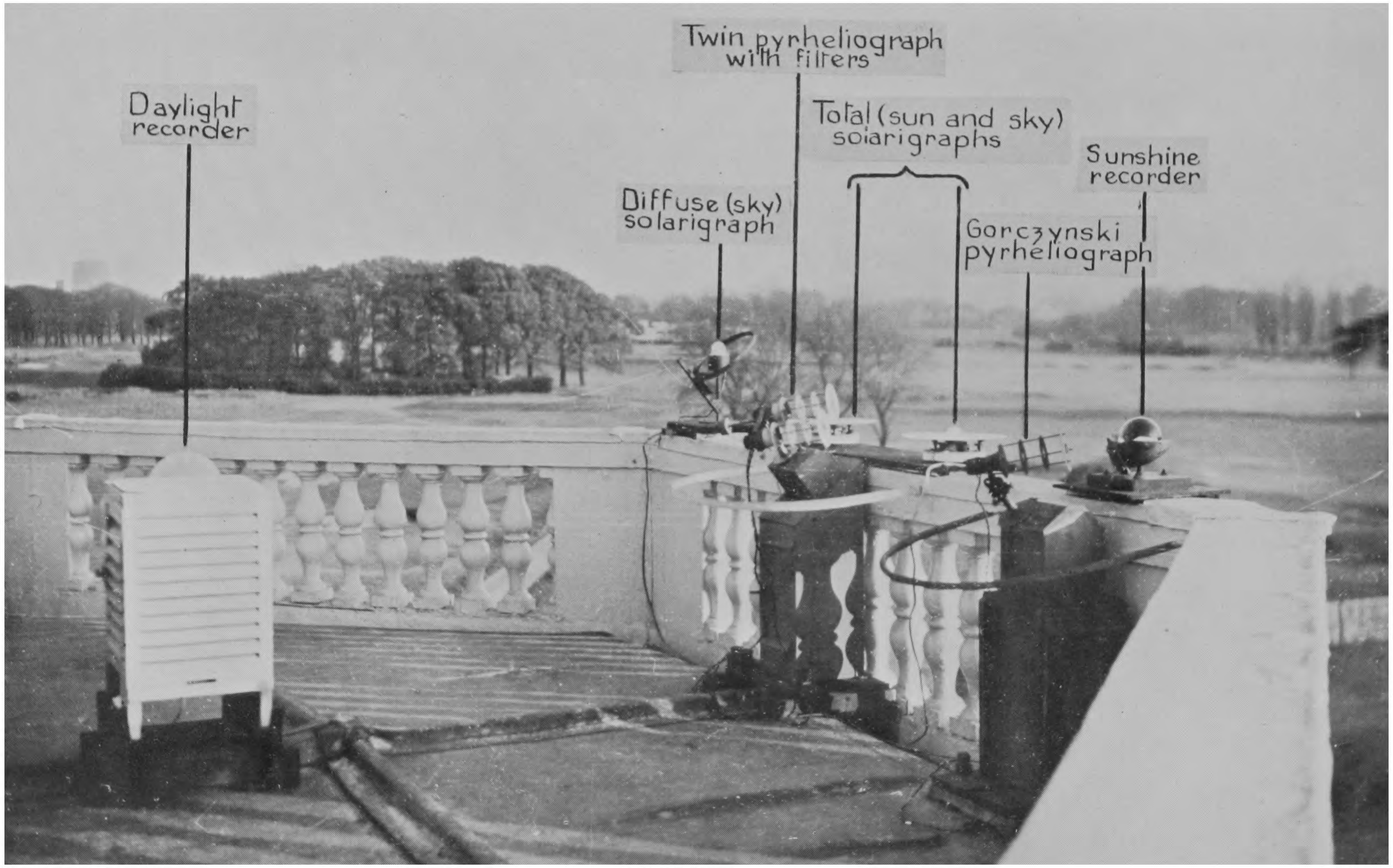


FIG. 1—SOLAR RADIATION EQUIPMENT AT KEW OBSERVATORY

# SOLAR RADIATION AT KEW OBSERVATORY

## INTRODUCTION

Records of direct solar radiation have been continuously maintained at Kew Observatory since July 1932 and intermittently for a few years before then. As these records form one of the few sources of information on solar radiation in the British Isles, and because of their interest to meteorologists as well as to architects, specialists in building research, heating and fuel engineers and agricultural and fishery authorities, it is desirable to summarise the data.

Though the material to be discussed is concerned primarily with direct solar radiation received on a surface maintained normal to the direction of the radiation, measurements of the radiation received on a horizontal surface from sun and sky and from the sky alone have also been made at Kew Observatory since July 1946. As information about these aspects of solar radiation is probably more immediately useful in many practical applications than data concerning direct radiation of normal incidence, some preliminary results from the first year's measurements are given in the second part of the discussion.

## PART I—DIRECT SOLAR RADIATION OF NORMAL INCIDENCE

### § 1—INSTRUMENTS USED

Except for a radical reconditioning in 1945 (see § 2), the instrumental equipment at Kew Observatory and the conditions of exposure have remained the same throughout. A Gorczynski pyrheliograph, which receives the radiation, consists of a Moll large-surface thermopile (80 thermocouple junctions) on an equatorial mounting, driven by a robust pendulum clock. With slight changes in elevation each day to keep pace with changing solar declination the heliostat ensures that the thermopile surface is kept normal to the direct radiation from the sun. A wire frame attached to a collar which fits on to the thermopile holder carries three metal diaphragms spaced outwards from the thermopile so that the angular aperture allows only radiation from the sun and a narrow annulus of sky to fall on the thermopile. The thermopile is protected by a glass cover, and its output is led into a (Richard) recording millivoltmeter.

The transmission characteristics of the glass cover are not precisely known; but as the instrument is standardised by an Ångström compensation pyrheliometer with unshielded black strips, the radiation intensities tabulated from the Gorczynski records are in effect the intensities incident on an unprotected thermopile surface—provided the solar radiation transmitted by the glass cover bears a constant relation to the total radiation falling on the glass surface. As the limit of transmission of ordinary clear glass a few millimetres thick is usually $2{\cdot}8$ to $3\mu$ the proportion of total radiation cut off is probably very small; furthermore the absorption bands of the main variable absorber in the atmosphere in this region ($\phi$, $\psi$ and $\Omega$ of water vapour) are within the spectral range transmitted by glass.

Up to now it has not been practicable at Kew Observatory to measure the proportion of red radiation in the total intensity. This is now being done by use of a twin heliostat carrying two thermopiles screened by filters, so that the spectral components of the direct radiation are continuously recorded. Fig. 1 shows the arrangement of the Gorczynski pyreheliograph and other radiation equipment on the roof of the Observatory.

## § 2—STANDARDIZATION OF INSTRUMENTS

On suitable days when the sky in the neighbourhood of the sun is free of cloud a measurement of the intensity of direct solar radiation, $I$, is made using an Ångström compensation pyrheliometer, No. 24, which was calibrated at Uppsala and has been compared from time to time with other substandard pyrheliometers. Investigations at the National Physical Laboratory[1]* showed that the error of the scale of the Ångström instrument by which the Kew standardization measurements were made did not exceed 0·5 per cent., and more recent inter-comparisons with other pyrheliometers have shown that the Kew standard instrument has maintained its constant unchanged. Comparison of the pyrheliometer values of $I$ with the simultaneous values registered by the Gorczynski instrument give a factor, $F$, for relating the continuous records to the standard scale.

The value of $F$ was originally fixed at 1·00 by adjustment of the resistance in the thermopile circuit; it normally varies only slightly from month to month and shows no progressive drift. Fluctuations greater than 2 or 3 per cent. of the long-period mean value of $F$ are exceptional, and when both thermopile (with its recorder) and pyrheliometer are functioning satisfactorily, it is legitimate to smooth them out as being attributable to inaccuracies of timing in the standardization experiments or in the record, or to inaccurate setting in one or other of the two instruments.

TABLE I—FACTOR $F$ BEFORE AND AFTER RECONDITIONING OF THERMOPILE

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Date $F$ | Date $F$ | Date $F$ | Date $F$ | Date $F$ | Date $F$ | Date $F$ | Date $F$ | Date $F$ | Date $F$ | Date $F$ | Date $F$ |
| 1943 | 13 1·10<br>21 1·21 | 3 1·15 | 5 1·29<br>9 1·24<br>12 1·30<br>16 1·23<br>17 1·21<br>18 1·29 | 7 1·10 | 13 1·17<br>14 1·26<br>18 1·08<br>19 1·17 | 28 1·06 | 1 1·11<br>2 1·13<br>27 1·18 | 17 1·23 | 22 1·28<br>23 1·19<br>24 1·20<br>27 1·23 | — | 10 1·14<br>19 1·24<br>25 1·31 | 2 1·28<br>22 1·27<br>30 1·18 |
| 1946 | 3 0·97<br>12 0·99 | 27 0·97 | 23 0·99<br>26 1·01 | 1 1·00<br>3 1·01<br>16 1·02<br>20 0·99 | 28 1·02 | 28 1·01 | 3 1·00<br>10 1·00 | — | 27 0·99 | 11 1·01<br>24 1·02 | 4 1·01 | 4 1·00<br>10 0·98<br>20 1·00 |

From the summer of 1932 until near the end of 1937, $F$ remained practically constant at 1·00; but in 1938 it began to increase (indicating decreasing sensitivity of the thermopile), at first slowly and almost imperceptibly, then more rapidly until, by the latter part of 1944, it had become 1·26. During those years of progressive change in $F$, its variability also increased to 12–15 per cent. of its mean value. Table I gives for comparison the $F$ values for 1943 and 1946 by which latter year the thermopile had been repaired. A smooth progressive change in sensitivity of the thermopile could be taken account of by making corresponding changes in the reduction factor of the records; but the serious question remained: was the increased variability in $F$ an indication of real short-period changes of sensitivity superposed on the progressive drift?

Unfortunately the circumstances of the period during which these uncertainties were taking place were against providing an easy answer. Comparison observations between the pyrheliograph and the pyrheliometer had been made as frequently as practicable; but even without the war-time shortage of trained observatory staff and the need for attention to more urgent matters, the normal climate of England ensures that there are seldom more than one or two days a month when conditions are suitable for satisfactory standardization measurements.

* The index numbers refer to the bibliography on p. 37.

## § 3—CORRECTIONS TO THE 1938–45 MATERIAL

When the thermopile was examined in 1945 a number of its junctions were found to have decayed, probably owing to electro-chemical effects arising from deposition of moisture and oxidation. It seemed very likely that spurious contacts had been effected between adjacent elements, thus disrupting the continuous series linkage of the elements and putting a proportion of them in parallel. Now on this evidence it was easy enough to account for long-period changes (progressive or discontinuous) in the sensitivity of the pile but the short-period variability remained unexplained. Any hypothesis required that some of the defective contacts should right themselves for short intervals (of the order of hours or a few days) and then seriously deteriorate again, as had been indicated by the fluctuations in $F$ on those few occasions when it had been possible to make standardising measurements against the Ångström pyrheliometer on successive days. It did not seem practicable that this could have occurred.

As all the hourly values of direct solar radiation had already been tabulated and reduced to energy units assuming a steady factor of 1·00, corrections were made to the tabulations from 1937 onwards; and, as there was no satisfactory basis for taking account of the short-period fluctuations, the adjustments were applied over periods of a year or part of a year as shown by the adopted values of $F$ given in Table II. At this early stage, the intention was to provide only long-term averages of radiation; if day-to-day changes had actually taken place in the behaviour of the thermopile in the general course of its deterioration they would probably not affect the monthly and annual means to any substantial extent.

TABLE II—ADOPTED VALUES OF $F$

| | |
|---|---|
| 1933–37 .. .. | 1·00 |
| 1938 .. .. | 1·03 until October<br>1·04 by steps to 1·15 through November and December |
| 1939 .. .. | 1·15 throughout |
| 1940 .. .. | 1·16 |
| 1941 .. .. | 1·17 |
| 1942 .. .. | 1·18 |
| 1943 .. .. | 1·20 till July 31 then 1·23 |
| 1944 .. .. | 1·26 |
| 1945 .. .. | 1·20 till March. After repair of the thermopile the resistance of the thermopile circuit was adjusted to restore $F$ to its original value of 1·00. |

As will be explained in § 5, it was subsequently decided to form estimates of the maximum direct radiation likely to be recorded at Kew; this was done using the records from the unexceptional years 1945 and 1946 after the thermopile had been reconditioned. When the radiation values $I$ for exceptionally clear conditions in those years were compared with the adjusted data for the 1938–44 period, some isolated hours were found in the 1938–44 data with radiation intensities above the "ceiling" values. For example, the ceiling intensity deduced for local midday in May was 1·33 cal./cm.$^2$/min., but the intensity as tabulated using the adjusted factor 1·20 for May 18, 1943 was 1·43 cal./cm.$^2$/min. On that occasion, and therefore presumably on other occasions, it is likely that the mean factor which had been accepted did not truly represent the sensitivity of the thermopile. Reference to Table I shows that May 1943 was in the period when the daily values of $F$ fluctuated wildly, and that the adoption of the observed $F$ (1·08) instead of the smoothed value (1·20) would have brought the tabulated intensity on May 18 below the ceiling intensity. But how and where did the discontinuity between May 14 ($F$ = 1·26) and May 19 ($F$=1·17) occur, and how many similar variations in sensitivity occurred in the period when no standardizations had been possible? Some evidence was collected which showed that, while the progressive drift in the series of reduction factors $F$ was perhaps greater in the early winter months, the greatest fluctuations in the day-to-day values occurred in the summer months. This could be explained by varying effects of humidity and temperature on the thermo-electric junctions.

Having no other continuous radiation instrument with which to compare the pyrheliograph records, little could be done to reduce the uncertainties in the material; probably only the summer records were affected and those only on a few hours of isolated days of highest temperature and humidity (and therefore high radiation intensities). Faults in the measurement of $I$ by an instrument like the Gorczynski pyrheliograph almost always lead to recording $I$ intensities lower than the correct values, for example, by the heliostat being slightly off the sun through imperfect correction for sun's declination or hour angle; the inclusion of some days of questionably high values cannot therefore add seriously to the other uncertainties.

In the formation of monthly and annual means and diurnal variations for selected sets of days, it was therefore decided to accept those few days in which hourly $I$ intensities equalled or slightly exceeded the estimated ceiling values.

## § 4—MONTHLY AND ANNUAL TOTALS; ALL DAYS

Tables III and IV give the mean monthly and annual totals of direct solar radiation at Kew Observatory in calories per square centimetre for all days of the fourteen years of complete data, 1933 to 1946. A few of the more salient features of these tables are:

(1) The total direct solar radiation received at Kew in an average year is about 56,000 cal./cm.$^2$; in the last fourteen years it has ranged between 69,200 (1943) and 47,300 (1936) cal./cm.$^2$ The four months May to August contribute 56 per cent. to the year's total, and the four winter months only 10 per cent.

(2) A monthly total radiation of 10,000 cal./cm.$^2$ was exceeded only in May, June and July and only once in each of those months; totals below 1,000 occur in each of the four winter months November to February. The lowest recorded monthly total is 465 cal./cm.$^2$ (December 1933) and the highest is 12, 263 (May 1943); probably the next highest (June 1940 with 12,141 cal./cm.$^2$) is the more dependable value.

(3) October is the steadiest month of the year; the range between the highest and lowest October values in the series, as a percentage of the mean, is 44 per cent. February on this basis is the most variable month, 144 per cent. Of the summer months, June and August are less variable than July, 60 per cent. compared with 91 per cent.

TABLE III—MONTHLY TOTALS OF DIRECT RADIATION

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Means | | | | | | cal./cm.$^2$ | | | | | | |
| 1933–46 | 1,187 | 2,031 | 4,029 | 5,765 | 8,013 | 8,811 | 7,594 | 7,207 | 5,422 | 3,365 | 1,484 | 1,126 |
| 1933–41 | 1,167 | 2,015 | 4,124 | 4,689 | 7,189 | 8,665 | 7,650 | 6,965 | 5,618 | 3,427 | 1,467 | 1,011 |
| 1942–46 | 1,222 | 2,061 | 3,858 | 7,702 | 9,496 | 9,073 | 7,494 | 7,642 | 5,070 | 3,253 | 1,515 | 1,333 |
| Highest | 1,635 | 3,617 | 7,169 | 9,018 | 12,263 | 12,141 | 11,224 | 9,684 | 7,433 | 4,042 | 2,324 | 1,941 |
| (year) | (1937) | (1939) | (1938) | (1942) | (1943) | (1940) | (1934) | (1943) | (1934) | (1935) | (1940) | (1936) |
| Lowest | 586 | 692 | 2,191 | 3,148 | 5,494 | 6,976 | 4,308 | 5,305 | 2,334 | 2,561 | 918 | 465 |
| (year) | (1941) | (1940) | (1942) | (1941) | (1941) | (1934) | (1944) | (1939) | (1945) | (1946) | (1939) | (1933) |

TABLE IV—ANNUAL TOTALS OF DIRECT RADIATION

| 1933 | 1934 | 1935 | 1936 | 1937 | 1938 | 1939 | 1940 | 1941 | 1942 | 1943 | 1944 | 1945 | 1946 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | cal./cm.$^2$ | | | | | | | |
| 62,181 | 56,554 | 56,396 | 47,321 | 51,022 | 52,069 | 52,106 | 60,178 | 48,044 | 59,972 | 69,233 | 58,880 | 55,108 | 55,405 |

1933–46 56,033 1933–41 53,986 1942–46 59,720

The reason for giving separate means for 1942–46 in Table III is that an unexplained discontinuity was found in the 1942 data in the course of a minor inquiry (see § 5) into the relationship between $I$ and sunshine, $S$. As the same sunshine recorder was used throughout, the discontinuity had to be attributed to the measures of radiation. But the factor for reducing the radiation records had changed less than 1 per cent. between 1941 and 1942, and though there was a considerable scatter in $F$ in both years there was no occasion when a permanent discontinuity could be said to occur. Furthermore the re-conditioning of the thermopile in 1945 did not affect the $I/S$ relation: the same value was deduced for 1944 using the modified reduction factors for that year given in Table II as was deduced from the 1945 data after the repair of the thermopile. The discontinuity could not therefore be reasonably attributed to change in sensitivity through any deterioration which might not have been taken account of by the modified factors; in any event such omission would most probably have resulted in a change in the $I/S$ ratio in the direction opposite to that actually found, *viz.* from 36·1 for the earlier years to 44·4 for the years after 1942.

