PRECIPITATION AT ARMAGH OBSERVATORY 1838–1997

C.J. Butler, A.D.S. Coughlin and D.T. Fee

ABSTRACT

The meteorological series maintained at Armagh Observatory began in 1795 and are the longest in Ireland and among the longest in the British Isles. Here we present the monthly mean daily precipitation recorded at Armagh since 1838. Variations in the distribution of the rainfall during the year, over this period, are apparent, with a tendency for drier summers in recent decades. We find a significant correlation between the mean seasonal rainfall and the North Atlantic Oscillation index during autumn and winter, and there appears to be a negative correlation between the summer rainfall and the North Atlantic Oscillation index for the previous winter. A search for periodicities has been made and no evidence of an eleven-year cycle similar to the Sunspot cycle has been found. However, Fourier analysis reveals an approximate seven-year cycle in summer rainfall. We examine the evidence that this cycle may be linked either to the Taurid meteor stream or to the North Atlantic Oscillation.

C.J. Butler, A.D.S. Coughlin and D.T. Fee, Armagh Observatory, College Hill, Armagh BT61 9G, Northern Ireland.

INTRODUCTION

The greater public awareness of climate change that has developed over recent decades and the realisation that human activities may be one of the contributory causes of such change have engendered an increasing interest in long time-series of meteorological observations. The current paper is concerned with the compilation and calibration of one such body of data, namely the precipitation recorded at Armagh Observatory during the past 160 years. This study follows on and extends an earlier paper by Grew (1952).

A similar compilation of temperature data from the same site, covering the period 1795 to the present, has recently been published by Butler and Johnston (1996) and this will be extended by other work currently in progress to provide a complete and up-to-date archive of the comprehensive meteorological data bank existing for this site. It is intended that this archive should be made freely available to climatic research workers via the Internet (http://star.arm.ac.uk). With such information it may prove possible to calibrate proxy climate data, such as the long tree-ring index series for Northern Ireland (Baillie and Monro 1988), that are potentially available over much longer time-scales and that can subsequently be used to extend climate studies into the pre-instrumental era.

THE SITE

With a latitude of 54°21.2′N and longitude 6°38.8′W, the Observatory lies *c.* 700m north-east of the ancient centre of the small city of Armagh. It is situated on a fourteen-acre (previously twenty-acre) green-field site on the top of a small drumlin (hill) at an altitude of 60m above mean sea level and 20m above the surrounding valleys. The topography of the local countryside features many small hills of similar height, interspersed with shallow inter-drumlin valleys. This type of countryside is common throughout the north of Ireland and extends about 50km to the east, south and west of the City of Armagh. Approximately 20km north lies the southern edge of the Lough Neagh Basin. The Atlantic Ocean and Irish Sea lie about 100km west and 50km east of Armagh, respectively. The climate is temperate and heavily influenced by the proximity of the Atlantic Ocean and the prevailing westerly winds. In many respects it represents a typical *maritime* site. Sweeney (1985) and Betts (1997) have given comprehensive descriptions of the characteristics of the climate of Northern Ireland.

RAINFALL OBSERVATIONS

Armagh Observatory was founded in 1790 by the primate of Ireland, Archbishop Richard Robinson (see Bennett 1990). The first director was the Rev. James Archibald Hamilton, who, in addition to his astronomical interests, was concerned with the improvement of meteorological instruments and their use. Although he had made some meteorological observations from his former residence in Cookstown, Co. Tyrone, in the years 1783–4 and 1788 (Butler and Hoskin 1987), he

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did not start regular daily observations at Armagh Observatory until 1795. Temperature and pressure readings were recorded three times daily from that year, but rainfall measurements did not commence until January 1836. Before that some annual totals of rainfall were given, but, in the absence of any information on the instrument used, we have not been able to assess their reliability. During 1836 and 1837, rainfall readings were recorded sporadically using a 'Crossley' raingauge. However, the 'machinery' of this gauge was subsequently found to be unreliable and the 'common method' of measuring rainfall was subsequently adopted (using the square gauge S1). Regular readings with this gauge commenced on 1 January 1838. In Table 1 we list the raingauges that have been used for appreciable intervals of time at Armagh Observatory and give the siting of the various gauges and their period of use.

METHODS FOR STANDARDISATION OF OBSERVATIONS

Before standard equipment and procedures for meteorological observations were introduced in the late-nineteenth century and early- to mid-twentieth century, the design of raingauges varied considerably. It is important, therefore, when attempting to define long meteorological series that careful attention is paid to the standardisation of early measurements. Whilst one might expect that a sensitivity correction factor could be computed from the geometry of a gauge and its measuring cylinder, where it is known, other factors such as the exposure of the gauge are equally important (see Lamb 1977). Thus it is preferable to employ the overlapping periods of use of the various gauges to compute an empirical correction factor for each gauge in a particular location. The standard gauge to which all others are referred by this process is the eight-inch round gauge (I) in use from 18 January 1885 until 15 January 1964. The conversion of all data to the eight-inch standard has been undertaken because of the long period in which the gauge was in operation and its inherent accuracy. As there was no overlap between the eight-inch gauge (which does not survive) and the five-inch Meteorological Office standard that replaced it, we had to assume that there was no systematic difference in sensitivity between them. This assumption is justified by comparison with rainfall data from a neighbouring site, details of which are given in the next section. The conversion factors used were determined from the ratios of total annual precipitation for the period during which both gauges were in operation. For the earlier gauges several steps are required involving intermediate overlapping gauges; for instance, the ratio of S_2 to I involves the intermediary K, and the ratio of S_1 to I involves the two intermediaries

Table 1—Raingauges in use at Armagh Observatory, 1838–1997.

Name	*Period of use*	*Location*	*Conversion factor*	*Data used in Table 2*
Square (S1)	Jan. 1838–March 1861	Roof	1.31	Jan. 1838–Jan. 1854 (ex. Nov./Dec. 1851 and March/April 1852)
Round (R)	Sep. 1839–March 1874	Roof	0.85	Nov./Dec. 1851 and March/April 1852
Square (S2)	Nov. 1853–Dec. 1884	N Lawn	1.00	Feb. 1854–Dec. 1884[a]
Kew	May 1874–April 1885	N Lawn	0.96	—
Automatic (K)	May 1885–Dec. 1958	S Lawn A	0.96	—
Eight-inch (I)	Jan. 1885–April 1885[b]	N Lawn	1.00	Jan. 1885–April 1885
	May 1885–Jan. 1964[b]	S Lawn A	1.00	May 1885–Jan. 1964
Five-inch (J)	Feb. 1964–Jan. 1988	S Lawn B	1.00	Feb. 1964–Jan. 1988
	Feb. 1988–present	S Lawn C	1.00	Feb. 1988–present
Dines TSR (D)	Oct. 1946–Jan. 1964	S Lawn A	—	—
	Feb. 1964–Jan. 1988	S Lawn B	—	—
	Feb. 1988–present	S Lawn C	—	—

[a] Except (i) 1–17 May 1856, when mean of R and S1 used, (ii) July 1861, 29 October 1865, 9 October 1867, December 1870, April 1874, when R used, and (iii) May 1874, when K used.

[b] The date on which the eight-inch gauge was moved from the North Lawn to the South Lawn has not been unambiguously established; however, it is assumed that it was moved on the same date as the Kew Automatic, namely 11 May 1885.

