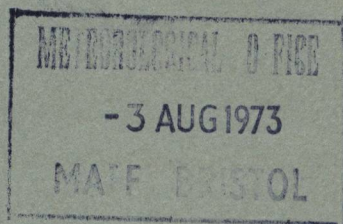


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METEOROLOGICAL OFFICE

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JUNE 1973 No 1211 Vol 102

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THE METEOROLOGICAL MAGAZINE

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AN ANALYSIS OF MONTHLY RAINFALL TOTALS REPRESENTATIVE OF KEW, SURREY FROM 1697 TO 1970

By B. G. WALES-SMITH

Summary. A very long series of monthly rainfall data representative of Kew is analysed in terms of frequency distributions of annual and seasonal totals, and in terms of return periods of rainfall amounts for given months, sets of consecutive months, and on a yearly basis. Trends in seasonal and annual rainfall are discussed.

Introduction. Planners and many others frequently ask if there have been trends in the rainfall of London and of other places. They seek advice on the frequency of wet winters, dry summers and so on. Water engineers have two main problems; the satisfaction of the ever-increasing demand for fresh water and the avoidance, or at least the control, of flooding. Agriculturists, too, are vitally concerned with trends in and frequencies of rainfall. These problems require detailed studies of the regional characteristics of the water cycle. The meteorological aspects of the cycle are, of course, rainfall and evaporation. In this article further investigations are made into a very long series of monthly rainfall totals which formed the basis of an earlier paper by the present author.¹ Work on the preparation of a companion series of evaporation estimates and measurements representative of Kew, for a similar study and for study in association with this rainfall series is now nearing completion.

Homogeneity of the series of annual totals. Although, as will be shown later in this article, there are some interesting trends, the series of annual totals passes a rough test for homogeneity. The 'run' test was applied. The median value is 23.71 inches (602.2 mm), with 137 totals above and 137 totals below this value. There were 132 'runs' (i.e. sets of one total or more, taken in chronological order, above or below the median value). These criteria define a point lying comfortably between the lower and upper 0.10 significance limits.

Frequency distributions of annual and seasonal totals. Totals, in 1-inch ranges of amount, were tabulated for years and seasons from 1697 to 1970. The 4-month and 2-month seasons used are those suggested by A. Bleasdale as being especially appropriate to U.K. rainfall studies. Frequency diagrams are shown as Figure 1. The simple dashed-line construction helps the eye to recognize the generally convex (upwards) shape of the left-hand parts and the generally concave shape of the right-hand parts of the diagram.

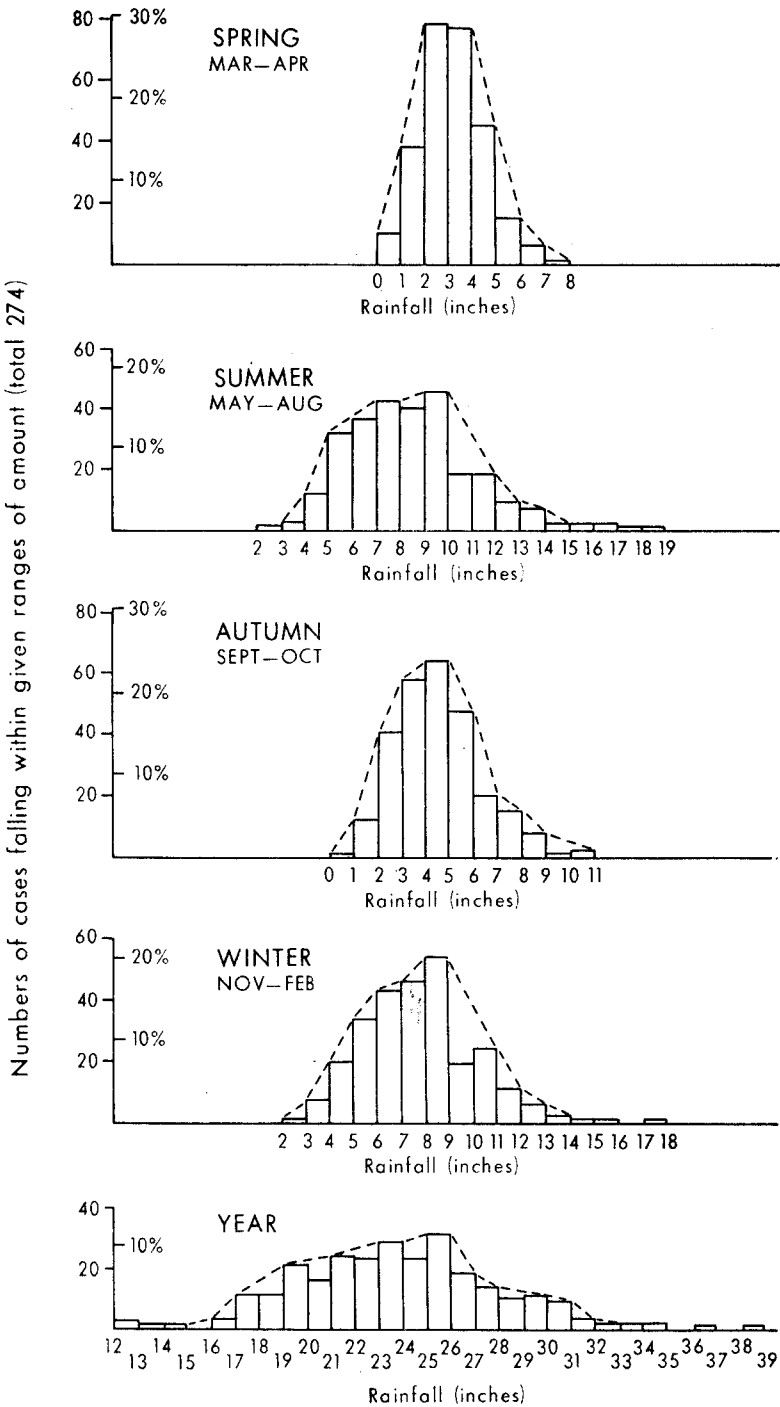


FIGURE 1—FREQUENCY DIAGRAMS OF SEASONAL AND ANNUAL TOTALS OF RAINFALL REPRESENTATIVE OF KEW, 1697-1970

Analysis by computer. The series was first analysed by a FORTRAN IV program designed and written by J. D. Bacon. The output consists of (a) the year numbers and rainfall amounts for the six wettest and six driest of each calendar month (ignoring change of calendar in September 1752) and (b) the same analysis for accumulations of months up to six, commencing with October and April. (The hydrologists' 'Water Year' begins with October.) In each of these 22 analyses the amounts likely (a) to occur or be exceeded and (b) not to be exceeded (on average), with return periods of from 5 to 200 years are obtained by empirical frequency.

The above analyses were carried out on the whole 274-year series and, for later study, on consecutive 50-year periods starting in 1721. Next the series was analysed by another FORTRAN IV program designed and written by K. Bruley. The output consists of frequency tables for desired periods. The table for the whole period was rewritten to give numbers of cases of less than stated amounts of rain and these figures were divided by 274 to give cumulative probability values.

Comparison of extreme values. The values of the six wettest and driest of each calendar month (a) in the whole series and (b) in consecutive 50-year sets were plotted. The generally random distribution of these extreme values through the series suggested that whilst the series might contain trends, it is, none the less, reasonable to subject it to frequency analysis.

Extreme-value analysis. Taking each month in turn, the 6 highest and 6 lowest values were plotted on extreme-value probability paper, using positions recommended by A. F. Jenkinson.²

$$P = \frac{m - 0.31}{n + 0.38}, \quad \dots (1)$$

where P is the cumulative probability plotting position, m is the ranking order, and n is the number of classes. In this case the value of n was 274 and m took values of 274 to 269 and 6 to 1.

The same procedure was followed with the 12 extreme values for sets of months beginning with October and April, for the 4- and 2-month 'seasons' May–August, September–October, November–February, March–April and for annual totals.

The empirical threshold estimates of monthly rainfall (obtained from Bacon's program) were plotted against their return periods (in years) and the cumulative probability values obtained from Bruley's table were plotted against the appropriate upper limits of classes. Lines of best fit were drawn by inspection through all the plotted points. There was little difficulty in fitting points up to 100 years' return period (probability 0.99) but rarer occurrences were, of course, hard to handle with any confidence. The method adopted was extreme caution in making estimates of 200-year events (i.e. to aim to err on the low side). Figures 2 and 3 show the estimates finally accepted. Envelopes to curves of values likely not to be exceeded, with given return periods, obtained by similar treatment on probability paper, are also shown. The 10 periods October–November through to October–March and April–May through to April–September were treated in the same way as the individual months. Because of the progressive increases in amounts, however, the

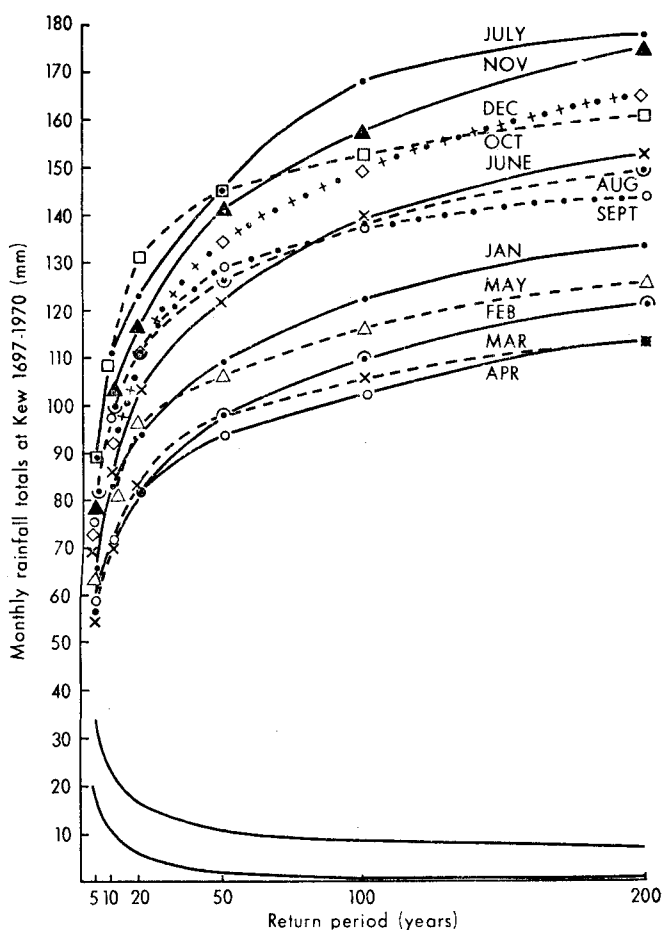


FIGURE 2—AMOUNTS OF RAINFALL LIKELY TO OCCUR OR TO BE EXCEEDED, IN GIVEN MONTHS, FOR RETURN PERIODS UP TO 200 YEARS (UPPER CURVES) AND ENVELOPES TO MONTHLY CURVES OF RAINFALL AMOUNTS LIKELY NOT TO BE EXCEEDED, EACH MONTH, FOR RETURN PERIODS UP TO 200 YEARS, AT KEW

probability curves representing the winter and summer halves of the Water Year could be plotted on only two sheets and comparisons of adjacent curves were very helpful in dealing with rare events. In drawing the curves of amounts not likely to be exceeded with given return periods use was made of the six lowest totals in each case. Figures 4 and 5 show the values finally accepted. The annual and the 4-month and 2-month seasonal values were processed in the same way as the other totals. The results are shown in Figure 6.