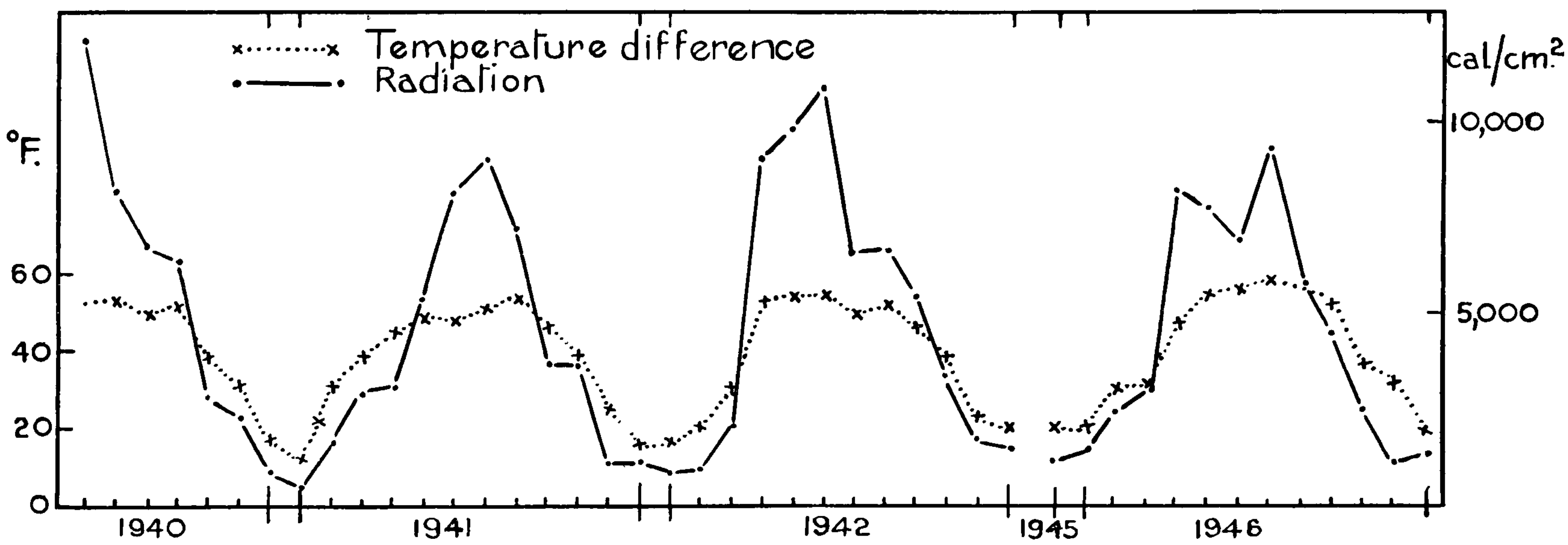


FIG. 2—DIRECT RADIATION AND DIFFERENCE BETWEEN SOLAR MAXIMUM AND SCREEN TEMPERATURE

As being the only other observational material at Kew with which direct solar radiation might be expected to have a rough relationship sufficient to indicate gross anomalies in radiation measurements, means were formed of the differences (solar maximum temperature — screen temperature) for 1940–42. The solar maximum temperature is the highest temperature reached each day in a thermometer with a blackened bulb within an outer evacuated bulb directly exposed to the sky. Fig. 2 shows that no useful inferences could be made from the comparison. In the months September to March of each year the radiation values broadly followed the temperature differences, whereas in the summer months the temperature differences remained relatively flat (about 45–55° F.), corresponding roughly with 5,000 cal./cm.$^2$, while the monthly totals of radiation rose to about 10,000 cal./cm.$^2$ There was no indication of a discontinuity in the sequence of radiation data relative to the temperature data.

No explanation can be offered for the discontinuity. It was therefore decided to split the data into two sets, one set for 1933 to 1941 and the other for the later years; the seasonal and diurnal variations are probably unaffected.

## § 5—DAILY TOTALS FOR VARIOUS CATEGORIES OF DAYS

Average daily totals for each month were formed for all days, and, for comparison, for a group of practically cloudless days; as cloud observations are made at Kew Observatory only at 3-hourly intervals, the first selection of cloudless days was made on the basis of values of percentage possible sunshine, but the selection was later modified to depend on the daily radiation totals themselves. At this stage it became apparent that the outcome of a comparison between radiation on an average day and that of a cloudless day depended on the degree of cloudlessness. It requires a highly skilled observer to detect the presence of thin cirrus cloud which may just be in process of formation, or cirrus cloud which has formed between the times of observation and is in process of dissipating again. On such occasions there may be little difference in the appearance of the sky but the effect on a record of radiation may be substantial. A more restricted set of cloudless days was therefore formed using as basis of selection standards of total radiation higher than in the first category.

An attempt was also made to estimate the maximum or ceiling values of radiation likely to be recorded at Kew on exceptionally clear occasions. The reasons for adopting the procedure actually used in forming these values may not be obvious until subsequent paragraphs (particularly § 10 and § 11) have been read, but it is desirable to describe the manner of formation at this stage. A catalogue was formed of peak values of $I$ recorded in the period May 1945 to January 1947, and after computing the sun's altitude, $h$, at the time of each value, dot diagrams of $I$ against $h$ were prepared for pairs of consecutive months. It is to be noted that the highest values cannot be selected just by inspection of records, except perhaps on consecutive days at times of the year when the sun's declination is practically stationary. Similar times on the records normally correspond with different values of $h$ and therefore with different optical path lengths. In comparing $I$ values for short periods on different days, it is therefore necessary to use $h$ as the parameter instead of time.

It may also be noted parenthetically that it was only after these dot diagrams had been constructed that the considerable range in $I$ values for similar values of $h$ in apparently equally clear-sky conditions was fully appreciated. It was early noticed that on two days of similarly cloudless sky and good visibility at the same time of year, one with an easterly air drift, the other west or north-westerly, the whole level of radiation could be altered by 10 to 15 per cent., but it was not clear until the peak values of $I$ were catalogued and compared against the optical paths of the radiation that, superposed on the relatively steady values on such days, there is generally an irregularly fluctuating variation, related presumably to temporary, though large scale, changes in air clarity through a considerable depth of atmosphere.

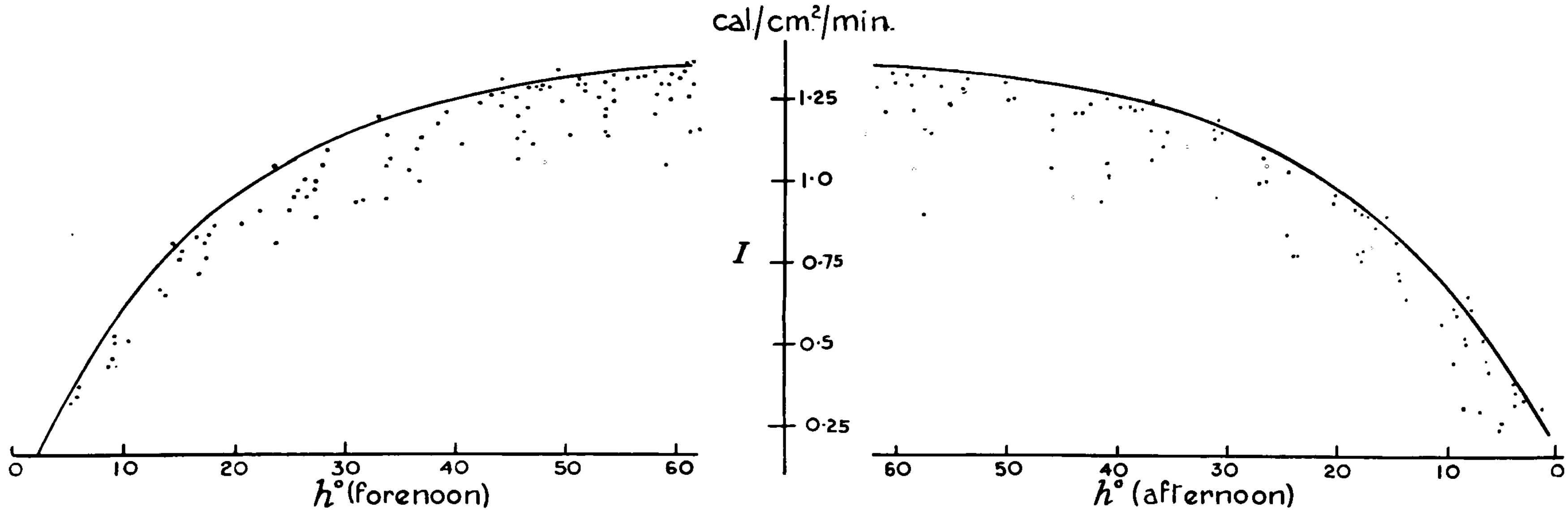


FIG. 3—RELATION OF INTENSITY OF DIRECT RADIATION, $I$, TO SUN'S ALTITUDE, $h$, ON CLEAREST OCCASIONS IN JUNE AND JULY TOGETHER

Fig. 3 reproduces the dot diagram from the June–July peak intensities and shows the envelope drawn to represent the peak or ceiling $I$ values for this pair of months; 62° is approximately the maximum $h$ at Kew, hence the break in the run of dots between forenoon and afternoon in the figure.

As no systematic difference was observable between the forenoon and afternoon $I$ intensities read from the envelopes, they were combined to form the six curves (one for each 2-monthly period) shown in Fig. 4.

At first sight the surprising feature about Fig. 4 is the practical identity of peak radiation intensities for corresponding *h*'s throughout the year. But apart from a seasonal variation in the " solar constant " of radiation, $I_0$, due to the elliptical form of the earth's orbit, there is no reason why the clearest atmospheric conditions in midsummer should not yield *I* intensities, for however short a time, which are approximately the same as in midwinter for similar path lengths. Actually the December–January peak intensity for $h = 15°$ is 52·0 cal./hr. and the corresponding figure for June–July is 49·4. The intensities for all altitudes from 10° to 40° are higher for the winter half-year than for the summer half-year. The difference is in the right direction and of the size to be accountable by the 7 per cent. change in $I_0$ from perihelion to aphelion.

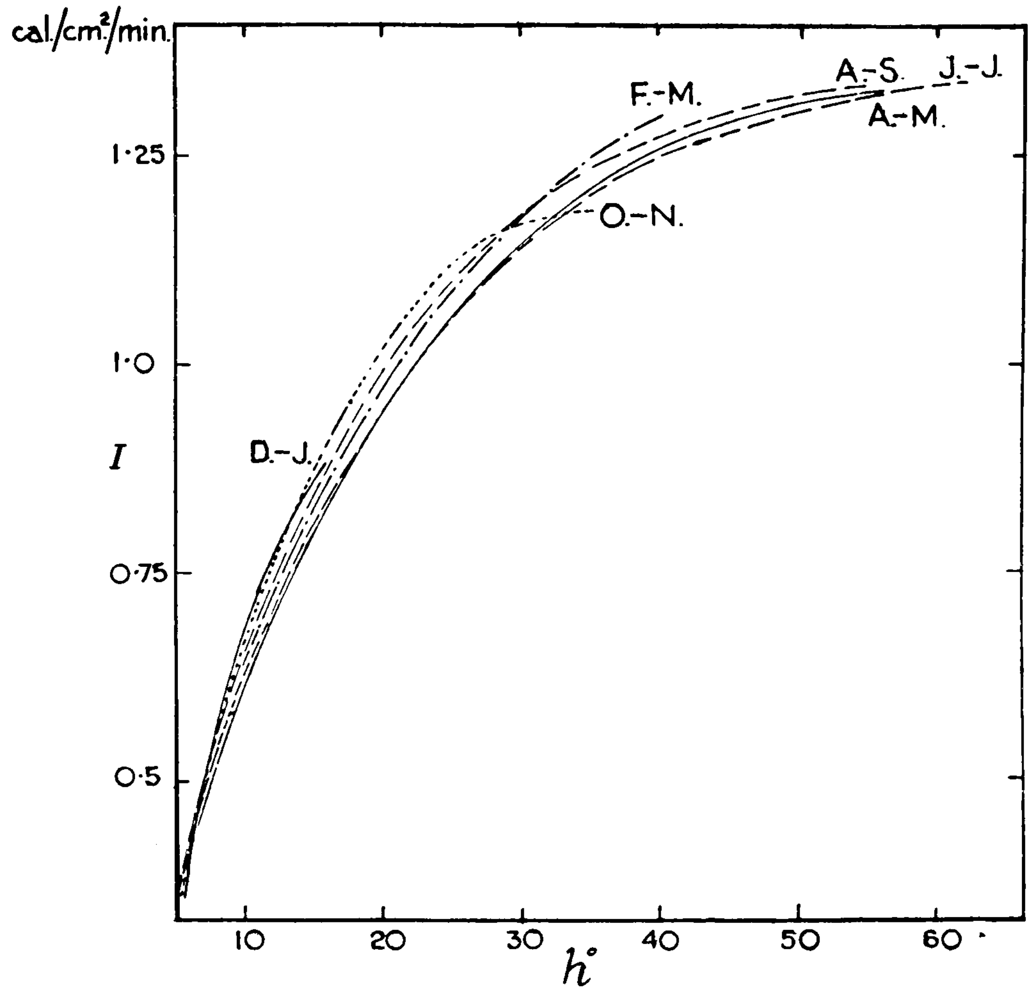


FIG. 4—RELATION OF INTENSITY OF DIRECT RADIATION, *I*, TO SUN'S ALTITUDE, *h*, ON CLEAREST OCCASIONS IN PAIRS OF MONTHS

To estimate the maximum *I* which could be received at Kew if the atmosphere were continuously as clear as on the occasions which produced those peak values, the changes in radiation intensity effected by the seasonal variation in solar constant were ignored, and the six curves of Fig. 4 were further combined into one curve relating ceiling intensities to *h*. From this curve, maximum *I* values at Kew were estimated for each month (mean hourly and daily totals).

The sets of mean daily values for each month derived from the four different categories of days described above are given in lines A to D of Table V; as the same letters and categories will be used again later in the discussion they are summarised as follows for easy reference:—

*Line A.*—All available days of recorded radiation in each month, 1933 to 1946, *i.e.* same basis as for Tables III and IV.

*Line B.*—Complete days selected from each month for their high total daily radiation. All the days of each month were selected on which the radiation had exceeded a value which was kept constant in all months of the same name, but which was varied from month to month to obtain a representative segregation of days. The limiting value in calories per square centimetre per day and the number of days selected were as follows:—

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Radiation .. .. | 150 | 250 | 350 | 450 | 600 | 650 | 550 | 500 | 450 | 350 | 230 | 200 |
| No. of days .. .. | 30 | 28 | 36 | 43 | 38 | 43 | 44 | 35 | 36 | 24 | 15 | 10 |

This group of high radiation days formed about 8 per cent. of the total number of available days.

*Line C.*—Very limited groups of 5 or 6 complete days selected for having the highest daily radiation recorded in the 14 Januaries, Februaries, etc.; these groups therefore represent only about 1 per cent. of all available days.

*Line D.*—Maximum recorded or ceiling values of daily radiation at Kew Observatory on exceptionally clear occasions; they were formed, as described above, from very short periods.

*Line E.*—The figures in line E of Table V, from Dorno[2], are means from five European observatories (Montpellier, Davos, Vienna, Warsaw and Potsdam); they are remarkably similar month by month to the Kew radiation totals for all days (line A).

*Line F.*—Computed totals according to Linke[3] of direct radiation from a clear sky in latitude 50° with a mean turbidity factor of 2·25 (see p. 25). The similarity with the corresponding Kew data in line D is noteworthy.

TABLE V—DAILY TOTALS OF DIRECT RADIATION FOR VARIOUS CATEGORIES OF DAYS

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. | Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | cal./cm.² | | | | | | |
| A | 38 | 72 | 130 | 192 | 258 | 294 | 245 | 233 | 181 | 108 | 49 | 36 | 154 |
| B | 196 | 295 | 451 | 550 | 701 | 742 | 654 | 603 | 534 | 418 | 279 | 223 | 519 |
| C | 260 | 346 | 591 | 685 | 766 | 877 | 819 | 773 | 607 | 490 | 342 | 237 | 566 |
| D | 338 | 495 | 679 | 849 | 971 | 1,035 | 999 | 895 | 748 | 571 | 379 | 291 | 687 |
| E | 43 | 74 | 132 | 199 | 281 | 310 | 305 | 272 | 194 | 98 | 51 | 32 | 166 |
| F | 375 | 525 | 712 | 882 | 983 | 1,055 | 1,018 | 932 | 766 | 599 | 414 | 295 | 712 |

A All days (1933–46)
B days of high radiation
C days of highest recorded radiation
D ceiling values at Kew Observatory
E means from five European observatories (*cf.* line A for Kew)
F computed values for clear sky in latitude 50° with turbidity factor 2·25 (*cf.* line D)

The notable points about Table V (see also Fig. 5) are:—

(1) The total direct radiation received on the average day at Kew (line A) is only from 11 per cent. (January) to 38 per cent. (June) of the value recorded on the clearest complete days (line C); the average for the year is under 25 per cent.

(2) On the class of days represented by line B, direct radiation reaches 75 per cent. of the maximum values at Kew (line D); and on the very limited number of very clear complete days (line C) it amounts to about 82 per cent. of the maximum. Had the process of selection been extended to making up days from groups of hours each of exceptionally high radiation value, a closer approximation to the limiting value would have been obtained, though probably not nearer than 88 or 90 per cent., because the ceiling values in line D were derived from the envelope of limiting intensities, obtained from short intervals often not longer than a few minutes.

(3) The percentages of theoretically possible bright sunshine, $S$, derived from the Campbell-Stokes recorder for the year as a whole in the three classes of days represented by

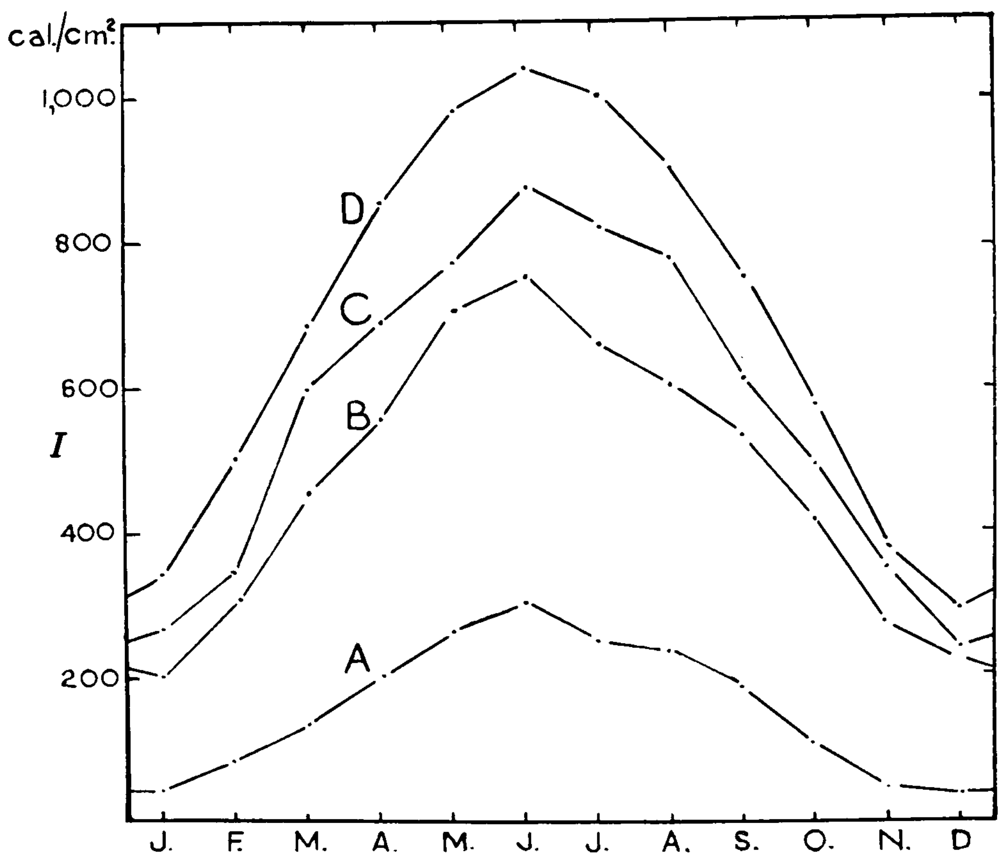


FIG. 5—DAILY TOTALS OF DIRECT RADIATION

A—all days
B—days of high radiation
C—days of highest recorded radiation
D—ceiling radiation values

lines A, B and C of Table V are 30, 76, and 82 per cent. The direct solar radiation, $I$, and the corresponding possible sunshine values, $S$, form a linear relation $I = 7{\cdot}87\ (S\text{–}10)$ when $S$ is not less than about 15–20 per cent. This relationship does not purport to be other than it is, *viz.* a rough connexion between the quantity $S$ taken over periods of the order of a year (in which $S$ is seldom as low as 10 per cent. in these latitudes) and direct solar radiation. It has been estimated that the equipment used at Kew Observatory for measuring direct solar radiation registers about $0{\cdot}2$ cal./cm.²/min. when the card of the Campbell-Stokes recorder begins to burn; but that effect is out-balanced by the over-estimation of sunshine by the Campbell-Stokes recorder when sunshine is intermittent. A burn representing two minutes of sunshine can result from a very few seconds of bright sunshine during breaks in cloud. It is likely that it is this effect of over-estimation by the Campbell Stokes recorder which is reflected in the term ($S$–10) in the relationship quoted above. It should also be mentioned that the maximum recordable sunshine at Kew Observatory on cloudless days days in summer probably does not exceed 96 per cent. of the theoretical length of day, with 85 per cent. as the corresponding figure for winter. But without going further into questions of the defects of sunshine recorders, and the significance of the percentages $S$ in relation to cloudiness, it is clear that the relationship between $S$ and the amount of cloud is not simple, so there is little purpose in considering the relationship between $S$ and $I$ in more detail, except to note that it gives the radiation corresponding with 96 per cent. of the possible sunshine as about 680 cal./cm.², whereas the $I$ value for the clearest days in line D of Table V is 687.