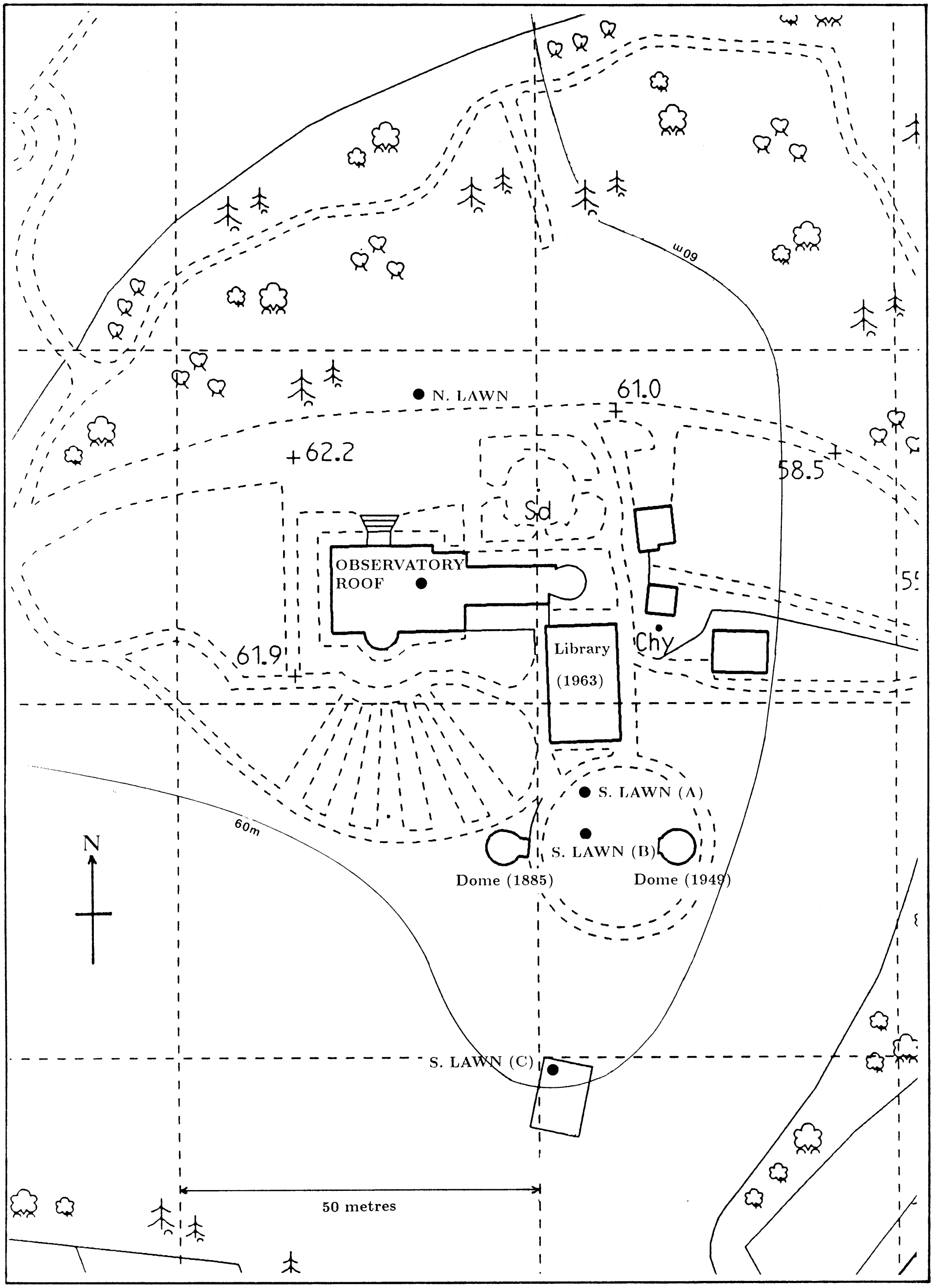

Fig. 1—The position of the various raingauges in use over the past 160 years at Armagh Observatory, from which data have been employed in this compilation, on a map showing the present layout of grounds and buildings. The automatic weather station erected by the Board of Trade in 1868, which was demolished in the early 1960s, lay close to the north end of the current library building. The position of the 60m contour is approximate (Based upon Ordnance Survey ace map, 1:1250 (1998), with the permission of the Controller of Her Majesty's Stationery Office (permit no. 1204), © Crown Copyright.)

Table 2—Mean daily precipitation per month, 1838–1997 (mm).

Year	*Jan.*	*Feb.*	*March*	*April*	*May*	*Jun.*	*Jul.*	*Aug.*	*Sep.*	*Oct.*	*Nov.*	*Dec.*
1838	1.18	1.78	1.47	1.95	1.39	3.59	2.79	3.38	1.47	0.95	3.37	1.91
1839	0.50	0.97	1.39	1.03	0.50	2.54	2.91	2.59	3.51	4.11	2.29	3.48
1840	1.93	1.24	0.33	0.43	2.24	2.21	2.97	2.11	2.03	0.86	0.61	2.24
1841	1.24	1.40	3.12	1.24	1.09	2.34	2.06	3.07	2.34	3.17	1.75	1.83
1842	1.40	3.23	1.60	0.03	3.76	1.57	2.46	2.06	3.02	1.50	3.35	1.27
1843	0.56	0.41	1.40	1.91	4.50	2.64	2.82	3.51	1.24	3.61	2.03	1.32
1844	1.27	1.60	0.86	0.89	0.08	3.20	2.24	2.77	2.29	2.79	1.30	0.51
1845	3.00	1.14	0.41	1.63	1.24	4.85	3.20	1.70	2.64	5.21	2.39	2.13
1846	2.21	0.89	1.83	2.11	1.24	1.60	3.00	3.23	3.25	3.86	2.13	1.24
1847	2.36	0.99	1.30	2.44	1.96	1.80	1.04	0.84	1.80	2.57	2.46	3.35
1848	0.74	2.97	2.16	2.49	1.07	2.97	3.25	3.00	2.64	2.24	1.75	1.17
1849	2.59	0.76	0.74	1.42	2.69	0.74	3.56	2.67	3.43	3.76	1.68	2.34
1850	3.00	1.63	0.76	2.82	2.69	2.36	2.90	2.16	2.59	1.63	1.73	0.99
1851	3.12	1.17	1.40	0.89	1.75	2.54	3.45	2.57	1.93	2.34	1.02	1.47
1852	3.23	2.67	0.89	1.04	1.75	5.89	2.03	3.25	1.93	2.59	6.30	5.28
1853	2.39	1.50	1.80	2.01	0.56	2.29	3.30	2.44	1.07	3.99	2.59	1.30
1854	3.20	1.40	1.35	0.15	2.39	3.81	3.63	2.11	1.40	2.39	2.11	3.43
1855	0.28	1.37	1.63	1.07	2.01	2.01	2.31	2.69	1.22	2.64	0.58	1.70
1856	1.88	1.42	0.69	0.89	2.64	1.70	1.24	2.16	2.67	1.17	1.17	2.97
1857	2.67	1.50	3.20	3.71	1.02	1.57	2.29	2.44	1.78	1.27	2.82	1.40
1858	1.19	1.17	0.86	4.42	2.69	0.89	2.51	2.72	1.55	1.98	0.97	3.00
1859	2.31	1.30	2.11	2.18	0.33	1.12	1.52	2.64	3.40	1.24	2.82	1.96
1860	2.87	1.02	1.68	1.24	2.51	3.17	1.14	4.06	0.84	1.73	1.55	1.73
1861	1.63	3.20	3.40	0.91	0.51	4.01	3.38	4.57	3.43	2.29	2.72	1.75
1862	3.84	0.86	2.49	2.34	3.51	2.90	3.28	1.98	1.45	3.91	1.50	2.72
1863	2.16	0.71	1.40	1.22	1.35	3.53	0.20	2.84	3.30	4.62	2.59	1.65
1864	1.50	1.17	1.88	1.68	1.52	1.09	1.40	1.83	2.49	2.03	4.78	1.73
1865	2.39	4.04	1.91	0.84	4.24	0.63	2.03	2.62	0.28	4.95	3.58	2.54
1866	3.78	2.36	2.54	1.27	0.99	1.83	2.62	2.72	3.05	1.52	2.59	3.20
1867	3.00	2.77	1.50	2.87	3.17	0.81	3.76	2.01	1.19	3.61	0.76	1.50
1868	2.13	2.59	2.92	2.16	1.55	0.79	0.74	2.11	1.35	1.70	2.57	4.06
1869	2.49	4.04	1.85	2.82	1.88	0.84	1.14	1.12	3.00	1.42	1.93	2.44
1870	1.73	0.71	0.51	0.46	0.46	0.38	1.04	1.35	2.41	6.22	1.27	4.52
1871	2.82	2.49	0.79	2.72	0.20	0.84	4.52	1.75	3.20	2.21	1.35	0.86
1872	2.84	3.38	1.93	2.72	1.22	2.79	1.75	1.65	3.23	3.76	3.35	4.37
1873	3.28	0.30	1.09	0.48	1.17	1.14	4.39	4.11	1.57	2.13	1.78	0.56
1874	1.40	1.50	0.86	2.21	0.89	0.74	2.64	3.10	2.74	2.92	2.62	2.34
1875	3.12	1.37	0.76	0.13	1.52	2.64	3.07	3.00	4.19	3.94	3.23	1.50
1876	1.14	3.17	2.62	1.27	0.36	1.22	1.68	1.80	2.01	2.64	2.13	5.51
1877	4.50	2.90	2.24	2.59	1.75	2.74	2.82	2.26	1.40	2.64	3.10	2.67
1878	2.79	1.24	1.45	1.07	3.33	2.97	0.15	2.24	3.48	2.41	1.40	1.35
1879	1.75	1.55	1.60	2.03	2.84	3.40	4.42	2.49	3.15	1.19	1.19	1.30
1880	1.12	2.21	1.63	3.40	0.86	3.66	4.75	0.89	3.02	0.86	2.67	2.24
1881	0.38	2.54	2.57	1.50	1.70	3.00	2.21	3.12	1.83	1.63	3.45	2.39
1882	1.78	1.55	2.51	2.54	2.72	2.41	3.71	2.03	2.87	1.98	4.60	2.77
1883	3.28	3.63	1.02	1.65	1.68	2.29	1.83	2.34	4.19	2.51	3.30	1.70
1884	3.66	3.05	2.29	1.65	2.46	0.76	2.95	1.91	2.41	2.62	2.06	2.95
1885	1.73	2.79	1.40	1.93	1.32	0.51	1.57	1.52	3.73	2.39	1.55	1.07
1886	3.51	1.78	2.06	1.12	2.90	1.37	2.46	2.01	2.82	3.84	2.41	3.51
1887	1.75	1.24	0.84	1.24	1.09	0.58	2.64	2.67	2.41	1.30	2.08	1.88
1888	1.45	0.25	2.49	1.14	1.93	4.11	3.66	1.93	0.94	0.99	3.56	2.11

Table 2—(continued)

