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A provisional long mean air temperature series for Armagh Observatory

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Abstract—Two long mean surface air temperature series are presented for Armagh Observatory; one based on twice daily 'spot' temperature readings, 1796–1882, and the other on daily maximum and minimum temperatures, 1844–1992. Our data confirm the correlation of temperature with solar cycle length, first suggested by Friis-Christensen and Lassen (*Science* **254**, 698, 1991) and, for this site, extend their result a further 65 years, back to the end of the 18th century. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

With mounting evidence for global warming over the past two decades the study of the causes of the change in the Earth's climate has gained increasing urgency. In particular we wish to know whether anthropogenic influences, such as the increase in greenhouse gas concentration in the atmosphere, or natural causes, such as solar variability or volcanic dust, are the principal agents of change. Computer modelling of the atmosphere provides a valuable tool to investigate the effects of such primary causes but, due to our poor understanding of all the mechanisms involved, it may give us false confidence in the state of our knowledge.

A case in point is the influence on climate of solar variability and in particular the influence of the various manifestations of solar activity such as enhanced X-ray and extreme ultraviolet radiation from the Sun. At present, our knowledge of how solar activity may influence climate is in a primitive state with many contending theories but very little direct evidence to support one mechanism over another. This has led meteorologists to ignore such influences until such time as there is agreement, first on how important they are, and secondly, on the physical mechanism responsible.

One way round this difficulty is to look at historical temperature series, either from instrumental measurements made over recent centuries, or proxy measurements of some related parameter, such as C_{14} concentration in tree rings, which can be determined over much longer time intervals. With all such series it is important to establish whether the effects one sees are global or local. Once a global temperature series has been established, the influences of the variations in the suspected contributory factors can be correlated with temperature and conclusions drawn as to their relative importance, for past climatic change. Then, if a correlation has been firmly established, even without a fully understood physical mechanism, it is possible to make some predictions as to how variability of the contributory factors may influence climate in the future.

One of the difficulties in establishing a global mean temperature series is that, prior to this century, only very few meteorological stations operated and these were mostly situated in Europe and North America. Thus the variation of the northern hemisphere climate is better known than that of the southern hemisphere but neither is accurately known prior to the middle of the last century.

Attempts to derive temperature series earlier than the second half of the 19th century are beset with many difficulties, such as: (i) significant errors in the thermometers which may be greater in magnitude than the actual temperature variation; (ii) changes in the siting of instruments; (iii) urban encroachment in the vicinity of the station; and (iv) gaps in coverage leading to a lack of continuity. To overcome some of these difficulties, several long temperature series have been formed by combining the data from a number of stations in certain geographical areas; e.g. central England (from 1659) or the eastern United States (from 1738). However, such composite series, where a station that goes out of operation is replaced by another, may suffer from hidden discrepancies caused by the shifts required to superimpose data from different sites, shifts which in general are of the same order of magnitude as the secular variation one is trying to establish. Thus long series from a single site can be of exceptional value if changes in the site and observing techniques have been minimal and observations made in a conscientious manner.

The series made at Armagh, Northern Ireland, which is one of the longest in the British Isles, is believed to be a particularly valuable record for the following reasons.

- The small diurnal and annual range in temperature in Northern Ireland implies a smaller statistical uncertainty in the mean temperature than for a more continental site.
- With a strongly maritime climate, temperatures are coupled to and moderated by those of the Atlantic Ocean. As a result, the temperature at Armagh is likely to be more representative of a large region and less affected by local influences than many more continental stations.
- There have been relatively few changes in the siting of the instruments which have been situated at the centre of the Observatory's 20 acre site on the top of a drumlin (small hill) in Armagh City.
- The relatively small effect of urban encroachment of the site. The population of Armagh has been roughly constant at 8000–14,000 people since the early 19th century. In addition any urban microclimate effect will be minimized by the windy maritime conditions.
- The great interest in meteorology of the third director, T.R. Robinson (inventor of the Cup Anemometer), and the longevity of his directorship (59 years) ensured a careful and conscientious approach to recording meteorological data at a time when this was less common than today.

AIR TEMPERATURE RECORDS AT ARMAGH OBSERVATORY

Daily air temperature measurements have been made at Armagh Observatory (longitude 6°38.9′ W, latitude 54°21.2′ N, altitude 64 m) from 1795 to the present day, excluding a period of nine years, from 1825 to 1833, for which no data have so far been found. Five main series exist. Series I—twice daily 'spot' external air temperature measurements, 1795–1825 and 1833–1882. Series II—daily maximum and minimum external temperatures, 1843–1993. Series III—wet and dry thermometer readings, once per day, sporadically, 1836–1843; twice daily, regularly, 1844–1883; once daily, regularly 1884–1991. Series IV—twice daily temperatures inside an unheated room from a thermometer attached to the barometer, 1795–1883. Series V—hourly wet and dry temperatures from the Automatic Weather Station operated at Armagh Observatory from 1869 to 1882 by the Board of Trade. Here we consider only the first two of these series, although we shall also refer, for calibration purposes, to Series V. Our results are provisional in the sense that they may possibly be modified in the future if additional or improved calibrations for thermometers become available. Also, to reduce the labour involved in this study, corrections for thermometer errors have been made to monthly means, rather than daily values. Future computerization of the data will facilitate correction on a daily basis.

Table 1. Greenwich mean time of 'spot' temperature measurements

Period	Morning	Evening
1 Jul 1795–31 May 1825	8:27	20:27
1 Jan 1833–30 Jun 1850	10:27	22:27
1 Jul 1850–31 Mar 1852	9:27	21:27
1 Apr 1852–18 Jan 1859	9:25	21:25
19 Jan 1859–3 Jan 1882*	10:25	22:25
4 Jan 1882–31 Dec 1882	10:00	22:00

* For the month of December 1861, readings were taken at 9:25 am/pm GMT.

Series I—external 'spot' temperature records

The 'external' temperature records, beginning in 1795, were initially made three times a day, at 8 am, noon and 8 pm, local time. From 1833, only twice daily measurements were recorded: at 10 am and 10 pm, local time. Later in the 19th century times of observation changed to first Irish Civil Time (Dublin Local Time) and later to Greenwich Mean Time. In Table 1, we list the GMT times at which 'spot' temperature measurements were made up until the date they ceased, 31 December 1882. Later we explain how twice daily 'spot' temperatures can be corrected for observation time and converted to a standard mean.

We have no certain evidence as to the identity of the thermometer used for the early measurements, 1795–1825; however, we believe it highly likely that a thermometer by Troughton, which was recorded in an early Observatory inventory, C 1796 (see M/S M91, Butler and Hoskin, 1987) and was found to be still in use at the Observatory in 1823 when Robinson arrived, was most likely employed. Robinson subsequently continued this temperature series (from 1833), using the same thermometer. With reference to this thermometer he remarked "It appears to have been made with great care; the freezing and boiling points are exact, and by comparison of the points within the annual range of temperature, I have not found an error greater than 0.2°(F)". The Troughton Thermometer was unfortunately broken in 1859, after which it was replaced by a Kew standard, which was employed until the series ended in December 1882. This second thermometer was, in October 1890, checked against a standard belonging to Mr Scott of the Meteorological Office, and also found to be accurate to within 0.2°F. In view of the reported accuracy of these two thermometers and the absence of any detailed calibration data we have assumed a thermometer error of zero for both instruments.

