AIR TEMPERATURES AT ARMAGH OBSERVATORY, NORTHERN IRELAND, FROM 1796 TO 2002

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ABSTRACT

Three independent mean temperature series for Armagh Observatory, covering the period 1796–2002 have been calibrated and corrected for the time of reading and exposure. Agreement between the three series is good in regions of overlap. With a short gap in the Armagh data from 1825 to 1833 filled by data from two stations in Dublin, the resulting series is the longest for the island of Ireland and one of the longest for any single site in the British Isles.

Over the past 207 years, we note that temperatures in Armagh, in all seasons, show a gradual overall trend upwards. However, there are seasonal differences: summer and spring temperatures have increased by only half as much as those in autumn and winter. This is partly due to the exceptionally cold winters and autumns experienced prior to 1820. Relative to the overall trend, warm periods occurred in Ireland, as in other parts of Europe, in the mid-19th century, in the mid-20th century and at the end of the 20th century. Relatively cool temperatures prevailed in the early 19th century, in the 1880s and in the 1970s. Thus, if the baseline against which current temperatures are compared were moved from the late 19th century to include the earlier warm period, the apparent warming at the end of the late 20th century would be correspondingly reduced.

A gradual decline in the daily temperature range at Armagh since 1844 may have resulted from higher minimum temperatures associated with increased cloudiness.

A 7.8 year periodicity is identified in winter and spring mean temperatures at Armagh, which is probably a consequence of the North Atlantic oscillation. Copyright © 2005 Royal Meteorological Society.

KEY WORDS: temperature; Northern Ireland; climate change; North Atlantic oscillation

1. INTRODUCTION

Our instrumental knowledge of climate change prior to the mid-19th century relies heavily on a few long meteorological series, most of which are from Europe. Even here, good instrumental series longer than 150 years are extremely rare, and it is essential that those that exist be carefully calibrated and standardized in order to make what comparison we can with modern measurements. Of particular importance are: (1) the longevity of the series; (2) the availability of meta-data concerning the instruments used and measurement practices; (3) knowledge of the position and exposure of instruments; (4) knowledge of any local time-dependent micro-climatic effects (e.g. from an urban heat island).

To date, only a handful of temperature series fulfil these broad criteria, and most, if not all of them, suffer from deficiencies at some time or another. Some long series (e.g. central England; Manley, 1974; Parker *et al.*, 1992) are in fact composite series, containing data from a number of sites. Although this can be an advantage in the sense that climate is being measured over a larger area than a single location, it can be a disadvantage if the same distribution of sites is not maintained (i.e. different sites are used at different times). The series presented here are almost entirely from a single location, namely the Armagh Observatory. They

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include three independent temperature series from the observatory site that overlap for substantial periods, thereby giving some added confidence in the results. Preliminary mean annual temperature data for Armagh have been published previously by Butler and Johnston (1996). Here, we give the mean monthly temperature, based on a new and more complete standardization of the three daily temperature series.

2. THE LOCATION OF THE OBSERVATORY

Armagh Observatory (lat. 54°21.2′N; long. 6°38.9′W) lies approximately 1 km northeast of the centre of the ancient city of Armagh. It is situated 64 m above mean sea level at the top of a small drumlin (hill) in an estate of natural woodland and parkland of circa 7 ha. To the north and east the observatory's estate is bounded by meadow, and from the southeast to the southwest by school playing fields and a town park known as 'The Mall'. Thus, the observatory is still largely surrounded by countryside similar to that which has existed since its foundation in 1790. Together with the fact that the population of Armagh when compared with other Irish and UK cities has increased relatively little since the late 18th and early 19th centuries (population 1816: 7,000; 1911: 7,600; 1991: 14,265), its rural environment has ensured that the observatory suffers from little or no urban micro-climatic effects (see Coughlin and Butler (1998)). In addition, with a relatively exposed site, in a fairly windy maritime climate, any urban climatic effects that did exist would be expected to be minimized.

3. DATA

3.1. Description

Meteorological data have been recorded daily at Armagh Observatory since July 1795. Initially, readings of temperature and pressure were taken three times a day, in the morning, at noon (or sometimes 2 p.m.) and the evening. Temperature was recorded both outside and inside the building with a standard thermometer. These readings continued till 31 May 1825. From 1 June 1825 until 31 December 1832, no data have been found. On 1 January 1833, the morning and evening readings resumed, from which time they continued until 31 December 1882. This series is referred to as the twice daily 'spot' temperature data set called Series I.

During the late 18th and early 19th centuries, maximum and minimum thermometers were developed and came into general use (Knowles Middleton, 1966). At Armagh, maximum and minimum thermometer readings commenced in August 1843. Since that time they have been read daily, though not always at the same time of day. This is the second series of temperature data from Armagh, termed Series II. This data set was supplied to the SNIFFER project team in 2003 for inclusion in their discussion of temperature series for Scotland and Northern Ireland (see Jones and Lister (2004)).

A third extensive set of independent air temperature data, in the sense that it was obtained with a different thermometer and calibrated independently, is that from the dry-bulb thermometer of the hygrometer. These readings commenced with morning readings in 1838, which then became twice-daily readings from 1844 to 1965. After 1965 the hygrometer readings reverted to once per day. The twice-daily series of dry-bulb readings is referred to as Series III.

Two further series of temperature readings from Armagh Observatory exist, namely Series IV, twice-daily temperatures from inside an unheated room from a thermometer attached to the barometer (1795 to circa 1950), and Series V, hourly wet and dry readings from the self-recording thermograph (SRT) of the automatic weather station (AWS) operated at Armagh from 1868 to 1883 by the British Board of Trade (see Report of the Meteorological Committee of the Royal Society (1867) and Butler *et al.* (2004a)). Here, we will make no further reference to Series IV; Series V, however, has been useful to determine the mean diurnal temperature profile throughout the year and to help calibrate the maximum and minimum thermometers in use at that time.

The parameter most often employed in the discussion of global climate change is the mean temperature. Though different definitions can be devised, that most commonly used in English-speaking countries is the

mean of the daily maximum and minimum temperature determined by maximum and minimum thermometers inside a suitable wooden screen. Thus, if we wish to combine temperature series containing data of a different kind (e.g. twice-daily air temperature measurements, as in Series I and III) with the mean of maximum and minimum, as in Series II, it is necessary to convert the twice-daily data to the equivalent of the mean of maximum and minimum. Fortunately, it has been shown by a number of studies that this can be quite easily done provided the time of observation is known and the readings are made at least twice daily and 12 h apart. In a later section we shall describe the procedure we have used to correct Series I and III.

The existence of a gap from June 1825 to December 1833 in the Series I data is a cause for concern. Regrettably, we have not been able to find any Armagh temperature data for this period. Fortunately, for a period in the early 19th century, Dunsink Observatory near Dublin maintained a climate series. However, though the readings were often made twice daily, as required for our exercise, they are sporadic with occasional gaps of several months. Irregular timing would normally have made the observations useless, but in this case, as the time of each individual observation was recorded, we can make an appropriate correction. From the overlap between the Armagh Series I and the Dunsink data we have been able to transform the Dunsink data for 1825–33 to Armagh and infill our Series I to cover almost the entire period 1796–1883.

3.2. Standardization of the data

For each of the three temperature series maintained at Armagh Observatory with which we are concerned here, namely Series I, II and III, we have investigated the various instrumental and exposure effects and, where necessary, we have made corrections. There are three general categories into which these corrections fall: (1) instrumental corrections relating to the particular thermometer in use at any one time; (2) corrections which relate to the time of observation; (3) corrections relating to the exposure of the thermometers. The second category of correction is particularly relevant to Series I and III, for which simple temperature readings were made at specified times. The third category, namely exposure, is the most difficult to correct for, as detailed information concerning the exact location and exposure of instruments is sometimes not available, particularly for the early data; and even when we know what the exact location was, it may no longer be possible to reconstruct the conditions prevalent at the time in order to determine a correction. One of the most important corrections of this type arises from the switch from the north-wall screen (NWS) type of exposure common in the early 19th century to the Stevenson screen, which became standard in many parts of the world from the late 19th century onwards. We shall show that this particular exposure effect is most important for Series II. In the following section we discuss each of the above types of correction separately for each series.

4. SERIES I: THE TWICE-DAILY EXTERNAL 'SPOT' TEMPERATURES

4.1. Instrumental correction

We have found no definite evidence as to the identity of the first thermometer used at the observatory for the thrice-daily temperature readings that commenced in 1795; however, it is highly likely that it was a thermometer by Troughton recorded in an early (c. 1796) inventory (M91; Butler and Hoskin, 1987). This thermometer was still in use at the observatory in 1823 when Thomas Romney Robinson arrived to take up his employment as Director, a position he retained for 59 years. Robinson (1859) remarked of the thermometer

> 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).

When the meteorological series was continued in January 1834, after the break since June 1825, the same thermometer was employed until it was broken on 24 May 1859. The series continued using a 'Kew standard' thermometer, which, when checked by Mr R.H. Scott from Kew in October 1890, was also found to be accurate to 0.2 °F. In view of the reported accuracy of these two thermometers, most likely the only ones employed for the series, and the absence of any more detailed calibration information, we decided not to make any instrumental corrections to the Series I data.

4.2. *Correction for time of reading*

Strictly speaking, to define the mean temperature of any day requires readings at regular intervals (e.g. hourly) throughout the 24 h day. However, owing to the shape of the mean diurnal temperature curve, just a few (three or four) equally spaced temperature readings can suffice to give a mean temperature accurate to $\pm 0.1\,°C$. Initially, at Armagh, readings were made thrice daily (8 a.m., noon (or 2 p.m.) and 8 p.m.); however, later readings were taken just twice per day, 12 h apart. Such twice-daily readings were known to give a reasonable approximation to the mean of the 24 h day. Lloyd (1849) made a thorough study of the accuracy obtainable with equally spaced temperature readings and concluded that, for Dublin, the optimum times to make such readings were 9:46 a.m. and 9:46 p.m. local time (10:11 and 22:11 GMT).

Both the time frame and the actual time of recording of the observations made at Armagh have changed over the centuries, with early observations taken according to local astronomical time and later observations according firstly to Irish (Dublin) Civil Time and later GMT. For the late 18th and early 19th century, morning readings are recorded at 20:00 h and evening at 08:00 h, for instance, following the astronomical practice of defining 00:00 h at mid-day. Later in the 19th century, with the coming of the railways, Civil Time was introduced in order to standardize the time system throughout the island of Ireland. Nevertheless, some of the meteorological readings continued to be made according to local (Armagh) time until the late 1930s, when all were finally moved to GMT. Undoubtedly, this was partly intended to ensure consistency with earlier data. In Table I we list the GMT at which observations for Series I and III were made at Armagh over the past two centuries. This list is compiled from many sources, but principally the meteorological record books at the Observatory (M117; Butler and Hoskin, 1987) and various reports by meteorological inspectors from the UK Met Office (see Garcia Suarez *et al.* (2004a)). For some quite extended periods, there is no specific mention of the time of day in the record heading, merely the annotation *morning* and *evening*, and in such cases it has been assumed that the time of readings remained the same as prior, unless specifically stated otherwise.