Year	Jan.	Feb.	March	April	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1889	1.70	1.50	1.40	2.69	2.59	0.23	2.39	5.46	1.78	2.57	1.32	1.85
1890	2.39	0.84	2.13	1.07	1.17	2.16	1.73	2.77	2.59	1.42	5.46	1.37
1891	1.09	0.18	1.27	1.55	2.16	2.01	1.52	3.89	1.45	2.79	2.06	3.84
1892	1.45	1.19	0.61	0.58	3.73	2.64	2.18	5.77	2.46	1.91	3.17	1.24
1893	1.30	2.54	0.81	0.79	0.91	1.35	1.78	3.73	1.19	2.24	1.35	2.29
1894	3.76	3.28	1.47	2.16	2.01	2.49	2.97	1.93	0.08	3.58	1.73	2.16
1895	1.78	0.30	2.77	1.07	0.20	1.63	4.47	4.06	0.61	3.00	2.54	2.79
1896	1.50	1.14	2.39	1.09	0.51	2.69	5.82	1.32	4.11	1.83	0.66	2.87
1897	1.17	1.63	3.43	2.51	1.17	4.78	1.57	4.37	1.37	1.85	2.13	3.25
1898	1.47	2.82	0.86	2.46	2.90	2.39	0.46	2.87	3.73	2.51	2.16	2.06
1899	2.29	2.44	1.42	2.92	3.10	2.01	1.65	1.70	3.02	1.40	2.36	2.79
1900	2.26	2.34	0.51	1.70	2.24	2.39	2.21	4.24	1.68	3.10	4.80	2.97
1901	2.59	1.14	1.88	2.49	1.45	1.93	0.66	3.53	2.51	2.84	3.28	2.44
1902	1.83	2.13	1.63	1.91	3.38	1.96	3.56	1.83	2.51	1.27	2.24	2.21
1903	4.06	2.54	3.61	0.97	2.54	0.91	2.72	3.38	2.69	3.20	1.63	1.93
1904	2.36	2.82	1.83	1.60	2.21	1.19	2.46	4.47	2.46	0.81	1.91	1.57
1905	1.91	1.60	2.82	1.73	1.32	2.57	1.45	5.26	1.52	1.19	2.11	1.40
1906	2.72	1.98	1.78	1.47	3.30	4.06	1.70	2.97	0.97	3.56	1.68	2.16
1907	0.94	1.65	2.34	1.98	3.05	3.84	1.83	2.24	0.79	3.43	2.21	2.03
1908	1.98	1.78	3.30	2.08	1.83	1.60	3.10	1.91	3.63	1.45	2.59	2.26
1909	1.98	1.22	2.13	2.59	1.40	1.85	2.29	1.63	1.57	3.91	0.94	2.49
1910	2.03	4.11	1.35	2.01	1.70	3.45	2.18	4.04	0.94	0.86	1.65	2.97
1911	7.42	2.51	0.97	1.98	1.52	1.30	2.21	1.37	1.27	2.21	2.57	4.32
1912	3.00	2.57	2.74	1.65	1.14	4.04	2.29	4.93	0.76	0.91	2.16	3.58
1913	3.02	0.91	2.49	2.84	3.10	3.38	1.27	0.79	3.51	3.05	2.49	2.36
1914	1.12	2.64	3.30	1.12	1.09	1.80	1.75	2.49	1.14	1.27	3.17	5.87
1915	2.34	3.23	0.71	1.80	0.71	1.47	3.07	2.31	1.24	1.85	1.45	4.24
1916	2.44	2.97	1.09	3.07	5.05	1.85	1.37	2.72	0.74	4.44	3.00	2.03
1917	1.35	2.34	2.24	2.24	2.46	2.59	2.06	3.76	1.60	3.45	3.25	1.60
1918	2.34	3.40	1.07	0.94	1.91	0.86	2.67	2.08	4.72	3.17	3.51	2.82
1919	3.38	0.84	1.98	1.02	1.52	1.73	0.51	2.67	2.67	1.22	1.63	4.95
1920	3.35	2.16	2.62	2.46	2.46	2.01	2.51	1.57	1.93	4.39	2.31	2.51
1921	3.56	0.89	2.13	0.76	1.68	0.25	3.00	2.90	1.04	2.29	2.39	2.69
1922	2.72	2.49	1.14	2.59	1.45	1.83	2.77	3.15	2.24	1.02	1.04	2.44
1923	2.11	4.93	1.22	2.69	1.17	0.91	1.80	4.04	2.95	2.87	3.20	2.44
1924	2.77	0.97	0.94	2.13	3.35	2.01	3.94	3.63	4.44	2.29	4.50	3.33
1925	1.80	3.25	0.99	2.39	3.78	0.91	3.10	1.52	2.21	2.03	1.32	2.08
1926	4.04	2.08	1.42	1.52	2.29	2.26	2.57	2.67	1.70	2.34	2.64	0.99
1927	2.74	1.30	1.93	1.12	1.27	2.46	2.18	3.71	4.47	1.85	2.90	1.50
1928	4.01	3.66	2.69	1.50	0.66	3.58	1.32	5.66	1.80	3.89	3.63	2.03
1929	1.07	2.06	0.28	0.71	2.26	1.57	2.08	4.52	1.22	4.60	2.95	4.85
1930	3.30	0.79	1.78	1.30	1.27	2.54	2.69	4.80	2.57	4.39	2.59	2.13
1931	2.26	2.64	1.19	2.87	3.02	4.27	4.70	1.70	1.65	1.63	3.99	2.11
1932	2.51	0.10	1.50	2.03	2.21	0.71	4.37	1.98	2.62	2.31	1.75	4.06
1933	1.73	2.57	1.65	0.74	2.13	0.97	2.26	1.24	0.13	1.65	0.79	1.35
1934	2.39	5.69	1.40	2.16	2.29	1.19	2.08	4.50	3.91	3.68	0.58	3.94
1935	1.17	2.97	1.02	1.78	0.69	3.48	0.94	2.29	3.20	2.77	3.25	1.91
1936	2.69	1.55	1.37	0.46	1.30	3.73	4.83	1.45	3.71	2.21	3.20	2.64
1937	3.78	3.10	1.88	1.91	0.89	1.80	2.67	2.39	1.98	2.26	1.09	1.83
1938	3.17	1.09	0.81	0.08	3.17	3.07	3.94	2.11	1.85	4.52	3.43	2.74

Table 2—(continued)

Year	*Jan.*	*Feb.*	*March*	*April*	*May*	*Jun.*	*Jul.*	*Aug.*	*Sep.*	*Oct.*	*Nov.*	*Dec.*
1939	5.36	1.85	2.59	2.03	0.99	1.65	3.63	1.32	1.52	2.97	4.19	1.96
1940	2.46	2.44	3.15	2.46	0.76	1.35	4.34	0.43	2.18	3.48	2.39	2.92
1941	1.35	2.67	2.87	1.42	1.96	0.53	2.34	3.17	0.84	2.90	3.12	1.17
1942	3.94	1.07	2.39	1.91	2.57	0.15	3.56	3.51	3.56	1.78	0.43	3.15
1943	3.23	1.55	0.91	1.12	2.72	2.49	2.13	3.25	1.70	2.26	1.91	1.80
1944	1.78	0.89	0.71	1.68	1.35	3.30	2.13	3.30	3.51	3.58	4.01	3.33
1945	1.68	2.41	1.07	1.32	2.87	3.53	2.84	1.37	2.11	2.72	0.38	2.03
1946	3.48	1.96	0.89	0.71	0.74	2.62	2.57	3.86	4.83	0.99	3.78	3.15
1947	1.80	0.94	3.68	3.05	2.92	3.17	2.67	0.46	2.18	1.60	3.38	2.62
1948	5.51	1.60	2.13	2.11	1.88	3.66	2.01	2.87	2.24	1.85	2.24	3.71
1949	1.98	2.29	1.73	1.85	1.55	0.84	2.24	2.49	2.08	4.14	2.06	3.84
1950	1.42	2.51	0.89	3.33	0.69	2.39	3.89	4.34	4.62	2.95	2.24	2.18
1951	2.16	2.74	2.29	1.45	1.22	1.78	2.74	3.61	5.28	0.69	4.65	3.40
1952	3.73	0.86	1.17	1.35	0.91	1.93	1.32	3.23	1.04	3.05	2.21	2.82
1953	0.79	1.30	0.23	1.85	1.22	2.01	3.40	2.69	2.79	1.24	2.44	2.90
1954	1.19	3.61	2.57	0.46	3.40	1.93	3.76	1.88	3.66	4.29	3.73	3.10
1955	2.74	3.23	0.89	2.34	2.26	3.63	1.65	0.89	3.05	1.19	1.78	3.38
1956	1.70	0.94	2.24	0.91	1.07	2.11	3.12	5.16	2.69	1.52	1.91	4.55
1957	3.68	1.83	2.01	0.99	1.98	1.19	3.02	4.55	3.28	2.87	0.84	3.53
1958	2.79	3.53	1.12	1.02	2.16	4.57	4.44	3.17	2.46	3.20	1.40	4.24
1959	1.80	0.91	1.91	2.46	1.09	1.68	2.72	0.84	1.30	1.57	2.72	3.73
1960	2.57	2.69	1.65	2.13	2.74	2.41	3.17	3.15	2.79	4.29	2.82	2.49
1961	2.95	2.79	0.89	4.39	2.49	1.35	1.52	2.06	3.12	3.28	1.93	2.06
1962	2.49	1.27	1.75	1.73	2.34	1.12	1.68	2.67	5.54	1.35	1.65	2.87
1963	1.27	2.26	2.92	2.36	2.29	4.04	1.22	3.33	1.93	3.23	4.65	0.63
1964	1.55	1.07	2.13	1.75	1.52	1.85	1.35	3.12	2.06	4.29	1.98	2.87
1965	3.63	0.28	2.01	2.46	1.80	2.87	2.11	2.87	2.26	1.91	3.94	3.12
1966	2.24	4.17	1.96	3.38	2.24	3.43	1.14	2.16	2.29	4.65	2.82	3.58
1967	1.65	2.57	2.01	1.40	3.51	0.97	3.02	2.69	3.86	3.99	1.80	2.18
1968	2.82	1.17	1.85	1.91	1.70	2.21	0.76	1.73	2.90	3.05	3.12	2.24
1969	3.56	2.11	1.07	2.16	3.30	2.01	1.19	1.75	0.71	1.19	4.27	2.44
1970	2.46	3.71	1.85	2.24	1.22	1.88	3.05	3.30	2.54	2.59	3.28	1.07
1971	1.55	1.96	0.94	2.77	1.60	3.15	1.75	3.51	1.07	1.22	2.72	0.56
1972	3.53	1.88	2.67	1.93	2.74	2.11	1.83	1.22	0.33	1.37	2.74	2.26
1973	3.00	2.24	0.86	1.75	1.80	0.86	2.31	2.39	1.65	1.78	2.44	2.13
1974	3.56	2.21	0.99	1.19	2.59	1.63	3.15	1.85	3.30	1.40	2.39	2.90
1975	3.56	0.71	1.32	1.30	0.51	0.51	1.09	1.52	4.78	1.96	1.37	0.58
1976	2.54	1.40	1.80	0.58	3.30	1.78	1.73	0.46	2.84	4.37	1.02	2.64
1977	2.90	4.17	2.08	1.68	0.63	1.80	0.71	3.15	1.57	2.13	3.15	2.24
1978	2.49	1.68	2.79	0.89	0.91	1.42	1.80	1.65	2.46	1.42	2.57	5.36
1979	1.98	0.69	2.34	2.46	3.20	1.75	1.12	3.48	1.37	3.63	3.30	2.95
1980	2.41	2.51	3.28	0.46	1.12	3.23	1.63	1.93	2.34	3.61	2.06	3.23
1981	1.65	1.68	3.48	1.60	3.15	2.82	2.06	1.14	4.57	3.56	2.34	2.24
1982	2.59	2.36	3.28	0.30	0.99	2.67	0.48	2.06	2.31	3.28	4.37	3.68
1983	2.46	1.22	2.57	2.01	2.16	1.35	0.48	1.04	2.26	2.97	0.94	3.58
1984	4.09	3.28	2.11	0.46	0.63	1.57	1.60	2.82	2.62	2.57	3.02	2.64
1985	1.52	0.84	1.85	1.68	2.03	1.83	3.20	4.42	2.95	1.37	1.35	1.93
1986	3.38	0.15	2.31	3.33	3.17	1.47	1.65	3.53	0.15	2.92	2.77	3.25
1987	0.99	1.27	2.51	1.40	0.89	3.05	1.17	3.40	2.54	4.14	1.57	1.09

S_2 and K. The conversion factors used are essentially the same as those derived by Grew (1952).