## § 6—FREQUENCY DISTRIBUTION OF DAILY TOTALS

The percentage frequency distribution of daily totals of direct radiation for each month (14 years: January–June; 15 years: July–December) is given in Table VI, in steps of 50 cal./cm.² to 200 cal./cm.², thereafter in steps of 100 to 900. June 20, 1944 (941 cal./cm.²) and July 17, 1943 (902 cal./cm.²) were the only two days on which the total tabulated radiation exceeded 900 cal./cm.², and they are in years when the intensities are somewhat questionable (see § 5). More certain are some of the 21 days when more than 800 cal./cm.² were recorded. They occurred as follows: April one day, May four days, June ten days, July five days, and August one day. At the opposite extreme, on nearly three quarters of all days in January and December the day's total of radiation was not more than 50 cal./cm.².

TABLE VI—PERCENTAGE FREQUENCY DISTRIBUTION OF DAILY TOTALS OF DIRECT RADIATION (ALL DAYS)

cal./cm.²

| | <50 | 51–100 | 101–150 | 151–200 | 201–300 | 301–400 | 401–500 | 501–600 | 601–700 | 701–800 | 801–900 | 901–950 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | per cent. | | | | | | |
| Jan. | 73 | 12 | 7 | 5 | 3 | .. | .. | .. | .. | .. | .. | .. |
| Feb. | 60 | 12 | 7 | 8 | 10 | 3 | .. | .. | .. | .. | .. | .. |
| Mar. | 40 | 14 | 11 | 10 | 9 | 10 | 4 | 2 | <1 | .. | .. | .. |
| Apr. | 31 | 11 | 10 | 8 | 12 | 11 | 8 | 5 | 3 | 1 | <1 | .. |
| May | 22 | 9 | 10 | 7 | 14 | 13 | 11 | 6 | 5 | 2 | 1 | .. |
| June | 16 | 10 | 9 | 9 | 15 | 12 | 8 | 9 | 6 | 3 | 2 | <1 |
| July | 22 | 11 | 11 | 8 | 15 | 11 | 7 | 7 | 4 | 3 | 1 | <1 |
| Aug. | 21 | 12 | 9 | 10 | 15 | 14 | 10 | 5 | 3 | 1 | <1 | .. |
| Sept. | 31 | 14 | 10 | 6 | 14 | 10 | 8 | 6 | 1 | .. | .. | .. |
| Oct. | 45 | 13 | 14 | 9 | 11 | 6 | 2 | 1 | .. | .. | .. | .. |
| Nov. | 69 | 12 | 10 | 4 | 5 | <1 | <1 | .. | .. | .. | .. | .. |
| Dec. | 73 | 12 | 8 | 4 | 3 | .. | .. | .. | .. | .. | .. | .. |

## § 7—DAILY VARIATION OF INTENSITY

Up to this stage in the analysis, daily totals have formed the basis of the treatment. But these totals alone would be of little use to an architect or to a heating engineer who sought to estimate the radiation falling on the side of a building facing a particular direction, or to a meteorologist who wished to examine the effect on radiation intensities of the diurnal convective processes in the atmosphere. To meet such needs it would be necessary to estimate the components of radiation over a sequence of hours, and this entails knowledge of (*a*) the azimuth and altitude of the sun for each hour and (*b*) hourly intensities of total radiation. These latter are given in Tables VII, VIII and IX for the three categories of days already used, *viz.* A all days, B days of high radiation totals, and C a very restricted category of the highest recorded daily totals. For comparison with these data, Table X gives the probable maximum (or ceiling) values of direct radiation at Kew Observatory derived in the manner described in § 5. The results for March, June and December in Tables VII to X are represented diagramatically in Fig. 6.

It is to be noted that Tables VII, VIII and IX are derived from the measurements of $I$ recorded over 60-min. intervals; as the radiation is seldom, if ever, steady throughout an hour, the intensities do not represent the highest momentary intensities reached within the hour.

The main features of the daily variations may be summarised as follows:—

(1) $I$ increases rapidly in the hours immediately following sunrise and decreases equally rapidly just before sunset. In the summer months there is a clear flattening of the curve of variation in the middle of the day. The explanation is that if $m$ is the thickness of the atmosphere through which a beam of radiation penetrates to reach the ground and $h$ the height of the sun above the horizon, $dm/dh$ is steep for small values of $h$ up to about 15°, then falls off rapidly above 30°. The following values illustrate this, the unit of $m$ being the optical thickness of atmosphere traversed by radiation from a zenith sun:—

| $h(°)$ | 3·1 | 5·2 | 5·9 | 6·8 | 7·8 | 9·3 | 11·3 | 14·3 | 16·4 | 19·3 | 23·5 | 30·0 | 41·7 | 60 | 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $m$ | 15 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3·5 | 3 | 2·5 | 2 | 1·5 | 1·15 | 1 |

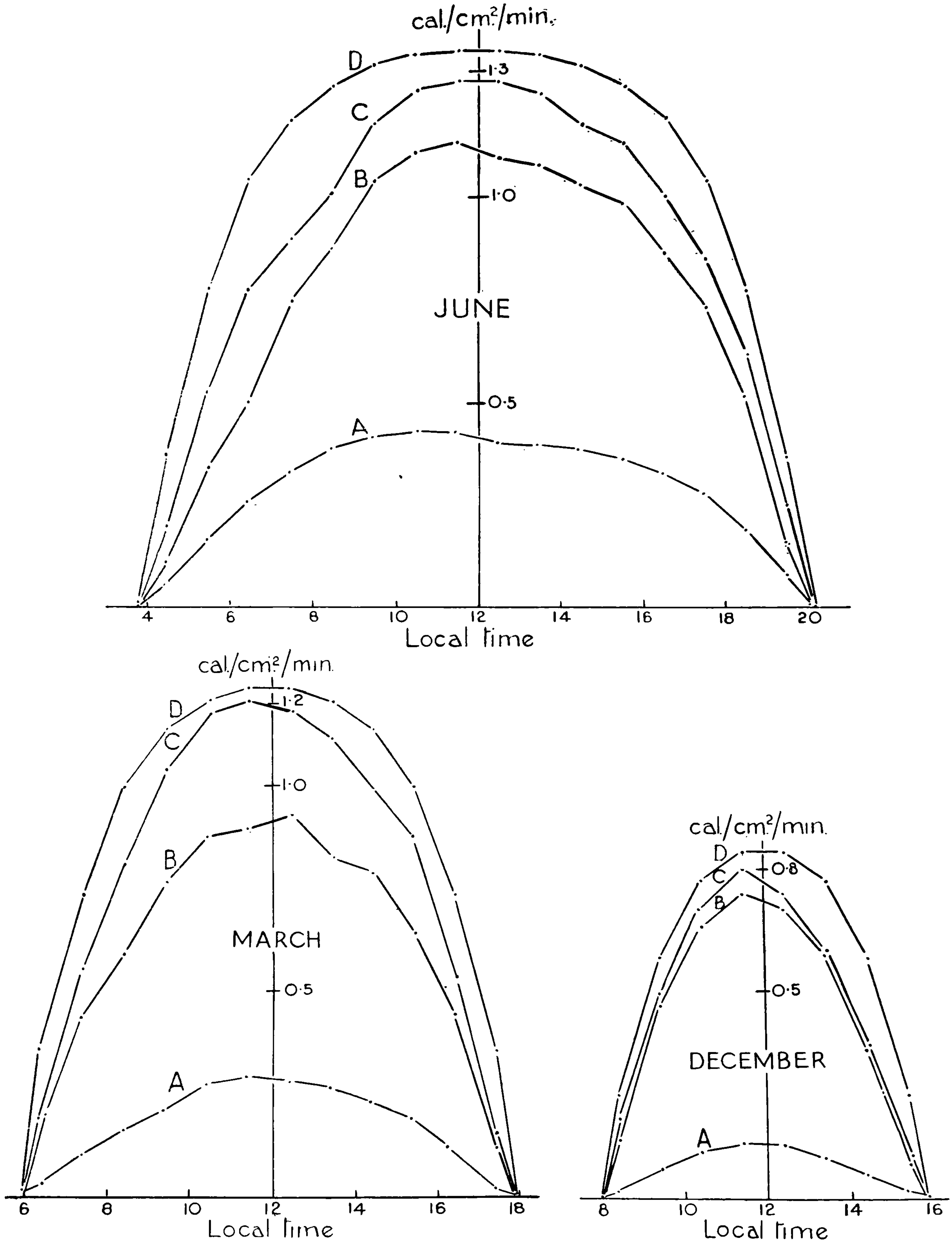


FIG. 6—RELATION OF INTENSITY OF DIRECT RADIATION TO LOCAL TIME

A—all days
B—days of high radiation
C—days of highest radiation totals
D—ceiling radiation values

TABLE VII—INTENSITY OF DIRECT RADIATION, $I$, : ALL DAYS (1933–46)

| | Hour ending (L.M.T.) 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | cal./cm.²/min. | | | | | | | | | |
| Jan. | .. | .. | .. | .. | ·001 | ·020 | ·072 | ·111 | ·120 | ·124 | ·103 | ·064 | ·024 | ·001 | .. | .. | .. | .. |
| Feb. | .. | .. | .. | ·001 | ·021 | ·085 | ·143 | ·184 | ·199 | ·184 | ·154 | ·125 | ·085 | ·023 | ·001 | .. | .. | .. |
| Mar. | .. | .. | ·001 | ·034 | ·106 | ·166 | ·207 | ·271 | ·273 | ·280 | ·261 | ·232 | ·190 | ·107 | ·028 | ·001 | .. | .. |
| Apr. | .. | ·001 | ·029 | ·130 | ·218 | ·263 | ·298 | ·339 | ·337 | ·344 | ·334 | ·301 | ·261 | ·204 | ·116 | ·028 | ·001 | .. |
| May | .. | ·019 | ·112 | ·205 | ·276 | ·331 | ·375 | ·416 | ·420 | ·395 | ·378 | ·352 | ·347 | ·299 | ·240 | ·131 | ·023 | ·001 |
| June | ·001 | ·054 | ·162 | ·258 | ·330 | ·382 | ·411 | ·428 | ·425 | ·401 | ·398 | ·383 | ·363 | ·330 | ·279 | ·192 | ·075 | ·001 |
| July | ·001 | ·040 | ·140 | ·228 | ·291 | ·310 | ·338 | ·370 | ·359 | ·340 | ·337 | ·328 | ·308 | ·277 | ·230 | ·148 | ·037 | ·001 |
| Aug. | .. | ·003 | ·063 | ·166 | ·244 | ·314 | ·344 | ·387 | ·379 | ·375 | ·365 | ·350 | ·317 | ·275 | ·205 | ·082 | ·004 | .. |
| Sept. | .. | .. | ·009 | ·090 | ·186 | ·246 | ·318 | ·349 | ·344 | ·338 | ·315 | ·280 | ·240 | ·184 | ·089 | ·006 | ·001 | .. |
| Oct. | .. | .. | .. | ·005 | ·064 | ·150 | ·201 | ·258 | ·259 | ·251 | ·224 | ·192 | ·139 | ·061 | ·005 | .. | .. | .. |
| Nov. | .. | .. | .. | .. | ·003 | ·049 | ·095 | ·133 | ·155 | ·150 | ·121 | ·087 | ·040 | ·003 | .. | .. | .. | .. |
| Dec. | .. | .. | .. | .. | ·001 | ·012 | ·061 | ·110 | ·125 | ·123 | ·097 | ·057 | ·016 | ·001 | .. | .. | .. | .. |

TABLE VIII—INTENSITY OF DIRECT RADIATION, $I$, ON DAYS OF HIGH RADIATION

| | Hour ending (L.M.T.) 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | cal./cm.²/min. | | | | | | | | | |
| Jan. | .. | .. | .. | .. | ·001 | ·121 | ·394 | ·621 | ·653 | ·626 | ·464 | ·283 | ·106 | ·002 | .. | .. | .. | .. |
| Feb. | .. | .. | .. | .. | ·104 | ·396 | ·642 | ·817 | ·836 | ·767 | ·584 | ·451 | ·263 | ·061 | ·001 | .. | .. | .. |
| Mar. | .. | .. | ·001 | ·153 | ·439 | ·588 | ·769 | ·877 | ·889 | ·939 | ·838 | ·792 | ·643 | ·445 | ·139 | ·001 | .. | .. |
| Apr. | .. | .. | ·079 | ·357 | ·599 | ·771 | ·848 | ·955 | ·977 | ·976 | ·944 | ·882 | ·768 | ·593 | ·326 | ·087 | ·001 | .. |
| May | .. | ·035 | ·247 | ·504 | ·650 | ·842 | 1·022 | 1·124 | 1·142 | 1·133 | 1·090 | 1·016 | 1·007 | ·867 | ·650 | ·408 | ·087 | ·003 |
| June | .. | ·110 | ·340 | ·592 | ·745 | ·876 | 1·033 | 1·102 | 1·129 | 1·093 | 1·072 | 1·026 | ·988 | ·862 | ·736 | ·512 | ·153 | ·004 |
| July | .. | ·105 | ·367 | ·571 | ·738 | ·805 | ·903 | ·979 | 1·006 | ·973 | ·904 | ·891 | ·849 | ·722 | ·602 | ·388 | ·097 | ·002 |
| Aug. | .. | ·005 | ·154 | ·431 | ·672 | ·852 | ·934 | 1·031 | 1·007 | ·990 | ·985 | ·907 | ·793 | ·636 | ·450 | ·180 | ·019 | .. |
| Sept. | .. | .. | ·023 | ·283 | ·588 | ·754 | ·902 | 1·020 | 1·037 | ·976 | ·881 | ·853 | ·753 | ·540 | ·268 | ·022 | .. | .. |
| Oct. | .. | .. | .. | ·031 | ·254 | ·629 | ·863 | ·956 | ·995 | ·821 | ·821 | ·692 | ·565 | ·247 | ·023 | .. | .. | .. |
| Nov. | .. | .. | .. | .. | ·028 | ·229 | ·585 | ·834 | ·870 | ·737 | ·572 | ·503 | ·266 | ·035 | .. | .. | .. | .. |
| Dec. | .. | .. | .. | .. | ·010 | ·139 | ·464 | ·652 | ·734 | ·699 | ·587 | ·359 | ·077 | .. | .. | .. | .. | .. |

TABLE IX—INTENSITY OF DIRECT RADIATION, $I$, ON SELECTED DAYS OF HIGHEST RADIATION

| | Hour ending (L.M.T.) 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | cal./cm.²/min. | | | | | | | | | |
| Jan. | .. | .. | .. | .. | .. | ·123 | ·517 | ·770 | ·823 | ·820 | ·666 | ·450 | ·160 | ·001 | .. | .. | .. | .. |
| Feb. | .. | .. | .. | .. | ·164 | ·517 | ·802 | ·912 | ·933 | ·738 | ·686 | ·588 | ·331 | ·088 | .. | .. | .. | .. |
| Mar. | .. | .. | .. | ·183 | ·550 | ·807 | 1·037 | 1·177 | 1·210 | 1·217 | 1·117 | 1·033 | ·887 | ·537 | ·103 | .. | .. | .. |
| Apr. | .. | .. | ·172 | ·567 | ·753 | ·939 | 1·063 | 1·147 | 1·167 | 1·106 | 1·114 | 1·081 | ·922 | ·767 | ·492 | ·133 | .. | .. |
| May | .. | ·043 | ·190 | ·693 | ·770 | ·947 | 1·097 | 1·183 | 1·143 | 1·147 | 1·117 | 1·057 | 1·123 | ·990 | ·697 | ·490 | ·077 | .. |
| June | .. | ·181 | ·525 | ·775 | ·892 | 1·006 | 1·172 | 1·253 | 1·272 | 1·272 | 1·244 | 1·172 | 1·131 | 1·006 | ·853 | ·611 | ·422 | .. |
| July | .. | ·136 | ·344 | ·664 | 1·036 | 1·108 | 1·167 | 1·172 | 1·181 | 1·189 | 1·147 | 1·086 | ·989 | ·875 | ·806 | ·553 | ·194 | .. |
| Aug. | .. | ·020 | ·337 | ·643 | ·877 | ·963 | 1·073 | 1·157 | 1·230 | 1·223 | 1·193 | 1·153 | 1·047 | ·873 | ·730 | ·350 | ·027 | .. |
| Sept. | .. | .. | ·031 | ·374 | ·710 | ·814 | ·957 | 1·107 | 1·024 | 1·048 | ·821 | ·983 | ·981 | ·800 | ·436 | ·038 | .. | .. |
| Oct. | .. | .. | .. | ·043 | ·280 | ·777 | 1·087 | 1·013 | 1·087 | ·983 | 1·047 | ·790 | ·660 | ·380 | ·027 | .. | .. | .. |
| Nov. | .. | .. | .. | .. | ·053 | ·263 | ·720 | ·927 | ·967 | ·847 | ·783 | ·783 | ·727 | ·340 | ·070 | .. | .. | .. |
| Dec. | .. | .. | .. | .. | ·017 | ·189 | ·469 | ·700 | ·792 | ·739 | ·625 | ·353 | ·058 | .. | .. | .. | .. | .. |

TABLE X—" CEILING " INTENSITIES OF DIRECT RADIATION, $I$

| | Hour ending (L.M.T.) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 4<br>21 | 5<br>20 | 6<br>19 | 7<br>18 | 8<br>17 | 9<br>16 | 10<br>15 | 11<br>14 | 12<br>13 |
| | | | | | cal./cm.²/min. | | | | |
| Jan. | .. | .. | .. | .. | .. | ·328 | ·713 | ·850 | ·925 |
| Feb. | .. | .. | .. | .. | ·358 | ·718 | ·925 | 1·040 | 1·090 |
| Mar. | .. | .. | .. | ·358 | ·732 | ·997 | 1·133 | 1·207 | 1·233 |
| Apr. | .. | .. | ·340 | ·725 | 1·015 | 1·170 | 1·243 | 1·283 | 1·300 |
| May | .. | ·163 | ·642 | ·960 | 1·143 | 1·237 | 1·293 | 1·320 | 1·333 |
| June | ·030 | ·370 | ·778 | 1·038 | 1·183 | 1·265 | 1·312 | 1·333 | 1·347 |
| July | ·018 | ·267 | ·700 | ·992 | 1·157 | 1·250 | 1·300 | 1·325 | 1·337 |
| Aug. | .. | ·050 | ·442 | ·817 | 1·070 | 1·200 | 1·267 | 1·300 | 1·317 |
| Sept. | .. | .. | ·083 | ·513 | ·867 | 1·075 | 1·188 | 1·242 | 1·266 |
| Oct. | .. | .. | .. | ·117 | ·503 | ·832 | 1·027 | 1·117 | 1·167 |
| Nov. | .. | .. | .. | .. | ·042 | ·462 | ·767 | ·905 | ·983 |
| Dec. | .. | .. | .. | .. | .. | ·242 | ·580 | ·767 | ·838 |

As will be discussed later (see § 11) the reduction in intensity is not simply proportional to $m$ but it is related to $m$. In winter the midday flattening is absent because the sun's altitude barely exceeds 15°. The flattening is emphasised in summer by convective processes carrying water vapour, dust, smoke and other particulate aggregates to greater heights in the atmosphere than in winter.