As mentioned earlier, current practice is to define the mean temperature as the mean of maximum and minimum for a particular day. Though this parameter differs from the true 24 h mean, it has reached widespread acceptance as the *daily mean* because of the ease of measurement of extrema and the fact that they are much less dependent on the time of reading. As Series I contains twice daily readings 12 h apart, these data require a correction to bring them to the same scale as the mean of maximum and minimum. This has been done in the present instance using the mean diurnal temperature curves for Armagh for each day of the year, based on the hourly temperature data recorded at Armagh from 1868 to 1882 by the SRT of the AWS (see Figure 1 and Report of the Meteorological Committee of the Royal Society (1867)). First, the published hourly data were entered into a computer file and mean temperature curves formed for each day of the year from 1874 to 1883. As these daily curves were still rather variable (due to too short a measurement period), they were further smoothed by applying a 15 day mean, i.e. including data for 1 week before and

Table I. GMT of temperature readings for Series I and Series III

Interval	Morning	Evening
1 Jul 1795–31 May 1825	08:27	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 1859–31 Dec 1881[a]	10:25	22:25
1 Jan 1882–31 Dec 1883	10:00	22:00
1 Jan 1884–31 May 1938[b]	09:25	21:25
1 Jun 1938[b]–31 Dec 2002	09:00	21:00

[a] For the month of December 1861, the readings were taken at 09:25 a.m./p.m. GMT.
[b] The exact date when the reading time moved from 09:25 to 09:00 GMT is unknown.

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Figure 1. The NWS of the SRT installed at Armagh Observatory by the Board of Trade in 1869. From *Quarterly Weather Report of the Meteorological Office for 1870*. HMSO: London

1 week following the date in question. Thus, each hourly datum point on each mean curve is the average of 150 individual readings. These curves were found to vary smoothly from day to day throughout the year. Examples of mean diurnal temperature curves over 15 day intervals for Armagh are shown in Figure 2. The original hourly data and the daily mean curve data are given in Butler *et al*. (2004a).

If T_{am} and T_{pm} are the twice-daily temperatures 12 h apart, and t_{am} and t_{pm} the temperatures for the same times from the mean curve for that date, and t_{max} and t_{min} are the maximum and minimum temperatures from the same curve, then the equivalent of the mean of maximum and minimum for that day is defined as

$$\frac{(t_{max} + t_{min}) - (t_{am} + t_{pm}) + (T_{am} + T_{pm})}{2}$$

Note that this expression is independent of the zero point of the mean curve and depends only on its shape. This procedure is basically similar in concept to that used in Butler and Johnston (1996) and by Klingbjer and Moberg (2003). In Butler and Johnston (1996), we found that the difference between monthly means of $t_{max} + t_{min}$ and $t_{am} + t_{pm}$ was approximately constant for any given time of observation in the range 8 : 30 to 10 : 30 (a.m. and p.m.). Thus, only a single zero-point shift was required to translate the parameter $(T_{am} + T_{pm})/2$ to the equivalent of the mean of maximum and minimum. Further study has shown this to be an oversimplification. A least-squares fit to determine α and β in the equation

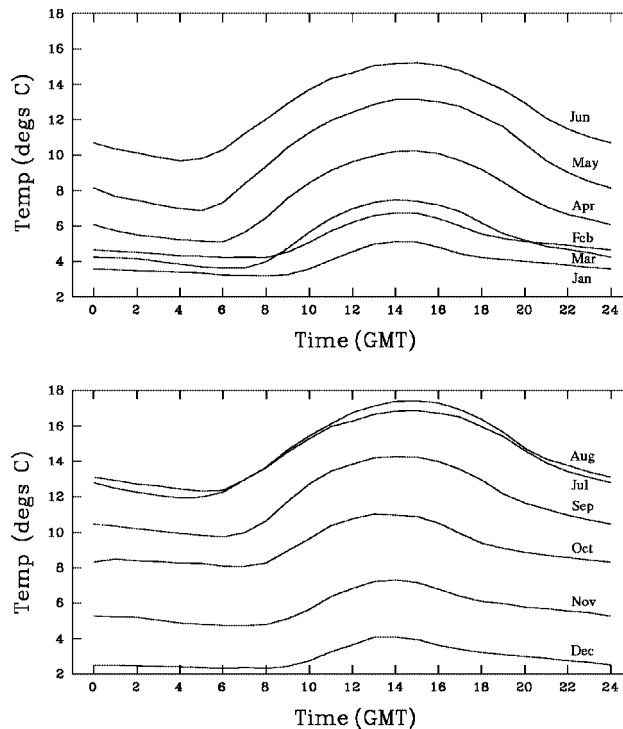$$t_{max} + t_{min} = \alpha(t_{am} + t_{pm}) + \beta$$

Figure 2. The mean diurnal temperature variation at Armagh Observatory over 15-day intervals centred on the 15th day of each month for: (top) the months January to June; (bottom) the months of July to December. These curves were determined from the SRT in an NWS (see Figure 1) for the years 1874–1883

where the relevant values of *t* are from mean monthly curves, rather than daily, has shown α to vary slightly from unity as the time of observation changes from 00 : 00 to 12 : 00 h. This also leads to a variation in the value of β. We mention this for the sake of completeness, as our new correction to Series I for the time of reading has been carried out using the mean daily temperature curves as described above, rather than with a simple zero-point correction as in Butler and Johnston (1996).

4.3. Correction for exposure

A plan of the observatory site showing the locations of the thermometers used for all three series, is shown in Figure 3. With reference to the location of the thermometers used for the twice-daily temperature Series I, Robinson (1859) reports that

it is 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 bright metal, which admits free access to air, but screens it from radiation.

It is likely that this was the location of the external thermometer from the time it was first set up on the East Tower in 1834 till Series I ended in December 1882. Prior to 1834, we assume that the thermometer was placed outside the Transit Room, which is adjacent to the East Tower and was built at the same time or soon after the main observatory building in 1789–90. These two sites would have been within a few metres of each other (see Figure 3). Adjacent buildings were not heated at the time. The bright metal casing referred to by Robinson was supported by brackets fixed to the window frame so that the thermometer could be viewed from inside the building through a central pane of glass which was hinged so that it could be opened when required. The height of the thermometer casing is 3.35 m above current ground level. A photograph of the light metal box is shown in Figure 4.
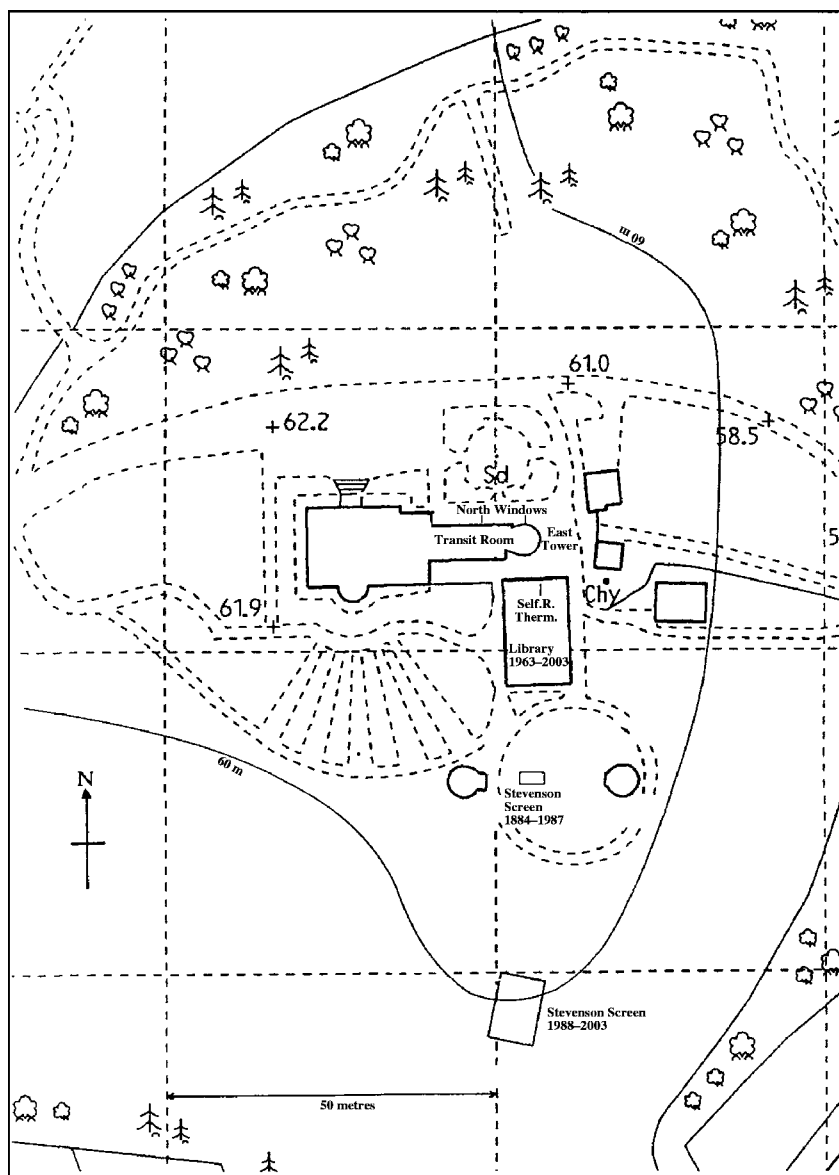
Figure 3. Plan of Armagh Observatory grounds, circa 2000, showing the locations of thermometers used in this study. The East Tower was built in 1827 and the Library in 1963 (based upon Ordinance Survey of Northern Ireland ace map 1:1250 (1998) with the permission of the Controller of Her Majesty's Stationary Office 'permit no. 50127' © Crown Copyright)

It is evident from the above description and the construction of the metal box, which still survives in its original location, that some care was taken to ensure that the thermometer was protected from the direct rays of the sun in the early morning and late evening hours during summer. The double casing of the box will have shielded the thermometer from direct heating in early morning and late evening and the ventilation helped to ensure that the temperature recorded was that of free air. Effectively, the exposure was that of an NWS with protection from direct solar radiation.

Nordli *et al.* (1997) and Moberg *et al.* (2003) have drawn attention to the possibility that early Scandinavian temperature measurements may have been biased upwards by solar heating in the early hours of summer mornings. They surmise that, even if direct solar heating was avoided, indirect diffuse radiation could have

Figure 4. The light metal box at the north window of the East Tower at Armagh Observatory (photographed October 2004). This box housed the external thermometers used for Series I and the hygrometer used for Series III over the period from 1834 until the installation of the Stevenson screen in January 1884. This figure is available in colour online at www.interscience.wiley.com/ijoc

been a problem. Although we cannot be certain that a similar situation did not prevail at Armagh at this time, it seems likely that Robinson's double metal box would have been effective in eliminating both direct and diffuse radiation at this site. Nevertheless, it is likely that the direct rays of the sun on clear mornings would have heated the adjacent stone walls, and this may have contributed to an anomalous reading on such occasions. However, whereas morning readings in Scandinavia before 1859 were made usually between 06:00 and 07:00 h (see Moberg *et al.* (2002) and Bergstrom and Moberg (2002)), in Armagh the readings were made between 08:00 and 10:00 h local time (see Table I). By this time, direct solar radiation would not have been a problem for 'spot' temperature measurements such as those in Series I. Nevertheless, the thermal capacity of the adjacent stone walls would tend to smooth temperature extrema and thereby affect maximum and minimum temperatures. We shall return to this point when discussing the exposure corrections for Series II.

Parker (1994) has discussed the differences between exposure effects using NWSs and the, now more common, Stevenson screen. He concludes that, for the determination of mean temperatures, there is little systematic difference between the two types of screen, provided direct radiation has been shielded.

Over the period December 2003 to October 2004, we tested this conclusion by monitoring the temperature inside the light metal box in the north window of the East Tower with a Gemini Datalogger Tinytag temperature sensor incorporating a 10 KΩ negative temperature coefficient-encapsulated thermistor previously calibrated in the Stevenson screen. Readings were recorded automatically every 0.5 h and read out at the end of the run.