It is important to ascertain the siting and exposure of the early thermometers during use. Robinson reports that, in 1823, when he arrived, the thermometer was placed outside the NE tower and subsequent to the construction of the East Dome, in 1827, was "established at (outside) a north window of the eastern tower of the Observatory, about 4 feet above the (Mural) circle's centre, and twelve feet from it in a horizontal direction, enclosed in a double casing of light metal, which admits free access to air, but screens it from radiation". These two sites would have been within a few metres of each other. The external thermometer is believed to have continued in this second position for the remainder of the Series, and indeed the metal casing is still there today (see Fig. 1). The height of the thermometer casing is 3.35 metres above current ground level. The adjacent buildings were not heated at the time of the use of the external thermometer and it is unlikely that there would be any systematic differences, due to exposure, between the readings made prior to and following 1827.

Accepted definitions of mean temperature vary; the most precise would be from continuous temperature records; however, such records are not available prior to the mid-19th century, and even then for very few sites. It is common practice to define the mean temperature as the mean of the daily maximum and minimum temperatures. The mean of twice daily 'spot' temperatures can be accurately converted to the mean of maximum and minimum by a simple zero-point correction; however, as our external 'spot' temperatures were not always made at the same time of day (see Table 1), the corrections applied must take this into account. The corrections have been determined using published continuous and hourly temperature recordings made at Armagh by the Automatic Weather Station set up by the Board of Trade in 1869 and operated until the end of 1882 (see Bennett, 1990, pp. 134–135). In Fig. 2, we show the mean monthly spot temperature at 8:30, 20:30 GMT against the monthly mean of the maximum and minimum temperatures, also derived from the Automatic Weather Station. In Table 2, we list the corrections determined from the regression lines of monthly mean 'spot' temperature at 8:30, 9:30 and 10:30 GMT and the monthly mean of maximum and minimum for 6 years during the period 1869–1882. The correction appears to be stable over this period. In Table 3 we list the mean annual observed 'spot' temperature 1796–1882, corrected to the scale of mean maximum and minimum used in Series II.

Series II—the maximum and minimum temperatures at Armagh Observatory, 1843–1992

In 1843, T.R. Robinson purchased maximum and minimum thermometers by Newman and included daily maximum and minimum readings in the duties of the assistant from 3 August of that year. Initially readings were made in the evening, but from 1 April 1852, readings were switched to the morning.

The thermometers were initially placed in the same ventilated metal box as the external thermometer and remained there till 1 January 1885 when they were transferred to a Stevenson Screen 43 m south of the earlier site. In 1987 the Stevenson Screen was moved a further 32 m south where it has since remained.

Regrettably, in May 1860, the maximum thermometer by Newman was broken and readings had to be continued using a 'Garden Maximum' until the arrival in December 1860 of a second maximum thermometer by Casella. No calibration data for the Newman Maximum have been found and therefore we have assumed its correction to be zero. The 'Garden Maximum' survives and has been calibrated recently. Maximum and minimum thermometers in use prior to 1900 are listed in Table 4. Note that this table differs from a previously published table by Butler (1994) in that we now believe the thermometer error of Negretti 3404 may have been more stable than was indicated in Dreyer's notes (we now assume that a single correction of −1.0°F applied from 1882 to 1899), and the inclusion of temperature dependent corrections for the Casella Maximum and the Newman Minimum described below.

The calibration of the early maximum and minimum thermometers was carried out on an occasional basis prior to 1900. During the period when J.L.E. Dreyer was director, 1882–1916, corrections were inscribed in the back of the original record books, but these were not applied to the readings before entry until after 1905, by which time thermometers were in any case generally reliable to 0.1°F. Publications by the Meteorological Office (Scott, 1884–1910) which purported to list maximum and minimum temperatures for Armagh, corrected for thermometer error, did not in fact always do so, as subsequent

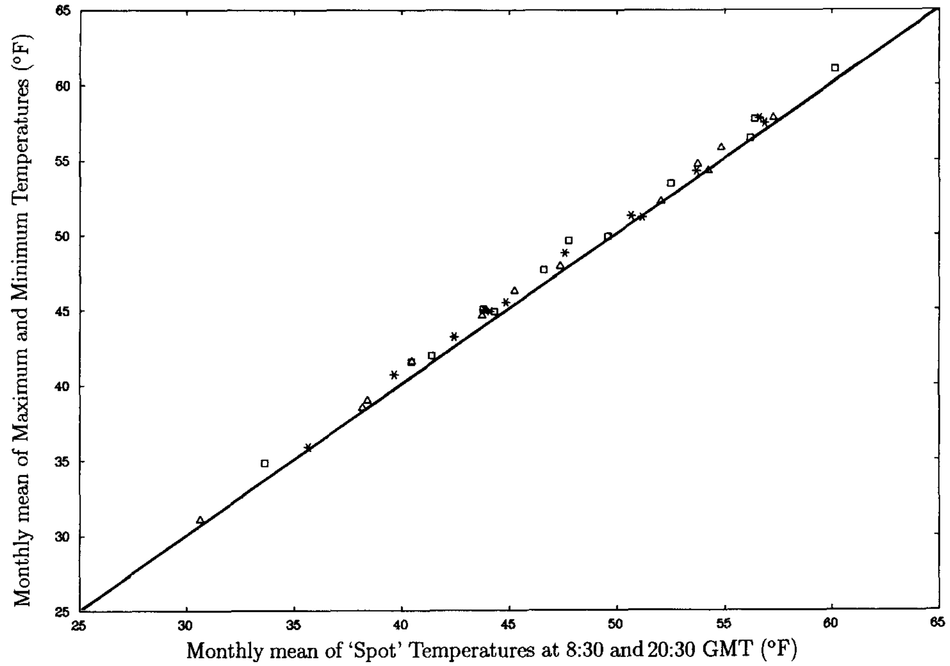

Fig. 2. Monthly mean of maximum and minimum temperatures against the monthly mean of 'spot' temperatures at 8:30 and 20:30 GMT for the years 1874 (squares), 1881 (triangles) and 1882 (asterisks). The relation $T_{\mathrm{Max,Min}} = T_{8:30,20:30}$ is shown. Note that there is a simple zero-point shift between the two 'means'.

studies have shown. Therefore our data are taken from the original sources.

The individual thermometer errors listed vary as a result of measuring errors, the standards used, and actual physical changes in thermometers with time. Usually, prior to *c.* 1900, only a single zero-point correction is given. Where possible, we have attempted to determine temperature dependent errors for the early thermometers, and, in some cases, these appear to be appreciable. This has been made possible by comparison with the records of the Automatic Weather Station which incorporated a photographically recording thermograph, (see Fig. 3). The temperature dependent thermometer errors for the Newman Minimum Thermometer, in use 1843–1882, and the Casella Maximum Thermometer, in use 1860–1882, are listed in Table 4. In Table 5, we list the mean annual observed maximum and minimum temperatures, corrected for thermometer error according to Table 4, on a monthly, rather than a daily, basis. The reality of the temperature dependent corrections is somewhat problematical as such effects could be a consequence of differences in exposure between the maximum and minimum thermometers in the metal box and the thermograph of the automatic weather station. However, we note the finding by Parker (1994) that mean temperatures from north wall screens have little or no overall bias compared to mean temperatures from Stevenson screens.