(2) On the average of all days (Table VII) the highest radiation intensities of the year occur during May and June in the hours just before noon, but even then they do not much exceed 0·42 cal./cm².min. On the best radiation days (Table IX) the intensity reaches 1·272 cal./cm.²/min. about midday in June; in this same very limited class of days during the months March to August the average intensity exceeds 1 cal./cm.²/min. (about 70 mw./cm.²) over the six-hour interval centred at local noon. The ceiling intensity (Table X) is 1·347 cal./cm.²/min. in the two hours centred at midday in June. In this connexion it may be observed that very few direct measurements of solar radiation at Kew Observatory in the period 1933–46 have given $I$ values above 1·3 cal./cm.²/min. The greatest intensities measured using the Ångström compensation pyrheliometer have been 1·36 cal./cm.²/min. on May 7, 1942, 1·34 cal./cm.²/min. on May 5, 1936 and June 29, 1938, and 1·33 cal./cm.²/min. on May 14, 1938—all for short periods of a few minutes and within half an hour of local noon.

(3) On the average day between June and September (Table VII) the time of greatest intensity is 10 a.m. to 11 a.m. local time; but on days of highest radiation values (Table IX) the greatest intensities are more likely to occur in the two-hour period centred at noon. This change in time of incidence is to be expected. On the average summer day the diurnal convective effects, which produce cloud and disperse surface dust and water vapour into the atmosphere, increase steadily till the early afternoon so that the period one to two hours before noon has the best chance of strongest direct radiation. The occasions of highest daily totals, on the other hand, are the days of continuously unclouded sky and good visibility associated generally with fresh north-westerly air of arctic origin, and brought to south-east England with the eastward movement of a high-pressure ridge after a rainy depression; subsidence in the anticyclonic circulation reduces the normal convective processes in the middle hours of the day. Hence the peak of radiation intensity on these days is attained near the time of highest solar altitude. These same diurnal processes also account for other asymmetries in Tables VII to IX. For example, the afternoon intensities in summer are on

the whole lower than the corresponding forenoon values, while in the winter and spring the forenoon and afternoon values equidistant from noon are approximately the same. As explained in § 5 no systematic difference was found between the forenoon and afternoon ceiling values (Table X) when reduced to the same path lengths.

## § 8—RADIATION INTENSITY, *I*, AS A FUNCTION OF SUN'S ALTITUDE, *h*

As will become apparent in subsequent sections it is necessary to express *I* as a function of sun's altitude instead of local time as in Tables VII to X. This has been done in Table XI for

TABLE XI—RELATION OF INTENSITY OF DIRECT RADIATION, *I*, TO SUN'S ALTITUDE, *h*

| | Sun's altitude (*h*) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 5° | 10° | 15° | 20° | 25° | 30° | 35° | 40° | 45° | 50° | 55° | 60° |
| | cal./cm.²/min. | | | | | | | | | | | |
| | (*a*) All days (A) | | | | | | | | | | | |
| Jan. | ·025 | ·058 | ·103 | .. | .. | .. | .. | .. | .. | .. | .. | .. |
| Feb. | ·023 | ·067 | ·108 | ·152 | ·192 | .. | .. | .. | .. | .. | .. | .. |
| Mar. | ·033 | ·095 | ·138 | ·175 | ·205 | ·247 | ·275 | .. | .. | .. | .. | .. |
| Apr. | ·035 | ·100 | ·150 | ·192 | ·228 | ·252 | ·275 | ·305 | ·327 | .. | .. | .. |
| May | ·052 | ·118 | ·177 | ·225 | ·262 | ·293 | ·322 | ·342 | ·353 | ·375 | ·397 | .. |
| June | ·065 | ·132 | ·195 | ·245 | ·285 | ·318 | ·345 | ·368 | ·383 | ·397 | ·408 | ·415 |
| July | ·055 | ·120 | ·173 | ·220 | ·253 | ·278 | ·292 | ·295 | ·317 | ·328 | ·333 | .. |
| Aug. | ·053 | ·122 | ·187 | ·227 | ·265 | ·298 | ·325 | ·340 | ·365 | ·385 | .. | .. |
| Sept. | ·043 | ·112 | ·167 | ·203 | ·235 | ·268 | ·298 | ·317 | .. | .. | .. | .. |
| Oct. | ·035 | ·095 | ·152 | ·187 | ·228 | ·255 | .. | .. | .. | .. | .. | .. |
| Nov. | ·033 | ·078 | ·122 | ·162 | .. | .. | .. | .. | .. | .. | .. | .. |
| Dec. | ·028 | ·072 | ·118 | .. | .. | .. | .. | .. | .. | .. | .. | .. |
| | (*b*) Days of high total radiation (B) | | | | | | | | | | | |
| Jan. | ·133 | ·290 | ·522 | .. | .. | .. | .. | .. | .. | .. | .. | .. |
| Feb. | ·095 | ·263 | ·448 | ·625 | ·787 | .. | .. | .. | .. | .. | .. | .. |
| Mar. | ·157 | ·347 | ·510 | ·605 | ·717 | ·802 | ·897 | .. | .. | .. | .. | .. |
| Apr. | ·128 | ·280 | ·425 | ·555 | ·667 | ·770 | ·828 | ·897 | ·958 | .. | .. | .. |
| May | ·100 | ·246 | ·372 | ·494 | ·612 | ·718 | ·826 | ·930 | 1·012 | 1·092 | 1·140 | .. |
| June | ·150 | ·322 | ·457 | ·583 | ·695 | ·767 | ·853 | ·923 | ·978 | 1·037 | 1·077 | 1·105 |
| July | ·153 | ·320 | ·467 | ·580 | ·665 | ·740 | ·792 | ·833 | ·882 | ·917 | ·950 | .. |
| Aug. | ·160 | ·317 | ·453 | ·573 | ·673 | ·767 | ·843 | ·902 | ·973 | 1·007 | .. | .. |
| Sept. | ·140 | ·358 | ·533 | ·657 | ·767 | ·843 | ·917 | ·990 | .. | .. | .. | .. |
| Oct. | ·120 | ·387 | ·597 | ·737 | ·855 | ·942 | .. | .. | .. | .. | .. | .. |
| Nov. | ·172 | ·397 | ·623 | ·800 | .. | .. | .. | .. | .. | .. | .. | .. |
| Dec. | ·203 | ·488 | ·697 | .. | .. | .. | .. | .. | .. | .. | .. | .. |

" all " days (A), and for days (B) selected for their high radiation values in the years 1933–46; these two groups of days were described by the same lettering in § 5. The method of derivation was as follows:—

(1) The sun's altitude at Kew at each exact local hour was computed for the first and last days of each month.

(2) From curves with solar altitude as ordinate and the local time as abscissa, hourly mean altitudes (estimated in various ways as checks) were read off.

(3) These hourly mean altitudes were plotted against the corresponding intensities, *I*, given in Tables VII and VIII and the value of *I* read off at 5° steps of altitude, the forenoon and afternoon values being noted separately and meaned as an additional check.

Table XII gives similar data for the ceiling intensities, described as category D in § 5.

The intensities in Tables XI and XII have not been corrected for seasonal changes in the solar radiation intensity outside the atmosphere on account of variations in the distance between sun and earth; the correction varies from $-3 \cdot 3$ per cent. in early January to $+3 \cdot 4$ per cent. in early July. Even if this correction were applied, the tables show that $I$ for any one solar altitude $h$ on days free of cloud in winter would remain preponderantly higher than the corresponding intensities in summer. At $h = 15°$ in Table XI (*b*), for example, no value between April and August is above $0 \cdot 47$ cal./cm.$^2$/min.; all the other monthly values at that altitude, except in February, are above $0 \cdot 5$ cal./cm.$^2$/min. That only November and December are above $0 \cdot 6$ is probably in part an accident of selection. As explained in § 5, category B days are those whose total radiation exceeded a limiting value set differently for each month so as to give a representative number of contributing days. The limits accepted for November and December (and perhaps to a lesser degree, October) were a little too high, with the result that the radiation quality of the days selected from those months is probably above the average of the remaining months of the year. This accident is instructive in showing how the selection of days for study of radiation processes can affect the results, and as each observatory has its own criteria of selection, this renders intercomparison of radiation data difficult and uncertain.

TABLE XII—RELATION OF MAXIMUM (CEILING) INTENSITY OF DIRECT RADIATION, $I$, TO SUN'S ALTITUDE, $h$

| | Sun's altitude ($h$) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 5° | 10° | 15° | 20° | 25° | 30° | 35° | 40° | 45° | 50° | 55° | 60° | 62° |
| | cal./cm.$^2$/min. | | | | | | | | | | | | |
| Dec.–Jan. | ·308 | ·620 | ·867 | .. | .. | .. | .. | .. | .. | .. | .. | .. | .. |
| Feb.–Mar. | ·357 | ·640 | ·827 | ·978 | 1·098 | 1·190 | 1·258 | 1·298 | .. | .. | .. | .. | .. |
| Apr.–May | ·372 | ·628 | ·812 | ·952 | 1·058 | 1·142 | 1·205 | 1·250 | 1·282 | 1·302 | 1·313 | (1·333) | .. |
| June–July | ·385 | ·648 | ·823 | ·955 | 1·058 | 1·137 | 1·200 | 1·248 | 1·285 | 1·310 | 1·328 | 1·337 | (1·340) |
| Aug.–Sept. | ·365 | ·635 | ·835 | ·988 | 1·105 | 1·185 | 1·240 | 1·277 | 1·303 | 1·322 | 1·340 | .. | .. |
| Oct.–Nov. | (·400) | ·657 | ·895 | 1·032 | 1·110 | 1·152 | 1·183 | .. | .. | .. | .. | .. | .. |

Table XII substantiates the contentions and procedure of § 5, where the formation of the maximum intensity values was described. True " maximum " intensities would be approximately the same in all months at the same solar altitude except for the effect of seasonal change in the distance of the earth from the sun on the " constant " value of solar-radiation intensity outside the earth's atmosphere.

It is not surprising that the direct solar radiation intensities in Table XI vary so irregularly from month to month. As details will be considered later (see § 11), the reader need only be reminded here that $I$ at station level depends primarily on three factors: (*a*) the thickness of atmosphere traversed, (*b*) its clearness and dryness (turbidity), and (*c*) seasonal change in the radiation outside the atmosphere. If factor (*a*) alone were active the greatest intensities would occur in June at the time of highest solar altitudes. But the off-setting effect of water vapour in absorbing radiation is greatest in summer, while the suspended matter, which diffusely reflects and absorbs the radiation, may play its greatest part in the winter months when the concentration near the ground is greatest, or in spring and summer when convection distributes it through greater thicknesses of the atmosphere. The seasonal variation in $I_0$ would, by itself, give the greatest ground intensities in winter and the smallest intensities in summer. The combined result of these factors varies with locality, and from year to year; it also depends on the incidence of dominating spells of weather, especially if the station is near a large city or industrial area.

## § 9—COMPONENTS OF DIRECT SOLAR RADIATION OF NORMAL INCIDENCE

Before applying the $I = f(h)$ values to the discussion of atmospheric absorption of solar radiation, it is useful to note how they are used for computing the total radiation falling on a surface other than one maintained normal to the direction of incidence. If $I$ denotes the total

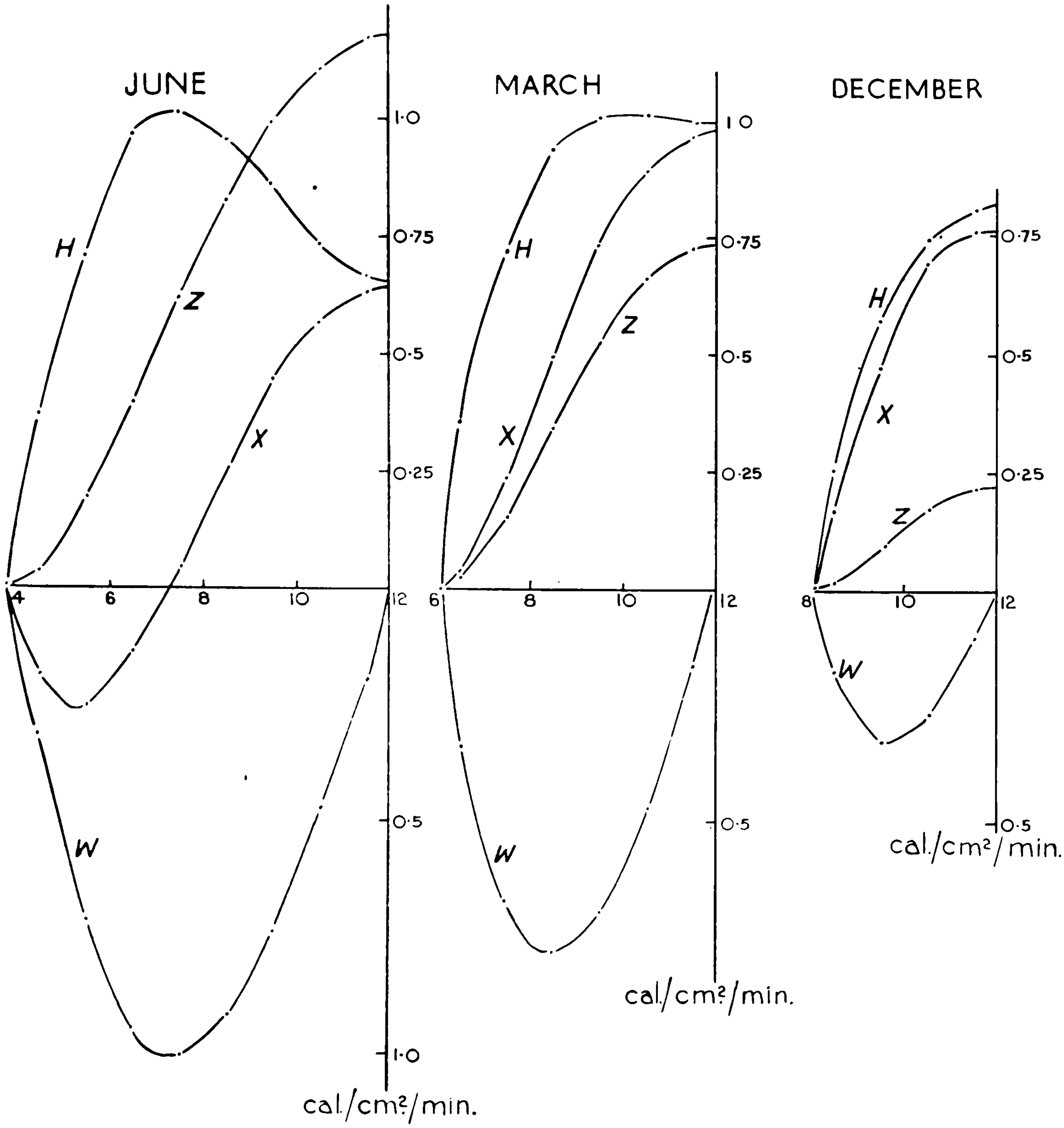


FIG. 7—COMPONENT INTENSITIES OF DIRECT RADIATION

$H$—horizontal component $W$—westward component
$X$—southward component $Z$—vertically downward component

intensity of direct solar radiation as recorded by the Gorczynski apparatus, and if the horizontal, south, west and vertically downward components be denoted by $H$, $X$ (south to north), $W$ (west to east) and $Z$. Then

$$H = I \cos h$$
$$X = I \cos h \cos A$$
$$W = I \cos h \sin A$$
$$\text{and } Z = I \sin h.$$

In these expressions $h$ and $A$ (measured positive from south through west) are the sun's altitude and azimuth, $h$ being derived from $\sin h = \sin \phi \sin \delta + \cos \phi \cos \delta \cos t$, and $A$ from

$\sin A = \cos \delta \sin t / \cos h$, (where $\phi$ is latitude, $\delta$ declination and $t$ the sun's hour angle), or from $\cos A = \tan \phi \tan h - \sin \delta / \cos \phi \cos h$; $\phi$ for Kew Observatory is 51° 28′ N.

With those primary components $H$, $X$, $W$ and $Z$ computed, it is easy to estimate the radiation which falls on other surfaces inclined to the principal directions. For example, the intensity is $(X - W) \cos 45°$ on a surface facing south-east, or, more generally, $(X - W) \cos 45° \sin \alpha + H \cos \alpha$ if the south-east-facing surface has its normal inclined at an angle $\alpha$ to the vertical; and the intensity is $X \sin \alpha + Z \cos \alpha$ on a south-facing surface with its normal inclined at an angle $\alpha$ to the vertical.