The agreement between the readings from the light metal box and a similar sensor placed in the Stevenson screen was remarkable, showing only a slight systematic difference of $\sim0.2\,°C$, in the sense that the former was warmer than the latter. Further, by applying the same method for converting twice-daily readings to the equivalent of maximum and minimum as described above, we were able to establish a correction to temperatures in the light metal box to the Stevenson screen of $-0.18 \pm 0.06\,°C$. This correction for exposure, which was not seasonally dependent, has been applied to the Series I data.

5. SERIES II: THE MAXIMUM AND MINIMUM TEMPERATURES

5.1. Instrumental correction

Owing to the physical disturbance required in reading and resetting maximum and minimum thermometers, they are broken more often than ordinary thermometers. In addition, maximum thermometers occasionally suffer from the detachment of parts of the mercury column, which can give rise to appreciable errors. Such errors may not be noticed for some time, with the result that a systematic error is introduced into the temperature series. Errors of this nature are more common in the early to mid-19th century before regular inspection by Met Office personnel was implemented.

Two maximum thermometers in use prior to 1883 have given rise to concern. One, a thermometer by Newman, introduced in August 1843 and broken in May 1860, has no calibration data. For this thermometer we have made no correction for instrumental error. It was replaced in December 1860, after an interim period when a garden maximum was used, by a maximum thermometer by Casella of Phillips type. We believe that, when first used, this thermometer had only a small error, which we have assumed to be zero (Whipple, 1921). It appears to have functioned satisfactorily until May 1863, when, from comparison with Series I, we see a sudden shift in level. When the readings of this thermometer were later checked against the maximum and minimum readings of the SRT of the AWS for April–May 1881 by Dreyer, he found an error of $3.2\,°F$, and, by comparison with earlier SRT data, he was able to show that a similar systematic error had existed in 1871. In view of the uncertainty as to when the error developed, we have adopted a zero correction from December 1860 to May 1863 and a stepped temperature-dependent correction that commences in June 1863 and is assumed to be stable from January 1872 until the thermometer was taken out of service in September 1882.

The temperature-dependent corrections for this thermometer have been derived by comparison of the daily maximum readings from the thermometer and the maximum temperatures recorded by the SRT of the AWS for the same days (Coughlin, 1998 : 42). For all other maximum thermometers that have subsequently been used at Armagh Observatory, detailed thermometer corrections are available from archived meta-data (Garcia Suarez *et al*., 2004a).

For all minimum thermometers except the first by Newman (employed from August 1843 to September 1882), calibration data are available from the archived meta-data. Using the same procedure adopted for the Casella maximum thermometer outlined above, a temperature-dependent correction for the Newman minimum has been determined (Coughlin, 1998). Details of the instrumental corrections for all maximum and minimum thermometers used in Series II are given by Butler *et al.* (2004b).

For the calendar year 1883, whilst the SRT of the AWS was still in operation, no ordinary mercury-in-glass or alcohol-in-glass maximum or minimum thermometers were used. For this year alone, the maximum and minimum data in Series II are taken from the SRT with no instrumental corrections applied.

5.2. Correction for time of observation

The principal advantage of maximum and minimum thermometers for the determination of mean temperature derives from the relative insensitivity of their readings to the time the reading is made. Nevertheless, substantial changes in the time of observation can have a small and systematic effect on the derived mean monthly, seasonal and annual values. Thus, long-term averages of evening readings can differ slightly from averages of morning readings. At Armagh, readings of maximum and minimum temperatures were initially made in the morning; but later, from around 1865 till December 1958, readings were made

in the evening. Subsequently, through instruction from the Met Office, readings reverted to the morning. An empirically determined correction for the effect of this 12 h change in the time of reading was made using the SRT data for 1875–76 (Coughlin, 1998). The corrections required were +0.08 °F for the maximum and +0.19 °F for the minimum, to be applied over the period (1865–1958) when observations were made in the evening (Coughlin, 1998). These corrections have been applied here to the monthly, seasonal and annual means, but not to daily values.

5.3. Correction for exposure

From detailed descriptions of the order in which instruments were read (M117; Butler and Hoskin, 1987; Garcia Suarez *et al.*, 2004a) written in 1846 and 1865, we can surmise that the maximum and minimum thermometers in use at those times were fixed in a horizontal position close to, or possibly on the sill of, the north window of the East (1827) Tower. This was essentially a NWS type of exposure. It would not have been possible for the maximum and minimum thermometers to have been placed inside the bright metal box that housed the external thermometer (used for Series I) and the hygrometer (used for Series III). Therefore, we do not know whether screening from early morning summer sunshine was provided. However, considering the care taken to screen the other thermometers, we would be surprised if similar provision was not made for the maximum and minimum thermometers. As, after this lapse of time, it seems unlikely that we can fully resolve this issue, we decided to standardize our maximum and minimum data over the period 1843–82 against the SRT of the AWS. The SRT also used a NWS type of exposure (see Butler and Johnston (1996: figure 3) for an illustration) which was situated on the north wall of the adjacent Meteorological Building (Butler *et al.*, 2004a), approximately 4 m east and 8 m south of the north window of the East Tower (see Figure 3) in which the bright metal box was fixed. From a comparison of the published readings of the SRT for 1874, 1876, 1881 and 1882 at the time of reading of the external thermometer, we have found only a very small systematic difference (0.16 °F, ∼0.1 °C) between the mean temperatures for both sites. Therefore, we believe the mean temperature at the position of the NWS of the SRT was very close to that at the north window of the East Tower, i.e. the exposure for the two sites was similar. However, even if there was a small difference in exposure between the two sites, this is likely to have been removed by our adoption of temperature-dependent thermometer corrections determined from comparison with the SRT, as discussed in Section 5.1.

A much more significant difference in exposure occurred when the maximum and minimum thermometers were moved in 1884 into a Stevenson screen situated well away from the influence of neighbouring buildings (see Figure 3). Parker (1994) found that, although mean temperatures determined from maximum and minimum thermometers in NWSs were not substantially different from those housed in Stevenson screens, the diurnal temperature range was significantly lower for NWSs than for Stevenson screens. This is evidently due to the proximity of masonry with a substantial thermal inertia.

Regrettably, no simultaneous readings were obtained in Armagh between the earlier NWS exposure of the SRT (or the bright metal box in the north window of the East Tower) and the Stevenson screen — the latter simply replaced the former. However, a very similar set of meteorological equipment had been set up at the Valentia Island Observatory in County Kerry; there, an identical SRT to that formerly at Armagh continued in operation in parallel with maximum and minimum thermometers in a Stevenson screen until the 1960s. In Table II we show the comparison of mean monthly maximum and minimum temperatures from the SRT with the mean monthly maximum and minimum from thermometers in the Stevenson screen at Valentia for the years 1955–59. There is a significant and consistent annual cycle in the differences between the two sets of readings, with a substantially larger diurnal variation evident in readings from the Stevenson screen. On average, in the Stevenson screen, the maxima are approximately 1.0 °F (0.56 °C) warmer and the minima 1.6 °F (0.89 °C) cooler than the NWS of the SRT. These findings are broadly consistent with those of Marriott (1879) and Parker (1994) for other types of NWS.

As the SRT in Valentia (which still survives) is identical to that formerly at Armagh, and the general conditions of the site broadly similar to that at Armagh (though Valentia is wetter and windier), we decided to adopt the Valentia data as the basis of our correction for exposure of the maximum and minimum data

Table II. Mean monthly differences in maximum and minimum temperatures recorded in a Stevenson screen and by the SRT in an NWS at Valentia Observatory, 1955–59

	Stevenson screen − NWS (°F)											
	Maximum						Minimum					
	1955	1956	1957	1958	1959	Mean	1955	1956	1957	1958	1959	Mean
Jan	1.0	0.6	1.2	1.0	1.2	1.00	−0.7	−1.3	−1.3	−1.3	−1.8	−1.28
Feb	1.2	1.1	1.3	1.1	0.7	1.08	−1.3	−1.6	−1.6	−1.3	−1.6	−1.48
Mar	2.1	1.0	0.9	0.9	1.3	1.24	−1.5	−1.6	−1.3	−1.9	−1.8	−1.62
Apr	1.7	1.2	1.0	1.3	0.6	1.16	−1.6	−1.4	−1.9	−2.8	−1.8	−1.90
May	0.7	0.6	0.7	1.0	1.2	0.84	−1.8	−2.0	−2.3	−1.8	−1.9	−1.96
Jun	0.4	0.0	1.0	0.6	0.1	0.40	−1.9	−1.8	−2.2	−2.0	−1.9	−1.96
Jul	0.6	0.0	0.9	0.5	0.7	0.59	−2.3	−2.1	−2.0	−2.1	−1.9	−2.08
Aug	0.7	0.7	1.3	1.1	1.8	1.12	0.3	−1.4	−2.0	−1.8	−1.6	−1.30
Sep	1.4	1.3	1.1	1.8	2.9	1.70	−1.3	−1.6	−1.8	−1.8	−1.2	−1.54
Oct	1.2	1.6	0.9	0.9	1.6	1.24	−1.1	−1.4	−2.0	−1.7	−1.7	−1.58
Nov	1.1	0.5	1.3	0.9	1.3	1.02	−1.9	−1.6	−1.7	−2.0	−1.1	−1.66
Dec	0.8	0.4	0.7	0.8	1.1	0.76	−1.0	−1.7	−1.7	−1.5	−2.4	−1.66
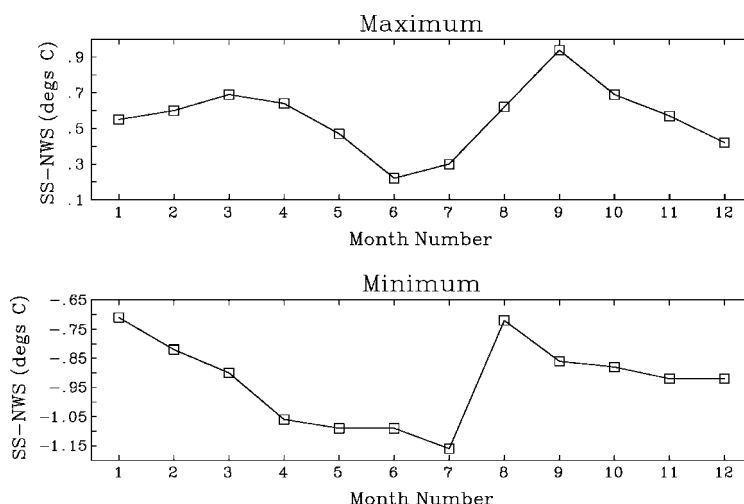
Figure 5. The difference between the mean monthly temperature extrema measured by the SRT in an NWS and the standard maximum and minimum thermometers in a Stevenson screen at Valentia Observatory from 1955 to 1959

from Armagh prior to the introduction of the Stevenson screen in January 1884. The correction for exposure to the daily maximum and minimum temperatures in the interval 1843–83 is shown in Figure 5. It is based on the mean monthly difference between the Stevenson screen and the SRT of the maximum and minimum temperatures at Valentia over the 5 year period 1955–59. This correction has been applied to the Armagh Series II data from 1843–83. On average, this has the effect of raising the mean maximum temperature by 0.55 °C, lowering the mean minimum by 0.93 °C, and lowering the mean temperature by 0.19 °C over this period compared with the uncorrected data.