By using the same principle of extreme caution as employed with 200-year events rough estimates have been made for 500- and 1000-year events and are given in Table I. These rough estimates have been made only because they may be of some value and because it was fairly simple to make them with all the working sheets readily available. The estimates for individual months are almost certainly the least trustworthy of all.

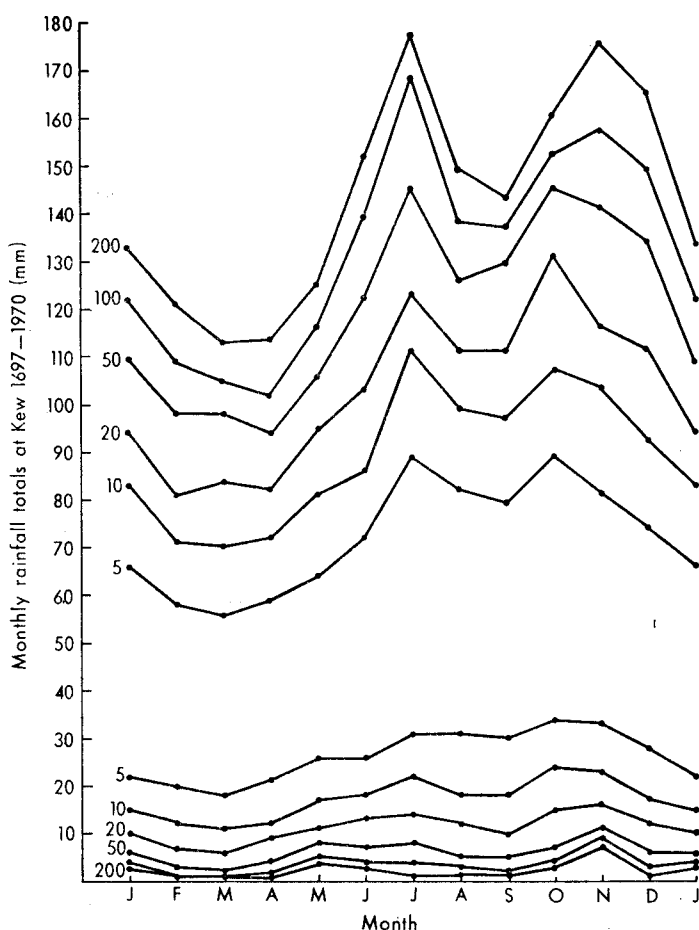


FIGURE 3—AMOUNTS OF RAINFALL LIKELY TO OCCUR OR TO BE EXCEEDED IN EACH MONTH OF THE YEAR (UPPER CURVES) AND AMOUNTS OF RAINFALL LIKELY NOT TO BE EXCEEDED (LOWER CURVES) FOR GIVEN RETURN PERIODS, AT KEW. Numbers to the left of the curves are return periods in years.

Dates of extreme events. The year dates of the six wettest and driest examples of (a) individual months, (b) given sets of months, (c) 'seasons' and years are given in Tables II, III and IV. It is interesting to note that the wettest and driest summers, autumns and winters in the 274-year series (Table IV) all occurred in the last 100 years, 1871-1970. This raises the often discussed question of whether very long sets of data should be analysed in terms of frequency. Perhaps the last 50 to 100 years belong to a population slightly but significantly different from the preceding century or so.

In an attempt to investigate this the 6 wettest and driest of each 'season' in the century 1871-1970 were tabulated (Table V). The numbers in brackets show the ranks of events in the whole 274-year series.

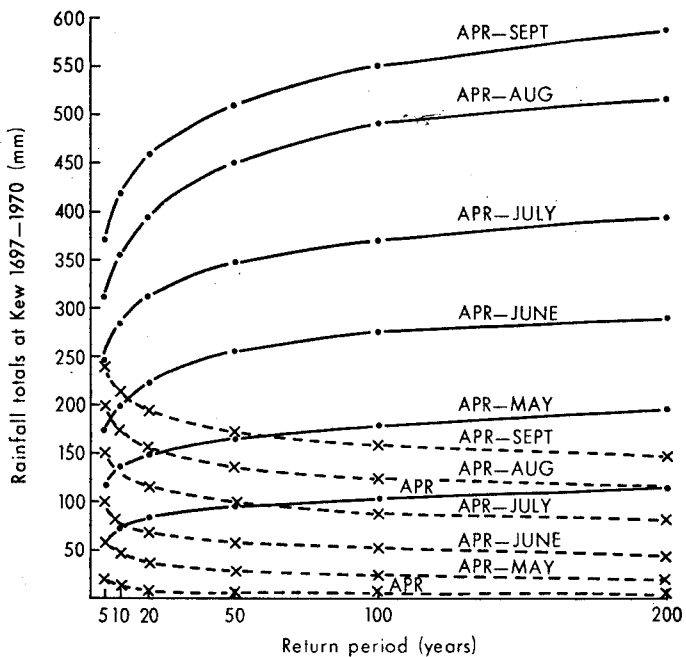


FIGURE 4—AMOUNTS OF RAINFALL AT KEW IN GIVEN SETS OF CONSECUTIVE MONTHS FOR RETURN PERIODS UP TO 200 YEARS
· — · Likely to occur or to be exceeded. x -- x Likely not to be exceeded.

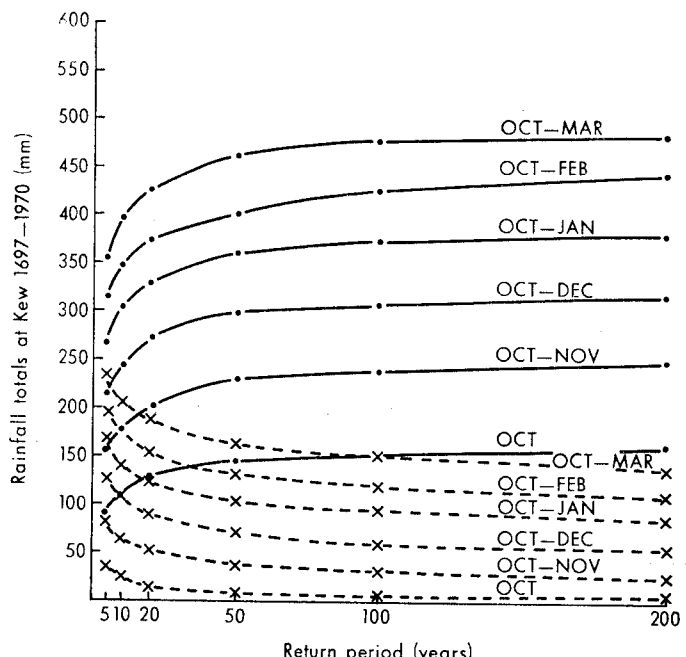


FIGURE 5—AMOUNTS OF RAINFALL AT KEW IN GIVEN SETS OF CONSECUTIVE MONTHS FOR RETURN PERIODS UP TO 200 YEARS

TABLE I—EXTRAPOLATION OF PROBABILITY DIAGRAMS TO PROVIDE ESTIMATES IN MILLIMETRES OF VALUES OF EXTREMELY RARE RAINFALL AT KEW

Probable extreme values

| WET | Return periods | | Year | Return periods | |
|------------|----------------|------------|------------|----------------|------------|
| | 500 years | 1000 years | | 500 years | 1000 years |
| Jan. | 137.2 | 142.2 | | 292.1 | 279.4 |
| Feb. | 127.0 | 132.1 | | | |
| Mar. | 121.9 | 127.0 | Apr.-May | 17.0 | 15.7 |
| Apr. | 124.5 | 129.5 | Apr.-June | 42.7 | 40.6 |
| May | 134.6 | 142.2 | Apr.-July | 72.4 | 67.3 |
| June | 172.7 | 188.0 | Apr.-Aug. | 104.1 | 96.5 |
| July | 185.4 | 190.5 | Apr.-Sept. | 134.6 | 127.0 |
| Aug. | 162.6 | 175.3 | | | |
| Sept. | 152.4 | 160.0 | Oct.-Nov. | 20.3 | 17.8 |
| Oct. | 167.6 | 175.3 | Oct.-Dec. | 45.7 | 41.9 |
| Nov. | 190.5 | 200.7 | Oct.-Jan. | 73.7 | 67.3 |
| Dec. | 172.7 | 175.3 | Oct.-Feb. | 96.5 | 90.2 |
| | | | Oct.-Mar. | 124.5 | 115.6 |
| Year | 980.4 | 1021.1 | | | |
| | | | Mar.-Apr. | 7.6 | 6.3 |
| Apr.-May | 205.7 | 213.4 | May-Aug. | 83.8 | 76.2 |
| Apr.-June | 307.3 | 322.6 | Sept.-Oct. | 22.9 | 17.8 |
| Apr.-July | 424.2 | 436.9 | Nov.-Feb. | 73.7 | 68.6 |
| Apr.-Aug. | 533.4 | 546.1 | | | |
| Apr.-Sept. | 612.1 | 629.9 | | | |
| | | | | | |
| Oct.-Nov. | 254.0 | 261.6 | | | |
| Oct.-Dec. | 322.6 | 330.2 | | | |
| Oct.-Jan. | 388.6 | 398.8 | | | |
| Oct.-Feb. | 447.0 | 452.1 | | | |
| Oct.-Mar. | 487.7 | 492.8 | | | |
| | | | | | |
| Mar.-Apr. | 177.8 | 182.9 | | | |
| May-Aug. | 485.1 | 515.6 | | | |
| Sept.-Oct. | 266.7 | 274.3 | | | |
| Nov.-Feb. | 429.3 | 457.2 | | | |