In Fig. 4 we show the mean annual maximum, minimum and mean temperatures, 1844–1992, together with smoothed running means. We note the rather similar behaviour of the mean maximum and minimum temperatures; high in the 1840–1860 period, low from 1880 to 1900 and rising in the 20th century to a peak around 1950, followed by a shallow minimum around 1970 and a subsequent further rise to current

Table 2. Zero point corrections (°C) applied to mean 'spot' temperatures to convert to the scale of mean of maximum and minimum

Year	Observation time (GMT)		
	8:30, 20:30	9:30, 21:30	10:30, 22:30
1869	0.32	—	—
1874	0.73	0.52	0.11
1876	0.41	0.34	0.08
1878	0.49	—	—
1881	0.32	0.20	−0.11
1882	0.36	0.29	−0.11
Adopted Means °C	0.39	0.34	0.00

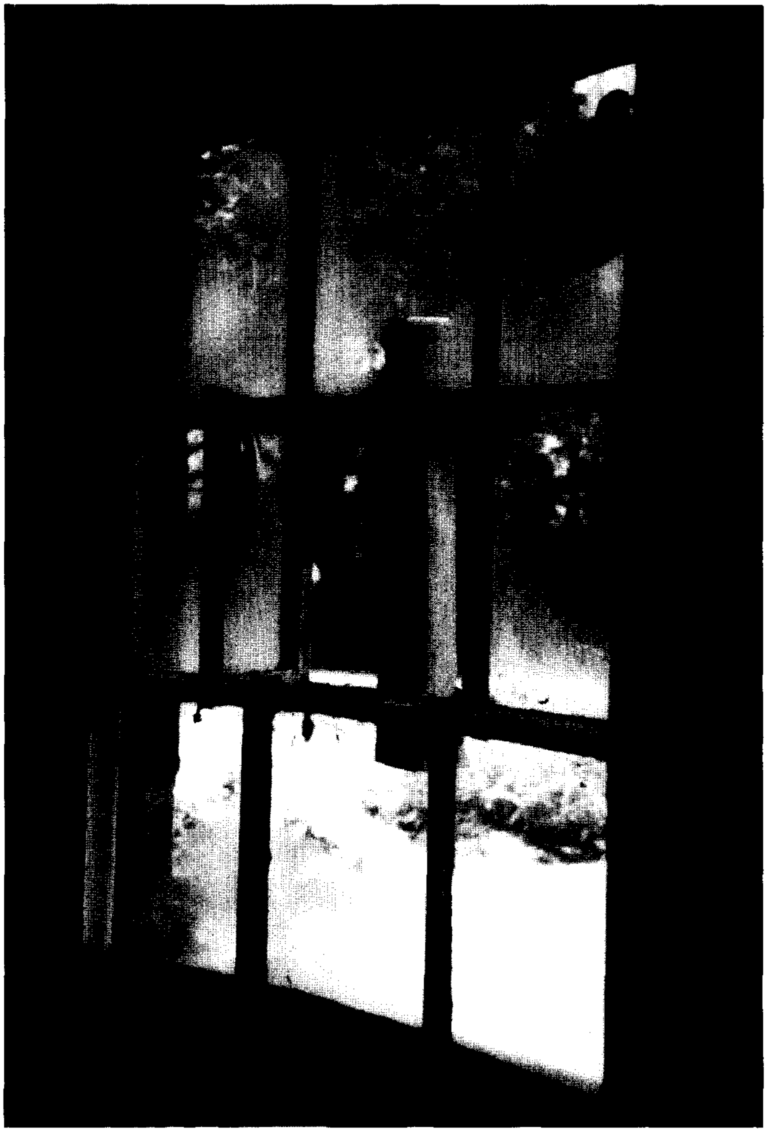

Fig. 1. The light metal box, placed in the north window of the Eastern Tower at Armagh Observatory which contained the 'external' and maximum and minimum thermometers prior to their removal to a Stevenson Screen in 1885. The hinged central pane of the upper window sash allows access to the thermometers from an inside staircase. Adjacent buildings were unheated at the time.

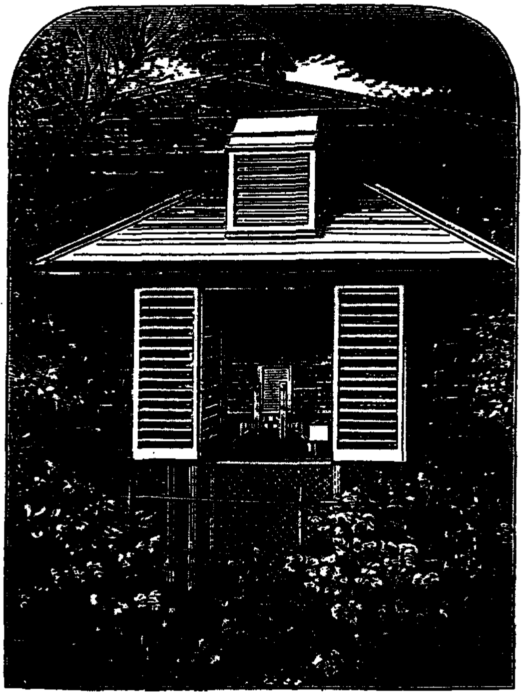

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Fig. 3. The continuously recording thermograph screen on the north wall of the Meteorological House, erected at Armagh Observatory by the Board of Trade in 1869 (from the *Quarterly Weather Report of the Meteorological Office for* 1870, HMSO, London).

Table 3. Series I—provisional annual mean temperatures, 1796–1824, 1834–1882. Mean annual observed 'spot' temperature and equivalent to mean of maximum and minimum

Year	Annual mean spot temp. °C	Equivalent mean of Max/Min °C	Year	Annual mean spot temp. °C	Equivalent mean of Max/Min °C
1796	7.4	7.9	1844	8.9	8.9
1797	8.3	8.7	1845	8.9	8.9
1798	8.1	8.5	1846	9.8	9.8
1799	6.8	7.2	1847	9.2	9.2
1800	8.0	8.4	1848	8.7	8.7
1801	8.8	9.2	1849	8.9	8.9
1802	7.4	7.8	1850	9.2	9.4
1803	8.1	8.5	1851	9.1	9.4
1804	8.0	8.4	1852	9.1	9.4
1805	7.8	8.2	1853	8.2	8.6
1806	8.2	8.6	1854	9.0	9.4
1807	7.8	8.2	1855	8.2	8.5
1808	8.1	8.5	1856	8.9	9.3
1809	8.2	8.6	1857	9.8	10.2
1810	8.3	8.7	1858	9.1	9.4
1811	8.9	9.3	1859	9.2	9.2
1812	7.8	8.1	1860	7.4	7.5
1813	7.4	7.8	1861	9.0	9.0
1814	7.3	7.7	1862	9.0	9.0
1815	8.8	9.2	1863	9.1	9.0
1816	7.2	7.6	1864	8.4	8.5
1817	7.5	7.9	1865	9.3	9.3
1818	8.2	8.6	1866	8.9	8.9
1819	7.5	7.9	1867	8.7	8.7
1820	7.6	8.0	1868	9.5	9.5
1821	8.3	8.7	1869	8.9	8.9
1822	8.4	8.8	1870	8.6	8.6
1823	7.2	7.6	1871	8.9	8.9
1824	8.4	8.8	1872	9.0	9.0
—	—	—	1873	8.7	8.7
1834	9.8	9.8	1874	9.1	9.1
1835	8.9	8.9	1875	9.2	9.2
1836	8.7	8.7	1876	9.0	9.0
1837	8.8	8.8	1877	8.7	8.7
1838	7.9	8.0	1878	8.9	8.9
1839	8.2	8.2	1879	7.4	7.4
1840	8.4	8.4	1880	8.9	8.9
1841	8.5	8.5	1881	8.1	8.1
1842	8.1	8.0	1882	8.8	9.0
1843	9.0	9.0	—	—	—

levels. Also we note the exceptionally high minima for the period prior to the 1880s, particularly in 1846, the year of the great Irish Famine.