The temperature monitoring inside the light metal box in the north window of the East Tower described in Section 4.3 has allowed a direct determination of the above correction for exposure based on data for the 9 months January–September 2004. The results imply a correction of 0.42 °C to the maximum and −0.95 °C to the minimum, very similar to those derived from the Valentia data. As the latter were derived from a

more extended period, covering all seasons, we have used these corrections to correct Series II readings for exposure.

6. SERIES III: TWICE-DAILY TEMPERATURES FROM THE DRY-BULB THERMOMETER OF THE HYGROMETER

The wet- and dry-bulb temperatures were recorded twice daily from 1844 to 1965; subsequently, readings have been made only in the morning. Because the derivation of humidity depends on the difference between the wet- and dry-bulb temperatures, systematic errors in either of these two thermometers should have been quickly detected. This effectively ensured that thermometers for Series III were carefully monitored for any calibration changes that developed over the period of use. Calibration data, which are available for all thermometers used for Series III, are listed by Garcia Suarez *et al.* (2004b) together with the twice-daily calibrated readings.

In many respects we know Series I and III to be essentially similar. For instance, the description of the recording procedure in 1846 and 1865 shows that the locations of the instruments and the times of their reading were almost identical for Series I and III, with both sharing the bright metal box in the north window of the East Tower. However, as they rely on different thermometers, we consider them to be an independent series. As with the maximum and minimum thermometers employed for Series II, the hygrometer was moved in January 1884 from the north window of the East Tower to a Stevenson screen situated well away from the observatory buildings. Again, as with Series I, only a small ($-0.18\,^{\circ}$C) correction was required prior to 1884 for this change in exposure. However, we have made a correction for the time of observation in order to convert the twice-daily dry-bulb temperature to the equivalent of the mean of maximum and minimum. To do this, we have employed exactly the same procedure as for Series I (outlined in Section 3.2) using the mean diurnal temperature curves from the SRT from 1874 to 1883.

7. THE DUNSINK PATCH, 1825–33

It is not clear from the meteorological records at Armagh Observatory or the meta-data why no meteorological data exist for the period June 1825 to December 1833. Either the data were not recorded or the record books have been subsequently lost. The gap in the records is surprising, as the existing data entries continue to the bottom of the last page in the ledger for 1825 and no mention is made of stopping the series. One would have assumed that the readings were continued in another ledger which has since become lost; however, no evidence for this conclusion has been found, in spite of several searches. It is almost as though the assistant ran out of paper and decided there and then to terminate the series. The conclusion that no data were in fact recorded is reinforced by the lack of Armagh data for those years in a published comparison of the temperature at Armagh with that of the Ordnance Survey Office at the Phoenix Park and the Royal College of Surgeons, Dublin (Cameron, 1856).

Fortunately, however, in the late 18th century and 19th century, meteorological readings were made at Dunsink Observatory (lat. $+53°23.3'$, long. $-06°20.2'$, altitude 85 m), near Dublin, and continued until the late 19th century. Records included daily temperatures from an internal and external thermometer (Butler *et al.*, 2004c). Regrettably, the readings were not made at the same time of day; but, as the times of readings were recorded (in local mean astronomical time) alongside the temperature, we can use a modification of the method described for Series I (Section 4.2) to convert these external readings to the equivalent of the mean of maximum and minimum. Readings were often made three times a day, and occasionally four times a day. However, frequently no readings were made, and this absence of data could continue for extended periods of several months. Normally, non-continuous data such as this would be of limited value; however, as in this case it covers the gap in the Armagh data, it is well worth the effort to standardize the Dunsink material to infill the long Armagh temperature series.

First, the surviving and readable data from Dunsink for 1818–50 were digitized. As no calibration data for the Dunsink thermometers were available, no correction for thermometer error was made. This, in any

Table III. Mean differences between monthly mean temperatures (°C) at Armagh and Dunsink Observatories for periods prior to (1821–24) and following the gap (1836–40) in Series I

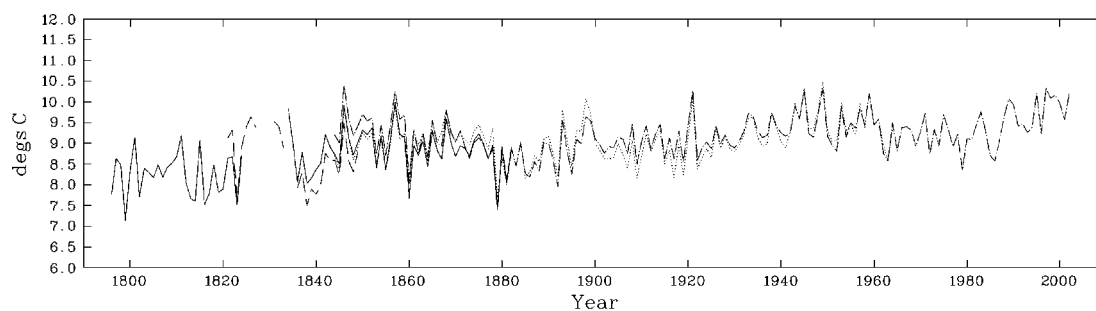| Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.09	−0.16	0.06	0.14	−0.40	−0.33	−0.44	−0.15	−0.31	−0.31	−0.30	−0.22

Figure 6. Mean annual temperatures at Armagh Observatory 1796–2002 from three independent sets of observations. Series I (continuous line), Series II (dashed–dotted line) and Series III (dotted line) and the Dunsink patch (dashed line)

case, is not thought to be a serious shortcoming, as we must transform the Dunsink data to the equivalent in Armagh using overlapping data from both stations. Thus, any calibration errors and/or differences due to exposure would, to a first approximation, be taken care of by the zero-point shifts to be applied to Dunsink data to transform them to the equivalent at Armagh.

Following the procedure outlined in Section 4.2, we determined the equivalent mean of maximum and minimum for each day with two or more readings at Dunsink. Then, for the overlapping period, prior to and following the Armagh gap, namely 1821–24 and 1836–40, in which data from both sites were available, we were able to establish the shift required to convert mean temperatures at Dunsink to Armagh. This shift was seasonably variable, as might have been expected considering the locations of the two cities. The monthly mean differences in temperature (Armagh–Dunsink), as listed in Table III, are quite small, ranging from +0.07 °C in January to −0.44 °C in July. They reflect the differences in latitude and altitude of the two sites. Though their seasonal variation may be reasonably reliable, the zero-point difference would be much less reliable, depending as it does on the calibration of the thermometers used and their exposure.

7.1. Comparison of the Dunsink patch and Armagh Series I

In Figure 6 we show the mean annual temperature from Series I, together with the Dunsink annual mean temperatures for 1821–48 converted to the equivalent at Armagh using the seasonally dependent zero-point correction given in Table III. We note that there is, in general, reasonable agreement where overlap occurs, but that the converted Dunsink data are significantly warmer than Armagh by ∼0.3 °C from 1821 to 1824 and cooler by the same amount from 1834 to 1848. This discrepancy could arise from exposure changes at either Dunsink or Armagh, or both, or from an unrecorded thermometer change at Dunsink. In spite of this discrepancy, we feel that the Dunsink data remain our best available option for filling in the gap in the Armagh data.

8. THE MEAN MONTHLY DATA AND DATA COMPLETENESS

In Table IV, we list the mean monthly temperature (equivalent of mean of maximum and minimum) from the average of the three Armagh series. Over the interval 1825–33, the data from Dunsink transformed to Armagh have been used.

Table IV. Mean monthly temperature (°C) at Armagh Observatory, 1796–2002[a]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1796	7.4	4.4	3.9	8.4	8.3	11.2	12.4	13.0	12.4	7.2	3.0	0.6
1797	4.5	5.4	3.9	6.4	9.9	11.6	15.9	15.5	12.3	9.3	4.8	4.1
1798	4.2	3.6	4.4	8.6	11.0	14.4	13.4	14.7	11.6	7.8	4.3	2.7
1799	2.3	2.6	3.4	4.8	8.0	11.7	13.6	12.9	11.4	7.6	5.1	1.6
1800	2.8	3.1	4.4	8.1	9.7	11.9	15.4	15.7	12.0	8.7	5.1	3.0
1801	4.8	4.9	6.5	8.0	10.3	13.2	14.9	16.7	13.9	9.6	4.9	1.6
1802	1.7	4.1	5.8	8.5	9.2	11.7	11.2	13.4	10.4	7.9	4.5	3.8
1803	2.4	4.5	5.9	7.8	9.6	12.6	16.5	14.1	10.3	8.9	4.0	3.7
1804	5.1	3.7	4.7	6.5	12.5	14.5	12.8	12.9	11.3	8.5	5.3	1.8
1805	2.2	4.0	6.7	8.2	9.7	11.6	14.9	13.4	12.4	6.2	5.4	3.1
1806	3.1	3.8	5.2	7.4	11.3	14.0	14.4	14.5	10.8	8.9	5.1	3.0
1807	2.2	3.2	2.7	7.8	11.4	14.1	16.9	16.1	7.3	10.5	1.7	3.9
1808	3.6	3.8	4.2	7.1	13.0	13.2	16.0	16.2	12.1	5.5	4.2	1.9
1809	1.6	5.3	7.1	6.6	13.8	12.9	14.0	13.0	11.3	10.0	3.5	2.8
1810	2.7	2.8	5.3	8.6	9.8	15.4	15.2	14.1	11.8	9.2	4.5	4.1
1811	1.6	4.5	6.8	8.6	11.5	13.8	17.3	13.9	11.9	10.2	6.2	3.4
1812	3.3	5.8	4.5	6.4	11.8	13.7	12.9	14.1	11.9	6.8	3.8	1.8
1813	1.6	3.6	5.0	5.6	8.9	11.7	13.4	12.2	12.3	8.9	4.9	3.7
1814	−2.2	3.5	4.0	9.8	10.1	12.7	13.6	12.9	11.5	7.0	4.3	3.7
1815	2.1	6.4	6.1	8.3	13.0	14.5	15.7	15.3	13.0	9.1	3.5	1.9
1816	3.0	3.1	3.8	6.0	9.2	11.6	12.6	14.0	11.1	9.8	3.7	2.2
1817	4.6	5.8	5.1	7.2	6.9	12.2	13.8	13.1	11.3	5.5	6.5	1.6
1818	2.3	2.9	4.0	5.0	10.0	14.3	15.4	13.5	11.3	11.2	8.6	2.9
1819	3.6	3.9	5.8	6.9	9.3	10.9	14.1	15.8	11.0	7.4	2.8	2.0
1820	0.7	4.4	5.9	7.7	9.3	12.5	14.1	13.2	10.9	6.6	4.8	4.4
1821	4.6	3.5	5.6	7.8	7.9	12.8	14.0	14.6	12.8	9.6	5.9	4.1
1822	4.3	4.5	6.4	6.9	9.4	15.3	14.9	14.3	10.4	8.5	6.4	2.7
1823	1.6	1.9	5.0	6.2	10.0	10.9	12.3	14.1	11.4	6.8	6.5	3.2
1824	4.6	4.7	4.8	7.2	10.0	13.6	15.5	14.9	12.7	8.6	4.6	3.2
1825	3.9	4.2	6.2	8.9	10.7	13.0	16.9	16.0	14.6	10.6	4.7	3.2
1826	2.6	6.1	6.0	8.8	11.0	16.4	16.4	15.7	12.9	10.5	3.7	5.6
1827	3.8	1.8	5.9	7.9	10.6	13.0	15.9	14.6	13.2	10.9	8.3	*6.8*
1828	6.3	5.8	6.9	7.5	—	—	—	*14.7*	13.8	*10.1*	7.6	*8.3*
1829	*1.1*	*6.0*	*4.7*	*5.7*	*10.9*	*14.1*	*13.1*	*12.1*	*10.5*	8.2	5.8	3.6
1830	—	—	—	—	—	—	15.2	12.6	11.0	10.1	6.5	2.7
1831	3.0	5.0	6.3	8.4	10.5	14.2	15.3	15.8	12.6	11.6	6.2	5.4
1832	5.0	4.9	6.1	8.5	9.9	13.7	15.1	15.0	12.9	10.2	*6.3*	5.2
1833	3.8	5.0	3.3	7.1	12.3	12.6	15.8	13.9	11.5	9.6	6.1	5.5
1834	6.0	5.8	6.7	7.7	11.9	13.1	15.4	14.4	13.5	10.2	6.9	6.1
1835	4.2	4.8	5.8	8.2	9.9	13.1	14.4	15.4	11.6	8.0	7.0	5.4
1836	4.5	3.7	4.4	6.5	11.2	13.4	13.1	13.0	10.2	8.1	4.5	4.0
1837	3.7	5.5	2.7	4.6	9.0	13.8	16.0	14.1	12.1	10.3	6.6	6.6
1838	1.6	1.3	4.9	5.9	9.4	12.8	14.1	13.8	12.1	9.0	5.7	5.3
1839	2.5	4.2	4.6	6.8	8.9	12.9	13.7	13.2	11.3	8.6	6.8	4.2
1840	4.5	3.4	5.3	9.1	10.3	12.7	12.5	14.8	10.4	7.6	5.9	3.7
1841	1.6	4.0	7.5	7.6	11.2	12.4	12.7	14.0	12.9	7.7	5.2	4.9
1842	3.0	4.7	6.3	8.6	10.6	14.3	13.6	14.9	12.6	7.9	5.9	7.9
1843	5.0	2.2	6.2	7.5	9.4	12.5	13.8	14.2	14.0	7.3	6.1	7.9
1844	4.7	2.8	5.3	9.4	11.4	13.4	14.1	13.1	13.0	8.8	7.2	3.2
1845	4.1	4.3	3.8	8.9	9.8	13.4	13.2	13.5	11.4	9.9	6.9	4.4