TABLE II—RAINFALL AMOUNTS IN MILLIMETRES FOR THE SIX WETTEST AND SIX DRIEST MONTHS AT KEW, 1697-1970

| Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| <i>Wettest</i> | | | | | | | | | | | |
| 136.7 | 126.5 | 118.4 | 121.9 | 140.7 | 183.1 | 177.8 | 165.6 | 145.0 | 169.9 | 189.0 | 169.4 |
| 1749 | 1951 | 1947 | 1829 | 1777 | 1903 | 1828 | 1878 | 1918 | 1744 | 1755 | 1747 |
| 127.5 | 120.4 | 102.9 | 111.8 | 116.8 | 147.3 | 174.5 | 149.6 | 139.5 | 151.1 | 171.7 | 166.6 |
| 1877 | 1763 | 1851 | 1744 | 1817 | 1860 | 1782 | 1941 | 1775 | 1841 | 1940 | 1914 |
| 120.1 | 104.4 | 100.3 | 98.3 | 115.6 | 135.6 | 165.1 | 134.4 | 136.1 | 151.1 | 157.0 | 146.6 |
| 1943 | 1879 | 1916 | 1878 | 1703 | 1797 | 1779 | 1912 | 1896 | 1880 | 1970 | 1876 |
| 117.6 | 102.9 | 100.1 | 97.5 | 111.0 | 129.5 | 157.2 | 132.6 | 135.4 | 150.6 | 154.4 | 136.9 |
| 1764 | 1937 | 1914 | 1756 | 1865 | 1838 | 1806 | 1737 | 1768 | 1891 | 1810 | 1915 |
| 109.5 | 102.4 | 99.1 | 95.5 | 106.7 | 117.1 | 150.6 | 128.3 | 130.6 | 149.9 | 152.4 | 135.1 |
| 1939 | 1866 | 1821 | 1809 | 1824 | 1728 | 1956 | 1879 | 1797 | 1865 | 1852 | 1779 |
| 109.2 | 94.0 | 96.5 | 93.0 | 105.9 | 116.8 | 139.2 | 123.2 | 127.0 | 147.1 | 134.4 | 132.1 |
| 1828 | 1812 | 1818 | 1800 | 1734 | 1852 | 1853 | 1931 | 1839 | 1882 | 1951 | 1821 |
| <i>Driest</i> | | | | | | | | | | | |
| 3.1 | 0.0 | 0.8 | 2.3 | 4.8 | 1.0 | 0.0 | 0.5 | 0.0 | 2.0 | 6.9 | 0.0 |
| 1766 | 1821 | 1929 | 1938 | 1896 | 1925 | 1800 | 1750 | 1804 | 1788 | 1749 | 1788 |
| 3.3 | 2.3 | 1.3 | 2.3 | 5.1 | 5.1 | 2.5 | 1.8 | 1.8 | 3.8 | 7.4 | 2.5 |
| 1731 | 1959 | 1731 | 1855 | 1833 | 1921 | 1825 | 1727 | 1754 | 1947 | 1945 | 1829 |
| 4.8 | 2.3 | 2.0 | 2.3 | 5.6 | 6.3 | 3.8 | 2.0 | 2.5 | 4.1 | 9.9 | 2.8 |
| 1802 | 1891 | 1781 | 1840 | 1956 | 1923 | 1921 | 1726 | 1959 | 1969 | 1956 | 1762 |
| 6.1 | 2.5 | 2.3 | 2.5 | 7.4 | 6.3 | 6.9 | 2.3 | 2.5 | 4.6 | 10.2 | 6.1 |
| 1705 | 1725 | 1944 | 1893 | 1880 | 1757 | 1864 | 1940 | 1795 | 1809 | 1727 | 1926 |
| 6.3 | 3.3 | 2.3 | 2.5 | 7.6 | 6.6 | 7.6 | 2.5 | 2.8 | 6.3 | 10.7 | 8.1 |
| 1779 | 1895 | 1796 | 1817 | 1844 | 1932 | 1835 | 1818 | 1969 | 1708 | 1867 | 1933 |
| 6.6 | 4.3 | 2.5 | 3.8 | 8.4 | 7.1 | 10.2 | 2.5 | 3.3 | 8.1 | 10.9 | 9.1 |
| 1810 | 1932 | 1768 | 1912 | 1895 | 1962 | 1955 | 1742 | 1743 | 1781 | 1699 | 1844 |

TABLE III—SIX WETTEST AND SIX DRIEST OF SETS OF 1 TO 6 CONSECUTIVE MONTHS STARTING IN OCTOBER AND APRIL AT KEW, 1697-1970, WITH RAINFALL AMOUNTS IN MILLIMETRES

| Oct. | Oct.- Nov. | Oct.- Dec. | Oct.- Jan. | Oct.- Feb. | Oct.- Mar. | Apr. | Apr.- May | Apr.- June | Apr.- July | Apr.- Aug. | Apr.- Sept. |
|----------------|---------------|---------------|---------------|---------------|---------------|-------|--------------|---------------|---------------|---------------|----------------|
| <i>Wettest</i> | | | | | | | | | | | |
| 169.9 | 247.7 | 317.5 | 379.5 | 463.0 | 483.4 | 121.9 | 202.4 | 312.9 | 421.4 | 521.2 | 603.3 |
| 1744 | 1852 | 1821 | 1876 | 1914 | 1914 | 1829 | 1878 | 1903 | 1903 | 1903 | 1903 |
| 151.1 | 245.1 | 308.9 | 379.0 | 428.5 | 479.8 | 111.8 | 185.2 | 273.6 | 384.6 | 512.8 | 579.6 |
| 1841 | 1841 | 1755 | 1914 | 1865 | 1876 | 1744 | 1703 | 1879 | 1879 | 1879 | 1879 |
| 151.1 | 237.2 | 306.1 | 373.4 | 423.9 | 476.8 | 98.3 | 177.3 | 272.3 | 363.5 | 497.6 | 527.8 |
| 1880 | 1939 | 1841 | 1929 | 1876 | 1755 | 1878 | 1879 | 1878 | 1728 | 1878 | 1782 |
| 150.6 | 232.9 | 304.5 | 365.0 | 412.5 | 469.9 | 97.5 | 167.9 | 271.8 | 357.4 | 469.9 | 522.5 |
| 1891 | 1940 | 1929 | 1755 | 1755 | 1865 | 1756 | 1777 | 1860 | 1782 | 1782 | 1878 |
| 149.9 | 229.1 | 303.5 | 363.5 | 400.8 | 466.9 | 95.5 | 162.8 | 266.2 | 349.3 | 444.5 | 517.4 |
| 1865 | 1755 | 1852 | 1911 | 1882 | 1911 | 1809 | 1782 | 1703 | 1703 | 1828 | 1768 |
| 147.1 | 228.6 | 290.1 | 357.1 | 397.8 | 455.9 | 93.0 | 162.6 | 256.5 | 342.9 | 436.4 | 515.1 |
| 1882 | 1960 | 1779 | 1852 | 1911 | 1915 | 1800 | 1819 | 1824 | 1860 | 1860 | 1860 |
| <i>Driest</i> | | | | | | | | | | | |
| 2.0 | 17.8 | 17.8 | 74.7 | 104.7 | 127.8 | 2.3 | 16.5 | 29.0 | 60.7 | 85.9 | 130.6 |
| 1788 | 1788 | 1788 | 1879 | 1933 | 1724 | 1938 | 1844 | 1870 | 1921 | 1921 | 1921 |
| 3.8 | 30.2 | 63.5 | 79.0 | 108.2 | 147.8 | 2.3 | 19.1 | 44.2 | 70.1 | 131.3 | 151.6 |
| 1947 | 1708 | 1879 | 1788 | 1714 | 1879 | 1855 | 1870 | 1938 | 1938 | 1870 | 1959 |
| 4.1 | 31.0 | 66.8 | 88.9 | 118.1 | 155.7 | 2.3 | 19.3 | 56.1 | 80.0 | 133.9 | 161.0 |
| 1969 | 1947 | 1714 | 1834 | 1724 | 1890 | 1840 | 1762 | 1844 | 1870 | 1896 | 1705 |
| 4.6 | 36.3 | 68.6 | 90.9 | 122.2 | 158.5 | 2.5 | 19.6 | 56.9 | 82.5 | 135.1 | 172.7 |
| 1809 | 1733 | 1933 | 1714 | 1890 | 1933 | 1893 | 1896 | 1921 | 1762 | 1864 | 1870 |
| 6.3 | 37.3 | 71.1 | 99.1 | 129.8 | 162.6 | 2.5 | 24.9 | 57.4 | 86.6 | 138.7 | 172.7 |
| 1708 | 1897 | 1834 | 1933 | 1931 | 1931 | 1817 | 1795 | 1806 | 1781 | 1938 | 1714 |
| 8.1 | 39.6 | 73.7 | 112.8 | 130.3 | 165.9 | 3.8 | 29.2 | 58.2 | 89.4 | 141.2 | 174.5 |
| 1781 | 1809 | 1871 | 1858 | 1879 | 1730 | 1912 | 1785 | 1895 | 1705 | 1714 | 1893 |

TABLE IV—SIX WETTEST AND SIX DRIEST SEASONS AND YEARS AT KEW, 1697-1970, WITH RAINFALL AMOUNTS IN MILLIMETRES

| Spring (Mar.-Apr.) | Summer (May-Aug.) | Autumn (Sept.-Oct.) | Winter (Nov.-Feb.) | Year |
|-----------------------|----------------------|------------------------|-----------------------|-------|
| <i>Wettest</i> | | | | |
| 180.3 | 476.5 | 263.7 | 432.8 | 969.5 |
| 1818 | 1903 | 1880 | 1914-15 | 1903 |
| 166.1 | 435.4 | 256.8 | 385.8 | 922.0 |
| 1848 | 1879 | 1744 | 1876-77 | 1824 |
| 163.8 | 412.0 | 251.5 | 372.4 | 876.3 |
| 1964 | 1782 | 1841 | 1755-56 | 1821 |
| 161.8 | 411.0 | 224.3 | 348.2 | 863.9 |
| 1756 | 1860 | 1808 | 1950-51 | 1852 |
| 161.5 | 399.3 | 221.5 | 341.9 | 844.8 |
| 1862 | 1878 | 1903 | 1763-64 | 1841 |
| 161.3 | 383.5 | 219.5 | 321.6 | 841.0 |
| 1851 | 1828 | 1960 | 1911-12 | 1879 |
| <i>Driest</i> | | | | |
| 8.6 | 58.9 | 6.9 | 68.1 | 308.4 |
| 1840 | 1921 | 1969 | 1933-34 | 1921 |
| 8.9 | 97.3 | 28.2 | 82.5 | 311.7 |
| 1938 | 1959 | 1941 | 1714-15 | 1714 |
| 11.9 | 99.1 | 33.0 | 84.3 | 345.7 |
| 1796 | 1780 | 1834 | 1744-45 | 1731 |
| 13.2 | 105.2 | 33.5 | 87.1 | 370.8 |
| 1893 | 1899 | 1947 | 1703-04 | 1723 |
| 13.5 | 109.2 | 41.1 | 87.6 | 416.1 |
| 1781 | 1818 | 1890 | 1724-25 | 1864 |
| 16.8 | 109.7 | 41.1 | 96.0 | 417.3 |
| 1852 | 1714 | 1964 | 1890-91 | 1840 |

TABLE V—SIX WETTEST AND SIX DRIEST SEASONS AT KEW, 1871–1970, WITH RAINFALL AMOUNTS IN MILLIMETRES

| Spring (Mar.–Apr.) | Summer (May–Aug.) | Autumn (Sept.–Oct.) | Winter (Nov.–Feb.) |
|-----------------------|----------------------|------------------------|-----------------------|
| <i>Wettest</i> | | | |
| 163.8 | 476.5 | 263.7 | 432.8 |
| 1964 | 1903 | 1880 | 1914–15 |
| (3) | (1) | (1) | (1) |
| 161.0 | 366.5 | 221.5 | 385.8 |
| 1947 | 1917 | 1903 | 1876–77 |
| | | (5) | (2) |
| 137.2 | 349.3 | 219.5 | 348.2 |
| 1919 | 1941 | 1960 | 1950–51 |
| | | (6) | (4) |
| 133.9 | 332.7 | 208.0 | 321.6 |
| 1888 | 1946 | 1885 | 1911–12 |
| | | | (6) |
| 131.3 | 312.4 | 207.0 | 318.8 |
| 1951 | 1958 | 1882 | 1929–30 |
| 127.0 | 307.9 | 196.9 | 311.7 |
| 1940 | 1924 | 1896 | 1940–41 |
| <i>Driest</i> | | | |
| 8.9 | 58.9 | 6.9 | 68.1 |
| 1938 | 1921 | 1969 | 1933–34 |
| (2) | (1) | (1) | (1) |
| 13.2 | 97.3 | 28.2 | 96.0 |
| 1893 | 1959 | 1941 | 1890–91 |
| | (2) | (2) | |
| 27.2 | 105.2 | 33.5 | 96.8 |
| 1943 | 1899 | 1947 | 1908–09 |
| | (4) | (4) | |
| 27.9 | 119.1 | 41.1 | 105.7 |
| 1929 | 1896 | 1964 1890 | 1879–80 |
| | | (5) (6) | |
| 31.2 | 131.3 | 50.0 | 112.3 |
| 1955 | 1911 | 1959 | 1873–74 |
| 34.5 | 132.1 | 51.3 | 113.3 |
| 1957 | 1940 | 1919 | 1931–32 |

Numbers in brackets show the ranks of events in the whole 274-year series.