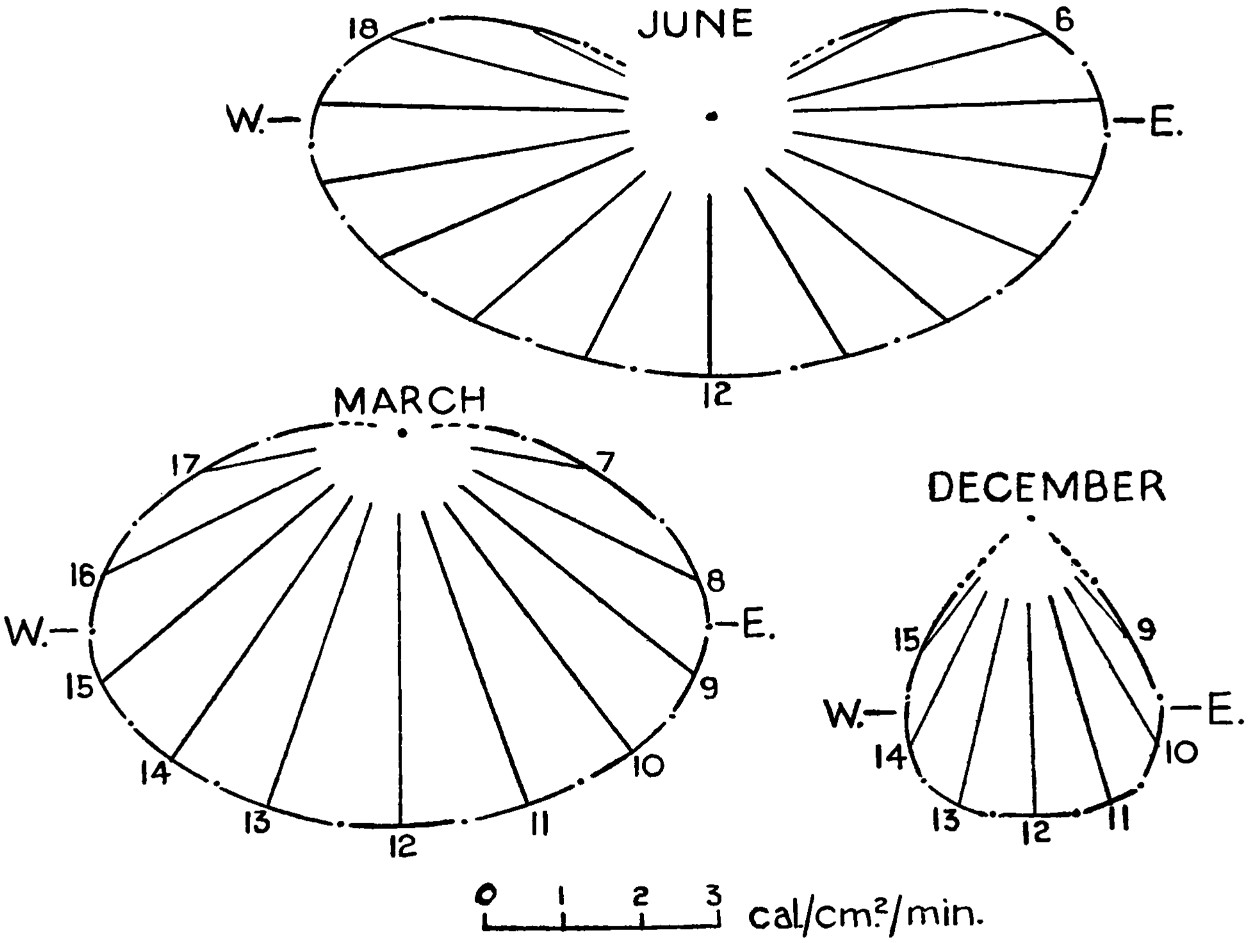


FIG. 8—HORIZONTAL COMPONENT INTENSITIES

The daily radiation components have been computed for the clearest conditions (category C of § 5) at Kew, and are illustrated in Fig. 7 for the three representative months March, June and December. Except possibly for $H$, their main features could have been inferred without computations from a consideration of the simultaneous changes in $I$, $h$ and $A$ as functions of local time. As shown in Fig. 8 the variation of intensity $H$, which determines the energy falling on a vertical surface rotated so as to be always perpendicular to the line of the sun's azimuth, shows two maxima in June, at local noon $\pm 4\frac{3}{4}$ hr. In March the maxima are at 10 a.m. and 2 p.m., and in midwinter they merge into a single midday maximum.

TABLE XIII—DIRECT RADIATION FALLING ON VARIOUS SURFACES ON CLEAREST DAYS

| Position of surface | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | cal./cm.² | | | | | | |
| Normal to radiation | 338 | 495 | 679 | 849 | 971 | 1,035 | 999 | 895 | 748 | 571 | 379 | 291 |
| Vertical towards sun | 327 | 467 | 602 | 695 | 739 | 753 | 748 | 701 | 643 | 526 | 364 | 285 |
| Vertical facing south | 291 | 376 | 405 | 356 | 279 | 233 | 230 | 281 | 387 | 397 | 316 | 251 |
| Vertical facing north | .. | .. | .. | 8 | 43 | 70 | 52 | 16 | 1 | .. | .. | .. |
| Vertical facing west | 64 | 117 | 186 | 257 | 298 | 319 | 286 | 246 | 217 | 145 | 77 | 53 |
| Horizontal .. | 81 | 159 | 288 | 449 | 575 | 642 | 569 | 465 | 356 | 209 | 99 | 59 |

The hour-to-hour values of the radiation components were used to form Table XIII in which are compared the amounts of radiation which fall on differently orientated surfaces at Kew in the clearest conditions, that is, on the days characterised by the maximum or ceiling values as defined earlier. To obtain approximate values for other categories of days, the entries in Table XIII should be adjusted in the ratio A/D, B/D or C/D where A, B, C and D are the daily totals in Table V. Points of interest in Table XIII are:—

(1) a south-facing surface receives less direct solar radiation in June and July than in any other month of the year; at Kew it receives most in March and October.

(2) in June a horizontal surface receives more than ten times as much direct radiation as in December. It can readily be inferred from the data discussed above that it is less advantageous in these latitudes for a house to have its four walls facing the cardinal directions than for the walls to be built to face north-east, south-west, etc.

## § 10—RADIATION INTENSITY AS A FUNCTION OF AIR MASS

The thickness of atmosphere or, more precisely, the length of the optical path through the atmosphere traversed by a beam of direct solar radiation, depends on the sun's altitude and the sea-level height of the place of measurement. The unit of thickness or air mass, $m$, is the optical length through the atmosphere when the sun is in the zenith. Assuming the atmosphere to be made up of concentric homogeneous strata, $m = \sec. Z$ where $Z$ is the sun's zenith distance. Tables of $m$ have been worked out by Bemporad with corrections for refraction and for a standard surface pressure, $p_0$; a few representative values were quoted in § 7. Values of $m$ from tables should be corrected for pressure, $p/p_0$, but this refinement has not been introduced in this analysis.

The greatest solar altitude at Kew (62°) corresponds with $m = 1 \cdot 13$; the sun spends 64 per cent. of its time above the horizon at or below an altitude of 30° ($m = 2$), and only 20 per cent. is spent above 41·7° ($m = 1 \cdot 5$).

TABLE XIV—RELATION OF INTENSITY OF DIRECT RADIATION, $I$, TO AIR MASS, $m$

| | Air mass ($m$) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 6·0 | 5·0 | 4·0 | 3·0 | 2·0 | 1·5 | 1·25 |
| | | | | cal./cm.²/min. | | | |
| | High radiation days | | | | | | |
| Jan. | ·300 | ·383 | ·547 | .. | .. | .. | .. |
| Feb. | ·300 | ·375 | ·500 | ·700 | .. | .. | .. |
| Mar. | ·333 | ·400 | ·500 | ·590 | ·800 | .. | .. |
| Apr. | ·253 | ·330 | ·410 | ·542 | ·770 | ·920 | .. |
| May | ·225 | ·308 | ·368 | ·493 | ·718 | ·960 | 1·130 |
| June | ·368 | ·447 | ·530 | ·657 | ·853 | ·997 | 1·090 |
| July | ·327 | ·367 | ·465 | ·587 | ·753 | ·865 | ·970 |
| Aug. | ·310 | ·370 | ·457 | ·597 | ·793 | ·970 | 1·050 |
| Sept. | ·342 | ·412 | ·527 | ·673 | ·892 | 1·047 | .. |
| Oct. | ·367 | ·467 | ·608 | ·782 | ·997 | .. | .. |
| Nov. | ·395 | ·508 | ·683 | ·870 | .. | .. | .. |
| Dec. | ·508 | ·595 | ·713 | .. | .. | .. | .. |
| | Occasions of "ceiling" intensity | | | | | | |
| Dec.-Jan. | ·580 | ·697 | ·833 | .. | .. | .. | .. |
| Feb.-Mar. | ·615 | ·698 | ·803 | ·963 | 1·188 | .. | .. |
| Apr.-May | ·600 | ·697 | ·783 | ·933 | 1·137 | 1·260 | 1·307 |
| June-July | ·620 | ·697 | ·803 | ·948 | 1·137 | 1·265 | 1·327 |
| Aug.-Sept. | ·607 | ·697 | ·810 | ·970 | 1·183 | 1·288 | 1·333 |
| Oct.-Nov. | ·630 | ·727 | ·862 | 1·013 | 1·157 | .. | .. |

By interpolating in Tables XI or XII which give $I$ computed as a function of solar altitude or by referring directly to the curves from which those tables were derived, values of radiation at integral values of $m$ are obtained. The latter procedure was adopted to obtain the data for B category days (see § 5) in Table XIV, except that the monthly radiation–altitude graphs were smoothed. As the higher of the forenoon and afternoon values were accepted in the process of smoothing, some of the entries in the column $m = 2$ of Table XIV are slightly higher than the corresponding figures in the 30° altitude column of Table XI.

Table XIV confirms the inference made in § 8 that the standard of selection of representative days of high radiation was higher in November and December, and probably also in October, than in the other months of the year. But even allowing for this artificial effect, none of the columns of the first part of Table XIV shows any clear evidence of a seasonal variation in $I$. In the four columns $m = 6$ to $m = 3$ where at least ten months are represented, $I$ for February to March is greater than for any of the summer months. But keeping in mind the comments of § 8 in this connexion, this evidence by itself does not justify accepting a spring maximum as a normal feature of direct radiation intensity at Kew.

## § 11—ATMOSPHERIC TRANSMISSION OF DIRECT SOLAR RADIATION

The preceding discussion has been concerned with the basic results derived from continuous recording of direct solar radiation incident on a thermopile surface maintained normal to the direction of the radiation. The remaining paragraphs in this part of the paper will deal with the main atmospheric factors which contribute to the variations of this radiation and with various measures of atmospheric turbidity.

In spite of the many discussions of this subject, mainly in German, Scandinavian and American journals, it is difficult to obtain a clear picture of the quantitative contributions made by the various processes which deplete the energy in a direct beam of solar radiation while traversing the atmosphere. The instrumental equipment used, the treatment of the data, the selection for special attention of particular depleting processes and the nature of the transmission coefficient used to express the degree of depletion vary from country to country and even from one institute to another within the same country. For ordinary purposes the intensity of direct radiation, $I_0$, outside the atmosphere may be taken as 1·94 cal./cm.$^2$/min. with a simple correction for the earth's distance from the sun. If the intensity, $I$, at a sea-level station on a day in mid June when the sun's altitude is 30°, is measured as 1·050 cal./cm.$^2$/min., then the transmission coefficient $q$, or fractional radiation transmitted through unit thickness of atmosphere, is obtained from $I = I_0 q^2$. In this hypothetical case $q$ is 0·736. In this simple way, transmission coefficients can be deduced immediately from such information as that provided in Tables XI and XII. In default of an internationally acceptable procedure some important meteorological institutions have indeed adopted the hybrid transmission factor $q$ as used above in discussing their data. But except to provide a rough numerical index for comparing the state of the atmosphere in regard to its depleting effect on solar radiation at one instant in one locality with its state at another instant in the same locality, $q$ has very limited value and little physical significance. For the relation between $I$ and $I_0$ using $q$, or its alternative in terms of an absorption coefficient $I = I_0 e^{-am}$ in which $a = -\log_e q$, is valid only for monochromatic radiation and only for particular physical processes.

Nevertheless, if measures of total direct radiation, as distinct from simultaneous measures of two or more of the partial spectral components, are the only recorded material at a station, there is practically no alternative to the adoption of the above procedure or a variant of it. Various investigators (*e.g.* Linke, Ångström, Gorczynski) have proposed and used turbidity factors, coefficients of turbidity, etc.; but all of them postulate an integration over a range of wave-lengths, and some even over a variety of depleting phenomena which should not be grouped together.

Before examining transmission phenomena further, it is desirable to consider the main physical processes which reduce the intensity of a direct solar beam. They are:—

(1) Scattering, by molecules and particles of size less than the wave-length of the radiation.

(2) Selective absorption by (*a*) atmospheric gases, (*b*) ozone, (*c*) water vapour.

(3) Diffuse reflection, by molecular aggregates and particulate matter of size greater than in (1).

(4) Combination of scattering (or diffuse reflection) with absorption.

(5) Reflection from, and absorption by, cloud.

Molecular (or fine particle) scattering varies with the wave-length, $\lambda^{-4}$, and as the distribution of energy in the spectrum alters with the thickness of the atmosphere penetrated (*i.e.* with the sun's altitude $h$), the amount of scattering also changes with $h$. There can therefore be no simple transmission (or extinction) coefficient to take account of molecular scattering which is valid throughout the whole range of wave-lengths in a solar beam and over all values of $h$. By estimating the energy in the radiation outside the atmosphere in successive spectral intervals (with a correction for the extreme ultra-violet) and by careful measurement of the radiation received at the earth's surface in the same intervals in the clearest atmospheric conditions, confirmation of the computed loss of energy by Rayleigh scattering has been obtained by Fowle[4] and Feussner and Dubois[5], and expressed in terms of a single transmission coefficient which for practical estimates can be identified with $q$ in Bouguer's law $I = I_0 q^m$. Values of this coefficient for air-mass thicknesses $m = 1$ to 8 and the corresponding values of the transmitted radiation (taking $I_0 = 1 \cdot 940$ cal./cm.$^2$/min.) are given in Table XV.

TABLE XV—TRANSMISSION COEFFICIENT FOR MOLECULAR SCATTERING

| Air mass, $m$ | 1 | 2 | 3 | 4 | 6 | 8 |
|---|---|---|---|---|---|---|
| Corresponding sun's altitude, $h$ | 90° | 30° | 19·3° | 14·3° | 9·3° | 6·8° |
| Coefficient, $q$ | ·907 | ·915 | ·921 | ·926 | ·935 | ·942 |
| Transmitted, $I$ (cal./cm.$^2$/min.) | 1·76 | 1·62 | 1·52 | 1·43 | 1·30 | 1·20 |

From this table we see that molecular scattering alone accounts for the loss of 16 per cent. of the initial intensity when the sun's height is 30°, and 33 per cent. at 9° ($m = 6$). At local noon at Kew at the summer solstice ($m = 1 \cdot 13$) the loss is 10 per cent.

As regards item (2) in the above list, although the absorption of solar radiation by oxygen is of fundamental importance for some phenomena in the atmosphere, the contributions to total depletion made by oxygen absorption and by other atmospheric gases except ozone, are negligible for our purpose. The effect of ozone is subject to large variations, of place and time and synoptic situation; but, taking 3 mm. of ozone as an average quantity, Cabannes and Dufay[6] estimated that absorption in the range below $0 \cdot 4\,\mu$ is about $4 \cdot 9$ per cent. of the initial intensity, $0 \cdot 5$ per cent. between $0 \cdot 4$ and $0 \cdot 8\,\mu$ and $0 \cdot 1$ per cent. above $0 \cdot 8\,\mu$. Ozone therefore accounts for about $0 \cdot 106$ cal./cm.$^2$/min.

Selective absorption by water vapour has been studied principally by Abbot and Fowle. Measuring the radiation energy in specific groups of wave-lengths and simultaneously estimating the amount of water vapour in the atmosphere by the broadening and intensification of the absorption bands in the red and near infra-red, Fowle[7], has given the following empirical relation for the partial reduction, $\Delta I$, of energy due to water vapour distributed in an air mass, $m$, corresponding with a mean value $e$ (in millimetres) of vapour pressure at the surface:—

$$\Delta I = 0 \cdot 10 + 0 \cdot 0054\, me$$

Average values of $e$ for Kew Observatory for representative months give the figures in Table XVI for air masses 2 and 4. It is particularly to be noted that Fowle's expression connecting $\Delta I$ and $e$ is valid only for the averages of many occasions. For individual cases it is necessary to use more direct measures of the amount of water vapour in the atmosphere obtained, for example, by the spectrometer or by estimation from radio-sonde observations.

TABLE XVI—REDUCTION IN DIRECT RADIATION, $I$, BY WATER VAPOUR ABSORPTION

| $m$ | Jan. | Apr. | July | Oct. | Year |
|---|---|---|---|---|---|
| | | cal./cm.²/min. | | | |
| 2 | ·154 | ·166 | ·211 | ·182 | ·178 |
| 4 | ·210 | ·233 | ·323 | ·264 | ·255 |

The amount of diffuse reflection by suspended matter of size greater than the radiation wavelength, and the reduction in energy due to absorption after scattering or reflection cannot be directly estimated even approximately. There is no known method of obtaining an independent measure of the suspended matter (smoke, dust, spores, nuclei, ions, etc.) in a column of the atmosphere, and, even if there were, the range of size and nature of the particles would preclude application of any physical law to the calculation of their effect on radiation. All that can be done with this group of agencies is to attribute to it the residual depletion after account has been taken of the other factors.

Reflection from, and absorption by, cloud sheets or particles is normally excluded from this kind of inquiry by restricting the measurements of incoming radiation to occasions of no visible cloud between the sun and station. But unless the sky is under constant observation this procedure can be only partially successful. It is frequently noted in such work that comparatively large changes in recorded radiation take place within a minute with an apparently clear sky in the neighbourhood of the sun. These changes are due in many cases to the movement across the line of sight of the pyrheliometer of pockets of atmosphere where cloud is just dissipating or forming though the cloud density is not sufficient to make it discernible at ground level.