As mentioned earlier, much depends on the exposure of the gauges. Whilst the conversion factors listed in Table 1 should provide correction for exposure effects, on average, there is no doubt that effects due to differences in exposure will remain in some daily data, for instance when winds are strong and gusty. Two locations that were used for some early measurements and would no longer be considered suitable are the 'Observatory Roof', a platform between two 45° sloping roof sections, and the 'Front Lawn', which lies 20.7m north of a building 9m high and roughly in the direction of the prevailing west-south-westerly (rain-bearing) wind. The growth of natural vegetation is also likely to influence measurements. In Fig. 1 we show the location of all the gauges that have been used to construct this data bank superimposed on a modern map of the buildings and grounds.

In Table 2 we list the mean daily precipitation per month for the period 1838–1997 using the conversion factors given in Table 1. The periods for which the compilation in Table 2 employs data from the various gauges are given in column 5 of Table 1.

For comparison with other sites we have also determined the mean daily precipitation per season. These data, together with the annual mean, are tabulated on a yearly basis in Table 3.

RESULTS

In Fig. 2 (upper panel) we show the mean daily precipitation per month over the entire period 1838–1997. This diagram shows a fall in precipitation from February to April, an increase from May to August and a levelling off from September to January. The wettest month overall, however, is August, when sea temperatures are high and thundery conditions add to the gradually increasing late summer rainfall. Lamb (1995) has commented on the tendency for the storm tracks that normally pass over the British Isles to move further north in September, with a resulting drop in rainfall in the British Isles during this month and an increase in Iceland.

It is of interest to historians and climatologists to identify any change in the overall mean annual precipitation over the last two centuries and in the distribution of precipitation during the year. In Fig. 3 (lower panel) we show the annual mean daily precipitation for each year between 1838 and 1997. In Fig. 4 we show similar plots for the four seasons: winter (DJF), spring (MAM), summer (JJA) and autumn (SON). The smoothed lines passing through the data have been determined using a Gaussian smoothing function with a full width at half maximum of 11.8 years. As expected, the range in variability of the precipitation is greater in winter, summer and autumn than in spring, when precipitation is least.

There was a gradual increase in the mean annual precipitation from around 2.08mm/day when systematic records began in 1838 to around 2.39mm/day in 1960. This was noticed by Grew (1952), who also spotted a similar increase in the number of days on which non-zero rainfall was recorded at Armagh. This trend was reversed in the 1960s and 1970s as a result of a greater prevalence of drier summers since the 1960s.

It might have been suspected that the apparent fall in annual rainfall since the 1960s could be due to the changeover from the eight-inch to the standard five-inch gauge. However, by comparing the total annual precipitation at Armagh with that at a neighbouring site on the Agricultural Research Station in Loughall, which lies approximately seven miles north-east of Armagh and has operated since 1957, it can be shown that the apparent drop in rainfall does not arise from the change in gauge. The Loughall site is generally drier than Armagh. The ratio of total precipitation at Loughall to that at Armagh was 0.91 ± 0.01 for the five years

Table 2—(continued)

Year	*Jan.*	*Feb.*	*March*	*April*	*May*	*Jun.*	*Jul.*	*Aug.*	*Sep.*	*Oct.*	*Nov.*	*Dec.*
1988	4.19	2.64	3.48	1.02	1.65	1.24	2.95	2.79	2.59	2.87	1.14	2.16
1989	1.50	1.73	2.62	3.00	0.63	1.14	1.17	2.84	1.63	3.00	0.84	1.75
1990	2.84	5.49	1.30	1.63	1.37	2.31	1.02	2.92	0.76	4.78	1.70	3.15
1991	2.06	1.19	2.77	3.00	0.20	1.91	0.63	0.84	1.32	2.67	2.82	2.95
1992	1.91	1.37	3.10	2.36	1.19	1.75	1.91	4.72	2.13	1.52	3.38	2.03
1993	2.92	0.63	1.24	2.74	4.19	2.16	2.54	1.85	3.25	1.30	1.50	4.55
1994	2.92	3.86	2.79	2.21	1.27	1.24	1.91	3.66	2.11	1.24	1.85	3.53
1995	3.38	3.20	1.96	1.09	0.84	0.97	1.30	0.33	2.01	4.34	5.03	1.30
1996	2.48	2.27	1.56	3.11	2.55	0.77	1.75	2.69	0.92	2.45	2.54	1.55
1997	0.61	3.38	0.94	1.15	2.73	3.05	3.07	1.39	1.19	2.17	2.74	2.76

Table 3—Mean daily precipitation per season, 1838–1997 (mm).

Year	*Winter (DJF)*	*Spring (MAM)*	*Summer (JJA)*	*Autumn (SON)*	*Annual*
1838	—	1.60	3.25	1.93	2.10
1839	1.13	0.97	2.69	3.30	2.15
1840	1.07	0.99	2.44	1.17	1.60
1841	1.63	1.83	2.49	2.41	2.06
1842	2.16	1.80	2.03	2.62	2.11
1843	0.74	2.59	3.00	2.29	2.16
1844	1.40	0.61	2.74	2.13	1.65
1845	1.55	1.09	3.25	3.40	2.46
1846	1.75	1.73	2.62	3.07	2.21
1847	1.52	1.91	1.22	2.29	1.91
1848	2.36	1.91	3.07	2.21	2.21
1849	1.50	1.63	2.31	2.95	2.18
1850	2.31	2.08	2.46	1.98	2.11
1851	1.75	1.35	2.84	1.75	1.98
1852	2.46	1.22	3.73	3.61	3.07
1853	3.05	1.45	2.67	2.54	2.11
1854	1.96	1.30	3.17	1.96	2.29
1855	1.70	1.57	2.34	1.47	1.63
1856	1.68	1.40	1.70	1.68	1.73
1857	2.39	2.64	2.11	1.96	2.13
1858	1.24	2.67	2.03	1.50	2.01
1859	2.21	1.55	1.75	2.49	1.91
1860	1.96	1.80	2.79	1.37	1.96
1861	2.18	1.60	3.99	2.82	2.64
1862	2.16	2.77	2.72	2.29	2.57
1863	1.85	1.32	2.18	3.51	2.13
1864	1.45	1.70	1.45	3.10	1.93
1865	2.72	2.34	1.75	2.95	2.51
1866	2.90	1.60	2.39	2.39	2.36
1867	3.00	2.51	2.18	1.85	2.24
1868	2.08	2.21	1.22	1.88	2.06
1869	3.53	2.18	1.04	2.11	2.08
1870	1.63	0.48	0.91	3.30	1.75
1871	3.28	1.24	2.36	2.26	1.98
1872	2.36	1.96	2.06	3.45	2.74
1873	2.64	0.91	3.23	1.83	1.83
1874	1.14	1.32	2.16	2.77	2.01
1875	2.29	0.81	2.90	3.78	2.36
1876	1.93	1.42	1.57	2.26	2.13
1877	4.29	2.18	2.62	2.39	2.64
1878	2.24	1.96	1.78	2.44	1.98
1879	1.55	2.16	3.43	1.85	2.24
1880	1.55	1.96	3.10	2.18	2.29
1881	1.73	1.93	2.77	2.31	2.18
1882	1.91	2.59	2.72	3.15	2.62
1883	3.23	1.45	2.16	3.33	2.46
1884	2.79	2.13	1.88	2.36	2.39
1885	2.49	1.55	1.19	2.57	1.80
1886	2.11	2.03	1.96	3.02	2.49
1887	2.16	1.07	1.96	1.93	1.65

Table 3—(continued)