Table IV. (*Continued*)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1846	7.2	6.7	6.0	7.5	11.3	16.9	15.3	15.7	14.8	9.7	7.6	2.1
1847	5.0	3.5	5.8	7.0	11.5	13.3	16.8	14.4	11.3	10.1	7.9	4.9
1848	1.8	5.9	5.7	7.0	13.2	13.0	14.3	12.8	12.6	8.6	5.8	5.4
1849	4.7	6.6	6.9	6.0	11.0	12.5	14.6	14.7	12.9	8.5	7.5	3.4
1850	3.0	7.0	5.9	9.0	10.0	14.2	15.2	13.9	11.9	8.6	7.7	6.7
1851	5.1	5.6	6.0	7.5	10.1	13.4	13.8	15.1	13.2	10.3	4.9	6.1
1852	4.6	5.0	5.6	8.9	10.9	12.4	16.8	15.3	12.1	8.5	6.0	6.3
1853	4.2	1.8	4.6	7.6	10.9	14.0	14.2	14.4	11.9	9.3	6.3	2.7
1854	4.0	5.1	7.4	9.4	9.8	12.1	13.8	14.6	13.7	9.1	6.0	5.6
1855	3.5	0.0	3.8	8.3	8.9	13.1	16.5	15.2	13.1	9.0	5.8	4.0
1856	3.2	5.9	5.0	7.9	9.4	12.8	14.4	16.3	11.9	11.4	6.9	5.0
1857	3.5	5.3	5.3	7.3	10.9	15.3	15.3	16.2	14.2	10.9	7.7	8.5
1858	6.1	4.2	5.8	8.0	10.8	14.9	13.6	14.8	13.6	8.4	4.8	6.4
1859	5.4	5.9	7.4	6.9	11.7	14.3	16.8	15.1	12.1	8.4	5.9	2.0
1860	3.3	3.0	5.0	6.4	11.2	11.9	14.1	12.8	10.6	9.0	4.9	2.3
1861	4.5	4.6	5.5	7.9	11.4	15.0	14.2	15.2	12.6	10.4	3.9	4.5
1862	5.3	5.3	5.2	8.0	10.7	11.9	13.0	14.1	12.8	9.4	3.4	6.5
1863	4.6	5.9	6.9	8.1	10.0	12.9	13.9	13.9	10.6	8.8	7.9	6.2
1864	3.7	1.9	4.8	9.3	11.9	12.3	14.6	13.3	12.1	8.9	5.7	4.1
1865	2.0	3.6	4.2	9.4	11.0	15.1	15.5	14.5	15.4	9.7	6.0	6.9
1866	5.1	3.8	4.6	7.9	9.8	13.8	14.9	13.6	10.8	10.0	6.8	6.2
1867	1.6	6.5	3.3	8.7	10.6	13.7	14.1	15.4	12.8	9.4	5.7	4.9
1868	4.4	6.3	7.2	9.2	11.6	14.2	16.7	15.1	12.9	8.1	4.9	6.2
1869	6.0	7.1	4.2	9.2	8.0	12.4	16.4	14.5	13.1	10.4	6.2	2.5
1870	3.7	3.4	5.8	8.7	10.9	14.2	16.1	15.4	13.5	9.1	4.8	1.3
1871	2.1	7.1	7.0	8.5	11.3	13.2	14.4	15.6	11.6	9.7	5.1	4.0
1872	4.3	6.5	6.6	8.0	9.1	12.9	15.8	14.8	12.3	7.5	5.7	4.2
1873	4.6	2.5	5.2	8.1	9.8	14.2	14.9	14.4	11.3	7.7	5.8	6.4
1874	5.3	5.2	7.2	9.3	9.8	13.6	15.8	14.2	12.1	8.7	7.1	1.2
1875	6.6	3.8	5.8	8.9	11.6	12.9	13.8	15.6	13.9	9.2	5.1	3.8
1876	4.8	4.3	3.8	7.4	9.9	13.0	15.5	14.9	11.9	10.9	6.5	5.7
1877	4.8	5.7	5.1	6.4	8.9	13.8	13.8	14.0	11.2	9.8	6.1	4.7
1878	5.0	6.3	6.0	8.9	10.8	13.9	16.0	15.7	13.2	10.1	2.9	−0.5
1879	0.6	3.3	4.6	5.9	8.8	12.6	13.0	13.7	11.4	8.6	5.5	1.8
1880	3.8	5.9	6.6	7.5	9.7	13.7	13.9	16.3	13.5	6.3	5.5	4.1
1881	−0.9	3.9	5.1	6.7	11.0	12.4	14.1	12.7	11.9	8.0	8.5	3.2
1882	5.8	6.9	7.0	7.5	10.7	12.2	14.2	14.3	11.0	9.6	5.0	2.4
1883	5.2	5.7	3.1	7.5	9.5	12.1	12.9	14.1	12.0	9.1	5.3	5.0
1884	6.0	5.1	6.2	7.1	10.0	12.8	14.6	15.1	13.1	9.1	5.2	3.9
1885	4.0	5.2	4.5	7.2	8.0	12.0	14.9	13.4	11.2	7.1	6.3	4.5
1886	2.2	3.5	4.6	6.8	9.2	12.7	14.3	14.4	12.0	10.3	7.0	1.8
1887	4.1	5.2	4.5	6.1	10.0	15.9	16.0	14.5	11.0	7.8	4.8	3.5
1888	5.2	3.2	3.2	6.7	10.2	12.6	13.0	13.5	11.2	8.9	7.8	5.7
1889	5.1	3.8	5.9	6.8	11.8	14.0	13.8	13.5	12.6	8.2	7.4	5.6
1890	5.9	4.4	6.4	7.4	11.0	13.2	13.5	13.0	14.2	10.4	6.4	2.9
1891	3.3	6.4	4.2	6.1	9.0	14.2	14.3	13.8	13.5	8.6	5.4	5.2
1892	2.8	4.4	3.3	7.4	10.9	12.5	13.3	14.0	11.3	6.6	7.2	3.3
1893	3.8	4.9	7.8	9.6	12.3	14.7	15.1	15.8	12.1	9.0	5.3	5.3
1894	3.7	6.0	6.7	9.1	8.4	12.5	14.7	13.4	10.8	9.0	7.4	5.5
1895	0.5	−0.2	6.0	8.0	11.7	14.0	13.8	14.5	14.3	6.7	6.7	4.0