TABLE XVII—DEPLETION OF DIRECT RADIATION BY VARIOUS AGENCIES ON CLEAREST DAYS (D OF § 5)

| | Air Mass 2 | | | | | | | | Air Mass 4 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dec. Jan. | Feb. Mar. | Apr. May | June July | Aug. Sept. | Oct. Nov. | Mean | % | Dec. Jan. | Feb. Mar. | Apr. May | June July | Aug. Sept. | Oct. Nov. | Mean | % |
| | cal./cm.²/min. | | | | | | | | cal./cm.²/min. | | | | | | | |
| Molecular scattering | .. | ·322 | ·311 | ·306 | ·311 | ·321 | ·314 | 41 | ·531 | ·524 | ·507 | ·496 | ·505 | ·521 | ·514 | 46 |
| Ozone | .. | ·120 | ·118 | ·108 | ·095 | ·090 | ·105 | 14 | ·104 | ·120 | ·118 | ·108 | ·095 | ·090 | ·106 | 9 |
| Water vapour | .. | ·159 | ·173 | ·205 | ·206 | ·175 | ·184 | 24 | ·217 | ·218 | ·246 | ·310 | ·311 | ·249 | ·258 | 23 |
| Suspended matter | .. | ·188 | ·172 | ·121 | ·110 | ·226 | ·164 | 21 | ·320 | ·312 | ·257 | ·160 | ·184 | ·247 | ·247 | 22 |
| Total depletion | .. | ·789 | ·774 | ·740 | ·722 | ·812 | ·767 | .. | 1·172 | 1·174 | 1·128 | 1·074 | 1·095 | 1·107 | 1·125 | .. |

The discussion in the foregoing paragraphs is illustrated by Tables XVII and XVIII. Table XVII uses the maximum (or ceiling) radiation intensities, and Table XVIII uses the intensities from days of high total radiation though not necessarily completely free of cloud. The entries in the first line of each table are derived from the appropriate columns of Table XIV, using values of $I_0$ corrected for earth's distance at the middle of the period. The figures which purport to give the depletion due to ozone absorption were derived from the considerations outlined in the foregoing discussion, and are included in the table only to illustrate the probable size of the ozone contribution relative to the other agents. A correction (which may have doubtful validity) was applied to take approximate account of the seasonal change in amount of ozone in the latitude

TABLE XVIII—DEPLETION OF DIRECT RADIATION ON SELECTED DAYS OF HIGH RADIATION (B OF § 5)

| | Air Mass 2 Mar. | May | June | Sept. | Mean | % | Air Mass 4 Jan. | Apr. | July | Oct. | Mean | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | cal./cm.²/min. | | | | | | cal./cm.²/min. | | | | | |
| Molecular scattering .. .. | ·320 | ·309 | ·306 | ·313 | ·312 | 28 | ·531 | ·510 | ·496 | ·518 | ·514 | 36 |
| Ozone .. | ·121 | ·118 | ·105 | ·092 | ·109 | 10 | ·113 | ·120 | ·105 | ·089 | ·107 | 7 |
| Water vapour | ·163 | ·179 | ·211 | ·199 | ·188 | 17 | ·210 | ·233 | ·323 | ·264 | ·257 | 18 |
| Suspended matter | ·557 | ·574 | ·503 | ·422 | ·514 | 46 | ·604 | ·654 | ·489 | ·473 | ·555 | 39 |
| Total depletion | 1·161 | 1·180 | 1·125 | 1·026 | 1·123 | .. | 1·458 | 1·517 | 1·413 | 1·344 | 1·433 | .. |

of Kew. The effect due to water-vapour absorption was derived using Fowle's relationship from normals of vapour pressure at Kew, not from estimates of actual amount of precipitable water on the days concerned, as is desirable.

At air mass 2, according to Table XVII, the most important factor which reduces radiation on exceptionally clear days is molecular scattering (41 per cent.); water vapour (24 per cent.) and diffuse reflection and absorption by suspended matter (21 per cent.) are next in order of importance. Ozone accounts for about 14 per cent. of the total depletion. For air mass 4 the percentages are, for scattering 46 per cent., for water vapour 23 per cent., and for suspended matter 22 per cent. Table XVII which includes data for all months of the year shows that the effect of suspended material in depleting radiation is greatest in December–January, and least in June–July. In the class of days of high total radiation (76 per cent. of possible sunshine) represented in Table XVIII, the depletion with air mass 2 due to dust and other particulate matter accounts for nearly half (46 per cent.) of the total loss; scattering contributes 28 per cent. and water vapour 17 per cent. The last column of Table XVIII shows that at lower solar altitudes (air mass 4) in the same class of days the losses due to suspended matter and to scattering are more nearly equal.

## § 12—MEASURES OF ATMOSPHERIC TRANSMISSION OR TURBIDITY

As mentioned at an earlier stage in this discussion, the equipment for recording radiation at Kew Observatory has recently been extended to include a second actinograph carrying two thermopiles covered by coloured glass filters mounted on a heliostat. After preliminary standardizations and comparisons now in progress, each thermopile will record a particular range of the solar spectrum. There will therefore be available measurements of two spectral components of direct solar radiation as well as the total radiation, and from these it will be practicable to compute indices of atmospheric turbidity of greater reliability than can be derived from readings of total radiation alone. Meanwhile it is desirable to indicate the nature of the various indices that have been proposed and to use them for comparing the Kew Observatory data with those from other localities.

*The transmission coefficient* ($q'$).—This is the simplest and crudest measure of the state of the atmosphere as regards its depletion of solar radiation; it is derived from $I = I_0 q'^m$ applied throughout the range of the spectrum and without attempt to distinguish it from the true $q$ as applied to monochromatic radiation and to particular depleting agencies. As can be seen from Table XIX where $q'$ values are given for air masses 2 and 4 for maximum intensities and for the days of high radiation at Kew, $q'$ is not independent of the air mass $m$.

The $q'$ values for Potsdam in Table XIX are of interest. They are based on figures given by Marten[8], and, judging by that author's description of the sky conditions when the measurements were made, they are to be related to the "maximum intensity" data at Kew rather than to any of the other groups of days used in this discussion. The mean $q'$ of the six pairs of months for Potsdam is the same as for Kew, *viz.* 0·806; but whereas Potsdam has a clear maximum in winter and minimum in midsummer, the seasonal range at Kew is negligible.

It should be added that the value used throughout this section for $I_0$ (1·94 cal./cm.²/min.) has been corrected for earth's distance.

TABLE XIX—TRANSMISSION COEFFICIENTS, $q'$

| | $m$ | "Ceiling" radiation intensities Dec. Jan. | Feb. Mar. | Apr. May | June July | Aug. Sept. | Oct. Nov. |
|---|---|---|---|---|---|---|---|
| Kew .. | 2 | .. | ·775 | ·771 | ·778 | ·788 | ·767 |
| | 4 | ·803 | ·798 | ·800 | ·809 | ·807 | ·813 |
| Potsdam .. | 4 | ·830 | ·815 | ·797 | ·783 | ·787 | ·817 |

| | | Days of high total radiation | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $m$ | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
| Kew | 2 | .. | .. | ·639 | ·632 | ·615 | ·674 | ·633 | ·648 | ·682 | ·715 | .. | .. |
| | 4 | ·722 | ·708 | ·711 | ·679 | ·664 | ·729 | ·705 | ·701 | ·724 | ·747 | ·766 | ·772 |

*Linke's turbidity factor* ($T$).—Linke's turbidity factor is derived from an extension of the same basic formula, expressed in the form $I = I_0 e^{-am}$, where $a$ is an absorption coefficient ($-a = \log_e q$). Using the term extinction to describe the total depletion in a beam of solar radiation whether attributable to true scattering, to absorption, to diffuse reflection or combinations of these processes, Linke[9] put the coefficient of total extinction $a = a_g + wa_w + sa_s$ where $a_g$ is the contribution by Rayleigh scattering, $a_w$ the absorption coefficient for water vapour and $a_s$ the coefficient describing the effects produced by suspended molecular aggregates and particles; $w$ and $s$ are measures of the content of water vapour and suspended matter (not water vapour) in the beam. Linke then expressed his turbidity factor, $T$, in terms of the contribution due to true molecular scattering $a_g$ by putting $T = (a_g + wa_w + sa_s)/a_g$ so that the extinction law became $I_m = I_0 e^{-Ta_g m}$ from which $T$ could be computed as $\log_e (I_0/I_m)/(ma_g)$.

The usefulness of the factor $T$ derived in this way depends on the assumption that the separate depletions of solar radiation by water vapour and by particulate material both vary with wave-length in the same way as the depletion by true molecular scattering. This is hardly justified. Scattering is inversely proportional to $\lambda^{-4}$, while the exponent for diffuse reflection by larger aggregates may be anywhere between 0·5 and 4, and absorption follows a quite different law. So long as $T$ includes a two-fold integration (over $\lambda$ and $m$) and also attempts to provide for a variety of different physical processes, it cannot be a satisfactory, much less a unique, index. Notwithstanding these and other objections, Linke's factor has been fairly widely used, the values (which are usually between 1·5 for mountain stations and 5 or 6 for stations in industrial localities) being interpreted as the equivalent number of dry and clean atmospheres which together would produce the same degree of depletion as the actual atmosphere through which the beam reaches the station.

Judged by the representative values of $T$ given in Table XX the turbidity factor at Kew Observatory is probably seldom less than 2·3, and is more usually 5 or higher. The precise value depends so much on how the radiation data used in the evaluation have been selected (or, in the case of stations without continuous records of direct radiation, on the criteria of sky conditions adopted for making direct measurements over a few minutes by pyrheliometer or actinometer), that there is little profit to be derived from comparison with $T$ values at other stations. As most comparable with the Kew conditions for maximum radiation intensities the following values[3] for low-level stations are, however, of interest.

| | Winter | Summer |
|---|---|---|
| Potsdam .. .. .. | 1·99 | 2·72 |
| Frankfurt-on-Main .. | 3·08 | 3·79 |

In support of Linke's contention that $T$ does not in fact vary substantially with air mass when other variables remain the same, the maximum radiation data in Table XIX give a mean value of $T = 2{\cdot}83$ for both $m = 2$ and $m = 4$; the corresponding figures for good radiation days are 4·75 and 4·53.

As the basic data used in section (*a*) of Table XX were not direct measurements and as the values in section (*b*) are effected by selection of the days, particularly in the last two or three months of the year, a further set of independent values of the turbidity factor $T$ were computed. These were derived from the highest recorded values of normal direct radiation during the two hours centred at local noon in each available month of the three years 1945–47. The year's mean for this group of occasions is 2·79, but instead of being practically steady from month to month as in section (*a*) of the table, these independent values of turbidity have a minimum in the spring and a maximum in late summer.

TABLE XX—TURBIDITY FACTOR, $T$, AND COEFFICIENT OF TURBIDITY, $\beta$

(*a*) " Ceiling " radiation intensities

| | Dec. Jan. | Feb. Mar. | Apr. May | June July | Aug. Sept. | Oct. Nov. |
|---|---|---|---|---|---|---|
| $m = 2$ | | | | | | |
| $T$ | .. | 2·84 | 2·90 | 2·80 | 2·66 | 2·97 |
| $\beta$ | .. | ·062 | ·073 | ·064 | ·052 | ·068 |
| $m = 4$ | | | | | | |
| $T$ | 2·87 | 2·94 | 2·92 | 2·77 | 2·79 | 2·70 |
| $\beta$ | ·060 | ·065 | ·064 | ·048 | ·046 | ·049 |

(*b*) Days of high total radiation

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $m = 2$ | | | | | | | | | | | | |
| $T$ | .. | .. | 5·00 | 5·13 | 5·44 | 4·41 | 5·11 | 4·85 | 4·28 | 3·75 | .. | .. |
| $\beta$ | .. | .. | ·190 | ·204 | ·225 | ·158 | ·186 | ·175 | ·142 | ·116 | .. | .. |
| $m = 4$ | | | | | | | | | | | | |
| $T$ | 4·24 | 4·49 | 4·45 | 5·05 | 5·36 | 4·13 | 4·56 | 4·64 | 4·22 | 3·81 | 3·48 | 3·37 |
| $\beta$ | ·132 | ·145 | ·139 | ·134 | ·179 | ·114 | ·121 | ·122 | ·111 | ·099 | ·089 | ·083 |

(*c*) Occasions of highest recorded values

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $T$ | 2·80 | 2·89 | 2·73 | 2·29 | 2·67 | 2·92 | 2·90 | 3·07 | 2·81 | 2·82 | 2·81 | 2·81 |

*Ångström's coefficient of turbidity* ($\beta$).—In contrast with Linke's turbidity factor which aims at giving a measure of the total extinction effects of scattering, absorption and diffuse reflection in terms of the scattering effect as unity, Ångström's coefficient[10, 11] refers only to the suspended matter; the effects of pure scattering and water-vapour absorption are separately estimated. The loss of radiation intensity $dI_\lambda$ at a wave-length $\lambda$ is given by

$$dI_\lambda' = -\beta I_\lambda \frac{dm}{\lambda^a}$$

where the exponent $\alpha$ depends on the average size of the suspended particles, and, according to Ångström, may normally be taken as 1·3. The loss by true scattering can be provided for by a transmission coefficient $q$, so that, excluding absorption by water vapour,

$$I_\lambda = I_{0\lambda}\, q_\lambda^m e^{-\beta m/\lambda^{1\cdot 3}},$$

where $I_{0\lambda}$ and $I_\lambda$ are the intensities at wave-length $\lambda$ before and after penetrating the air mass $m$. This is only valid if there is no selective absorption in the neighbourhood of $\lambda$. The total $Q_m$ measured on the ground is obtained from

$$Q_m = \int_0^\infty I_{0\lambda} q_\lambda^m e^{-\beta m/\lambda^{1\cdot 3}} \, d\lambda - F.$$

In this expression $F$ is the absorption by water vapour, which is independently calculated. Ångström's expression for $Q_m$ can be applied to total radiation intensity but, like Linke's turbidity factor, it is preferable to use it in conjunction with simultaneous measurements of total radiation and one of its major spectral components.

One of the obvious weaknesses in Ångström's treatment arises from the necessity of assigning a fixed value to the exponent $\alpha$. Almost certainly, $\alpha$ is a complex function of the size distribution of the suspended matter in the atmosphere, and therefore varies considerably with time and locality, and with the synoptic situation and previous history of the air over the station of measurement. As regards the treatment of water vapour, there is a choice between measuring separately the radiation in that region of the solar spectrum which is free from the major bands of water-vapour absorption, or of using an empirical relationship such as that due to Fowle. As this uses surface vapour pressure as a measure of the total water in the atmosphere it is therefore rather inadequate; at the best it can be used only for groups of synoptically similar days with approximately similar humidity distributions in the atmosphere.

For comparison with the values of the coefficient of turbidity, $\beta$, worked out for other localities, the data of Table XIV have been used to provide the $\beta$ values for Kew given in Table XX.

It may be noted that if a relationship existed between $T$ and $\beta$, then computed values of $T$ might be used to estimate the amount of water vapour in the atmosphere. The corresponding values of $T$ and $\beta$ in Table XX are, indeed, linearly related; for air mass 2 the approximate expression is $T = 1\cdot 8 + 1\cdot 7\,\beta$. Feussner[12] found a similar relationship for the short-wave bands of solar radiation, but Kimball and Hand[13] found that estimates of water vapour so derived did not compare successfully with more direct measurements.

# PART II—DIRECT AND DIFFUSE SHORT-WAVE RADIATION FROM SUN AND SKY ON A HORIZONTAL SURFACE

## § 13—INTRODUCTION AND INSTRUMENTS USED

As explained in the Introduction, equipment was set up at Kew Observatory in June 1946 for continuous recording of the total short-wave radiation from sun and sky, $T$, which falls on a horizontal surface, and, separately, the diffuse radiation from the sky alone, $D$. As information on these two aspects of solar radiation is complementary to the data on direct solar radiation of normal incidence described in Part I, a summary of the first fourteen months' results may usefully be given here. It is to be noted that both the $T$ and $D$ data to be discussed refer only to short-wave radiation within the range $0\cdot 3\mu$ and $3\mu$; whether it comes from an apparently blue sky, when its maximum intensity is about $0\cdot 4\mu$, or from dense cloud when the maximum is shifted to $0\cdot 8\mu$, $D$ is simply solar radiation which has been scattered and diffused by molecules, molecular aggregates, suspended matter or cloud particles in its progress through the atmosphere.

The two similar thermopiles used for receiving the $T$ and $D$ radiation are exposed horizontally on the south balustrade of the Observatory roof near the Gorczynski pyrheliograph. Each pile has 14 thermojunctions arranged to form a square of one centimetre side, set flush with the edge of a heavy cast-metal cup with which the cold junctions are in thermal contact. The thermopile surface is covered by two glass hemispherical domes 1 mm. thick and 30 mm. and 50 mm. in diameter, sealed to the edge of the cup. The space above the junctions and under the inner glass dome is kept dry by a dessicator let into the bottom of the cup by an airtight screw. In the same plane as the junctions, the thermopiles are surrounded by a circular metal guard-ring to prevent radiation from below the horizontal plane through the thermopile falling on the junctions. The output of both thermopiles is led off to a thread recorder so that both $T$ (sun and sky) and $D$ (diffuse radiation alone) are recorded on the same chart.

To cut off the direct sun radiation from one thermopile, a ring of strip brass is mounted so that, with slight movements of the ring each day along a polar axis, direct radiation from the sun is prevented from falling on the thermopile. The breadth of the ring is such that at its distance from the thermopile (13·5 cm.) this is just effected. A correction is applied to the tabulated values of diffuse sky radiation to take account of the fraction of sky radiation which is also cut off by the ring: the correction varies from 7 per cent. in midsummer to 3 per cent. in midwinter. An additional constant correction is applied to take account of obstructions to a clear horizon.

Fig. 1 shows the arrangement of the two thermopiles and the rest of the radiation equipment on the Observatory roof.

## § 14—CALIBRATION OF THE THERMOPILES

The details of calibration of the two thermopiles supplied with the instruments have been used for reduction of the records. By eclipsing the direct solar rays from the fully exposed, $T$, thermopile at the same time as measurements of the intensity of direct solar radiation, $I$, are made with the standard Ångström pyrheliometer, it has been confirmed that the calibration factor used for this thermopile is approximately consistent with the scale values adopted for the other radiation equipment. The results of more extensive tests in future months covering a greater range of solar altitudes than has been possible in this first year's recording may necessitate the adoption of a modified factor. But any such change is not likely to exceed 2 per cent. of the value hitherto used, so that the results to be discussed in subsequent sections can be taken as of the same general order of accuracy as radiation measurements made elsewhere with this type of equipment, *viz.* within about 5 per cent.

A brief reference should be made to the influence on the results of the two glass hemispherical domes which protect the thermopiles. Earlier models of this kind of solarimeter with only one small glass dome of thickness greater than one millimetre had been found by Gorczynski[14] to have a sensitivity which varied with the sun's altitude; with a single dome of 30 mm. diameter the sensitivity at altitudes below 10° was only about half the sensitivity above 60°. The defect was attributed to the formation of caustics on the thermopile by the inner surface of the dome. By introducing a second and larger dome and also by reducing the thickness of the glass, the effects of this and other optical defects of the solarimeter are said to have been substantially lessened. According to Mörikofer[15], the variation of the standardization factor over the normal range of sun's altitudes is only a few per cent., and is not a simple function of the altitude. This has been tested for the Kew instruments by tabulating values of the ratio $r = (T - D)/I \sin h$ where $I$ is the direct solar intensity normal to the direction of the radiation and $h$ is the sun's altitude. Using the maker's calibrations for the $T$ and $D$ thermopiles, the ratio is practically constant, though slightly greater than unity, over the range $20° < h < 60°$, then increases somewhat for values of $h < 20°$

## § 15—MONTHLY AND DAILY TOTALS OF $T$ AND $D$

Table XXI gives the monthly totals and daily means of short-wave radiation from sun and sky, and the diffuse radiation from the sky alone on a horizontal surface. The table is based on the hourly tabulations of records of $T$ and $D$ from July 1946 to August 1947, the "year" being formed by the single representative months September 1946 to June 1947, together with the means of the two Julys and the two Augusts. Owing to minor troubles in the early stages of recording, the basic tabulations were not complete for both *T* and *D* for every day of each month. The monthly totals and daily means for *T* and *D* in the first four lines of Table XXI are derived from the same sets of complete days in each month, the totals being made up to complete months by corrections proportional to the number of missing days while the means are derived directly from the number of days of completely recorded data, which number is the same for *T* and *D* in each month.