Extreme-value plotting positions were calculated, using the formula shown in equation (1) with $n = 100$ years and with m taking values from 100 to 95. The six wettest and six driest values for each 'season' (1871–1970) were plotted on the same sheets of extreme-value probability paper as had been used to plot data from the whole 274-year period. Differences between 100-year and 274-year curves may be summarized as follows :

Changes introduced by using 1871–1970 data only

| | |
|--------|---|
| Spring | Wet : Reduce thresholds (Figure 6) as follows : 20-yr by 13 mm; 50-yr by 10 mm; 100-yr by 5 mm |
| | Dry : No change |
| Summer | Wet : Reduce thresholds 20-yr by 31 mm; 50- and 100-yr by 23 mm; 200-yr by 20 mm |
| | Dry : Reduce thresholds 50-yr by 8 mm; 100-yr by 13 mm; 200-yr by 15 mm |

- Autumn

Wet : No change

Dry : Reduce thresholds
20-yr by 5 mm; 50-yr by 13 mm; 100-yr by 15 mm; 200-yr by 18 mm
- Winter

Wet : No change

Dry : No change

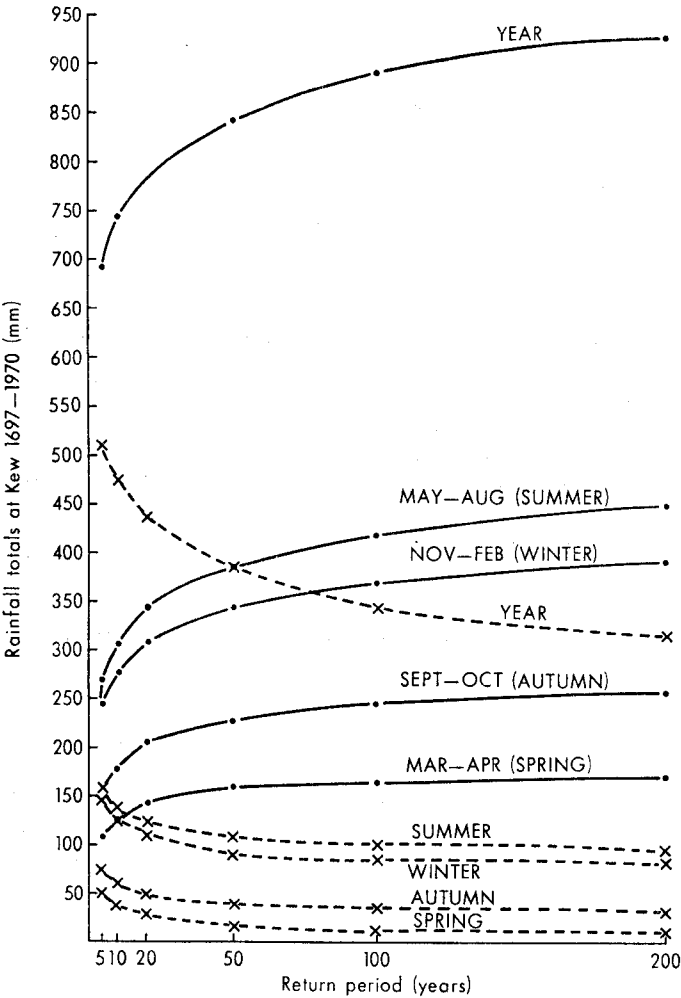


FIGURE 6—AMOUNTS OF RAINFALL AT KEW IN A YEAR OR IN GIVEN SETS OF CONSECUTIVE MONTHS FOR RETURN PERIODS UP TO 200 YEARS

· — · Likely to occur or to be exceeded.

x — x Likely not to be exceeded.

Another comparison can be made by considering the apparent status of the extreme values for 'seasons' from the whole 274-year series judged by the 274- and 100-year curves.

Year dates and return periods

| | | Spring 1818 | Summer 1903 | Autumn 1880 | Winter 1914-15 |
|-----|--------|-------------------|---------------------|---------------------|------------------------|
| Wet | 274-yr | 400 years | 400 years | 400 years | 500 years |
| | 100-yr | 400 years | > 500 years | 400 years | 400 years |
| Dry | 274-yr | 1840 400 years | 1921 5000 years? | 1969 5000 years? | 1933-34 1000 years? |
| | 100-yr | 400 years | > 1000 years | > 400 years | 1000 years? |

The recent 'summer' (1972) with only 74.8 mm of rainfall, would rank as a 200-300-year event judged by 1871-1970 data and could even be ranked as a 1000-year event in the whole 274-year series.

Trends in the series. The monthly totals of the whole series, added together for the seasons suggested by A. Bleasdale, are plotted as diagrams (Figures 7 to 10). The 'second extremes' in each decade are joined up by straight lines, the decadal extremes being shown as unconnected points. This has been done because extreme cases are often out of step with general trends; 10-year averages are shown as broken lines. The distances between the average points and the 'second extremes' show, roughly, how nearly the averages approximate to median values or, in other words, roughly how the individual year points are distributed for any season and decade.

As can be seen in Figure 11, decadal averages of annual totals rose from relatively low values at the beginning of the eighteenth century to a peak in the early nineteenth century, followed by several long-period undulations about an average value somewhat higher than that of the first half of the eighteenth century.

The decadal extremes show the same long-period trend with a steady rise to higher maxima and minima from the beginning of the record to the early nineteenth century. Since 1903, maxima have returned to the levels characteristic of the eighteenth century and the extreme dry year of the whole record (1921 with 308.4 mm) was the first year with rainfall less than 400 mm since 1731.

Summers (Figure 8), although erratic, show the same general trends very well. In the central 13 decades there have been 15 summers with ≥ 12 inches (304.8 mm) and only 9 in the outer 14 decades. For ≥ 15 inches (381.0 mm) the numbers are 5 and 1 respectively. Turning from wet summers to dry winters, we find only 10 winters with ≤ 5 inches (127.0 mm) in the central 13 decades but 18 in the outer 14 decades. For ≤ 4 inches (101.6 mm) the numbers are 2 and 6 respectively. Thus in the central period there were more very wet summers and fewer very dry winters and in the outer decades fewer very wet summers and more very dry winters.

'Autumn' (Figure 9) shows up as a remarkably reliable period, for rainfall, since the early nineteenth century, but with a slow downward trend, so that decadal averages in the twentieth century have almost returned to the values characteristic of the early eighteenth century.

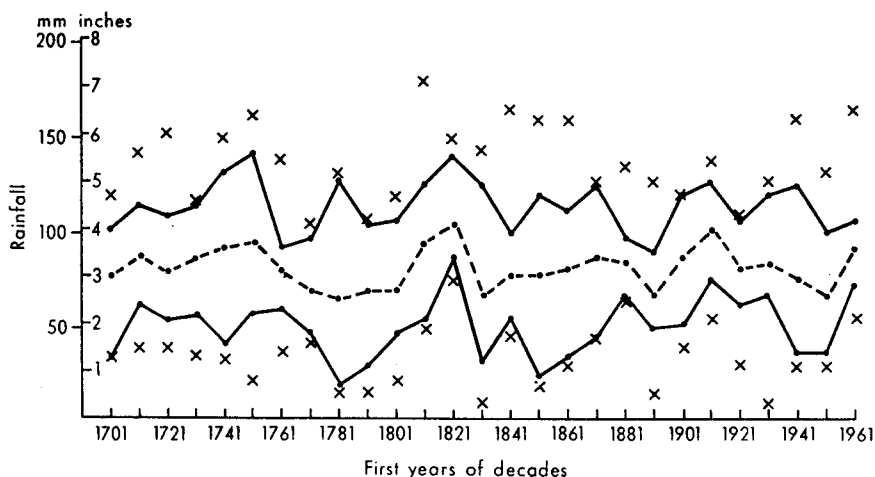


FIGURE 7—SPRING RAINFALL REPRESENTATIVE OF KEW

Uppermost curve : second wettest in each decade. Lowest curve : second driest in each decade. Middle curve (broken) : decadal average. x : wettest or driest in each decade.