Table IV. (*Continued*)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1896	5.7	6.9	6.5	9.3	12.3	14.8	14.2	13.3	11.9	6.2	5.6	3.8
1897	2.3	6.5	6.1	6.3	9.5	13.6	15.4	14.6	11.3	10.3	8.2	5.6
1898	7.6	4.8	5.1	8.8	9.5	13.0	14.3	15.2	14.5	10.7	7.1	7.5
1899	4.1	5.5	6.2	7.7	9.6	14.8	15.5	16.8	12.3	9.6	9.3	4.2
1900	4.8	2.0	4.1	8.6	10.1	14.1	15.8	14.2	12.7	8.9	6.2	6.9
1901	4.6	3.2	4.4	8.0	11.5	12.6	16.4	14.3	13.0	9.1	6.3	3.4
1902	4.4	2.3	7.0	7.3	8.6	12.7	13.6	13.6	12.7	9.4	7.3	5.1
1903	3.9	7.1	5.9	6.6	10.3	12.3	14.1	13.2	12.4	9.4	6.2	3.8
1904	4.5	3.4	4.7	8.0	10.0	13.1	14.9	13.8	12.1	9.6	6.4	4.9
1905	5.5	5.1	6.2	7.1	11.0	14.3	15.8	13.4	11.4	7.5	4.6	6.9
1906	5.2	3.0	5.4	6.9	9.2	13.5	14.2	15.6	12.8	9.4	7.3	4.2
1907	4.8	3.5	7.0	7.0	9.4	11.2	14.3	13.1	13.3	8.9	5.6	4.5
1908	4.0	6.0	4.8	6.0	11.7	13.3	14.9	13.6	12.4	11.8	7.6	5.4
1909	4.9	4.9	3.6	8.0	10.3	11.6	13.5	14.6	11.4	9.1	4.2	3.5
1910	3.8	4.6	6.4	6.8	10.3	13.6	13.9	14.5	12.3	10.2	3.8	5.9
1911	4.7	4.9	5.2	7.4	12.0	13.0	16.0	16.0	12.5	9.0	5.4	5.4
1912	4.1	5.2	6.7	9.1	10.7	12.8	13.6	11.7	11.0	8.3	6.5	6.3
1913	4.7	5.4	5.5	7.4	10.1	12.6	13.6	14.4	12.8	10.6	8.0	4.8
1914	4.7	6.7	5.6	9.2	10.1	13.6	14.8	15.3	12.8	10.3	6.3	2.9
1915	3.6	3.5	5.7	8.5	10.0	13.5	13.7	14.1	13.1	9.1	3.5	4.3
1916	7.5	3.5	3.6	7.8	10.2	11.3	14.8	15.7	13.2	10.2	7.1	2.9
1917	2.4	3.1	4.4	5.3	10.9	12.7	15.1	14.6	13.0	7.1	8.4	3.7
1918	4.2	7.1	6.1	7.0	11.5	12.9	14.1	15.0	10.0	8.8	6.1	6.7
1919	3.7	3.3	3.5	7.7	12.3	12.5	13.7	14.8	11.9	8.9	3.0	5.2
1920	5.0	6.7	6.3	7.1	10.7	13.4	13.1	13.2	12.7	10.6	8.5	4.1
1921	7.3	5.9	6.7	8.1	10.1	14.0	16.7	13.5	13.1	12.1	7.1	7.4
1922	4.6	5.5	5.0	5.0	11.4	12.4	12.6	12.7	11.5	8.4	7.1	5.4
1923	6.4	6.2	6.9	6.8	8.2	12.2	15.5	13.5	11.6	9.3	3.4	5.0
1924	5.7	4.7	4.5	6.5	10.1	12.9	13.7	13.5	11.7	9.3	7.7	7.0
1925	5.9	4.2	5.6	6.8	9.7	13.8	15.1	14.6	11.3	10.4	4.3	3.6
1926	5.7	6.8	6.3	9.1	9.4	12.9	16.0	15.1	13.2	7.8	5.6	4.8
1927	4.8	5.5	6.8	7.5	10.4	10.8	14.9	14.9	11.4	10.4	6.2	3.5
1928	5.3	6.3	5.7	7.6	10.7	11.8	14.3	14.2	11.9	10.2	7.1	4.9
1929	3.2	3.9	6.5	6.7	10.7	12.5	14.8	14.0	13.8	9.0	6.5	5.1
1930	4.4	1.9	5.1	7.8	10.6	14.0	14.3	14.0	12.8	9.9	5.9	5.2
1931	3.8	4.4	4.9	7.6	10.4	13.4	14.3	13.8	11.6	9.1	7.5	6.9
1932	7.2	4.2	5.3	6.5	10.1	14.5	14.9	14.9	11.7	8.5	6.7	6.2
1933	3.3	4.4	7.3	9.2	11.0	14.3	16.4	15.9	13.9	10.1	5.8	4.2
1934	5.8	5.2	4.9	6.7	10.4	14.4	17.1	13.8	13.0	9.5	6.4	8.1
1935	5.5	5.7	6.9	7.7	10.5	13.4	15.3	15.2	12.3	9.2	5.7	2.9
1936	3.0	3.6	6.9	6.4	10.6	13.7	14.4	15.7	13.4	9.7	5.1	5.8
1937	5.4	4.9	3.4	9.1	11.5	13.3	14.8	15.6	12.4	8.8	6.4	3.2
1938	5.5	5.8	9.5	7.9	10.0	12.8	14.0	14.7	13.5	10.3	8.6	4.3
1939	3.2	6.7	6.5	8.4	11.3	13.7	14.2	15.3	12.9	8.3	8.2	4.0
1940	1.5	4.8	6.3	8.7	11.6	15.7	13.7	15.1	12.0	9.6	6.4	4.3
1941	1.0	3.4	5.8	6.5	9.6	14.1	15.2	14.0	14.6	10.7	6.8	6.4
1942	4.0	3.0	6.3	9.0	10.6	13.9	14.6	14.9	12.5	9.4	5.5	7.2
1943	5.7	6.9	7.2	9.9	10.8	13.8	15.3	14.3	12.4	10.7	6.7	5.2
1944	7.0	4.8	6.2	10.2	11.2	12.7	15.4	15.8	11.9	8.7	6.1	4.9
1945	1.2	7.7	9.0	9.8	11.2	13.4	15.6	15.6	14.2	11.3	7.9	6.8

Table IV. (*Continued*)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1946	4.3	6.1	6.3	9.3	10.0	12.7	14.5	13.6	12.9	10.1	7.6	3.9
1947	3.7	0.4	3.5	8.1	11.7	13.9	14.7	17.4	13.6	11.3	7.2	5.3
1948	4.1	5.1	8.7	8.9	10.7	12.5	14.7	14.3	13.0	10.1	8.7	6.0
1949	6.5	6.8	6.7	9.6	10.5	14.9	15.7	15.5	14.7	11.2	7.0	5.7
1950	6.1	5.0	8.2	7.4	11.4	14.9	14.9	14.3	11.9	9.8	4.9	1.9
1951	4.1	3.2	4.7	6.6	9.4	13.2	15.1	14.0	13.4	10.7	7.9	5.5
1952	2.5	4.3	7.1	9.4	12.0	13.0	15.5	14.9	10.4	9.2	4.8	3.8
1953	4.8	5.9	5.9	6.9	12.6	13.5	14.5	14.9	13.9	10.4	8.3	7.3
1954	4.5	4.4	6.5	8.2	10.6	12.6	13.3	13.7	11.7	11.2	6.6	7.1
1955	3.3	2.1	4.6	9.8	9.6	12.8	16.9	17.0	13.8	9.2	8.2	6.2
1956	3.9	2.7	7.3	8.1	11.4	12.8	14.8	13.0	13.2	9.7	7.5	6.8
1957	5.2	5.9	9.6	8.9	10.6	14.4	14.9	14.6	11.9	10.4	6.8	5.7
1958	4.3	5.3	4.3	8.1	9.9	13.2	15.1	14.7	14.5	10.8	8.1	4.6
1959	2.3	5.9	7.8	8.7	12.4	14.3	15.8	16.1	13.8	12.3	7.0	5.7
1960	4.4	3.7	6.9	9.6	12.8	14.9	14.3	14.2	12.6	10.1	6.8	3.0
1961	3.9	7.5	9.2	9.2	10.8	13.4	13.9	14.3	13.4	10.0	6.4	2.9
1962	4.6	5.5	3.7	7.9	10.2	13.0	14.0	13.7	12.2	10.6	6.4	4.5
1963	0.0	1.5	6.8	8.3	9.9	14.0	14.3	13.7	12.4	11.1	7.1	3.7
1964	5.7	5.1	5.5	8.7	12.1	13.0	14.9	14.5	13.3	9.3	6.9	3.9
1965	3.1	3.8	5.9	8.4	11.4	14.1	13.4	14.0	11.8	10.9	4.5	4.5
1966	4.0	5.7	7.8	7.0	11.1	15.1	14.6	13.9	13.9	9.2	4.9	5.3
1967	5.0	5.6	6.8	8.9	9.6	13.8	15.4	14.6	13.1	9.5	5.9	4.6
1968	5.3	2.3	6.4	7.9	9.5	14.3	14.6	15.3	13.0	12.2	6.8	4.2
1969	4.7	1.2	3.9	7.5	10.7	13.3	15.9	15.5	13.3	12.7	4.2	4.3
1970	3.7	2.8	4.9	7.0	12.7	15.8	14.2	15.4	13.3	10.4	6.7	4.5
1971	5.1	5.6	5.9	8.0	11.0	12.1	15.9	14.6	13.9	11.5	6.6	6.6
1972	3.7	4.3	5.8	8.4	10.1	11.2	15.1	13.5	11.5	10.1	5.5	5.7
1973	5.2	4.3	6.3	7.3	10.7	14.4	15.3	15.3	13.2	8.9	6.0	5.0
1974	6.1	5.1	5.6	8.4	10.3	12.6	13.9	14.4	10.9	7.5	5.2	7.0
1975	5.9	5.2	5.1	8.7	10.1	14.0	16.3	16.8	12.1	10.5	6.3	5.4
1976	5.5	4.8	5.5	8.7	10.7	15.7	16.4	16.3	12.2	8.8	5.5	1.8
1977	2.3	4.1	6.8	7.3	9.9	12.4	16.0	14.4	12.3	11.4	4.1	6.0
1978	3.2	3.1	6.1	6.7	11.7	12.9	14.4	14.5	13.5	11.8	8.2	4.3
1979	0.8	2.3	4.2	7.2	8.9	13.6	15.3	13.9	12.3	10.7	6.6	4.4
1980	2.5	5.2	4.8	9.1	11.3	13.0	13.8	15.1	14.0	8.7	6.7	5.2
1981	5.3	4.3	7.5	8.4	10.9	12.9	14.8	15.7	13.6	7.0	7.1	1.5
1982	3.6	5.2	6.2	9.4	10.9	14.5	16.0	14.8	13.0	9.4	6.1	4.1
1983	5.7	2.9	7.1	6.3	10.0	13.6	18.0	17.0	13.0	9.9	7.2	6.5
1984	2.5	4.5	5.1	8.6	10.1	14.6	16.1	16.5	12.4	9.8	5.9	5.3
1985	0.6	3.8	5.0	8.8	10.4	12.5	15.1	13.6	14.0	10.6	4.0	6.0
1986	3.6	1.0	5.7	5.8	10.5	14.4	14.8	12.4	11.6	10.4	7.1	5.6
1987	3.1	4.2	5.1	9.6	10.6	12.0	15.9	15.1	12.4	8.4	6.7	5.6
1988	4.5	4.9	6.7	8.9	11.1	14.8	14.1	14.5	12.8	9.9	5.9	7.8
1989	7.1	5.9	6.8	6.6	12.1	14.2	18.2	15.2	13.0	11.3	6.6	3.9
1990	6.2	5.7	8.4	8.0	12.4	13.0	15.9	16.1	12.0	10.9	6.4	4.2
1991	3.5	3.0	7.3	7.9	11.2	11.9	16.4	16.0	13.7	9.4	6.5	6.2
1992	4.9	6.0	7.5	8.1	12.3	15.0	15.1	13.8	11.7	7.5	7.1	4.5
1993	5.8	6.6	6.6	9.2	10.5	14.1	14.3	13.9	12.0	7.7	5.4	4.9
1994	4.8	3.0	6.9	7.6	9.8	12.9	15.7	14.1	12.1	10.1	9.6	6.0
1995	4.6	6.0	5.4	9.0	10.9	14.2	17.0	18.2	13.2	12.4	8.2	3.4

(*continued overleaf*)

Table IV. (*Continued*)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1996	6.2	3.6	5.4	8.8	8.9	13.7	15.2	14.8	13.4	11.2	5.7	3.9
1997	4.5	6.3	8.1	9.3	11.2	12.8	15.7	17.1	13.1	10.6	9.0	6.4
1998	4.9	8.3	8.1	7.4	12.0	13.1	14.6	15.3	13.9	10.2	7.0	6.3
1999	5.0	5.8	7.3	9.5	12.1	12.9	16.5	15.4	14.5	10.8	7.8	4.6
2000	5.2	6.3	7.9	7.2	11.6	14.0	15.5	16.0	14.1	9.9	6.3	5.1
2001	3.1	4.6	5.0	7.7	12.5	13.2	15.3	15.4	13.4	12.4	8.1	4.1
2002	6.8	6.4	7.7	8.9	11.4	13.5	14.5	15.8	13.8	9.4	8.7	5.4

[a] Values in italics signify mean monthly Dunsink data (converted to the equivalent of the mean of maximum and minimum at Armagh) with more than three missing days in the month, but less than 10 days. Values in italics and underlined signify mean monthly Dunsink data with more than 10 days missing.

Over the initial period of Series I, 1796–1824, 28 days' data were missing. Of these, 18 were isolated days and, therefore, will not have a significant effect on the monthly means. However, November 1796 had 8 days missing. For this month, the mean temperature in Table IV is shown in italics. In the second period of Series I, 1834–82, only 14 days have missing data, which again will have no significant effect on the means for the months during which they occur. For Series II there are only 28 days with missing data over the period January 1844 to December 2002, most of which occur in the early years of the series. For Series III, 1844–1964, there are significantly more days with lost data than in the other two series, namely a total of 128 days in 121 years. Most of these are single days in a month, but there are 10 months over the period with two missing days and 4 months with three. Two months, June and July 1880, account for 12 and 18 missing days respectively. The data from Series III have not been used in Table IV for these months.