Year	*Winter (DJF)*	*Spring (MAM)*	*Summer (JJA)*	*Autumn (SON)*	*Annual*
1888	1.19	1.85	3.23	1.83	2.06
1889	1.78	2.24	2.69	1.88	2.13
1890	1.70	1.45	2.21	3.15	2.08
1891	0.89	1.65	2.46	2.11	1.98
1892	2.16	1.65	3.53	2.51	2.24
1893	1.70	0.84	2.29	1.60	1.70
1894	3.10	1.88	2.46	1.80	2.31
1895	1.42	1.35	3.38	2.06	2.11
1896	1.80	1.32	3.28	2.21	2.16
1897	1.88	2.36	3.58	1.78	2.44
1898	2.51	2.08	1.91	2.79	2.24
1899	2.26	2.49	1.78	2.26	2.26
1900	2.46	1.47	2.95	3.20	2.54
1901	2.24	1.93	2.03	2.87	2.24
1902	2.13	2.31	2.44	2.01	2.21
1903	2.95	2.36	2.34	2.51	2.51
1904	2.36	1.88	2.72	1.73	2.13
1905	1.70	1.96	3.10	1.60	2.08
1906	2.03	2.18	2.92	2.06	2.36
1907	1.57	2.46	2.64	2.13	2.18
1908	1.93	2.41	2.21	2.57	2.29
1909	1.83	2.03	1.93	2.13	2.01
1910	2.87	1.68	3.23	1.14	2.29
1911	4.29	1.50	1.63	2.01	2.46
1912	3.30	1.85	3.76	1.27	2.49
1913	2.51	2.82	1.80	3.02	2.44
1914	2.03	1.83	2.01	1.85	2.24
1915	3.81	1.07	2.29	1.52	2.03
1916	3.23	3.07	1.98	2.72	2.57
1917	1.91	2.31	2.79	2.77	2.41
1918	2.44	1.30	1.88	3.81	2.46
1919	2.34	1.50	1.63	1.83	2.01
1920	3.48	2.51	2.03	2.87	2.51
1921	2.31	1.52	2.06	1.91	1.96
1922	2.64	1.73	2.59	1.42	2.08
1923	3.15	1.70	2.26	3.00	2.51
1924	2.06	2.13	3.20	3.73	2.87
1925	2.79	2.39	1.85	1.85	2.11
1926	2.74	1.75	2.49	2.24	2.21
1927	1.68	1.45	2.79	3.07	2.29
1928	3.05	1.63	3.53	3.10	2.87
1929	1.73	1.09	2.72	2.92	2.34
1930	2.97	1.45	3.35	3.17	2.51
1931	2.34	2.36	3.56	2.41	2.67
1932	1.57	1.91	2.36	2.24	2.18
1933	2.79	1.50	1.50	0.86	1.42
1934	3.15	1.96	2.59	2.72	2.82
1935	2.69	1.17	2.24	3.07	2.13
1936	2.06	1.04	3.33	3.05	2.44
1937	3.17	1.55	2.29	1.78	2.13

Table 3—(continued)

Year	*Winter (DJF)*	*Spring (MAM)*	*Summer (JJA)*	*Autumn (SON)*	*Annual*
1938	2.03	1.35	3.05	3.28	2.49
1939	3.33	1.88	2.21	2.90	2.51
1940	2.29	2.13	2.03	2.69	2.36
1941	2.31	2.08	2.01	2.29	2.03
1942	2.06	2.29	2.41	1.93	2.34
1943	2.64	1.57	2.62	1.96	2.08
1944	1.50	1.24	2.92	3.71	2.46
1945	2.46	1.75	2.59	1.73	2.03
1946	2.49	0.79	3.02	3.20	2.46
1947	1.96	3.23	2.11	2.39	2.36
1948	3.25	2.03	2.84	2.11	2.64
1949	2.67	1.70	1.85	2.77	2.26
1950	2.59	1.63	3.53	3.28	2.62
1951	2.36	1.65	2.72	3.53	2.67
1952	2.67	1.14	2.16	2.11	1.98
1953	1.63	1.09	2.69	2.16	1.91
1954	2.57	2.13	2.51	3.89	2.79
1955	3.02	1.83	2.06	2.01	2.26
1956	2.01	1.40	3.45	2.03	2.34
1957	3.35	1.65	2.92	2.34	2.49
1958	3.28	1.42	4.06	2.36	2.84
1959	2.31	1.83	1.75	1.85	1.91
1960	3.00	2.18	2.92	3.30	2.74
1961	2.74	2.59	1.65	2.77	2.41
1962	1.93	1.93	1.83	2.84	2.21
1963	2.13	2.51	2.87	3.28	2.51
1964	1.09	1.80	2.11	2.77	2.13
1965	2.26	2.08	2.62	2.69	2.44
1966	3.17	2.51	2.24	3.25	2.84
1967	2.59	2.31	2.24	3.23	2.46
1968	2.06	1.83	1.57	3.02	2.13
1969	2.64	2.18	1.65	2.06	2.13
1970	2.87	1.78	2.74	2.79	2.44
1971	1.52	1.78	2.79	1.68	1.91
1972	1.98	2.44	1.73	1.47	2.06
1973	2.49	1.47	1.85	1.96	1.93
1974	2.64	1.60	2.21	2.36	2.26
1975	2.39	1.04	1.04	2.69	1.60
1976	1.50	1.91	1.32	2.74	2.03
1977	3.23	1.47	1.88	2.29	2.18
1978	2.13	1.52	1.63	2.16	2.11
1979	2.67	2.67	2.11	2.77	2.36
1980	2.62	1.63	2.26	2.67	2.31
1981	2.18	2.74	2.01	3.48	2.51
1982	2.39	1.52	1.73	3.33	2.36
1983	2.46	2.24	0.97	2.06	1.93
1984	3.66	1.07	2.01	2.74	2.29
1985	1.68	1.85	3.15	1.88	2.08
1986	1.83	2.95	2.21	1.96	2.34
1987	1.83	1.60	2.54	2.74	2.01

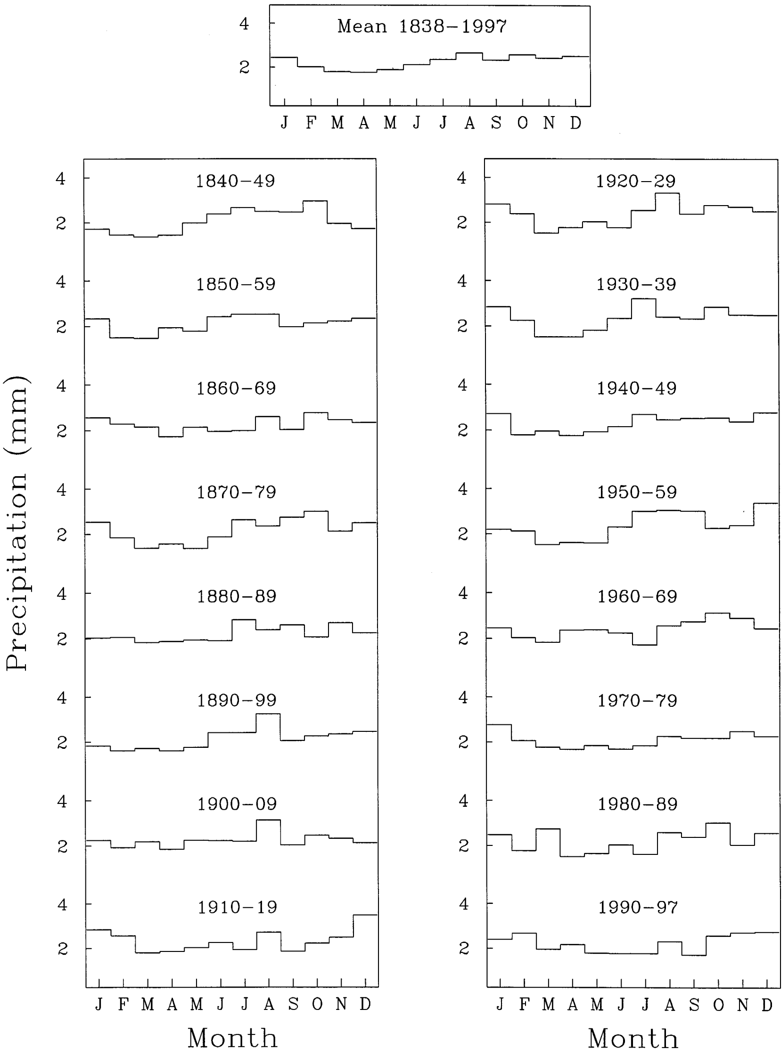

Fig. 2—Upper panel: mean daily precipitation per month for the period 1838–1997; lower panel: mean daily precipitation per month for decadal intervals, 1840–1997.

preceding the change in raingauge and 0.92 ± 0.02 for the five years following the change. Therefore we are confident that the observed fall in precipitation is a real effect. Sweeney (1985) has drawn attention to the dramatic decline in the number of days in Ireland during which a 'westerly' circulation type dominates: from around 80 days per annum in the 1940s to 50 days per annum in the 1970s. As the 'westerly' regime is responsible for about a quarter of all rain in Ireland, a decline in its frequency might be expected to be accompanied by reduced annual rainfall. This presumably is the explanation for the fall in Armagh rainfall since the 1970s.

Figure 5 shows the smoothed annual precipitation during summer and winter against year. From it, there appears to be a slight negative correlation between summer and winter rainfall, i.e. that drier winters are associated with wetter summers and vice versa, particularly over the period 1838–1940. However, the correlation coefficient of -0.19 is barely significant at the 7% level. A decade-by-decade summary of the average variation of seasonal precipitation is given in Table 4 and illustrated in the lower panel of Fig. 2.

To summarise the results of Table 4 and Fig. 2, we note that the first two decades of the series, 1840–59, were characterised by rather wet summers and dry winters, whereas in the following two decades, 1860–79, winters were wetter. The trend to wetter than average winters returned in the decades 1910–29. For the last two-and-a-half decades of the series, 1970–97, drier summers have prevailed.