Comparison of Series I and Series II mean temperature

Over the period 1844–1882, both external thermometer measurements and maximum and minimum temperatures were recorded. This makes it possible to compare the two series and check for systematic errors due to changes in the thermometers. In Fig. 5 we show the difference between Series I and Series II mean temperatures as a function of time. We note: (i) that Series II appears to be systematically warmer than Series I prior to 1850;* (ii) a discontinuity in 1859, following the replacement of the Troughton ther-

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*It has been pointed out by the referee that this may be due in part to the switch in the time of reading the maximum and minimum thermometers from evening to morning from 1 April 1852. However, the differences for 1850/1851 appear to be consistent with later values. In view of this, no adjustments have been made to Series II for the times of reading of the maximum and minimum thermometers.

Table 4. Corrections for maximum and minimum thermometers in use from 1843 to 1900

Type	Thermometer	Period of use	Range °F	Correction °F
Maximum	Newman	Dec 1843–May 1860	—	—
	Casella 'Garden'	May 1860–Dec 1860	Full	−0.1
	Casella	Dec 1860–Sep 1882	$T < 52$	−2.0
			$T = 55$	−2.5
			$T = 60$	−3.0
			$T > 60$	−3.0
	Negretti 3404	Oct 1882–Oct 1899	Full	−1.0
Minimum	Newman	Dec 1843–Sep 1882	$T < 38$	+1.0
			$T = 40$	+0.8
			$T = 45$	+0.1
			$T = 50$	−0.5
			$T = 55$	−1.2
			$T > 55$	−1.2
	Casella 427	Oct 1882–Nov 1899	Full	+0.0

mometer with the Kew standard; (iii) a systematic discrepancy in 1860, the year during which the maximum thermometer was broken and a Garden Maximum used; and (iv) a positive discrepancy in 1861–1862, after the installation of the Casella Maximum. We believe the latter suggests that the Casella Maximum may have not had such a large negative error in the first year of its use, but that the error developed in the period 1860–1863 and thereafter remained relatively stable. It has not been possible to provide a detailed calibration of this thermometer prior to 1869 when the Automatic Weather Station came into operation; however,the roughly constant differences in Fig. 5, from 1868–1882, suggest that during this period the thermometer had developed a large, but constant, error which is satisfactorily removed by the calibration given in Table 4. Figure 5 suggests that there may be a systematic difference of ~0.1°C in the mean temperatures, determined above, in the sense that Series I is approximately 0.1°C cooler than Series II.

THE VARIATION IN THE MEAN TEMPERATURE AT ARMAGH AND THE POSSIBLE LINK TO THE LENGTH OF THE SUNSPOT CYCLE

The suggestion that solar activity, as manifested by the appearance of sunspots, might influence climate has been made many times over the past one and a half centuries. Herman and Goldberg (1978) have exhaustively discussed the arguments for and against this proposal and concluded that, though the evidence was often inconclusive in any particular study, there was sufficient cumulative evidence in favour to justify its continued serious consideration. For most studies, the sunspot number has been the parameter commonly used as a solar activity index. Recently, however, Friis-Christensen and Lassen (1991) showed that if the length of the solar cycle were considered, rather than its amplitude, then a strikingly dramatic agreement in behaviour was found with that of the northern hemisphere mean air temperature.

Their comparison extended back to 1865. Prior to 1860, it becomes increasingly difficult to establish a global mean temperature due to the small number of stations operating. Therefore for comparison at earlier times, regional data must be used. Our data allow the comparison to be extended, for this site at least, to the end of the 18th century.

The solar cycle length is known with reasonable precision back to the middle of the 18th century and, prior to 1860, shows (after inversion) two peaks, one at *c.* 1760 and the other at *c.* 1840. If the Friis-Christensen and Lassen (1991) correspondence is valid, we would expect the mean air temperature to peak near these decades. Our data, shown in Fig. 6(b) suggest that the temperatures in Ireland were indeed higher than average in the 1840–1860 period. The effect is seen in both Series I and Series II data. The higher than average temperatures that occurred in Ireland at this time may have contributed to the Great Famine which was caused by fungal attack of the potato crop during the second half of the decade 1840–1850. In Series II, the highest mean maximum occurred in 1846, the first year of the Great Famine. However, 1846 appears marginally less extreme in Series I as the third highest annual mean temperature, after 1857 and 1834. The crucial factor for potato blight,

Table 5. Series II—provisional annual mean maximum, minimum and mean of maximum and minimum temperatures, 1844–1992*