Owing to the sporadic nature of the Dunsink material, for an appreciable number of months the data are incomplete; in order not to lose too much coverage, we list in Table IV in ordinary type the mean values for months with three or fewer missing days with data. In italics, we give the means for months with more than three, but less than ten, missing days, and values which are both in italics and underlined signify months for which Dunsink readings were missing on more than 10 days in the month. The four months October, November and December 1829 and July 1830 are derived from observations made at the Ordnance Survey Office, Phoenix Park, Dublin (Cameron, 1856), converted to the equivalent of the mean of maximum and minimum at Armagh. The data for these few months could be described as a patch within a patch. Finally, we note in Table IV that there is a 6 month gap in the Dunsink patch from January to June 1830. So far, we have not come across any data from the island of Ireland that can be used to fill this small remaining gap.

9. COMPARISON OF THE THREE ARMAGH SERIES

9.1. Annual means

In Figure 6 we show the annual mean temperature from each of the three series from Armagh, together with the Dunsink patch. The agreement between the three series, where they overlap, is good, with both long-term trends and year-to-year variations following very similar behaviour in the different series. It should be pointed out that, except for the Dunsink patch 1825–33, the three series are entirely independent, with no arbitrary zero-point shifts applied to ensure agreement.

Apart from the year-to-year variability, we note in Figure 6 the following decadal trends in the mean annual temperature at Armagh: (1) a cool period prior to 1820; (2) a warmer period 1825–*c*.1870 which peaks about 1830; (3) a cool period at the end of the 19th century; (4) a warm period 1940–60, (5) a cooler period 1960–80; (6) a gradual warming over the past two decades. Whilst there has been an exceptional number (five) of warm years over the past decade (1993–2002), when the mean annual temperature at Armagh has reached 10 °C or above, annual temperatures of this level have been reached before, e.g. in 1828 (based on

readings made at Dunsink), 1834, 1846, 1857, 1921, 1945, 1949 and 1959, so we are not yet beyond the range of *normal* variability.

As far as decadal trends are concerned, some of those seen in the Armagh series (e.g. points 3, 4, 5 and 6) have been noted in other individual series (e.g. Moberg *et al*., 2002; Bergstrom and Moberg, 2002). However, the mid-19th century warming has received relatively little attention. It is important to establish the reality, or otherwise, of this period of warming, as it provides a template against which later warmings can be compared. We postpone further discussion of this to a later section, where we look at the comparison with other long European temperature series.

9.2. Seasonal means

The seasonal dependence of the trends outlined above is of interest, both from the point of view of possible instrumental causes and true climatic changes. In Figure 7 we show the seasonal mean temperatures at Armagh over the past 207 years.

We note the following: (1) there is significantly larger year-to-year variability in winter and spring than in summer and autumn; (2) the spring and summer curves are relatively flat compared with autumn and winter; (3) all seasons show some evidence for a warming in the mid-19th century and at the middle and end of the 20th century; (4) autumns and winters were, on average, cooler by $\sim$1 °C prior to 1820; during this period there was a higher frequency of cold winters than has occurred since (12 in 25 years $T \leq 4$ °C); (5) the cool period at the end of the 19th century is evident in all seasons, but particularly spring, when temperatures were nearly 1 °C below average; (6) there has been only one cold winter ($T \leq 4$ °C) in the past 15 years; however this is not unprecedented, as there was a similar period of mild winters in the 1920s and 1930s. Our conclusions here are broadly in accordance with those of McElwain and Sweeney (2003), which were based on data from a number of sites in Ireland over a shorter period since 1890.

9.3. Series II: maximum, minimum temperatures and the daily temperature range

In Figure 8 we plot the annual mean maximum and minimum temperatures and the daily temperature range (DTR) from Series II. On both year-to-year and decadal time scales the behaviour of mean maxima and mean
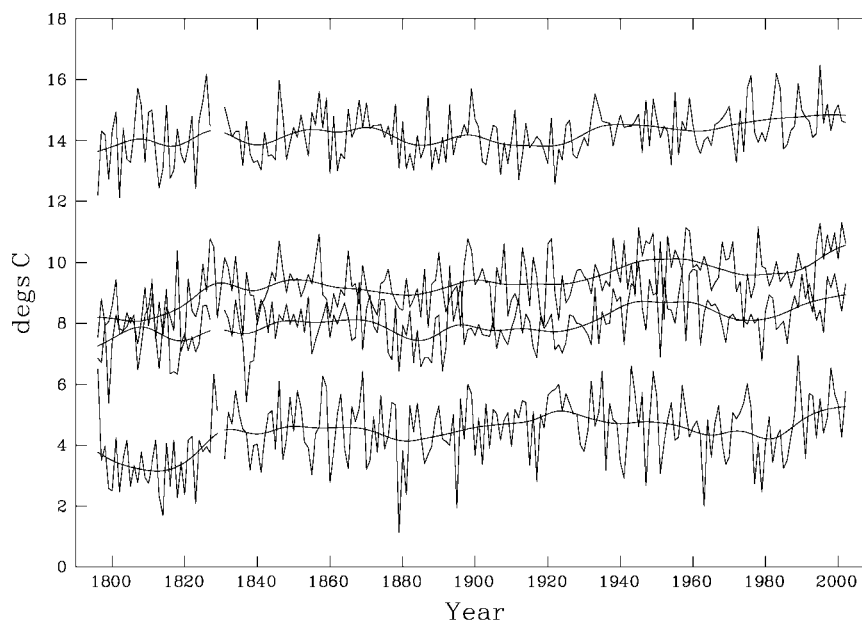
Figure 7. Mean seasonal temperatures at Armagh Observatory from the mean of Series I, II, III and the Dunsink patch. In ascending order from the bottom: winter, spring, autumn, summer
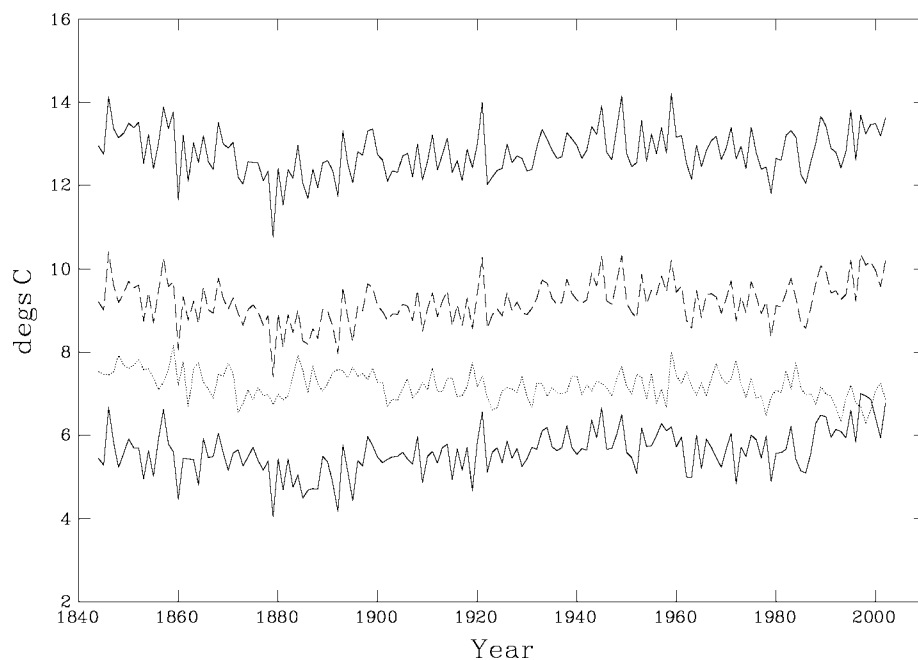
Figure 8. Mean annual maximum, minimum and mean temperatures and the DTR (maximum minus minimum) at Armagh, 1844–2002. Maximum (top continuous line), minimum (bottom continuous line), mean (dashed line), DTR (dotted line)

minima is generally similar, with warm periods in the mid-19th century and in the middle and at the end of the 20th century. The coolest period in both maximum and minimum was the penultimate decade of the 19th century. There appears to be a decreasing trend in the DTR, which is more pronounced at the beginning and end of the series than in the middle. Palle and Butler (2001) have remarked on the gradually increasing cloud levels over Ireland since the late 19th century that is seen from declining numbers of sunshine hours, as well as other data. The gradual decline in DTR, seen in Figure 8, would be consistent with such an increase in cloudiness. We have looked to see whether there is any seasonal dependence in the DTR present in our data, but we have found no significant effect.

10. COMPARISON OF THE ARMAGH TEMPERATURE SERIES WITH OTHER NORTHWEST EUROPEAN SERIES

Though the Armagh temperature series, as with all series from a single site, is essentially *local*, it is of particular interest to make a comparison with other long temperature series in order to establish which, if any, characteristics are purely local and which are indicative of conditions over a wider area. The geographical location of Armagh, close to and on the eastern margin (windward) of the North Atlantic, ensures that its climate is strongly influenced by the ocean and thereby representative of a larger region than just Northern Ireland. Indeed, it has been shown by Palle and Butler (2001) that cloud cover over Ireland is strongly correlated with cloud cover over the North Atlantic and even over oceans in mid–high latitudes, globally. Thus, conclusions based on local site-specific series, such as that from Armagh, can have much wider repercussions for our understanding of how climate in Europe has changed over the past 200 years.

In this section we compare the Armagh series with that for central England (Manley, 1974; Parker *et al.*, 1992). and two long series from southern Sweden, namely Stockholm (Moberg *et al.*, 2002) and Uppsala (Bergstrom and Moberg, 2002). We have not included a third series for northern Sweden recently published by Klingbjer and Moberg (2003).

The central England series, which is the longest such temperature series in the world, is formed by fitting together temperature series from a number of sites in England. Currently, it is maintained by the Hadley Centre from readings at four sites, namely: Rothampsted, Malvern, Squires Gate and Ringway. Since 1974 it has been adjusted for urban warming effects.

The two long temperature series maintained by the Stockholm and Uppsala Observatories have been compared and homogenized by Moberg and Bergstrom (1997). Urban warming effects have been corrected. Unlike British and Irish stations, where Stevenson screens came into general use in the late 19th century, readings were taken at Uppsala and Stockholm in NWSs well into the 20th century.

In Figure 9 we show the mean annual Armagh temperature series together with the central England series and the average of the Uppsala and Stockholm series since 1790. The agreement between the Armagh and central England series is good, with rises and falls closely corresponding in time. Over the 208 years in common, the temperature at Armagh has been generally cooler than central England by an amount varying from 0 to 1 °C. One might have suspected that this was due to calibration errors; however, this looks less likely when we note that even in the mid-20th century, when calibration problems do not arise, the difference between the two series has varied over the range 0.0 to 0.7 °C. Around 1800, the difference is rather larger, with Armagh ~1.0 °C cooler than central England.

As Uppsala and Stockholm are relatively close geographically and their temperature series follow each other, we have formed an average of the two series. We show in Figure 9 that, whereas the Swedish data have significantly larger annual variability, the peaks and troughs in the smoothed curves correspond approximately with those in the central England and Armagh series. Nevertheless, it appears that there is a delay in the peaks of the central England and Armagh data of the order of several years compared with the Swedish data. This is particularly noticeable in the peaks that occur in the 1820s and the 1940s. This delay is possibly due to the greater oceanic influence on the data from the British Isles compared with Sweden.