CYCLIC VARIABILITY IN PRECIPITATION

BACKGROUND

Evidence for cyclic variability in climatological data has been the subject of numerous investigations (see references in Burroughs 1992). Frequently, a quasi-biennial cycle has been found in both temperature and rainfall data, resulting per-

Table 3—(continued)

Year	*Winter (DJF)*	*Spring (MAM)*	*Summer (JJA)*	*Autumn (SON)*	*Annual*
1988	2.64	2.06	2.34	2.21	2.39
1989	1.80	2.08	1.73	1.83	1.83
1990	3.35	1.42	2.08	2.41	2.44
1991	2.13	1.98	1.12	2.26	1.85
1992	2.08	2.21	2.79	2.34	2.29
1993	1.85	2.72	2.18	2.01	2.41
1994	3.78	2.08	2.26	1.73	2.39
1995	3.38	1.30	0.86	3.78	2.13
1996	2.01	2.40	1.75	1.97	2.05
1997	1.85	1.61	2.50	2.03	2.10

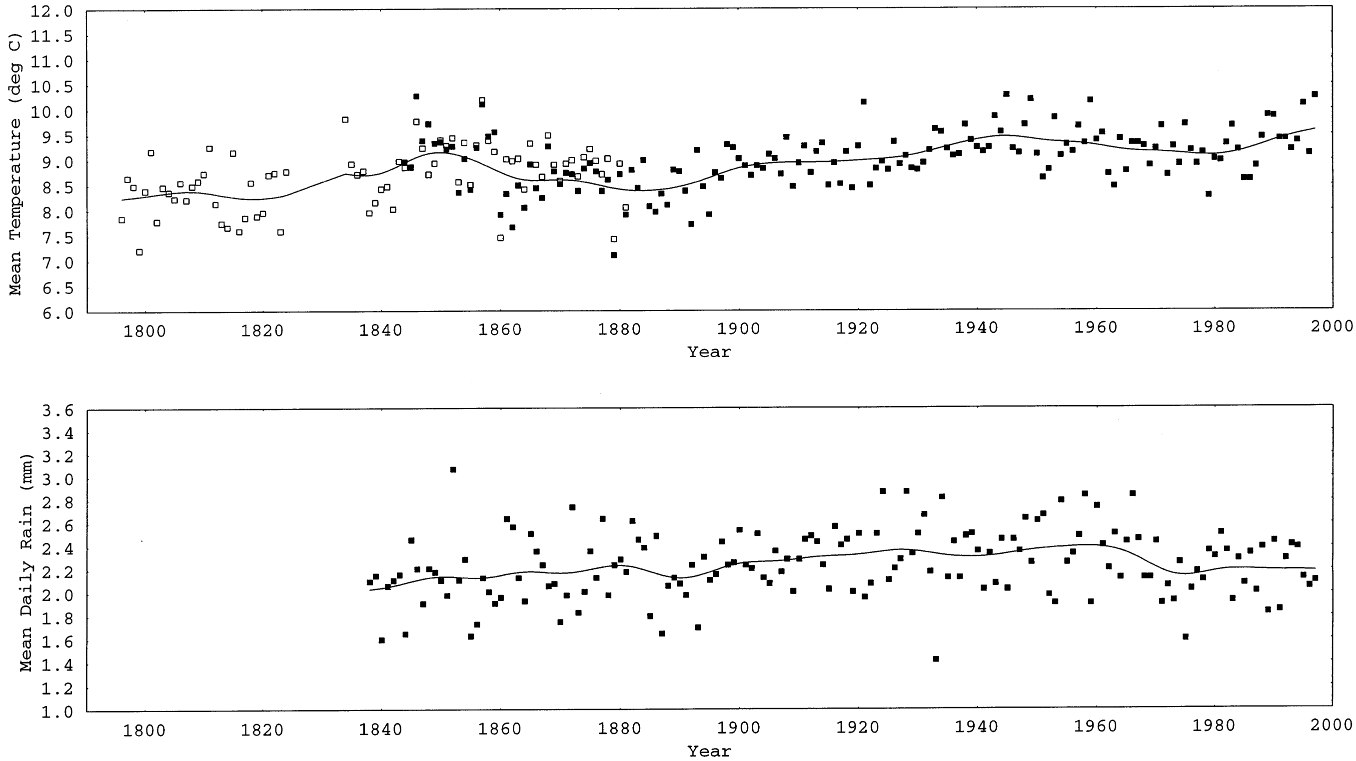

Fig. 3—Lower panel: solid squares = mean daily precipitation per year for the period 1838–1997; upper panel: mean temperature at Armagh, 1796–1996, from Butler and Johnston (1996) (open squares = Series I; solid squares = Series II). The smoothed curves are produced with a Gaussian smoothing function with a full width at half maximum of 11.8 years.

haps from the well known quasi-biennial cycle of stratospheric winds (Labitzke and van Loon 1990). Cycles of eleven and 22 years, probably associated with the sunspot cycle, have also appeared from time to time. Such a cycle was suspected by Grew (1952) in the Armagh rainfall from 1840 to 1949.

METHODS

In order to assess such effects in the current data set, we have undertaken power spectrum analysis of the seasonal and mean rainfall series. For each precipitation series the mean value has been subtracted and the Fourier Transform computed using the FTRANS routine in the Starlink Spectral Analysis Package DIPSO (see Howarth *et al.* 1993).

RESULTS

The winter, autumnal and annual series show no significant peaks in their power spectra. However, the summer and spring series do show signs of periodicity (see Fig. 6). Both series include 2.4 years as one of the most prominent peaks in their power spectrum; in summer it is the third highest peak and in spring it is the highest, suggesting that a quasi-biennial periodicity is present in the Armagh data. However, a prominent peak of 7.1 years is very conspicuous in the summer season power spectrum. When the data are folded in phase with this period, all twelve driest summers spread over a phase interval of 0.5. If we divide the data into two equal parts, 1838–1917 and 1918–97, and recompute the power spectra, we find that the seven-year period persists as the strongest period in both series, although it is stronger in the nineteenth century than the twentieth century. Although such periodicities often come and go in meteorological data series, it seems that this one must have continued for a significant part of the series. Similar periodicities of around six years and 2.4 years have been identified in the Kew and Manchester rainfall series for the summer season (Burroughs 1992, p. 39; Tabony 1979). The proximity of these periodicities in data sets independent of our own suggests that they are a genuine characteristic of the British Isles region.

In an Irish context, we may note further that a seven-year cycle has previously been identified in meteorological data recorded at Glendoen, Co. Donegal. The original manuscript record of this finding is dated 7 January 1883 and is included in a folder of meteorological observations for this site covering the period 1846–83, which is held in the Observatory archives (see Butler and Hoskin 1987,

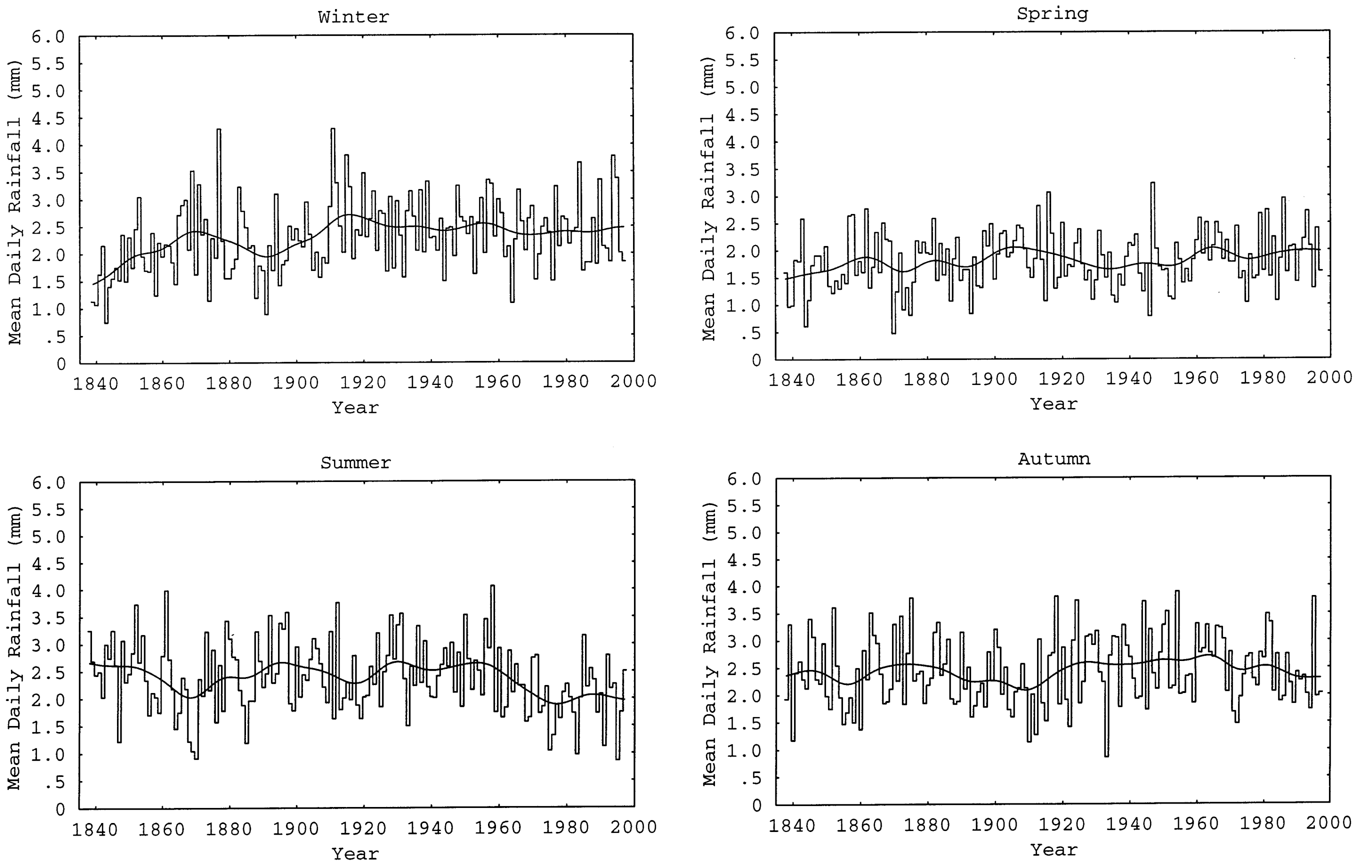

Fig. 4—Mean daily precipitation per season for the period 1838–1996 (smoothed curves as for Fig. 3).