Year	Maximum °C	Minimum °C	Mean °C	Year	Maximum °C	Minimum °C	Mean °C
1844	12.4	6.1	9.2	1904	12.3	5.3	8.8
1845	12.2	6.0	9.1	1905	12.7	5.5	9.1
1846	13.6	7.4	10.5	1906	12.8	5.3	9.0
1847	12.7	6.5	9.6	1907	12.2	5.2	8.7
1848	12.6	5.8	9.2	1908	13.1	5.8	9.4
1849	12.9	6.3	9.6	1909	12.2	4.8	8.5
1850	12.7	6.5	9.6	1910	12.6	5.3	8.9
1851	12.7	6.3	9.5	1911	13.2	5.4	9.3
1852	12.8	6.3	9.6	1912	12.3	5.2	8.8
1853	11.7	5.5	8.6	1913	12.8	5.6	9.2
1854	12.3	6.2	9.3	1914	13.1	5.6	9.3
1855	11.7	5.6	8.7	1915	12.3	4.7	8.5
1856	12.4	6.6	9.5	1916	12.6	5.3	8.9
1857	13.3	7.3	10.3	1917	12.1	4.9	8.5
1858	12.9	6.5	9.7	1918	12.8	5.5	9.2
1859	13.2	6.3	9.8	1919	12.3	4.6	8.4
1860	11.1	5.2	8.1	1920	12.8	5.7	9.3
1861	11.3	6.1	8.7	1921	13.8	6.4	10.1
1862	10.1	6.1	8.1	1922	12.0	5.0	8.5
1863	11.7	6.2	8.9	1923	12.2	5.5	8.8
1864	11.4	5.4	8.4	1924	12.3	5.6	9.0
1865	12.3	6.4	9.4	1925	12.4	5.2	8.8
1866	11.6	6.1	8.9	1926	12.9	5.8	9.4
1867	11.3	6.1	8.7	1927	12.5	5.3	8.9
1868	12.6	6.7	9.6	1928	12.7	5.5	9.1
1869	12.1	6.2	9.2	1929	12.6	5.1	8.8
1870	12.1	5.7	8.9	1930	12.3	5.3	8.8
1871	12.1	6.2	9.1	1931	12.3	5.6	8.9
1872	12.0	6.3	9.1	1932	12.9	5.5	9.2
1873	11.8	5.9	8.8	1933	13.3	5.9	9.6
1874	12.3	6.1	9.2	1934	13.1	6.0	9.6
1875	12.3	6.3	9.3	1935	12.9	5.6	9.2
1876	12.3	6.1	9.2	1936	12.7	5.5	9.1
1877	11.8	5.8	8.8	1937	12.7	5.6	9.1
1878	12.1	6.0	9.1	1938	13.3	6.1	9.7
1879	10.4	4.7	7.6	1939	13.2	5.6	9.4
1880	12.2	6.1	9.1	1940	13.1	5.4	9.3
1881	11.3	5.3	8.3	1941	12.7	5.6	9.2
1882	12.0	6.1	9.0	1942	12.9	5.6	9.3
1883	11.0	5.6	8.3	1943	13.4	6.3	9.9
1884	11.8	5.9	8.9	1944	13.3	5.8	9.6
1885	11.5	4.4	7.9	1945	14.0	6.6	10.3
1886	11.1	4.6	7.8	1946	12.9	5.6	9.2
1887	11.8	4.6	8.2	1947	12.7	5.6	9.1
1888	11.3	4.6	8.0	1948	13.5	5.9	9.7
1889	11.9	5.4	8.7	1949	14.2	6.2	10.2
1890	12.0	5.3	8.6	1950	12.7	5.5	9.1
1891	11.8	4.7	8.3	1951	11.8	5.4	8.6
1892	11.2	4.1	7.6	1952	12.5	5.1	8.8
1893	12.7	5.7	9.2	1953	13.6	6.1	9.8
1894	11.9	5.1	8.5	1954	12.6	5.6	9.1
1895	11.5	4.3	7.9	1955	13.2	5.4	9.3
1896	12.2	5.3	8.8	1956	12.7	5.6	9.2
1897	12.1	5.2	8.6	1957	13.3	6.1	9.7
1898	12.7	5.9	9.3	1958	12.8	5.9	9.3
1899	12.8	5.7	9.3	1959	14.2	6.1	10.2
1900	12.7	5.4	9.0	1960	13.2	5.6	9.4
1901	12.6	5.2	8.9	1961	13.2	5.8	9.5
1902	12.1	5.3	8.7	1962	12.6	4.9	8.7
1903	12.3	5.4	8.9	1963	12.1	4.8	8.5

Table 5—*Continued.*

Year	Maximum °C	Minimum °C	Mean °C	Year	Maximum °C	Minimum °C	Mean °C
1964	12.9	5.9	9.4	1979	11.7	4.8	8.3
1965	12.4	5.1	8.8	1980	12.6	5.5	9.0
1966	12.8	5.8	9.3	1981	12.5	5.5	9.0
1967	13.1	5.6	9.3	1982	13.1	5.5	9.3
1968	13.2	5.4	9.3	1983	13.2	6.1	9.7
1969	12.6	5.2	8.9	1984	13.1	5.3	9.2
1970	12.9	5.6	9.2	1985	12.2	5.1	8.6
1971	13.4	5.9	9.7	1986	12.0	5.2	8.6
1972	12.7	4.7	8.7	1987	12.6	5.2	8.9
1973	12.9	5.6	9.3	1988	13.0	5.9	9.5
1974	12.5	5.4	8.9	1989	13.7	6.1	9.9
1975	13.5	5.9	9.7	1990	13.4	6.3	9.9
1976	12.9	5.5	9.2	1991	12.9	5.9	9.4
1977	12.5	5.3	8.9	1992	12.9	5.9	9.4
1978	12.4	5.9	9.1	—	—	—	—

* Data corrected for thermometer error on a monthly basis according to Table 4.

however, may be that the mean minimum computed for 1846 was exceptionally high (7.4°C); higher even than in recent decades.

In Fig. 6 we may note several pertinent points. First, there appears to be good overall correspondence between the sunspot cycle length and the mean temperature measured at Armagh since 1796. Secondly, there appears to be a delay of about a decade in the temperature maxima, in Fig. 6(b), compared to the maxima in Fig. 6(c) (sunspot cycle length inverted). This could possibly result from the thermal inertia of the Atlantic Ocean.

In Fig. 7, we show the mean temperature at Armagh, averaged over 11 year intervals centred on years of sunspot maximum and minimum, plotted directly against the length of the sunspot cycle (in

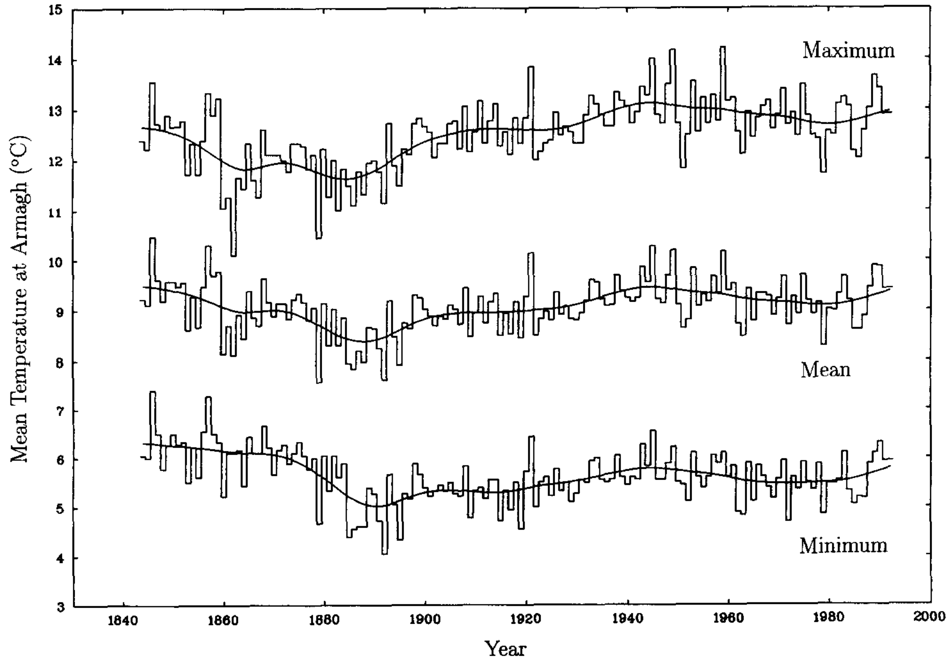

Fig. 4. Annual mean maximum, minimum and mean temperatures 1844–1992 (Series II). The smoothed curves are running means with a Gaussian profile of 5 years half-width.