The next four lines of Table XXI give for comparison corresponding data for direct solar radiation of normal incidence, *I*. The first pair of those lines is for the same period and made up in the same way as for *T* and *D* except that there was no need to correct the monthly totals for missing days; the second pair of lines, $\bar{I}$, is extracted from Tables III and V and gives the long-term values of *I* derived from the years 1933–46.

TABLE XXI—MONTHLY TOTALS AND DAILY MEANS OF *T* AND *D* RADIATION ON A HORIZONTAL SURFACE, AND OF DIRECT (NORMALLY INCIDENT) RADIATION, *I*

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. | Year | Period |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | cal./cm.$^2$ | | | | | | | | |
| *T* Total | 2,128 | 1,679 | 4,641 | 9,897 | 11,888 | 14,130 | 13,727 | 12,095 | 9,105 | 4,255 | 2,028 | 1,531 | 87,104 | July 1946–Aug. 1947 |
| mean | 66 | 60 | 150 | 330 | 383 | 471 | 443 | 390 | 304 | 137 | 67 | 49 | 238 | |
| *D* total | 1,389 | 1,251 | 3,070 | 5,089 | 6,327 | 7,082 | 8,013 | 6,017 | 5,638 | 2,810 | 1,364 | 1,018 | 49,068 | |
| mean | 45 | 45 | 99 | 170 | 204 | 236 | 258 | 194 | 188 | 91 | 45 | 33 | 134 | |
| *I* total | 1,860 | 842 | 2,838 | 7,796 | 8,297 | 10,070 | 8,111 | 8,903 | 4,515 | 2,561 | 1,240 | 1,416 | 58,449 | |
| mean | 64 | 30 | 91 | 260 | 268 | 323 | 257 | 281 | 163 | 81 | 44 | 46 | 159 | |
| $\bar{I}$ total | 1,187 | 2,031 | 4,029 | 5,765 | 8,013 | 8,811 | 7,594 | 7,207 | 5,422 | 3,365 | 1,484 | 1,126 | 56,033 | 1933-46 |
| mean | 38 | 72 | 130 | 192 | 258 | 294 | 245 | 233 | 181 | 108 | 49 | 36 | 154 | |
| | | | | | | per cent. | | | | | | | | |
| $D/T$ | 65 | 75 | 66 | 52 | 52 | 50 | 58 | 50 | 62 | 66 | 67 | 67 | 56 | |
| $I/T$ | 87 | 50 | 61 | 79 | 70 | 71 | 59 | 74 | 50 | 60 | 61 | 93 | 67 | |

The *I* data in Table XXI show that the "year" represented in that table was about 5 per cent. above the 1933–46 average in direct (normal incidence) radiation, but February, March (1947) and October, November (1946) were below average, particularly February when only 842 cal./cm.$^2$ were received on the Gorczynski pyrheliograph as compared with an average of 2,031 for the preceding fourteen Februaries.

The year's total of diffuse radiation, *D*, on a horizontal surface from the sky alone, 49,068 cal./cm.$^2$, was 56 per cent. of the total (sun and sky) radiation, *T*, and 84 per cent. of the direct radiation from the sun, *I*, on a surface normal to its direction. The monthly ratio $D/T$ varies between 0·5 and 0·75, the smaller ratios being associated with the summer months; $I/T$ is more irregularly variable between 0·5 and 0·93, the least and greatest values occurring in the same season.

Over the year the average daily *T* income is 238 cal./cm.$^2$ with a seasonal variation from about 50 cal./cm.$^2$ in midwinter to 470 in midsummer; diffuse sky radiation contributes 30–35 cal./cm.$^2$ on the average day in midwinter and 250–260 cal./cm.$^2$ in midsummer.

## § 16—EXTREME VALUES OF *T*, *D* AND *I*, AND THE SKY CONDITIONS WHICH PRODUCED THEM

Table XXII gives the highest and lowest daily totals of *T* and *D* in the period July 1946 to August 1947 with corresponding data for *I*. Of greater interest than the actual values are the sky conditions when they occurred. As would have been expected from the discussion of *I* in Part I of this memoir, the highest *I* occurred on a day when the sky was not more than 1 tenth clouded; the radiation from the sky alone on that day was only 16 per cent. of the total income from sun and sky together. The highest daily $T$, on the other hand, was recorded when the sky was about half covered with broken cumulus cloud; $D$ was then 29 per cent. of $T$. On the day of highest $D$ the sky was three quarters covered with broken low cloud (cumulus and stratocumulus) and some medium and high cloud (altocumulus, altostratus and cirrus) until near the end of the day; the total recorded sunshine was only 1·8 hr., being 11 per cent. of the possible. On that day the diffuse sky radiation was 83 per cent. of the total income from sun and sky together. On all three days of high $T$, $D$ and $I$ the visibility was very good.

TABLE XXII—HIGHEST AND LOWEST DAILY TOTALS OF $T$, $D$ AND $I$

| | Date | Extreme value of $T$ | Corresponding values of $D$ | Corresponding values of $I$ | Date | Extreme value of $D$ | Corresponding values of $T$ | Corresponding values of $I$ | Date | Extreme value of $I$ | Corresponding values of $T$ | Corresponding values of $D$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | cal./cm.$^2$ | | | | cal./cm.$^2$ | | | | cal./cm.$^2$ | | |
| Highest | 17.6.47 | 730 | 211 | 764 | 2.7.47 | 339 | 411 | 55 | 28.5.47 | 880 | 696 | 110 |
| Lowest | 6.2.47 | 7 | 3 | 0 | 6.2.47 | 3 | 7 | 0 | 6.2.47 | 0 | 7 | 3 |

The day of lowest $T$ (which also was the day of lowest $D$) was uninterruptedly overcast with dense low cloud; it was continuously foggy with intermittent rain and snow.

That the sky and visibility conditions on these isolated days of extreme $T$, $D$ and $I$ values are generally representative of the conditions for high values of the three kinds of radiation was confirmed by examining the records of observations on days in each season selected for their high $T$, $D$ and $I$ totals. In comparison with the best $I$ days which were the days of least cloud, the highest totals of sun and sky, $T$, radiation occurred when the sky was 2–6 tenths covered with broken cloud of fair-weather, vertically-structured type (cumulus), with extensive reflecting surfaces which do not substantially reduce the direct solar component, and contribute more by diffuse reflection of the direct sun's radiation than they provide by internal scattering. Without exception the highest $D$ totals, on the other hand, occurred on days when cloud amounts were never less than 7 tenths (though not overcast); the cloud was invariably broken and mixed, cumulus, stratocumulus and altocumulus predominating. The visibility was good to very good.

TABLE XXIII—DAILY TOTALS OF $T$, $D$ AND $I$ ON SELECTED GROUPS OF DAYS

| | No. of days | $T$ | $D$ | $I$ | $D/T$ | $I/T$ |
|---|---|---|---|---|---|---|
| | | cal./cm.$^2$ | | | % | % |
| Days of highest $T$ .. | 13 | 652 | 192 | 667 | 29 | 102 |
| Days of highest $D$ .. | 16 | 430 | 301 | 178 | 70 | 41 |
| Days of highest $D$ .. | 5 | 381 | 308 | 72 | 81 | 19 |
| Days of highest $I$ .. | 13 | 628 | 169 | 693 | 27 | 110 |
| All complete days .. | 117 | 431 | 220 | 294 | 51 | 68 |

Table XXIII gives the mean daily totals of radiation income for the three groups of days in the period May to August 1947 selected as having the highest values of $T$, $D$ and $I$. The second $D$ line relates to a limited group of days selected as having the highest $D/T$ ratios and the last line of the table gives the four-month averages for all complete days.

According to Table XXIII each square centimetre of horizontal surface at Kew Observatory on the average summer day receives 431 calories from sun and sky together; 51 per cent. of this is diffuse sky radiation. But on those days when the total radiation is greatest (*i.e.* when there are 2–6 tenths of broken cloud of cumulus type), the diffuse sky radiation falls to below 30 per cent.

of the total income; and, in those conditions, the direct solar radiation of normal incidence has about the same intensity as the total radiation intensity on a horizontal surface from sun and sky together. When the sky is at least 7 tenths clouded with a mixture of broken low cloud and patches of medium or high cloud, *i.e.* in the best conditions for high $D$ values, the proportion of $D$ to $T$ increases to 70 per cent. On certain days of this category, as shown by the second group of values for the brightest $D$ days in Table XXIII, the ratio $D/T$ can reach 81 per cent. When conditions are most suitable for the highest values of direct solar radiation, *i.e.* on days of uninterruptedly clear sky and clear atmosphere, $D$ may be less than a quarter of $T$ (cf. Table XXII).

## § 17—VARIATION OF $T$ AND $D$ ON DAYS OF HIGHEST $T$ AND $D$ INCOME

Table XXIV gives the hourly values of total and diffuse radiation likely to be received on a horizontal surface at Kew on the best days for these aspects of solar radiation. The manner of forming the daily variations was to select from the best radiation days those values of $T$ (or $D$) when the highest readings had been attained, so building up a composite complete day. The process was similar to that used for normal direct solar intensities as described in § 5, except that 60-minute intervals were used instead of intervals of a few minutes as for $I$. Because of this

TABLE XXIV—HIGHEST HOURLY VALUES OF $T$ AND $D$

| | Hour ending (L.M.T.) | | | | | | | | | | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | |
| | cal./cm.²/hr. | | | | | | | | | | | | | | | | | | cal./cm.² |
| $T$ | 1 | 6 | 16 | 31 | 48 | 61 | 73 | 81 | 87 | 87 | 80 | 68 | 56 | 42 | 30 | 17 | 4 | 1 | 789 |
| $D$ | 1 | 6 | 15 | 24 | 31 | 39 | 44 | 48 | 50 | 49 | 47 | 40 | 34 | 26 | 20 | 12 | 6 | 1 | 493 |

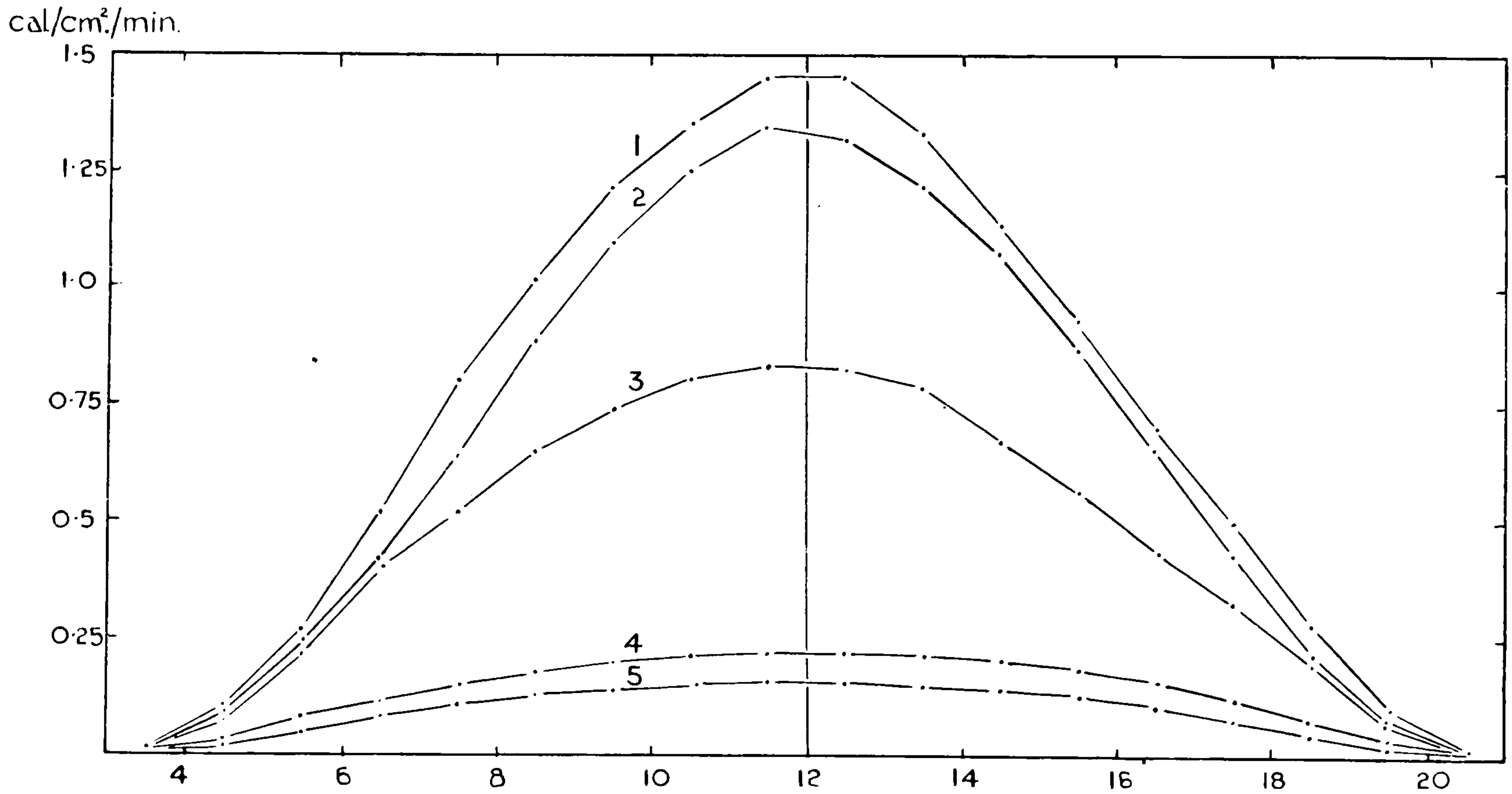


FIG. 9—DAILY VARIATION OF TOTAL AND DIFFUSE RADIATION

Curve 1—ceiling value of total radiation, $T$
Curve 2—total radiation, $T$, on cloudless days
Curve 3—ceiling value of diffuse radiation, $D$
Curve 4—diffuse radiation, $D$, on cloudless days
Curve 5—diffuse radiation, $D$, on cloudless and clear days

difference the occasions of peak values of $T$ (or $D$) did not require to be so accurately related to solar altitude. The hour-to-hour values of $T$ and $D$ on these composite days are plotted in Fig. 9, together with other curves to be referred to in § 18.

According to Table XXIV the limit of daily total of radiation, $T$, is about 800 cal./cm.$^2$; this is only 8 per cent. above the highest daily total actually recorded on a particular day, *viz.* 730 cal./cm.$^2$ on June 17, 1947. The corresponding daily limit of $D$, 493 cal./cm.$^2$, is 45 per cent. greater than was actually recorded on the day of highest $D$ total, July 2, 1947.

It is unlikely that these are true ceiling values in the sense of being the highest attainable in the most advantageous conditions at Kew, and in the sense in which the ceiling values of $I$ were derived as explained in § 5 and given in Table V, according to which the greatest daily total of $I$ likely to be received at Kew is 1,035 cal./cm.$^2$. Using recorded hourly values of $I$ from only three months, May to July 1947, a composite day can be formed with a daily $I$ total of 982 cal./cm.$^2$, so the estimated limit of 1,035 is clearly not impracticable. Now $I$ for the composite day, which gave the total of 789 cal./cm.$^2$ for $T$, was 794 cal./cm.$^2$, so confirming the first line of Table XXII that on the highest $T$ days $T$ is only slightly less than $I$. It therefore seems that a value only slightly less than 1,035 cal./cm.$^2$ is not an unreasonable upper limit to accept also for $T$. There is no similar process for allowing the limiting daily value of $D$ (493 cal./cm.$^2$) to be modified.

It will be understood from the considerations of the preceding section that the values for $T$ and $D$ in Table XXIV relate to two different types of sky conditions.

## § 18—DIFFUSE SOLAR RADIATION FROM A CLOUDLESS SKY

The preceding section has been concerned with high values of $T$ and $D$ radiation received on a horizontal surface at Kew. As has been explained these high values occur on days when the sky is partly covered with particular types of cloud, $T$ with 2–6 tenths cumulus cloud, and $D$ with 7–9 tenths of mixed broken cloud, preferably cumulus, stratocumulus and altocumulus. As reflection of direct solar radiation is an important contributing factor to high $T$ and $D$ values on those days, it is likely that isolated vertically structured cloud around a zone of the sky 25–45° above the horizon is the most effective distribution for the highest flux of diffuse radiation at the ground.

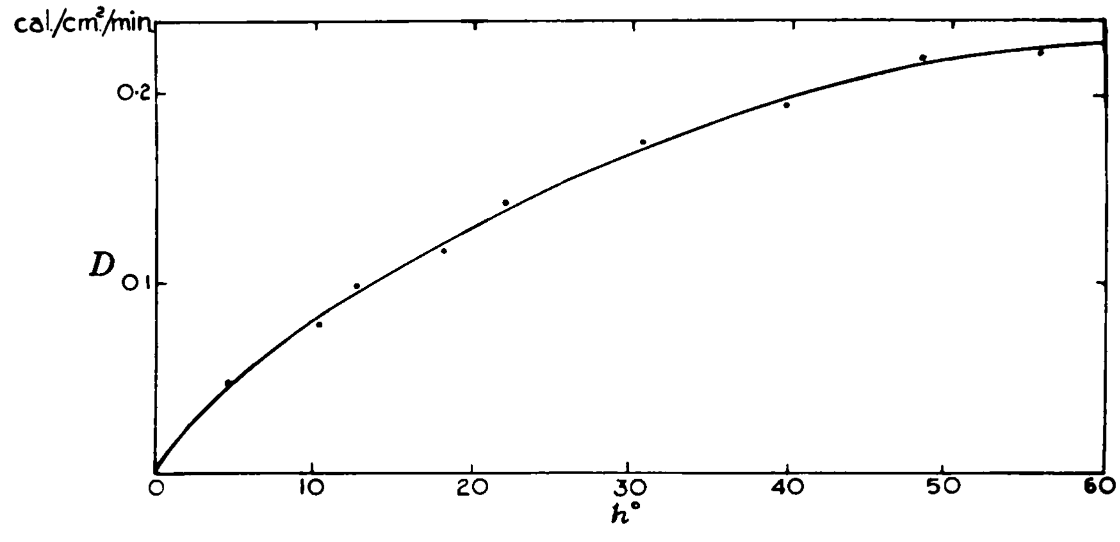


FIG. 10—RELATION OF INTENSITY OF DIFFUSE RADIATION, $D$, TO SUN'S ALTITUDE, $h$, ON CLOUDLESS DAYS

Of equal interest is the flux of diffuse radiation from a cloudless sky and also from a completely clouded sky, particularly in relation to solar altitude. Curve 4 in Fig. 9 shows the mean hourly variation of $D$ built up from a group of cloudless days and parts of days in summer. Of the complete days used, the day's total of $D$ income ranged from 110 cal./cm.$^2$ on the clearest day to 188 cal./cm.$^2$ on a day of heat haze; the turbidity factors (see § 12, p. 25) for direct solar radiation on these two days were 2·8 and 4·1. Had there been enough cloudless days in midsummer with uniformly clear atmosphere to form a smoothed curve corresponding with 110 cal./cm.² daily income curve 4 would probably have been reduced to curve 5 in Fig. 9.