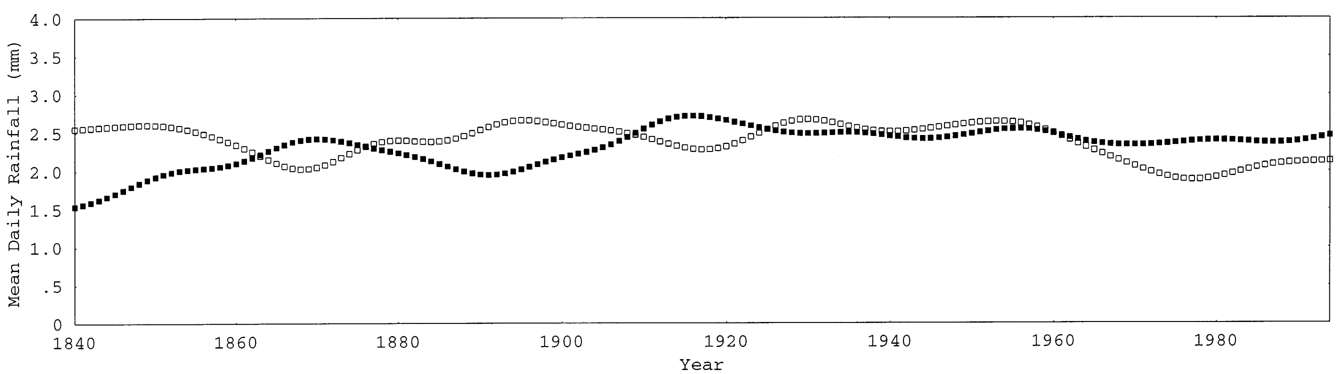

Fig. 5—Smoothed summer and winter precipitation against year (winter = solid squares; summer = open squares).

M32). Though unsigned, it seems likely that the author was the Rev. Henry Kingsmill (1802–88), rector of the parish of Conwall from 1836 to 1876. The author of the manuscript writes: 'The cycle of 11 years does not appear to be confirmed. This was imagined to depend on the spots of the Sun. Bacon mentions the belief prevalent in the "Low Countries" that there is a cycle of 35 yrs after which the seasons are similar. On comparison of a good n^{o} of years, from 1816 to 1879, I found a recurrence of like seasons of seven years or a multiple of 7.' Although the manuscript does not specify to which parameter of climate this comment refers, it seems too much of a coincidence that the only cycle established in the County Donegal data has a periodicity identical to that found in the Armagh summer rainfall.

To return to the Armagh data: in order to define more closely the time of year when this periodic effect occurs, we have undertaken power spectrum analysis of the data for the three summer months, June, July and August, separately. The periodicity of approximately seven years is present in the July and August monthly data but not the June data.

PRECIPITATION AND METEOR SHOWERS

The occurrence of this periodic effect in the rainfall for the months of July and August initially led us to suspect a link with the daylight Taurid meteor shower, which peaks on 30 June. Links between meteor showers and rainfall have been proposed in the past (see Bowen 1953; 1956), although subsequent work by Whipple and Hawkins (1956) disputed the connection. Whipple and Hawkins point out that the overall meteor flux is dominated by sporadic meteors with no preferred radiant and little seasonal variation and therefore a connection with rainfall is unlikely. Furthermore, we note that it is now well established that either the Taurid meteor stream is a product of the short-period (3.28 years) Comet Encke or they have a common progenitor. If there were to be any connection with Armagh summer rainfall, one would expect the period of 3.28 years to be prominent in the power spectrum, which is not the case. However, Asher and Clube (1993) have pointed out that resonance effects of the gravitational influence of Jupiter will constrain meteoric particles that share a common orbit into 'swarms', which are partially dispersed in their mean anomaly. The existence of such swarms in the Taurid stream has subsequently been confirmed by Asher and Izumi (1998) using Japanese meteor observations from 1972 to 1995. They note that successive encounters by the earth with the Taurid swarms would occur in intervals of three, four and seven years. It is tempting to suggest, therefore, that the seven-year periodicity in the summer rainfall originates from meteoric dust associated with the Taurid stream. However, the summer rainfall for the years of encounter predicted by Asher and Clube (1993) and given in their Table III for the twentieth century shows no obvious difference from the mean value for this century. It would nevertheless be of interest to compare the summer rainfall for the years of encounter during the nineteenth century, when the seven-year periodicity is most prominent, as it is known that Comet Encke was brighter and more active in the late eighteenth and the nineteenth century following its discovery in 1786.

Another candidate may have been Comet Pons–Winnecke, which has a period of 6.4 years and is known to have been responsible for the meteor shower that peaked on 30 June early in the current century. However, this meteor stream has not been observed since 1927 and is now considered completely lost (Lovell 1954, p. 354). Therefore, with present evidence, we cannot confirm that meteoritic material associated with either the Taurid or the Pons–Winnecke streams is the cause of the periodic component in the July/August rainfall at Armagh.

Table 4—A decadal comparison of seasonal precipitation with the mean for 1840–1997.

Period	*Characteristic*
1840–1849	Wet summers, dry winters
1850–1859	Wet summers, dry winters
1860–1869	Dry summers, wet winters
1870–1879	Dry springs, wet autumns
1880–1889	Average
1890–1899	Wet summers, dry winters
1900–1909	Slightly drier winters
1910–1919	Wet winters
1920–1929	Moderately wet winters
1930–1939	Average
1940–1949	Average
1950–1959	Wet summers
1960–1969	Wet springs, wet autumns
1970–1979	Dry summers
1980–1989	Slightly drier summers
1990–1997	Dry summers, wet winters

PRECIPITATION AND THE NORTH ATLANTIC OSCILLATION

The existence of oscillatory weather patterns for different parts of the globe has been known for some years, with El Niño probably the best-known example. The North Atlantic Oscillation (NAO) index, defined as the difference in pressure between the Azores and Iceland, causes a similarly variable weather pattern that affects the climate of Western Europe by modulation of the prevailing westerly air flow. The approximately seven-year periodicity evident in the summer rainfall at Armagh may be linked to a similar periodicity in the NAO.

Values for the NAO index have been tabulated on a monthly basis by the Climatic Research Unit of the University of East Anglia for the period 1825–1995 (see Jones *et al.* 1997). We have computed the seasonal average values for the NAO index for the period since 1838 covered by our rainfall data and subjected these to the same Fourier analysis package used previously. We find a prominent peak at 7.65 years in both the mean winter and the mean annual NAO index. As there is no corresponding periodicity in the summer NAO index, it appears, perplexingly, that the

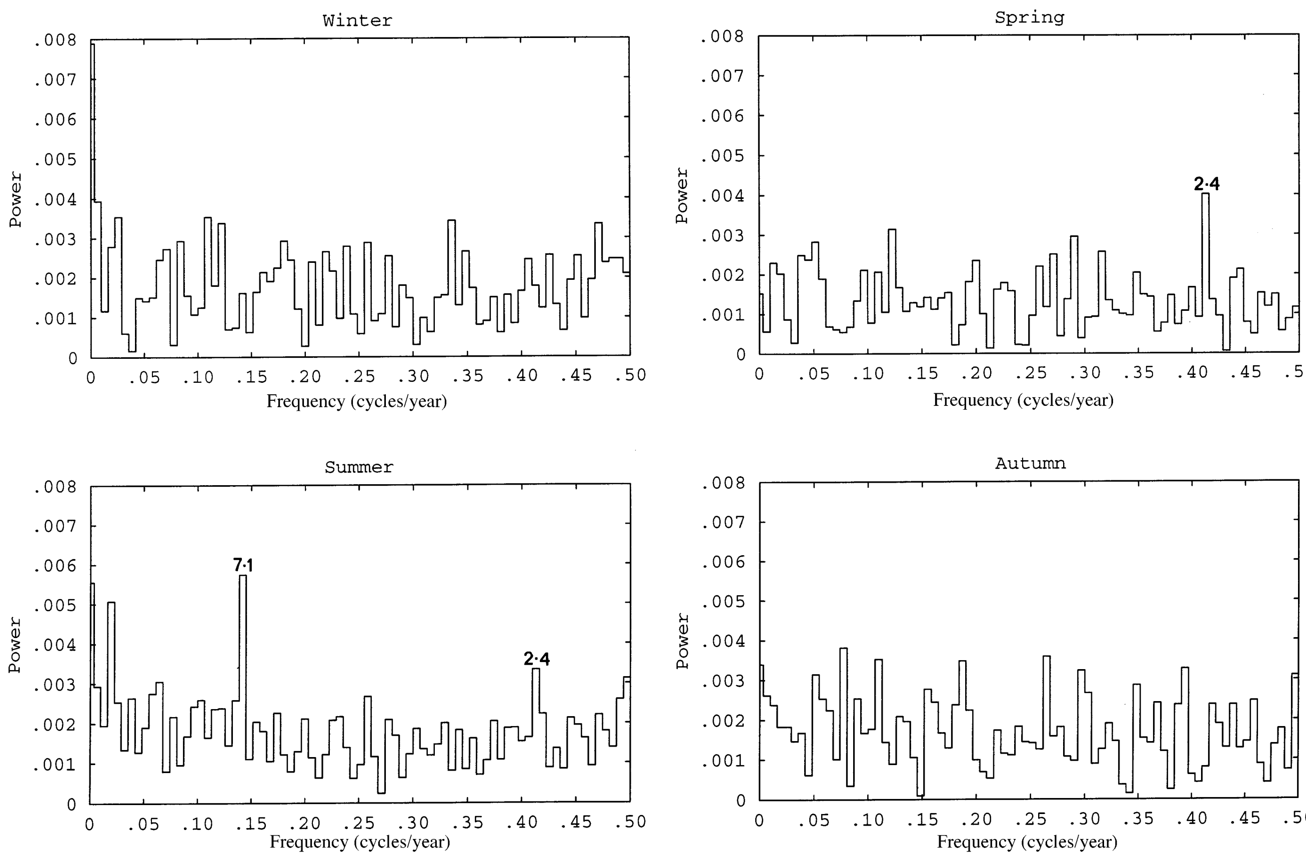

Fig. 6—Power spectra of mean seasonal precipitation. Note the periodicities of 2.4 years in the spring and summer series and 7.045 years in the summer series.

periodicity of 7.1 years in the Armagh summer rainfall may possibly be linked to a roughly similar periodicity of 7.6 years in the winter NAO index. If this is the case, we have no explanation other than that they have a common forcing.

Following the above investigation of periodicities, it was decided to check whether or not there was any direct correlation between the mean seasonal rainfall at Armagh and the mean seasonal NAO index (see Fig. 7). For the 158 common data points between 1838 and 1995, we derive the results listed in Table 5. The strongest correlation occurs between the autumnal rainfall and autumnal NAO index, with a probability of occurrence by chance of 0.002. A significant correlation is also found in winter and spring, with probabilities of occurrence by chance of <0.01 and <0.05 respectively.