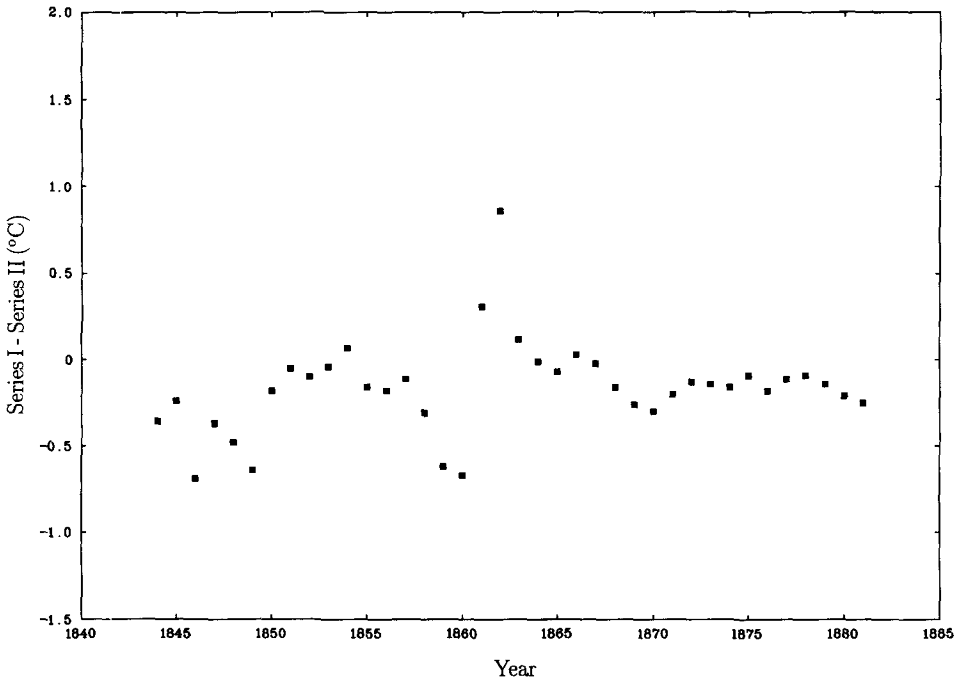

Fig. 5. Differences between Series I and Series II annual mean temperatures for the period in common 1844–1882. Note the discrepant points 1859–1862. The following factors may be partly responsible: (1) the original Troughton thermometer, used for 'spot' temperatures, was broken in 1859; (2) the Casella Maximum thermometer was broken in 1860; and (3) a Garden Maximum thermometer was employed for much of 1860.

years). A clear correlation is shown. The mean regression line T_{ARM} (in °C) = $14.42-0.5L_{SC}$ has been established from the data. The fact that the variance of the residuals from this regression line is only a quarter of the variance of the original data, suggests that solar activity, or something closely related to it, has been a dominant influence on the temperature of the lower atmosphere over the past 197 years. This does not imply that greenhouse gases would not be responsible for significant changes in the future, but it suggests that they have not been the principal agent of change over the past two centuries.

In the above discussion we have, following Friis-Christensen and Lassen (1991), used a value for the sunspot cycle length which has been smoothed with a long baseline filter. In the Appendix we discuss the measurement of the cycle length, the use of smoothing filters, and give the correlation coefficients for the various alternatives.

COMPARISON OF THE ARMAGH TEMPERATURE SERIES WITH THE CENTRAL ENGLAND AND EASTERN UNITED STATES SERIES

In Fig. 6, we show the running mean of the mean annual temperature for central England and the eastern United States, as given by Lamb (1977) and extended by Parker *et al.* (1992). It would be expected that the Armagh data would follow the central England variation closely, however, there are distinct differences. From Fig. 8, we note the following: (i) The amplitude of the variation in temperature at Armagh is slightly greater than that of the central England series. (ii) The general behaviour of the variation from 1860 to the present is similar, with peaks and troughs at roughly similar times, with the exception of the last minimum, which occurred in the late 1960s in central England, but did not reach its minimum at Armagh until the late 1970s. Thus the recent warming only began to take effect in Ireland after 1980, a decade later than in central England and the northern hemisphere generally. (iii) The peak in temperature at Armagh in the 1840–1860 period is not obvious in the Central England Series. Similarly, an earlier peak, *c.* 1830, which is seen in the Central England Series, is not evident in the Armagh data. However, this could be due, at least in part, to the break in the data at Armagh from 1825 to 1833. (iv) The agreement in trends between the Armagh series and the sunspot cycle length is not repeated with the central England and eastern United States data. Whilst this would mitigate against the suggestion that the effect is

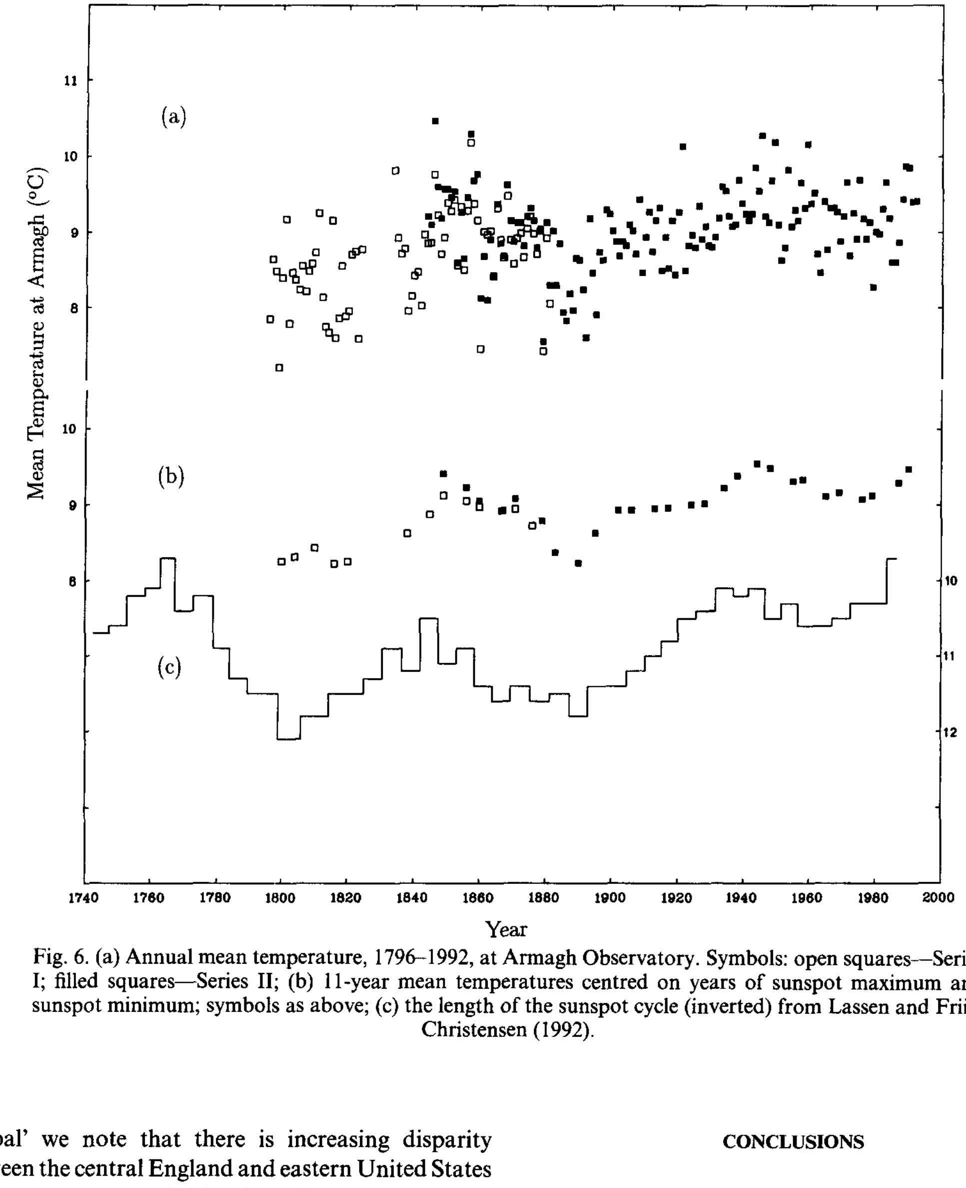

Fig. 6. (a) Annual mean temperature, 1796–1992, at Armagh Observatory. Symbols: open squares—Series I; filled squares—Series II; (b) 11-year mean temperatures centred on years of sunspot maximum and sunspot minimum; symbols as above; (c) the length of the sunspot cycle (inverted) from Lassen and Friis-Christensen (1992).