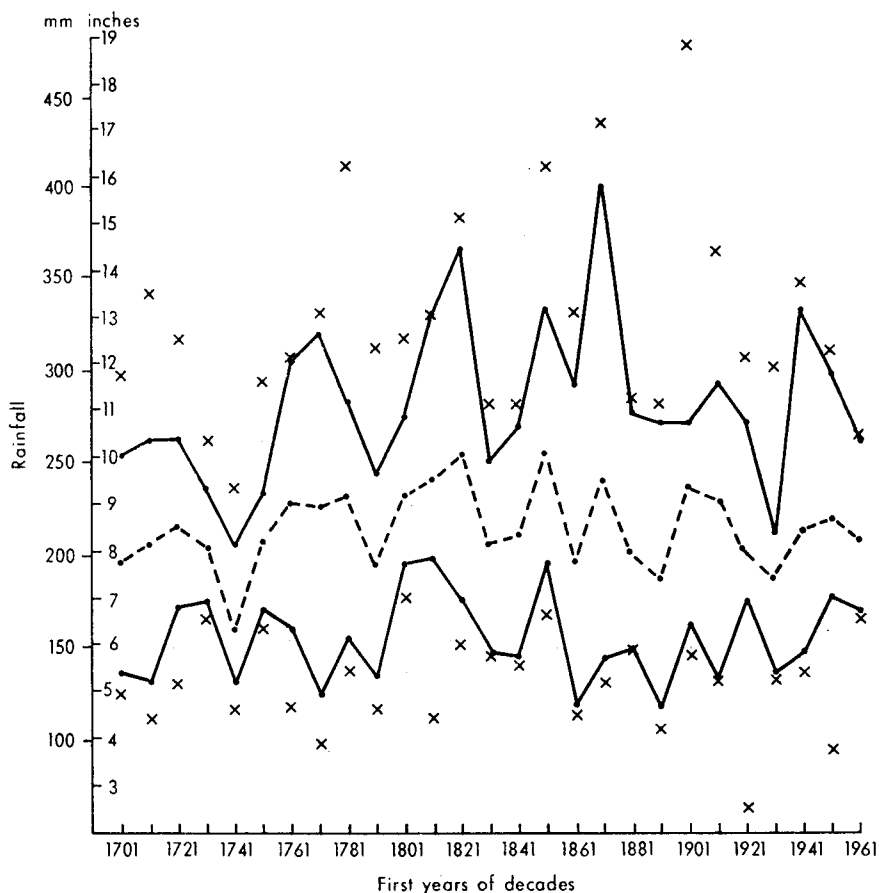


FIGURE 8—SUMMER RAINFALL REPRESENTATIVE OF KEW

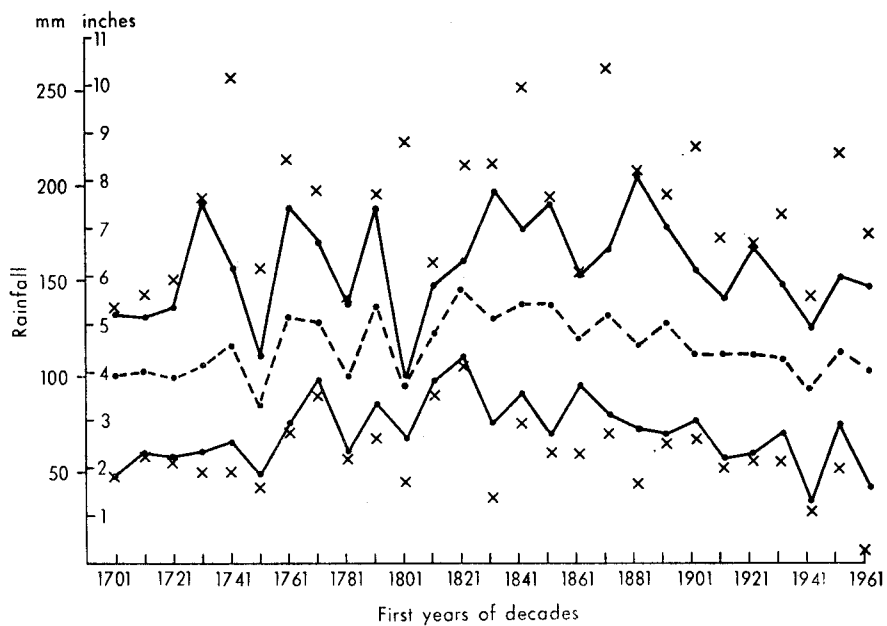


FIGURE 9—AUTUMN RAINFALL REPRESENTATIVE OF KEW

Uppermost curve : second wettest in each decade. Lowest curve : second driest in each decade. Middle curve (broken) : decadal average. x : wettest or driest in each decade.

Acknowledgements. In addition to the invaluable assistance of the computer programmers already mentioned the writer would like to thank Messrs A. Bleasdale, M. C. Jackson and A. F. Jenkinson for helpful advice and for comments on the draft of this article.

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551.593.653

NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1972

By J. PATON

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Observations of the night sky during the period from 26-27 May until 6-7 August when noctilucent clouds (NLC) may be observed in latitudes south of about 60°N are contained in Table I. On nights when noctilucent clouds were reported, the period of time during which the clouds were observed appears in the second column. Observations of the characteristics of the observed NLC are entered in the third column. The remaining columns contain observations from selected stations, the latitude and longitude of which are given to the nearest half degree. The maximum elevation and limiting azimuths of the observed cloud field at the stated times in Universal Time (UT) appear in the last two columns. On nights when skies are sufficiently clear of tropospheric clouds to permit the decision that NLC are absent, 'No NLC' is entered in the third column. When the prevalence of tropospheric clouds makes it impossible to decide whether or not NLC are present, 'Cloudy' appears in the third column.

TABLE I—DISPLAYS OF NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1972

| Date — night of | Times UT | Notes | Station position | Time UT | Max. elev. | Limiting azimuths degrees |
|--------------------|-------------|--------|---------------------|------------|---------------|---------------------------------|
| 26-27 May | | Cloudy | | | | |
| 27-28 | | No NLC | | | | |
| 28-29 | | Cloudy | | | | |
| 29-30 | | No NLC | | | | |
| 30-31 | | Cloudy | | | | |
| 31 May- 1 June | | No NLC | | | | |
| 1-2 June | | No NLC | | | | |
| 2-3 | | No NLC | | | | |
| 3-4 | | No NLC | | | | |
| 4-5 | | No NLC | | | | |
| 5-6 | | No NLC | | | | |
| 6-7 | | No NLC | | | | |
| 7-8 | | No NLC | | | | |
| 8-9 | | No NLC | | | | |
| 9-10 | | Cloudy | | | | |
| 10-11 | | No NLC | | | | |
| 11-12 | | No NLC | | | | |

TABLE I—continued

| Date — night of | Times UT | Notes | Station position | Time UT | Max. elev. degrees | Limiting azimuths |
|--------------------|-------------|---|--|--|--|---|
| 12-13 June | | No NLC | | | | |
| 13-14 | | No NLC | | | | |
| 14-15 | | Cloudy | | | | |
| 15-16 | | No NLC | | | | |
| 16-17 | | No NLC | | | | |
| 17-18 | | Cloudy | | | | |
| 18-19 | | No NLC | | | | |
| 19-20 | 2310-0130 | Faint to moderately bright display, of limited extent, consisting of veil and bluish-white bands and billows. | 57°N 2°W 55-5°N 3°W 55°N 3°W 54°N 0-5°W 54°N 1-5°W 53°N 0° 53°N 4°W 53°N 0-5W | 2400 0100 0045 0001 0115 0044 2350 0015 0115 0001 0015 | 10 60 20 11 30 9 7 5 7 5 6 | 053 360-045 020-030 360-010 340-020 340-025 360-010 015-032 360-016 340-020 350 |
| 20-21 | | Cloudy | | | | |
| 21-22 | | No NLC | | | | |
| 22-23 | | No NLC | | | | |
| 23-24 | | Cloudy | | | | |
| 24-25 | 2345-0045 | Wisps of NLC seen through low cloud. | 55-5°N 1-5°W | 2345 | 10 | 020-053 |
| 25-26 | 2145-0150 | Veils, bands, billows and whirls seen through gaps in low cloud over the British Isles, and more clearly over Denmark. | 57-5°N 7-5°W 57°N 2°W 55-5°N 12-5°E 53°N 0-5°E 53°N 0-5°W | 0148 0130 2145 2245 0140 2150 2310 | 60 40 5 12 20 7 | 060-100 340-040 310-325 360 360-045 290-010 310-350 |
| 26-27 | 2330-0150 | Widespread bands and whirls seen in poor observing conditions due to extensive cirrus. Seen from Aberdeen (57°N 2°W) to extend 'at morning twilight over entire northern half of sky up to and past zenith'. | 58-5°N 3°W 55-5°N 1-5°W | 2345 2345 | 30 25 | 340-050 |
| 27-28 | | No NLC | | | | |
| 28-29 | 2245-0050 | Faint veil and bands | 55-5°N 1-5°W | 2245 0050 | 8 5 | 330-030 350-045 |
| 29-30 | | No NLC | | | | |
| 30 June- 1 July | | No NLC | | | | |
| 1-2 July | | No NLC | | | | |
| 2-3 | 2300-0130 | Bright veil and bands visible through extensive cirrus | 56-5°N 3°W 55-5°N 1-5°W 55-5°N 3°W | 2330 2300 2400 0130 | 8 15 10 15 | 025 330-020 360-040 020 |
| 3-4 | 2220-2400 | Cloudy over British Isles. Greenish band and whirls observed from Denmark. | 56°N 10°E | 2258 | 12 | 320-060 |
| 4-5 | | No NLC | | | | |
| 5-6 | | Cloudy | | | | |
| 6-7 | 2100-2315 | Overcast over most of British Isles except the extreme south. Extensive display of veil, bands, billows and possibly also whirls observed from Dover. Reports also from Denmark. | 56°N 10°E 51°N 1-5°E | 2100 2230 2127 2145 | 15 20 95 90 | 340 340-020 350 |
| 7-8 | 2240-0150 | Brilliant display of greenish-white veil, bands, billows and whirls seen in gaps in extensive stratocumulus. The prevailing low cloud limited and made uncertain the measurements of elevations and azimuths. | 57°N 2°W 56-5°N 3°W 55-5°N 1-5°W 55-5°N 3°W 55-5°N 5°W 54°N 4-5°W 52°N 6-5°W | 2315 2345 2400 2304 2335 0020 0030 | 14 10 8 15 7 20 7 | 330-360 350-035 350-010 360-025 020-040 350 |
| 8- | | No NLC | | | | |
| 9-10 | | No NLC | | | | |