Fig. 10, which expresses $D$ from curve 4 of Fig. 9 in terms of sun's altitude, $h$, shows that the intensity of diffuse solar radiation on cloudless days in summer (with clearness of atmosphere corresponding with turbidity 3·2) is a function of $h$, having a maximum at Kew of 0·23 cal./cm.²/min. at $h = 60°$. On the clearest days this value probably does not exceed 0·20 cal./cm.². In these two sets of conditions the contributions of direct solar radiation to the total intensity on a horizontal surface would be 1·25 and about 1·28 cal./cm.²/min. respectively.

## § 19—DIFFUSE RADIATION FROM A CLOUDY SKY

For many practical purposes it is desirable to extend the analysis of the preceding section to cloudy conditions, and if possible to provide a relationship by which estimates of the daily income of diffuse radiation can be derived from a knowledge of cloud amount, type and thickness. If the diffuse income ($D$) could be estimated in this way, it would be a simple matter to estimate the total radiation ($T$) from sun and sky together, because $T = D + I \sin h$, and $I$ can be inferred in a much more direct manner than $D$ from measurements of sunshine or cloud amount. In the fourteen months over which the Kew $D$ material extends there have, however, been few occasions when the same type of sky has persisted throughout the day, except in winter when the variation of the sun's altitude is inadequate for the purpose. The analysis has therefore been based on groups of hours of apparently similar cloud amount, type and thickness; the relation between the short-interval flux of radiation on those occasions to daily totals will be developed in § 20.

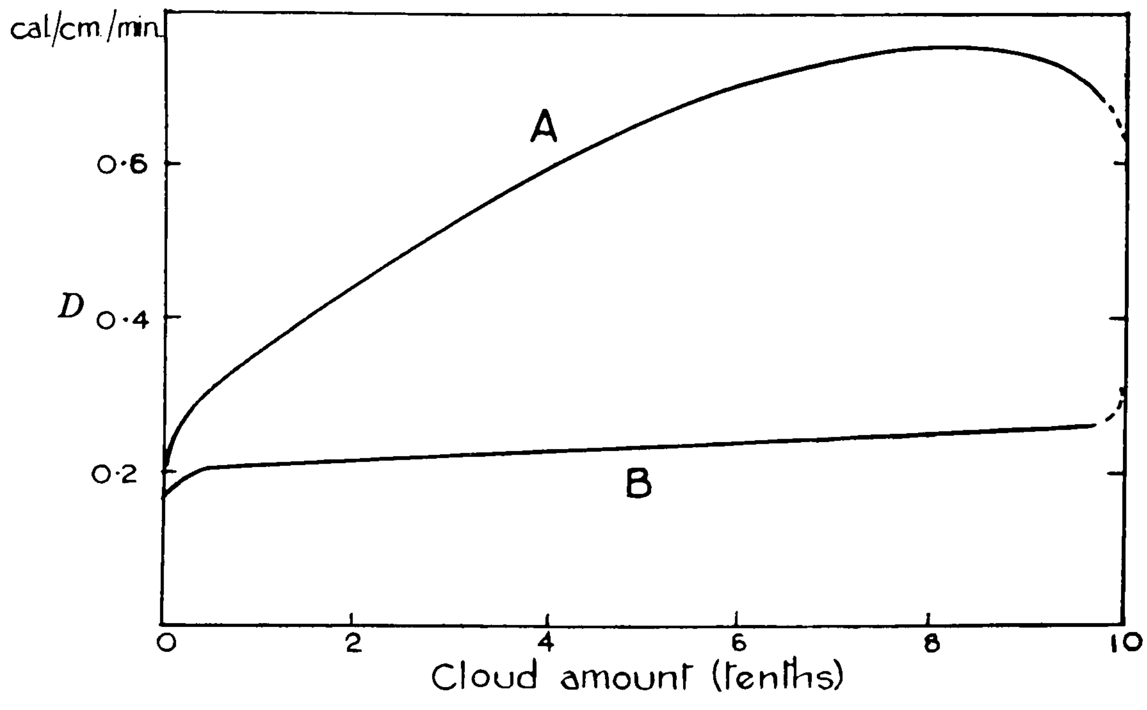


FIG. 11—VARIATION OF DIFFUSE RADIATION, $D$, WITH CLOUD AMOUNT

A—low and medium cloud, mainly Cu, Sc, Ac, thick As
B—high cloud, Cs, Ci, thin As

For reasons which will soon be obvious it has been impracticable to establish a numerical relationship between $D$ and the state of sky; an outline of the results of the analysis are summarised in Figs. 11 and 12, Fig. 11 being concerned primarily with the influence of changes in cloud amount on the flux of $D$ at the ground, and Fig. 12 with the effect of cloud density as characterised for this purpose by cloud type and thickness. The ordinates in both figures give the approximate $D$ intensities when the sun's altitude, $h$, is $30° < h < 50°$. As has been shown in the preceding section the actual intensities vary with $h$ but more slowly than with cloud amount or density at moderate values of $h$.

Curve A in Fig. 11 shows how the diffuse radiation increases from about 0·23 cal./cm.²/min. with a cloudless sky to about 0·75 cal./cm.²/min. when the sky is 8–9 tenths covered with cumulus, stratocumulus or altocumulus type of cloud. As the cloud merges to form a continuous sheet so that diffuse reflection of direct solar radiation is cut off, the sky radiation begins to decrease, at first slowly then more rapidly with increasing thickness of the cloud sheet (altostratus). If at this stage the cloud becomes thinner again, though remaining as a sheet (altostratus-cirrostratus), the radiation continues to fall to about 0·30 cal./cm.²/min. Thereafter, as illustrated in curve B, further dissipation leads to disintegration of the sheet, and the diffuse radiation decreases more slowly to its cloudless value of 0·20 to 0·25 cal./cm.²/min. depending on the haziness of the atmosphere.

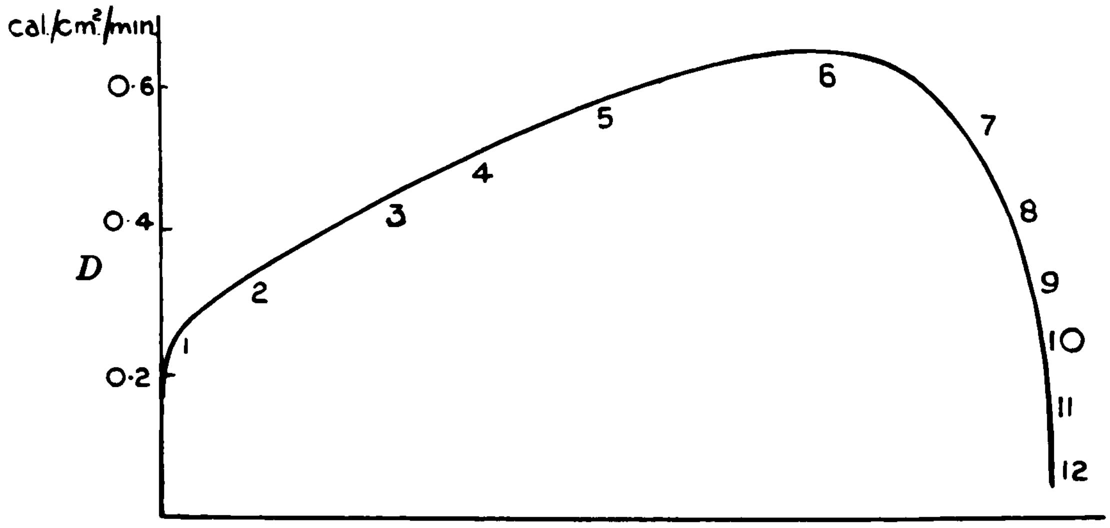


FIG. 12—VARIATION OF DIFFUSE RADIATION, $D$, WITH CLOUD TYPE AND DENSITY WITH COMPLETELY COVERED SKIES

| | | | |
|---|---|---|---|
| 1—Ci | 4—As | 7—Sc (heavy), As | 10—St |
| 2—Ci, Cs | 5—Ac, Sc | 8—As (thick) | 11—Ns |
| 3—Cs, As | 6—Sc, Cu | 9—As, St | 12—Cb, As |

Fig. 12 is intended to illustrate that this is not the whole story. With a completely clouded sky the intensity of diffuse radiation at ground level can assume a range of values from 0·25 cal./cm.²/min. with a thin veil of cirrus to about 0·65 cal./cm.²/min. as the cloud density increases through cirrus, cirrostratus, thin altostratus, etc. to a continuous sheet of stratocumulus. Thereafter, as the stratocumulus sheet thickens through altostratus to stratus and nimbostratus, the intensity decreases to 0·1 cal./cm.²/min., and finally, with heavy and extensive cumulonimbus and altostratus, to values of 0·05 cal./cm.²/min. or less.

The foregoing analysis illustrates the impracticability of devising a formula by which diffuse radiation income, and therefore total sun and sky radiation, can be related to the state of the sky. With 8 tenths cloud amount the $D$ intensity can range between 0·25 and 0·75 cal./cm.²/min., and with 10 tenths cloud between 0·05 and 0·65 cal./cm.²/min. The density and structure of the cloud are at least as important as its amount, and there is no simple way of allowing for them. Even when the structure of a cloud sheet as observed from ground level has appeared to remain the same over several hours, measurements of intensity of daylight now being made at Kew Observatory have shown that substantial changes in thickness, or density, or nature of the upper surface (as regards albedo) or changes in amount and type of higher cloud layers have been in progress. Daylight intensity could of course be taken as a measure of cloud density, and indeed there is close direct relationship between daylight intensity and $T$; but the maintenance of a thermopile to record radiation is no more difficult than the recording of daylight.

## § 20—RELATION BETWEEN INTENSITY AND DAILY INCOME OF DIFFUSE RADIATION

Although the relationship between $D$ and the state of sky is therefore too complex for a formula, the results illustrated in Fig. 13 can be utilised to estimate roughly the total amount of diffuse radiation falling on a horizontal surface on a day of specified cloud amount and type. Fig. 13 gives the relationship between $D$ intensity around midday and the day's total income of $D$ for sky conditions assumed to remain similar throughout the daylight hours. If, therefore, the intensity of diffuse radiation for the particular conditions of cloud type and amount in the middle of the day is deduced from Figs. 11 and 12, Fig. 13 gives approximately the day's total radiation in those conditions. The present objection to using this procedure is that Figs. 11 and 12 take account only of conditions of moderate sun's altitude.

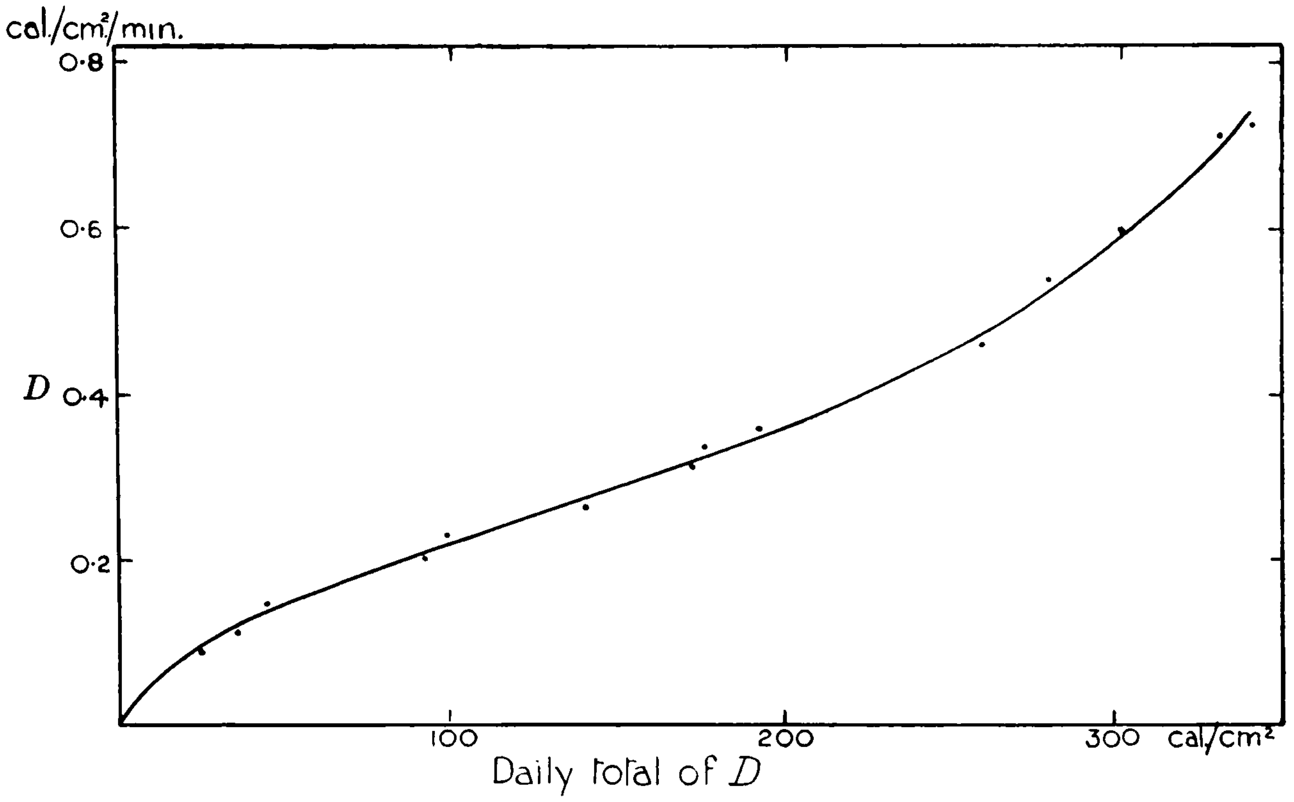


FIG. 13—RELATION BETWEEN MIDDAY INTENSITIES AND DAILY TOTALS OF DIFFUSE RADIATION, $D$

## § 21—DAILY VARIATION OF $T$ AND $D$

To illustrate the average relationship between $T$ and $D$ at various times of the year, mean daily variations of $T$ and $D$ were formed from all days in each month for which complete recordings were available in both $T$ and $D$. The months were grouped in four sets, November to January, February to April, etc. to represent seasonal change in behaviour. Daily variations were similarly formed for solar radiation of normal incidence, $I$, from the same sets of complete days. The results are reproduced in Fig. 14 in which the uppermost curve in each seasonal set is $T$, and the lowest one $D$.

Fig. 14 shows that even fourteen months' data are sufficient to illustrate the main daily features of the three radiation elements, which are:—

(1) Contribution of direct solar radiation to $T$ in the forenoon and afternoon hours is greater than in the hours immediately around noon. As this arises from a higher cloudiness and turbidity in the midday hours than when convection processes are relatively subdued, the effect is most conspicuous in summer and least in the winter months.

(2) Direct radiation on a surface normal to its direction and $D$ on a horizontal surface are of the same order of size.

(3) Direct and diffuse components of $T$ are complementary in the sense that when one decreases the other increases to keep the total sun and sky radiation approximately constant. This is a simple effect arising from broken cloud acting as a reflector and scatterer while reducing direct radiation intensity; it is best seen in the recordings for particular days, but the average result is still apparent in the $I$ and $D$ curves for spring and summer in Fig. 14.

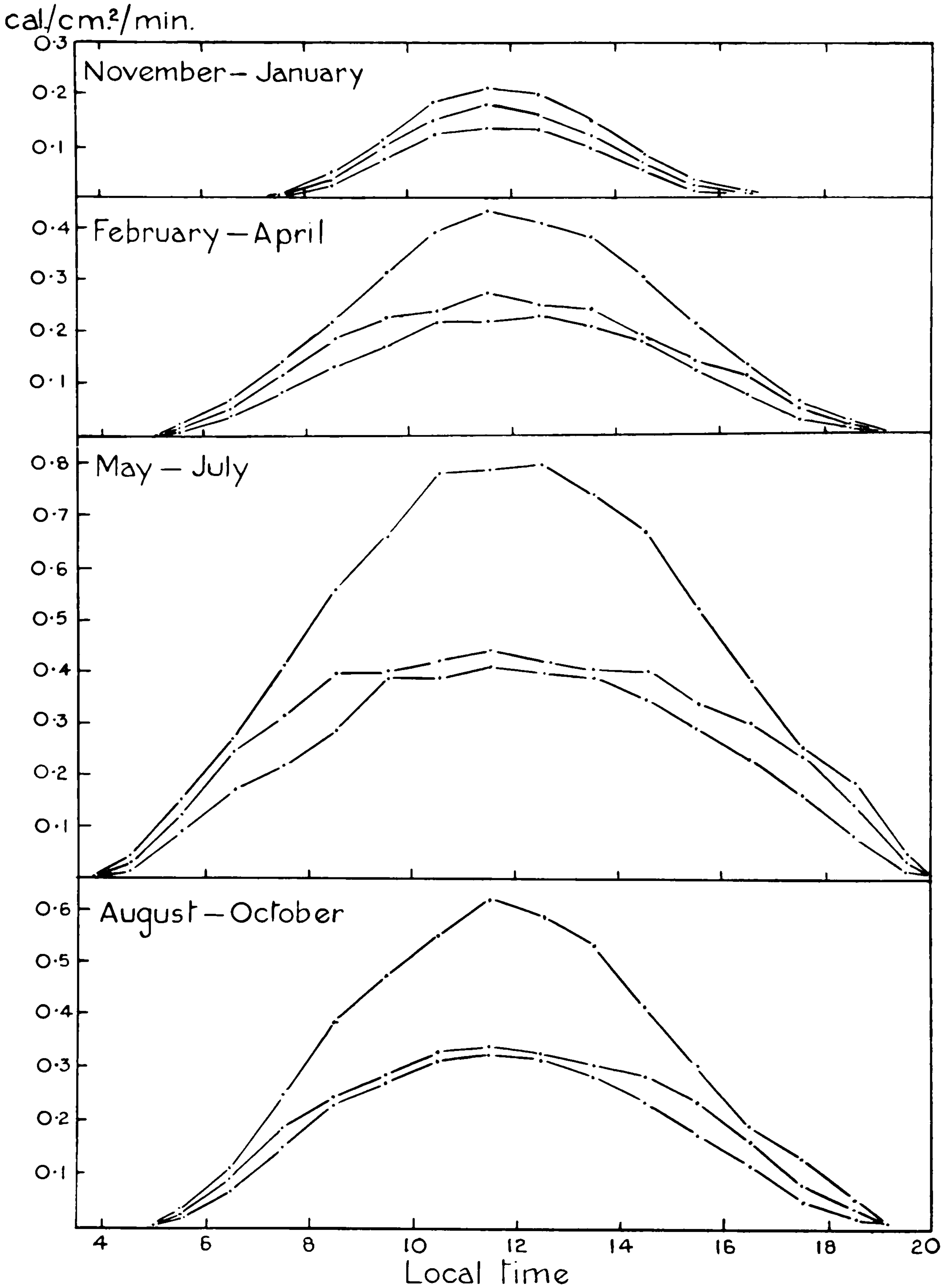


FIG. 14—DAILY VARIATION OF TOTAL, DIFFUSE AND DIRECT RADIATION

In each set, the total radiation, *T*, is the highest and diffuse radiation, *D*, the lowest curve

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