'global' we note that there is increasing disparity between the central England and eastern United States series as one moves further back in time, suggestive that the earlier data become increasingly less reliable. (v) Finally, we note that for Armagh the mean temperature was low at the end of the 18th century and the beginning of the 19th century and that this dip is a less conspicuous feature of the central England series. Though the Armagh Series I temperatures at this time are heavily dependent on the calibration of the 'external' thermometer and the corrections made for changes in the time of measurement, this period has been often reported in the literature as being significantly cooler than average (see Groveman and Landsberg, 1979, and Hameed and Gong, 1993), in agreement with our results.

CONCLUSIONS

Our data are derived from two independent temperature series, both of which show a rise in temperature in Ireland in the period 1840–1860, roughly coincident, though slightly delayed, with a reduction in the length of the sunspot cycle. Thus our data confirm a link between solar activity and the mean air temperature similar to that found by Friis-Christensen and Lassen (1991) over a more restricted interval.

How the solar dynamo, responsible for magnetic activity such as sunspots, can significantly change the temperature of the troposphere, is currently unknown. However, it is pertinent to note that Nimbus-ERB and SMM-ACRIM measurements given by Kyle *et al.*, 1993, show a significant increase in solar lumin-

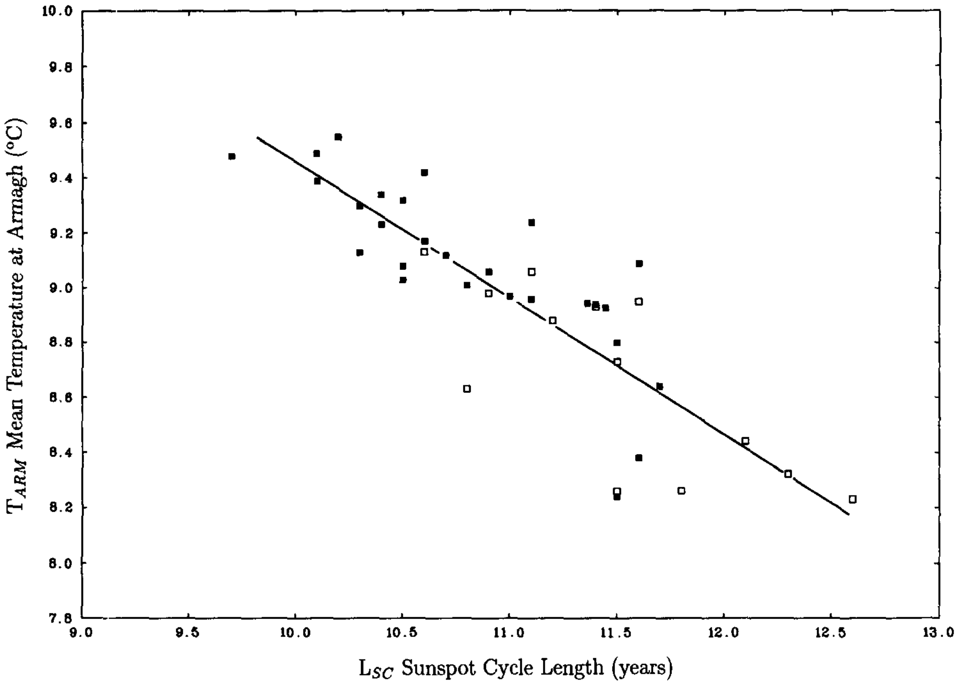

Fig. 7. The mean temperature at Armagh for 11-year intervals, centred on years of sunspot maximum and minimum, plotted against the sunspot cycle length. Symbols: open squares—Series I; filled squares—Series II. The mean regression line is shown.

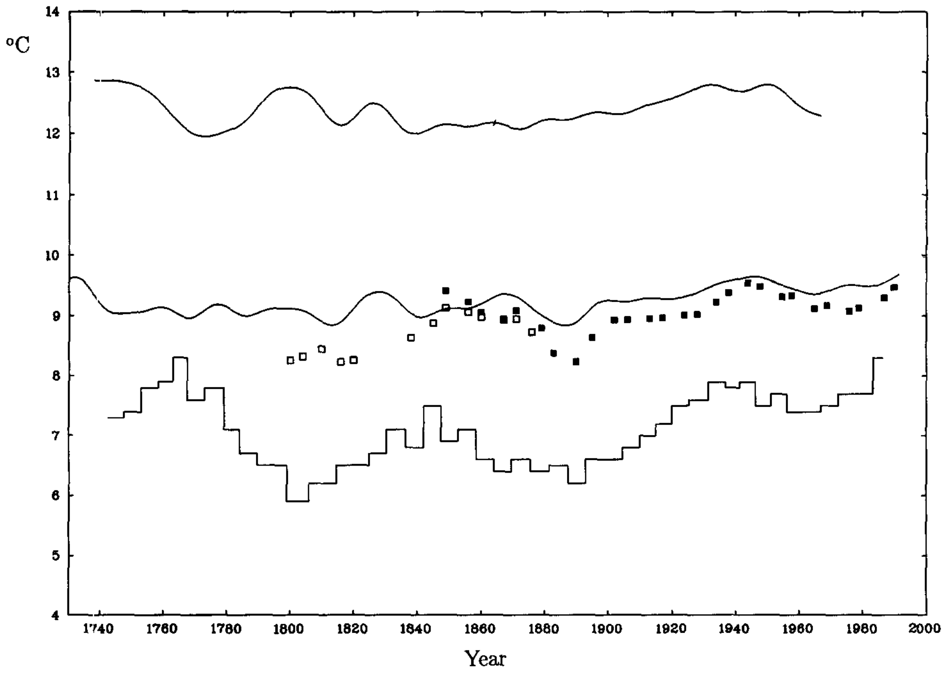

Fig. 8. Comparison of the Armagh temperature series with the central England and eastern United States Series given by Lamb (1977) and Parker *et al.* (1992). Continuous lines are running means of annual mean temperatures smoothed with a Gaussian profile of 5 years half-width: top—eastern United States; middle—central England. Symbols are for Armagh data: open squares—Series I; filled squares—Series II. The histogram (lower) shows the variation of the sunspot cycle length from Lassen and Friis-Christensen (1992).

osity with sunspot number over the past solar cycle. This is believed to be principally due to the increase in brightness of the faculae and bright network regions often associated with sunspots. These more than compensate for the reduction in luminosity caused by the presence of cool sunspots. Based on the SMM-ACRIM results, it has been shown by Lean *et al.* (1994), that the prolonged minimum in solar activity in the late 17th and early 18th centuries, termed the 'Maunder Minimum', could be expected to produce a global drop in temperature of $\sim 0.5°C$. Though this is insufficient by at least a factor of two to explain the Little Ice Age, which occurred at this time, it confirms the general trend.