TABLE I—continued

| Date — night of | Times UT | Notes | Station position | Time UT | Max. elev. degrees | Limiting azimuths degrees |
|--------------------|-------------|---|--|--|--|---|
| 10–11 July | 2200–0210 | Moderately bright display of veil and bands, 'with structure appearing almost to the zenith' at Oslofjord, Norway (59°N 10°E), between 2345 UT and 0045 UT. | 60°N 1°W 57.5°N 7.5°W 56.5°N 7°W 56°N 10°E | 2323 0050 0210 2340 0145 2200 0040 | 64 13 20 11 13 20 20 | 310–005 330–360 330–010 340–020 360–010 290–045 315–045 |
| 11–12 | 2245–0230 | Compacted bands, generally faint but occasionally bright in parts. | 57°N 2°W 56.5°N 3°W 55.5°N 1.5°W 55°N 1.5°W 54°N 0.5°W 53°N 0.5°E | 2300 2330 2250 2250 2345 2250 0145 0230 | 23 15 15 20 5 7 7 15 | 340–020 315–045 320–340 320–010 004 360 340 |
| 12–13 | 2105–0230 | Moderately bright display of veil, bands and billows. | 56.5°N 3°W 56°N 10°E 55.5°N 7.5°W 54.5°N 1.5°W 54°N 1.5°W | 0112 0133 2105 2200 0210 2300 0051 0200 0030 0130 | 10 17 10 23 6.5 2 4.5 6 4.5 5 | 345–070 045 315–045 030 350–010 350–045 340–020 330–040 330–040 |
| 13–14 | | No NLC | | | | |
| 14–15 | 2210–0200 | Faint bands seen through occasional gaps in extensive stratocumulus cloud. No measurements of maximum elevation possible. | 56.5°N 3°W 55.5°N 4.5°W | 2245 0045 0200 | | 345–360 010–020 010–020 |
| 15–16 | 2100–2300 | Veil and bands visible from Denmark, brightest at 2140 UT. Cloudy over British Isles. | 56°N 10°E | 2100 2200 2300 | 40 20 10 | 315 360 |
| 16–17 | 2230–2320 | Bright veil and compacted bands. | 56°N 10°E 54°N 4.5°W | 2230 2240 | 7 25 | 360–045 335–350 |
| 17–18 | 2230–2250 | Short-lived display of weak bands. | 56.5°N 3°W | 2230 | 5 | 360–020 |
| 18–19 | 2210–0230 | Moderately bright bands. | 56.5°N 7°W | 0130 | 13 | 340–020 |
| 19–20 | 2215 | Greenish bands visible from Denmark close to northern horizon for about 20 minutes. | 55.5°N 12.5°E | 2215 | 10 | |
| 20–21 | | No NLC | | | | |
| 21–22 | 2100–0230 | Bright display of veil and bands. | 58.5°N 3°W 56°N 10°E | 2400 2100 2320 | 20 10 7 | 315–360 360–045 315–045 |
| 22–23 | | Cloudy | | | | |
| 23–24 | | Cloudy | | | | |
| 24–25 | 0245–0310 | Bands seen through temporary clearance in extensive low cloud. | 54°N 4.5°W | 0245 | 10 | 360–055 |
| 25–26 | 2225–0300 | Bright bands and billows. | 57.5°N 6°W 56.5°N 7°W | 2400 0100 0200 0300 2225 2340 0150 0250 | 3 7 15 25 10 5 8 8 | 010–020 360–020 340–030 355–030 340–030 340–020 340–040 350–040 |
| 26–27 | | No NLC | | | | |
| 27–28 | | No NLC | | | | |
| 28–29 | | No NLC | | | | |
| 29–30 | | Cloudy | | | | |
| 30–31 | | Cloudy | | | | |
| 31 July– 1 Aug. | | Cloudy | | | | |
| 1–2 Aug. | | Cloudy | | | | |
| 2–3 | | No NLC | | | | |
| 3–4 | | Cloudy | | | | |
| 4–5 | 2245–0250 | Veil, bands, billows and whirls, accompanied by aurora. | 60°N 1°W 58.5°N 3°W | 2245 0200 0120 | 15 15 12 | 320–030 340–040 340–040 |
| 5–6 | | Cloudy | | | | |
| 6–7 | | No NLC | | | | |

The number of nights during which NLC were observed in 1972 was 22. An adjustment to this figure to account for unobserved occurrences on cloudy nights (17) may be made by assuming that NLC would be present on the same fraction of these nights as of clear nights (22 in 56) during the NLC season, 26–27 May to 6–7 August. This gives a frequency of 29 nights for 1972. Making the same adjustment, the frequencies for the years for which data are available (1967–71) are found to be 44, 39, 30, 20 and 22 respectively.

The first appearance of the clouds was later than normal by over a fortnight. If the NLC consist of ice crystals, as has been indicated by rocket experiments, then one may assume that either the attainment of the summer minimum of temperature at the mesopause or the flow of water vapour up through the mesosphere was delayed during the summer of 1972.

Four displays, on the nights of 19–20 and 25–26 June and 6–7 and 10–11 July, extended farther south than is normal; the display of 6–7 July extended so far southwards that it was observed south of the zenith at Dover.

The clouds receded northwards at the usual time of early August. They were last seen from Stornoway, Wick and Lerwick on the night of 4–5 August when they occurred simultaneously with aurora. Well-marked whirls became more prominent as this display progressed, an event which has been observed on several occasions^{1,2} when these two phenomena have occurred together.

The assistance of the many observers who, by providing visual observations, photographs and sketches, have made this analysis possible is gratefully acknowledged. These synoptic studies continue and new observers are invited to send their observations to the Balfour Stewart Auroral Laboratory, The University, Drummond Street, Edinburgh EH8 9UA, Scotland. Notes on the recording of observations will be supplied from the laboratory.

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551.586:631

THE 'GROWING SEASON' AT ESKDALEMUIR OBSERVATORY, DUMFRIESSHIRE

By R. W. GLOYNE

Summary. The dates of the commencement and end of the 'growing season' and its length for the years 1914 to date, were examined for Eskdalemuir, a station in the Southern Uplands of Scotland. The commencing date in spring showed a greater degree of variability (a standard deviation of 13–16 days according to period) than did that of cessation (8–11 days). Mean values of the length of the season were higher for the decades 1941–50 and 1951–60 than either before or since; however the successively increasing length for each of the years 1970–72 should be noted. The commencing date in most years was found to be closely related to the mean temperature for the month of April.

Introduction. In temperate climates it is a conventional practice to define a 'growing season' as that period of the year when mean temperature (sometimes relating to shallow depths in the soil, but more generally in the air at the standard height of 1.25 m from the ground, exceeds 5.6°C (42°F).

Although the growth of a wide range of indigenous species cannot be too closely linked with a particular level of mean temperature, experience shows that the 'growing season' so defined is a useful crude parameter for evaluating the impact of climate on many phases of agricultural production.

The increasing interest in the agricultural potential of the hill areas and the possibility of climatic variations on a scale of decades of years having significant impact upon agriculture, renders an analysis of the 'growing season' a matter of some interest. For this exercise data from Eskdalemuir Observatory (55° 19' N, 03° 12' W, 242 m above MSL) for the period 1914-72 were examined.

Data and procedures. From the readily available week-by-week averages of mean daily air temperature, the day of the year (D_1) on which the level of mean temperature rose above 42°F and that (D_2) on which it fell below 42°F were estimated from a smooth curve drawn through the weekly values. In some years values oscillated about 42°F before being sustained above (or below) this threshold; in such cases an estimate, subjectively derived from the run of the curve, was adopted. Transient excursions of the temperature above 42°F occurring either very early or very late in the year were ignored when defining the passage of the curve through the threshold value.

The sequences of values of D_1 and D_2 are plotted in Figure 1, values of L (the length of the 'season') in Figure 2, and in Figure 3 the associated length (L') of the 'non-growing season'. In Figure 4 is given a scatter diagram showing the relationship between D_1 and the mean temperature for the month of April. Statistical parameters for D_1 , D_2 and L , for 1914-20 and the subsequent decades 1921-30, etc. to 1961-70 are set out in Table I.

TABLE I—'GROWING SEASON' AT ESKDALEMUIR 1914-70, DECADAL AND PERIOD VALUES

| | Mean value | D_1 Range | S.D. | | Mean value | D_2 Range | S.D. | | Mean value | L Range | S.D. |
|---------|------------|----------------|------|--|------------|-----------------|------|--|------------|--------------|------|
| | | | days | | | | days | | | days | |
| 1914-20 | 19/4 | 8/4- 4/5 | 7 | | 4/11 | 20/10- 22/11 | 13 | | 199 | 184- 217 | 12 |
| 1921-30 | 21/4 | 3/4- 4/5 | 10 | | 30/10 | 17/10- 15/11 | 8 | | 192 | 173- 217 | 12 |
| 1931-40 | 11/4 | 3/3- 27/4 | 16 | | 3/11 | 19/10- 22/11 | 11 | | 206 | 175- 264 | 25 |
| 1941-50 | 6/4 | 11/3- 29/4 | 15 | | 4/11 | 23/10- 17/11 | 8 | | 213 | 184- 243 | 19 |
| 1951-60 | 8/4 | 16/3- 30/4 | 18 | | 9/11 | 19/10- 19/11 | 9 | | 215 | 187- 248 | 19 |
| 1961-70 | 10/4 | 1/3- 24/4 | 15 | | 4/11 | 27/10- 14/11 | 6 | | 209 | 195- 250 | 17 |
| 1914-40 | 17/4 | 3/3- 4/5 | 13 | | 2/11 | 17/10- 22/11 | 11 | | 199 | 173- 264 | 19 |
| 1941-70 | 8/4 | 1/3- 30/4 | 16 | | 6/11 | 19/10- 19/11 | 8 | | 212 | 184- 250 | 19 |

D_1 = Mean date of beginning of season; D_2 = Mean date of end of season; L = Length of season; S.D. = Standard deviation.

Discussion. (a) From 1914 to about 1930 and from 1962 to 1971, the date of the beginning of the 'season' (D_1 of Figure 1) varied between about 10 April (day 100) and 30 April (day 120); in the intervening period it fluctuated widely, and in 10 of the years (most markedly in 1938, 1945, 1948,

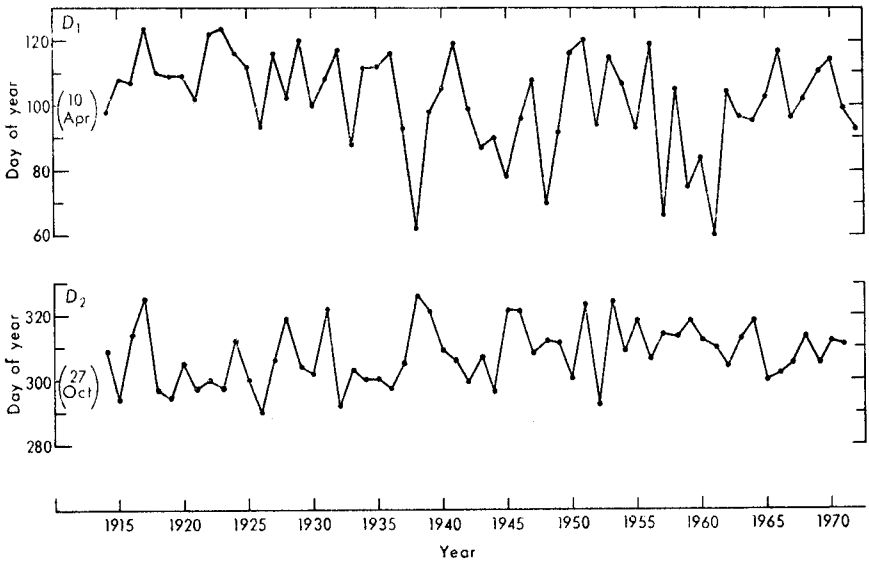


FIGURE 1—DATES OF THE BEGINNING (D_1) AND END (D_2) OF THE 'GROWING SEASON' AT ESKDALEMUIR

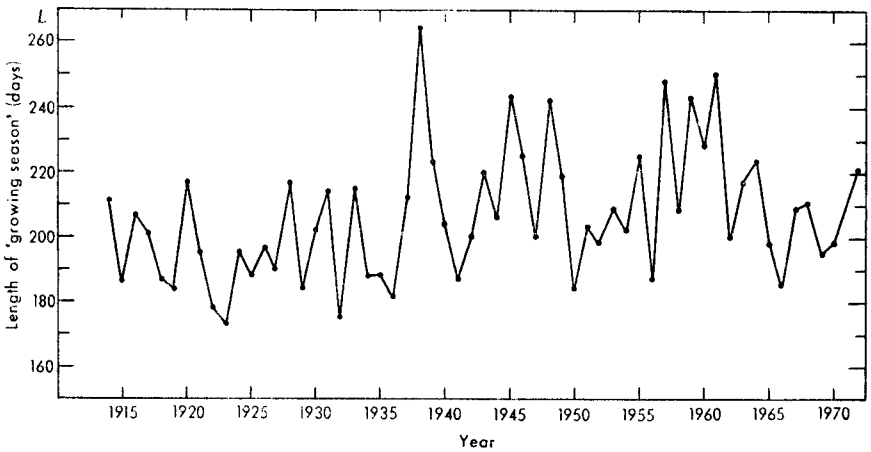


FIGURE 2—LENGTH (L) OF THE 'GROWING SEASON' AT ESKDALEMUIR

1957, 1959 and 1961) it occurred in the month of March. These dates are shown as anomalies in Figure 4; further examination of these cases revealed that all occurred with a monthly mean March temperature equal to or greater than 4.7°C (40.5°F).