Following our earlier discovery that a periodicity of seven–eight years is present in the summer rainfall and the NAO index for the previous winter, we also correlated the summer rainfall with the winter NAO index. The correlation coefficient of -0.231 goes in the opposite direction to those of the other significant correlations between seasonal rainfall and NAO index (which are all positive) and implies that a low winter NAO index leads, on average, to a higher rainfall during the following summer, with a probability of occurrence by chance of <0.02. From Table 5 and Fig. 7 we see that a high NAO index in winter leads, on average, to a higher rainfall during that season and a lower rainfall the following summer. This may be the cause of the apparent negative correlation between summer and winter rainfall seen in Fig. 5 for part of the period covered by our data.

PRECIPITATION AND THE SUNSPOT CYCLE

Grew (1952) suspected that the annual rainfall at Armagh contained a component related to the phase of the sunspot cycle. We have searched for this in our data, which covers a larger baseline, but find little evidence for any such dependence when the data for the whole series are considered. Nevertheless, it has often been noted that correlations between rainfall and sunspot cycle come and go: they may show a strong positive correlation for several decades, only to reverse the behaviour in subsequent years. The situation is complicated by the apparent dependence on geographical location. According to Clayton (1923), the British Isles lie in a region of the globe where the correlation be-

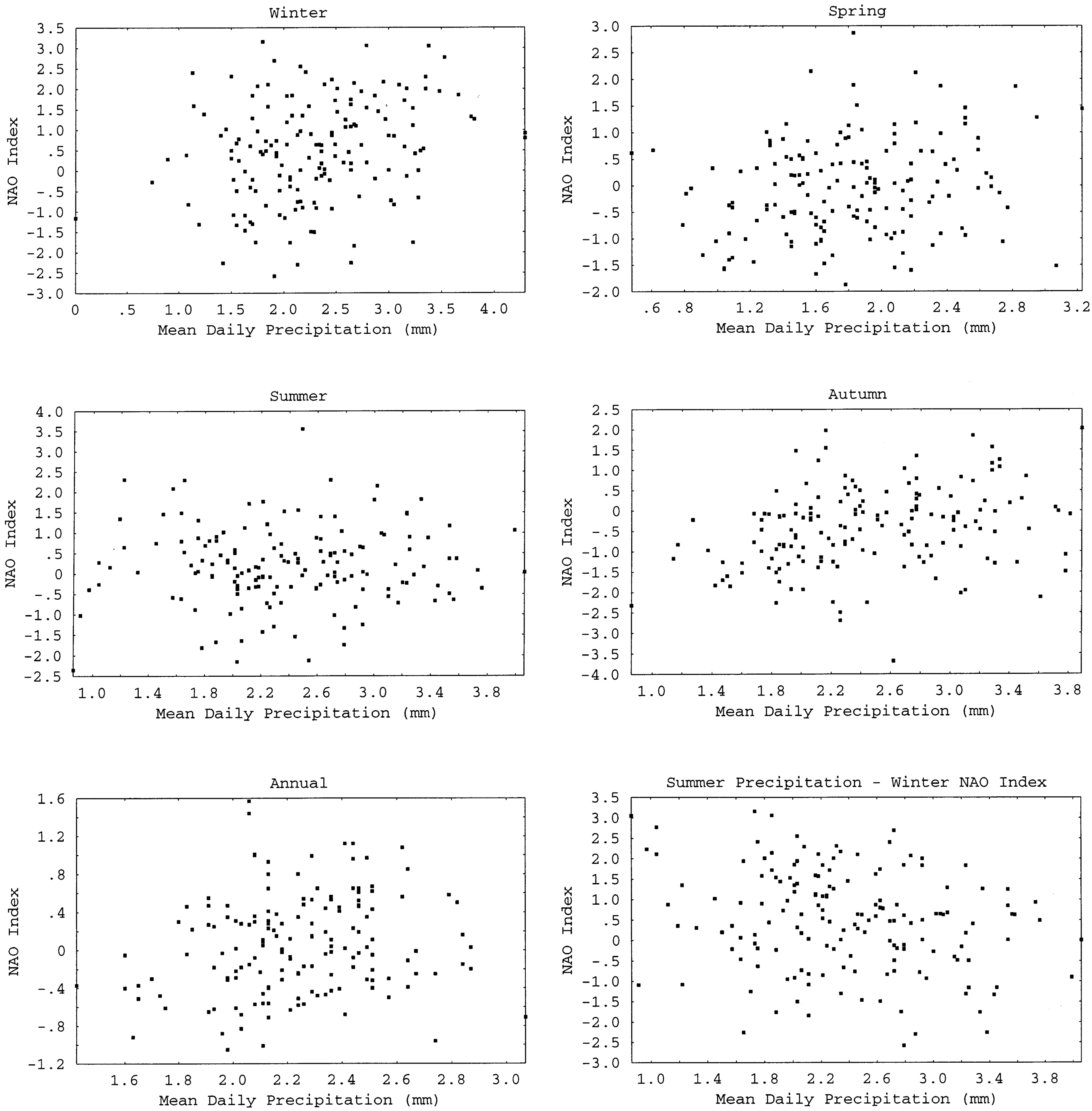

Fig. 7—Upper four panels: correlation of mean daily precipitation with the North Atlantic Oscillation index for each season; bottom left panel: correlation of annual mean daily precipitation with NAO index; bottom right panel: correlation of mean daily precipitation in summer with the NAO index for the previous winter.

tween rainfall and the phase of the sunspot cycle is weak. Our results tend to confirm this conclusion, as do the results from Kew (see King 1973).

COMPARISON OF THE PRECIPITATION AND TEMPERATURE SERIES

It is of interest to compare the trends of annual precipitation over the past century and a half with the variation in mean atmospheric temperature over the same period. In Fig. 3 (upper panel) we show the mean annual temperature from Series I and Series II of Butler and Johnston (1996), together with (lower panel) the annual precipitation listed in Table 3.

Firstly we note that the scatter in annual precipitation, in percentage terms, is about twice that for air temperature. Therefore it is more difficult to establish long- and short-term trends in precipitation than in temperature for this site. The general correspondence of the mean air temperature with the length of the solar cycle for this site has been discussed by Butler and Johnston (1996).

Secondly, we note a roughly constant upward trend, with a slope of $+0.003 \pm 0.001$mm/day/yr, in annual precipitation from the beginning of the series until approximately 1960. The only really significant departure from this trend is the dip in rainfall around 1890 close to, but possibly a little later than, a dip in mean air temperature. The generally upward trend in both mean air temperature and rainfall over the period 1890–1950 could be explained by the increased evaporation rate over the Atlantic as air temperature rises. A similar explanation would presumably be viable for the dip in temperature and precipitation around 1890. Between 1850 and 1880 the approximate correspondence between precipitation and temperature breaks down, with temperature around 1850 higher and rainfall lower than average. After 1970 the precipitation drops significantly and thereafter remains roughly at the level recorded at the beginning of the series.

CONCLUSIONS

We have presented mean monthly, annual and seasonal rainfall, corrected for instrumental sensitivity for the period 1838–1997 for Armagh Observatory. The mean annual rainfall increased steadily from 2.08mm/day at the beginning of the series to 2.39mm/day in the 1960s. Thereafter, it dropped back to its initial level. The overall change in the annual rainfall is likely to be a result of the changing circulation pattern identified by Sweeney (1985), namely a reduction since 1960 in the proportion of days on which a 'westerly' regime predominates over Ireland.

Changes are also evident in the seasonal rainfall at Armagh since 1838, with gradually increasing winter precipitation throughout the series. Summer rainfall, on the other hand, has fallen markedly since the 1970s, in line with similar findings for Great Britain (Jones and Conway 1997).

Table 5—Correlation between mean seasonal and annual rainfall and the North Atlantic Oscillation (NAO) index.

Rain	*NAO*	$R^2 (\times 10^2)$	*Significance*
Winter	Winter	6.3	$P < 0.01$
Spring	Spring	4.0	$P < 0.05$
Summer	Summer	0.2	ns
Autumn	Autumn	9.0	$P < 0.01$
Annual	Annual	2.5	ns
Summer	Winter	-5.4	$P < 0.05$

The movement of cyclonic weather patterns across Ireland is facilitated by high pressure around the Azores and low pressure over Iceland and Scandinavia. Thus it should come as no surprise that there is a correlation between the NAO index and the precipitation in Ireland. The correlation is strongest in winter and autumn. However, an apparent negative correlation between summer rainfall and the NAO index for the previous winter is more difficult to account for. It appears to indicate a hysteresis in the weather system, with the state of the NAO during the previous winter influencing the rainfall six months later.

A power spectrum analysis of the seasonal rainfall series for Armagh Observatory has given some interesting results. Although no significant periodicities are present in the winter and autumn data, a strong periodicity of 7.1 years shows up in the summer rainfall. This periodicity is stronger in the nineteenth than the twentieth century and is present in the monthly means for July and August but not June. The suggestion that the daylight Taurid meteor shower that peaks at the end of June may be responsible through the creation of aerosols by meteoric particles has been explored. It has been suggested that the Taurid complex is the principal source of interplanetary dust in the inner solar system (Whipple 1967). However, the evidence that the Taurids are linked to rainfall is conflicting, for although a seven-year interval between encounters with strong Taurid showers is predicted by a recent 'swarm' theory, other periodicities of three and four years should be at least as conspicuous. In addition, for the twentieth century no correspondence in the phase of the predicted encounters with summer rainfall peaks is seen.

A periodicity of 7.6 years in the North Atlantic Oscillation index for the winter season has been identified, which is tantalizingly close to that of 7.1 years found in the summer rainfall. As we have already noted a significant negative correlation between the winter NAO index and summer rainfall, this suggests that the periodicity in summer rainfall may be driven by the periodicity in the winter NAO index or, alternatively, that they have a common forcing.

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