More substantial, percentage increases in flux occur in the extreme ultraviolet and soft X-rays, associated with flares, which are also manifestations of high magnetic activity on the Sun. Though these are quite insufficient in overall energy terms to have a direct heating effect on the Earth's lower atmosphere, Herman and Goldberg (1978) have suggested that they may, through their effects on the upper atmosphere, trigger significant changes at lower levels. A recent paper by Haigh (1994) has considered the effect of solar spectral variability on the stratospheric ozone layer and the consequences for the solar radiation reaching the troposphere. Others (see Herman and Goldberg, 1978) have pointed to the possibility that changes in the solar particle flux may trigger changes in cloud formation that in turn will modulate the transmission, reflection and absorption of solar radiation. In conclusion we may remark that, even though the physical mechanism(s) for solar-activity induced changes in climate are still unresolved, there is mounting evidence that a speeding up of the solar cycle appears to be accompanied by an increase in the efficiency of the solar dynamo that ultimately leads to an increase in the temperature of the Earth's lower atmosphere.

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APPENDIX

Measurement of the length of the sunspot cycle and the use of smoothing filters

The length of the sunspot cycle can be determined in two ways: from the separation of consecutive maxima or consecutive minima. Either method results in a stochastic function because an error in the measurement of the position of any one of the extrema produces opposite effects on the lengths of the preceding and following cycles. Thus an error which leads to a shorter length for cycle n automatically leads to a longer length for cycle $n+1$. In order to overcome this built-in stochastic fluctuation, it is normal to smooth the cycle length with either a 1-2-1 or 1-2-2-2-1 filter. Friis-Christensen and Lassen (1991) used a mean of the cycle

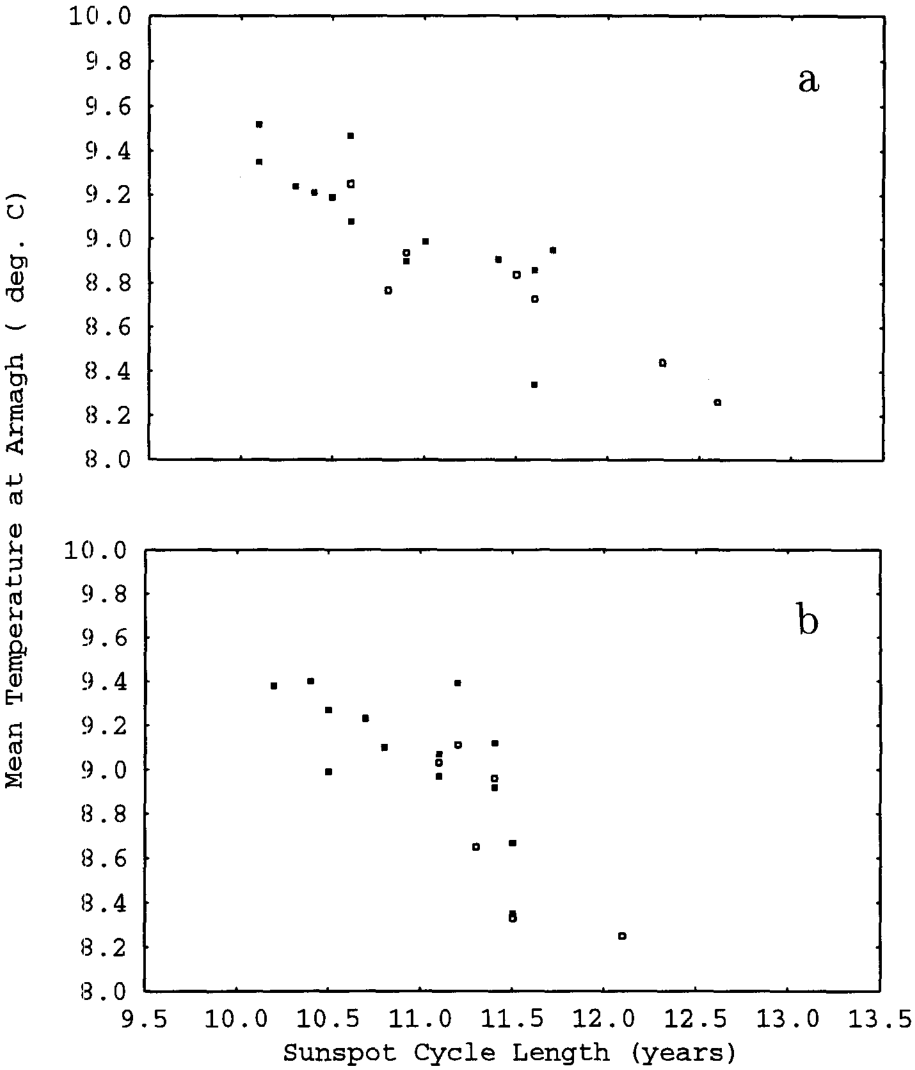

Fig. A1. The mean temperature at Armagh for 11-year intervals against the sunspot cycle length smoothed with a 1-2-2-2-1 filter, as determined from: (a) successive maxima in the sunspot number curve, and (b) successive minima. The value plotted for the sunspot cycle length has been shifted by one cycle to take into account the delay in the response of the temperature at Armagh discussed in Sections 3 and 4.

length determined from both maxima and minima of the sunspot number, smoothed with the second, longer baseline, filter. In Fig. 5 and Fig. 6 we have adopted a similar procedure.In order to test our belief that the correlation between sunspot cycle length and temperature is real, we decided to determine the coefficients of correlation between mean temperature at Armagh and the sunspot cycle length determined from maxima and minima separately. In addition we computed the correlation coefficient between mean temperature and the sunspot cycle length using both of the above mentioned filters. Both the raw and the smoothed cycle length values were taken from Lassen and Friis-Christensen

Table A1. Correlation coefficients of T_{ARM} and the Sunspot Cycle Length (SCL)

	SCL from Maxima			SCL from Minima		
	Zurich (raw)	1-2-1	1-2-2-2-1	Zurich (raw)	1-2-1	1-2-2-2-1
Correlation Coefficient	−0.496	−0.817	−0.894	−0.659	−0.787	−0.854

(1992). Further, in order to take out the delay of approximately a decade in the response of the temperature at Armagh, noted in Sections 3 and 4, we have shifted the data by one cycle, in the sense that the sunspot cycle length is moved forward by 11 years from its true mid-point. The correlation coefficients are listed in Table A1. We note that, independent of whether one uses maxima or minima to define the cycle length, the same picture emerges—i.e. that the correlation coefficient of the mean temperature against cycle length (raw) has a probability of less than 5% of occurrence by chance, and that this probability is less than 1% if one uses smoothed cycle periods (see Fig. A1). The fact that the long baseline filter gives significantly better results than the short baseline filter or the raw cycle length suggests that the link between the solar dynamo and the mean air temperature at Armagh is a gradual process that only becomes evident when data are smoothed over several cycles.