The need for caution in projecting any short-period trend is well indicated by the behaviour of D_1 from 1966 to date.

Decadal means of D_1 are set out in Table I. The fortuitous effect of selecting any particular period for averaging is well illustrated by the contrast between the mean value for 1961–70 and that given by a 10-year period 1962–71 (mean D_1 being 10 April and 14 April respectively).

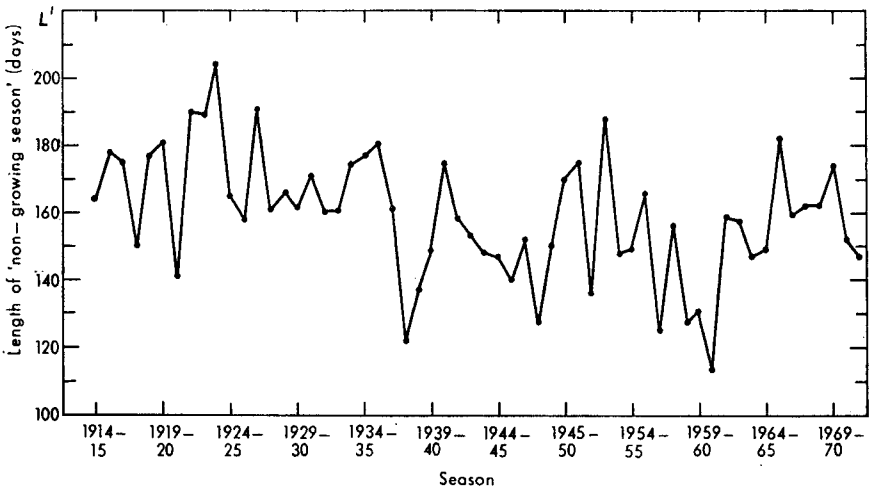


FIGURE 3—LENGTH (L') OF THE 'NON-GROWING SEASON' AT ESKDALEMUIR

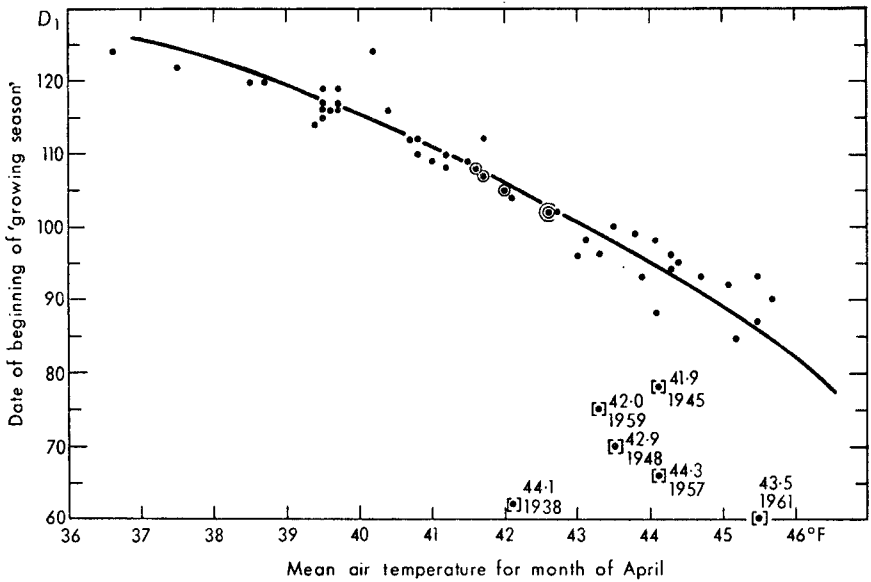


FIGURE 4—PLOT OF DATE (DAY OF YEAR) D_1 OF BEGINNING OF 'GROWING SEASON' AGAINST MEAN MONTHLY TEMPERATURE FOR APRIL — AND FOR SOME YEARS MARCH — AT ESKDALEMUIR (1914-70)

Encircled dots indicate repeated observations. Figures adjacent to plots in square brackets indicate mean temperature for *March* and year of occurrence.

(b) The date of the end of the season (D_2 of Figure 1) has fluctuated far less widely than has D_1 ; in most seasons this occurs between 24 October (day 297) and 16 November (day 320).

(c) The length (L) of the season (Figure 2) reveals the wide fluctuations in the 1936–61 period compared with the steadier behaviour prior to and subsequent to these years; furthermore the experience of long seasons (240 days or more) from the late 1930s to the early 1960s should not necessarily be regarded as typical on a long-term basis. It should also be noted that during this last-mentioned period, years occurred when the commencing date was as late, and the season as short, as was experienced more frequently during the preceding and the following periods. The effect of a very anomalous year 1938 on the value of the standard deviation of L for the 1931–40 decade (see Table I) underlines the need for caution when using this parameter for statistical estimation.

(d) In Figure 3 the data have been set out in terms of the length of the non-growing season. The 160(+) days prior to 1935–36, the more frequent shorter non-growing seasons from that date to 1960–61 and the more recent run of rather longer ones are evident.

(e) The arithmetic process of deriving a date such as D_1 or D_2 from the run of a mean temperature (T_m) necessarily implies a close association between the date and the value of T_m . However D_1 derived from the run of *weekly* means and the relationship between D_1 and a *monthly* mean is of some interest. A plot of D_1 against mean monthly temperatures for April is given in Figure 4 together with a free-hand 'best-fitting' curve.

There is a fairly satisfactory relationship between the date of D_1 (spanning the period 25 March to 5 May) and the mean temperature for April, unless the mean monthly March temperature was equal to or greater than 4.7°C (40.5°F); in all such cases and only in such cases the beginning of the season will occur in March and a March mean of 6.4°C (43.5°F) or more appears to be associated with a 'growing season' beginning in early March.

(f) To what extent the indications of the Eskdalemuir results can be regarded as representative for a substantial area of Scotland requires further investigation. However it is a matter of experience that maps of the 'temperature anomalies' (based upon mean monthly values) show a broad-scale coherent pattern over substantial areas, hence the year-to-year fluctuations in D_1 shown in Figure 4 (also those for D_2 and L) may be expected to be indicative of the experience over a wide area.

Secondly, a current parallel examination of the 'growing season' in south Norway from 1943 to date reveals the same contrast noted in Figure 1 between pre- and post-1961 behaviour.

Conclusions. Some tentative conclusions are :

(a) The date of the commencement of the 'growing season' at Eskdalemuir is considerably more variable than that of the end of the season.

(b) The frequent early dates of the beginning of the 'season' experienced in the 1936–61 period, and the associated prolonged seasons, are not typical of the pre-1936 or of the post-1961 eras. Alternatively expressed, the 'non-growing' ('winter') seasons prior to 1936 and since 1961–62 have tended to be longer than in the intervening years.

(c) The date of commencement of the 'growing season' is closely related to the mean temperature in the month of April, except when, and only when, the mean March temperature exceeds about 4.7°C (40.5°F), and in this case the season commences in March and possibly in early March.

EMBEDDED THERMOMETERS AND FORECASTS OF NIGHT MINIMUM TEMPERATURES AT WYTON

By W. G. RITCHIE and S. E. VIRGO, O.B.E.

Summary. This paper reports attempts to use temperatures obtained from thermometers embedded in soil and concrete to improve the accuracy of forecasts of night minimum air and concrete surface temperatures at Wyton.

Purpose of the experiment. Present methods of forecasting night minimum air temperatures use the properties of the air alone, but it has been suggested from time to time that better forecasts could be made if a method could be devised which incorporated the properties of the underlying soil; for example, Saunders¹ proposed the use of soil thermometers in 1952 and more recently Zdunkowski and Trask² have written a computer program which incorporates the properties of the soil. It might also be expected that temperatures measured inside the concrete of a road could be used to produce better forecasts of night minimum temperatures at the surface of the road. These conjectures led to the experiment with embedded thermometers described below.

Experimental arrangements. Thermometers were embedded with their bulbs at depths of 4 inches and 8 inches (10 cm and 20 cm) in an unused circle of mature concrete 25 yards (23 metres) in diameter and between 8 inches and 1 foot (20 cm–30 cm) thick in an open site on the airfield and at the same depths in the adjoining soil. A minimum thermometer, slightly tilted so that the bulb rested on the surface, was exposed near the thermometers embedded in the concrete, and the reading of this thermometer was taken to be the minimum surface temperature. In the rest of this paper this temperature will be called the minimum road surface temperature M_R (although the site was not actually a road) to accord with the nomenclature of previous papers.^{3,4,5} To prevent accidental damage without appreciably affecting the exposure of the surfaces to the sky, a light frame was placed over the concrete thermometers and a similar frame over the soil thermometers. The frames were of angle-strip aluminium, 1/10-inch ($\frac{1}{4}$ -cm) thick and $\frac{1}{2}$ -inch ($1\frac{1}{4}$ -cm) wide, in the form of an open 2-foot (60-cm) square with a 1-foot (30-cm) leg at each corner. The base of each leg was inserted into a piece of lead piping about 2-inches (5-cm) long to prevent movement by wind. All four embedded thermometers were read at 13 GMT daily, this being the time when night minimum temperature forecasts are made at Wyton.

Results.

1. *Forecasting night minimum air temperature.* The authors failed to find a method of using readings of the soil thermometers to improve forecasts of night minimum air temperature.
2. *Forecasting night minimum road surface temperature.* From data for the period October 1969 to September 1970, correlation coefficients were computed between the night minimum road surface temperature M_R and the previous day's 13 GMT temperatures at 4 inches (10 cm) and 8 inches (20 cm) in concrete and soil and air temperature and dew-point in the screen. All the

correlations were better for the winter than for the summer; this was fortunate as the aim was to improve frost forecasting. The three highest correlation coefficients were

| | |
|---|-------|
| between M_R and dew-point (screen) | 0.71 |
| between M_R and air temperature (screen) | 0.69 |
| between M_R and 4-inch concrete temperature | 0.66. |

It had been established previously that a regression equation set up for Watnall, giving M_R in terms of air temperature and dew-point at 12 GMT the previous day, was also valid for Wyton.⁵ To determine whether air temperature or 4-inch concrete temperature would be a better starting point for forecasting M_R , a new regression equation was set up giving M_R in terms of 4-inch concrete temperature and screen dew-point at 13 GMT the previous day. Data for October 1969 were excluded because it was an unusually warm October. The equation was

$$M_R = 0.40R_{13} + 0.54D_{13} - 3.1,$$

where R_{13} is the 4-inch concrete temperature at 13 GMT the previous day and D_{13} is the dew-point at the same time. Temperatures are in degrees Celsius.

For the nights during the periods October 1969 to April 1970 and October 1970 to April 1971 when no fronts passed between 12 GMT and 06 GMT, M_R was now forecast by three methods :

1. The indirect method. The first step was to forecast minimum air temperature by one of the recognized methods (McKenzie's method was used as it is convenient and as accurate as any other method⁶). The second step was to subtract a quantity which is a function of date alone and can be found from Ritchie's curve³ or Parrey's equation⁴ (these are essentially the same and give the same result).
2. Direct regression from air temperature and dew-point at 12 GMT the previous day.
3. Direct regression from 4-inch concrete temperature and dew-point at 13 GMT the previous day.

The forecasts were actually made after the event in order that mean wind speed and cloud amount could be estimated from observations in the Daily Register so as to eliminate any errors which might arise from inaccuracies in forecasts of these quantities.

The results obtained by the three methods are given in Table I. The error is reckoned as forecast value minus observed value in conformity with previous practice.^{5,7} Distributions of errors are normal. The table shows remarkable agreement between values obtained for the season October 1969 to April 1970 — the season used for calculating the regression equation in the third method — and those obtained from independent data for the season October 1970 to April 1971.

Conclusion and discussion. Although no method was found of improving the forecasting of night minimum air temperature by means of readings taken at 13 GMT of thermometers embedded in soil and concrete, readings of a thermometer embedded at a depth of 4 inches in concrete could be used in a regression equation to improve the accuracy of forecasts of night minimum road surface temperature, but the improvement relative to the indirect method was only slight.

TABLE I—MEAN ERRORS AND STANDARD DEVIATIONS OF ERRORS IN FORECASTS OF ROAD SURFACE MINIMUM TEMPERATURE M_R BY THREE METHODS

| | Oct. 1969– Apr. 1970 | | Oct. 1970– Apr. 1971 | |
|---|-------------------------|------|-------------------------|------|
| | Mean | S.D. | Mean | S.D. |
| | <i>degrees Celsius</i> | | | |
| Indirect method | 0.1 | 1.9 | 0.4 | 1.8 |
| Regression from air temperature and dew-point | 1.1 | 2.4 | 1.1 | 2.4 |
| Regression from 4-inch concrete temperature and dew-point | −0.1 | 1.5 | −0.1 | 1.6 |
| Number of occasions | 157 | | 165 | |
| S.D. = standard deviation. | | | | |

It is suggested that the reason might lie in the close correlation between the 13 GMT air temperature and the 13 GMT 4-inch soil temperature. For the seven months October 1969 to April 1970 the correlation coefficient was 0.88 — a very high value. This is strong evidence for arguing that air temperature and soil temperature are not independent variables, and taking soil temperature into account introduces no new information into the calculations.

Insolation warms the surface of the soil (the area of concrete is small and its effect on air and soil temperatures must be trivial by comparison), and heat is transported downwards in the soil to the 4-inch level and lower by conduction and upwards in the air to screen level and beyond by convection and turbulence. Presumably this mechanism is responsible for the close correlation between the 13 GMT air and 4-inch soil temperatures.

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REVIEWS

Understanding lightning, by Martin A. Uman. 220 mm × 140 mm, pp. 166, illus., The Oak Tree Press Ltd, Warwick House, 116 Baker Street, London W1M 2BB, 1972. Price: £2.75.

Dr Uman has spent 10 years or more in laboratory investigations into long sparks and research into lightning discharge. Much of this research has been sponsored by the United States Office of Naval Research, and during this time he has written many technical treatises on lightning and allied physical topics. With the present volume though, he turns his pen to a popular exposition designed for the non-scientist.

Experience in lecturing to high-school students and various lay societies has convinced Dr Uman that the same questions are always asked about lightning. In consequence, these questions have been used as chapter headings and so we have 'Why did Benjamin Franklin fly his kite?', 'How does a lightning rod work?', 'Does lightning never strike twice?', etc. There are 18 short chapters which fall into three groups. The first six chapters largely describe the behaviour of lightning whilst the second group of chapters attempts a physical explanation in simple terms of the processes occurring in the atmosphere. Towards the end of the book the subject matter becomes more speculative, answering questions such as 'Are UFO's and ball lightning related?' or 'Has lightning any practical use?'. The book is illustrated with some excellent photographs of lightning.

Almost inevitably the popular style leads to some looseness of phrase here and there, but on the whole the book provides an accurate description of lightning phenomena in accord with modern ideas. It is wellprinted and easy to read, so that the reader is encouraged to delve further. There are references at the end of each chapter to works which would enable the interested reader to establish his ideas on a more formal basis. Some of these books such as *Clouds, rain and rainmaking* by B. J. Mason or *The flight of thunderbolts* by B. F. J. Schonland are widely available, but other papers are in technical journals to which the lay reader is unlikely to have access. Probably the weakest aspect of the book is the way quantities are described, e.g. page 93 '... a few billionths of a second' or page 110 '... 1 000 000 watt-seconds per yard of channel length'. These units do not seem to be part of a scientific system nor are they likely to be readily appreciated by the non-scientist to whom the book is addressed.

It is difficult to imagine that anyone with some formal training in meteorology would prefer this book to other works which are available. It might well appeal to an uninformed member of the general public though, and be of value to teachers of elementary science in schools.

P. D. BORRETT

Clouds of the world, by Richard Scorer. 330 mm × 235 mm, pp. 176, *illus.*, David & Charles (Holdings) Ltd, South Devon House, Newton Abbot, Devon, 1972. Price: £12.60.

The book opens with the author's preface wherein he points out that the changing skies, although endowed through the ages with a spiritual existence, are mere physical and mechanical systems. It is his object to provide a simplified explanation in everyday terms of these systems, and this he does.

Professor Ludlam, another appreciative observer of clouds, gives a short history of cloud classification and suggests that current research into cloud physics supports a classification of clouds according to their genetic origin rather than to their form and shape.

The book is divided into 14 sections, each section dealing with a particular type of cloud. The sections are further subdivided to classify the clouds according to the processes which have caused their formation or affected their particular shape or location. Each section is prefaced by a concise text, well set out and clearly expressed, explaining the physical processes which caused the cloud to form or to take on a particular shape. The text is

illustrated by simple well-drawn diagrams. Subsections have further brief notes and in some cases diagrams drawing attention to a particular feature of interest and explaining the air motions which gave rise to it.

Every subsection is then profusely illustrated by numerous coloured and, in some cases, black and white photographs, each with an appropriate text setting out the point of interest. Where stereoscopic pictures help to illustrate a special feature, the author has thoughtfully provided a selection of such pictures, adding a note on how these can be viewed without any special apparatus.

There is a short appendix on photogrammetry and stereo-photography with two examples of the accurate analysis of clouds in three dimensions, using stereoscopic photographs. A useful note is given on the method of taking stereo pictures from the air or from the ground using an ordinary single-lens camera. A brief bibliography is followed finally by a comprehensive index. The latter enables the reader to refer to the text and photographs concerning the phenomenon in which he is interested.

The numerous photographs have been carefully selected to bring out the features the author wishes to emphasize. They have been very well printed and the colour reproduction is excellent. Only about half a dozen of the many colour pictures have not really reproduced sufficiently well. The black and white pictures are as great a credit to the printer as to the original photographer. The author is to be congratulated on his selection and the printer on his high standard of reproduction.

Richard Scorer does not give long and involved proofs for his statements of the physical processes of cloud formation but he has convincingly produced visual evidence, capable of being understood by the intelligent reader with only a slight knowledge of physics and dynamics. He has achieved his object of providing a reference book for the meteorologist and the undergraduate, setting out in readable terms the physical and mechanical processes of the clouds, a subject much neglected by standard textbooks.

This book should most certainly appear in all university and senior school libraries and in the larger public reference libraries. Its pictures alone would fascinate many, so it is a pity that its price, a penalty for such an extensive use of colour, will place it beyond the pocket of the man in the street.

R. K. PILSBURY

The application of micrometeorology to agricultural problems, WMO Technical Note No. 119, edited by L. P. Smith. 275 mm × 213 mm, pp. vi + 74, illus., Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1972. Price: Sw. fr. 10.

This publication, dealing with the planning and exploitation of fundamental research, further extends the range of topics dealt with in this very valuable series. As stressed (page xiii) the authors are concerned with the 'detailed examination on a micro-scale of the physical and meteorological processes taking place principally within the boundary layers between the top of a plant, tree or animal and the bottom of the roots in the soil'. Specifically they are not concerned with practical mesoscale phenomena such as, for example, 'frost hollows' — often incorrectly included under *micro*-meteorology; indeed they suggest (page 53) that 'micro-meteorology has little to offer at

present in a direct manner to the land-worker or practitioner; ... and [results] have to be processed and modified before they can be used in practice'. The vocabulary and level of sophistication are those of, say, Sutton's *Micrometeorology*. The work is in three parts.

In Part I (pages 1-24) the inputs into the biological systems of six physical processes are examined, viz. radiation, momentum transport, heat and heat-transfer processes, water transport, carbon dioxide and transfer of matter other than carbon dioxide, each being further considered in the context of four disciplines, viz. soil sciences, atmospheric sciences, plant sciences and animal sciences. Research priorities are suggested, e.g. under 'radiation' the topic of first importance is considered to be the surface temperature of vegetation.

Part II (pages 25-49) lists practical agricultural problems under five heads, viz., improvement to production, dangers to production, physiology and growth, strategy (e.g. land-use planning) and tactics (e.g. choice of crop variety); the physical processes involved are identified and the scientific disciplines in which these are to be studied. These latter relationships are further summarized (pages 41-49) and priority problems in the several disciplines suggested.

Part III (pages 51-53) briefly examines the administrative and organizational means required for progress — the questions of information storage, retrieval and exchange underly many of the topics mentioned. Some pertinent assistance is given in Appendix I (an unavoidably incomplete list of 'Organizations at which micrometeorological research was taking place in 1968-69'); and in Appendix II a limited bibliography is provided of some 60 items selected both for their intrinsic interest and for the useful literature references.

Meteorologists of all specialisms will benefit from even a cursory reading of this publication. Agricultural meteorologists and allied workers in the 'developed' regions will find many familiar topics assessed and placed in a novel context. Those in the 'developing' regions, and others involved in the planning, administration and implementation of projects in agriculture and allied industries, might well find an approach through Part II (pages 25 and 41-49) and Part III the most profitable. A similar analysis of the interactions between agriculture and meso-climatology (with emphasis upon practical application) might arguably be an extremely worth-while enterprise to set alongside this current publication.

R. W. GLOYNE

CORRECTION

Meteorological Magazine, March 1973, page 66: Equation (4) should read

$$\frac{dT_m}{dt} = \frac{1}{hc_p \rho} \cdot \frac{dQ}{dt} = \frac{dT}{dt} \quad \dots (4)$$



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