At the top of Figure 9 we show a series for the eastern USA (Landsberg *et al.*, 1968). Again, rises and falls of temperature follow those seen in the European series, suggesting that the variations seen in northwest Europe are indicative of changes over a wider area.
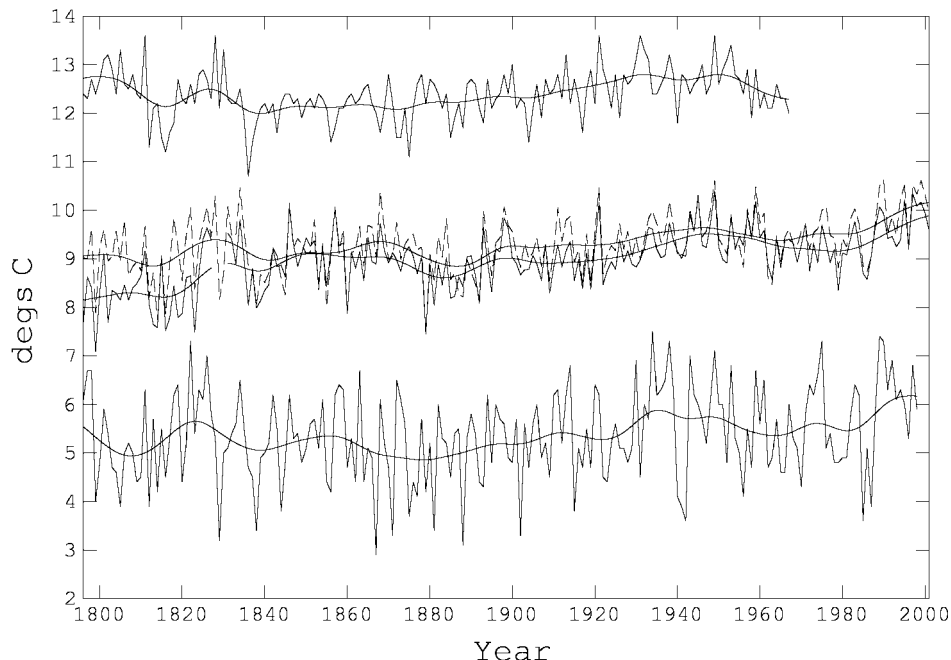

Figure 9. Mean annual temperatures at Armagh compared with the central England series, the mean of Uppsala and Stockholm and the eastern USA. In ascending order: Sweden, Armagh, central England and eastern USA. The central England series is shown with a dashed line to distinguish it from that for Armagh
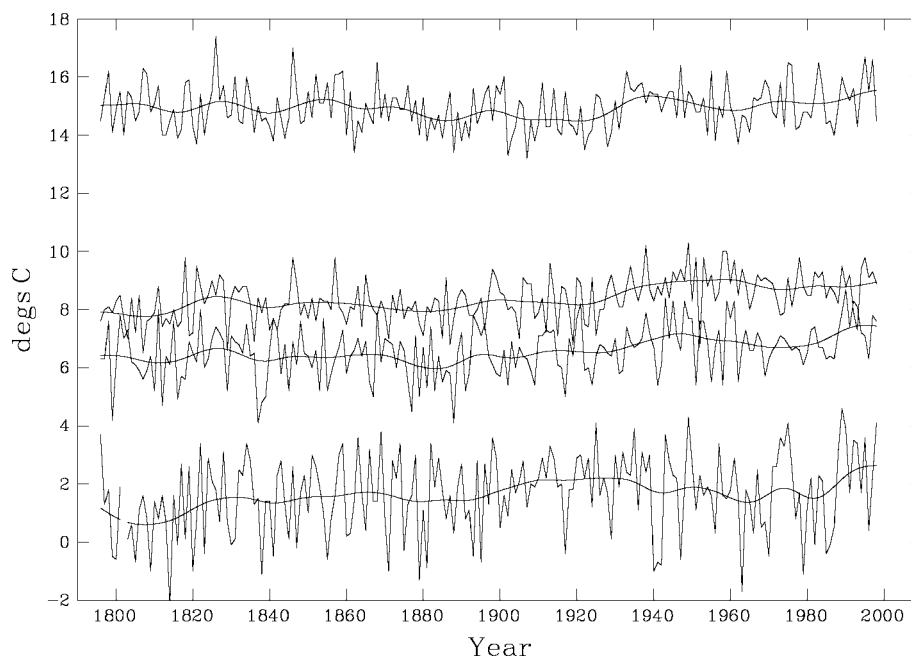
Figure 10. Mean seasonal temperatures averaged over the three series: Armagh, central England and Sweden. In ascending order: winter, spring, autumn, summer

In Figure 10 we show the variation of mean seasonal temperature over the period 1795–1995 for the average of central England, Armagh and Sweden. We note that in northwest Europe the mean summer temperature curve is more or less flat, whereas significant warming has occurred in winter ($\sim$1.6 °C) and to a lesser extent spring and autumn ($\sim$0.8 °C). This probably reflects the increasing surface temperature of the North Atlantic, which has a greater effect on land air temperature in winter than summer.

11. CYCLIC ANALYSIS OF ARMAGH TEMPERATURES

The search for cyclic variability in meteorological data has occupied many researchers in the past (see references in Burroughs (1992)). Periodicities varying from the quasi-biennial cycle to periods of decades or even centuries have been found. Frequently, such periodicities come and go in the data, indicative of the stimulation of a natural oscillation that subsequently dies down. Interest in these cycles has risen in recent years as a greater appreciation of their importance in regional climate has developed, with two prominent examples being the El Niño–southern oscillation of the Pacific and the North Atlantic oscillation (NAO; see Hurrell *et al.* (2003)). In addition to their direct effect on the weather pattern of the areas where they are defined, these pressure cycles appear to have teleconnections with weather patterns in other, more remote regions of the globe. For instance, it is thought that the NAO may teleconnect with El Niño/La Niña. As seasonal teleconnections may differ, we analyse the data on a seasonal basis.

There are two well-established techniques for analysis of cyclic variability in data such as the temperature data from Armagh: (1) Fourier analysis, leading to a power spectrum; (2) wavelet analysis, which identifies the periods of time during which any particular oscillation is present in the data.

In Figure 11 we show the Fourier transform of the Armagh temperature series over 208 years. We note the strong 7.8 year periodicity in the winter and spring temperature series. This is undoubtedly related to the NAO index, which also has a periodicity of 7.8 years in winter (Wunsch, 1999; Butler, 2001; Mills, 2004).

To ascertain over which intervals the 7.8 year periodicity is strongest, we subjected the same seasonal data to wavelet analysis. It was found that in spring the 7.8 year periodicity was strong in the 1830s, 1880s
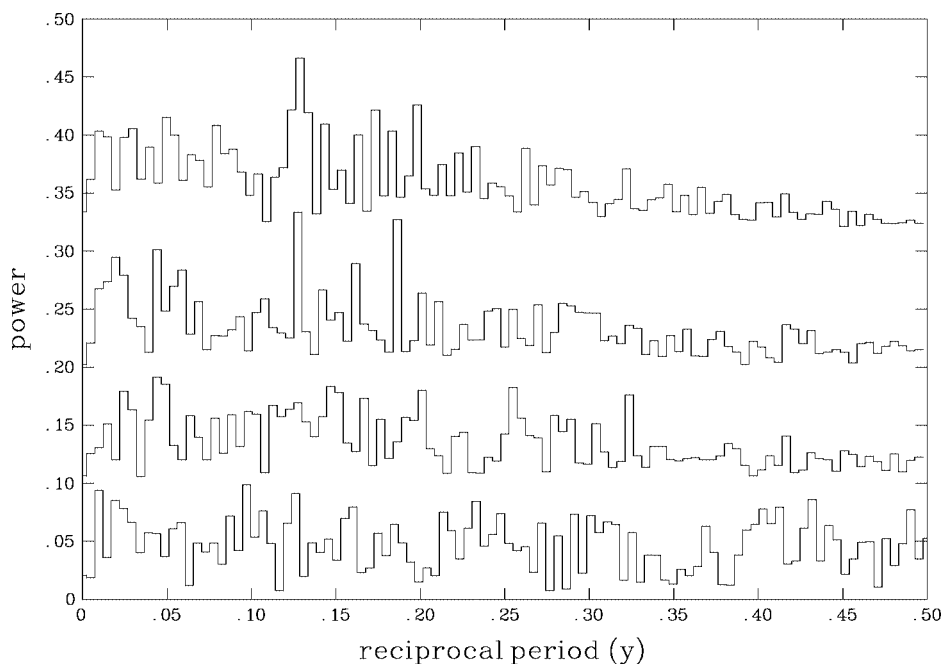
Figure 11. The power spectrum of the mean seasonal temperature at Armagh Observatory over the period 1796 to 2002. An arbitrary vertical shift has been applied to separate the seasons. In ascending order: autumn, summer, spring and winter. Note the peak at circa 7.8 years in the mean winter and spring temperatures, which is probably related to the NAO

and 1890s; in summer it was strong in the 1970s and 1980s; and in winter it was strongest over the period 1850–90 and the 1970s. Wavelet analysis of the NAO index indicated that the 7.8 year cycle was also strong in the NAO index at these times, thereby confirming the connection.

The period (7.8 years) of the cycle in winter and spring temperatures at Armagh is similar to that found previously by Butler *et al.* (1998) in summer precipitation at this site (~7.1 years). In that study it was also shown that the winter and autumn NAO indices were strongly correlated with the precipitation in the same seasons in Armagh. Such a correlation is expected, as the NAO is an index of westerly airflow over this region.

The earliest evidence we have found for the identification of an approximate 7 year cycle in meteorological conditions in Ireland lies in an unsigned manuscript in the Armagh Observatory archives (Butler and Hoskin, 1987; M32). This documents instrumental meteorological and phenological data from 1846 to 1883 at Glendoen near Letterkenny, County Donegal. It is believed to be the weather diary of the Reverend Henry Kingsmill, Rector of the Parish of Conwall, 1836–76. Whilst first noting that he could not establish an 11 year cycle dependent on the sunspot number, he continues 'On comparison of a good n° of years, from 1816 to 1879, I found a recurrence of like seasons of seven years or a multiple of 7'. This appears to be an early record of what we now recognize as the NAO.

12. CONCLUSIONS

We have standardized three temperature series from Armagh Observatory, Northern Ireland; namely (i) a twice-daily external temperature series, (ii) a series of maximum and minimum temperatures, and (iii) a series based on the dry-bulb reading of the hygrometer. Each series has been calibrated independently, taking into account thermometer errors, the time of reading and the exposure of the instruments. A gap in the Armagh data from 1825 to 1833 has been largely filled by data from Dunsink Observatory and the Phoenix Park, Dublin, transformed to Armagh.

In the extended periods of overlap, there is good agreement between the three Armagh series, both in year-to-year variability and long-term trends. Monthly mean temperatures have been formed from the mean of the three series and tabulated for the period January 1796 to December 2002. This is the longest temperature series for the island of Ireland and one of the longest from a single site anywhere in the British Isles.

Long-term trends are seen in both seasonal and annual mean temperatures, with spring and summer series relatively flat compared with autumn and winter. Prior to 1820 we note that autumns and winters were cooler by ∼1 °C. Later, we note a significant warming in the mid-19th century, which started in the late 1820s and continued till *c*. 1870. A cool interval at the end of the 19th century was followed by a period of rising mean temperatures that lasted till the mid-20th century. Finally, a slight cooling from 1960 to 1980 was followed by a gradual warming over the past two decades. In spite of the current warmer conditions, annual mean temperatures still remain within the range seen in the previous two centuries.

In the period of overlap, 1865–2002, we note that the features seen in the Armagh series are closely paralleled by features in the Northern Hemisphere mean temperature (Jones *et al.*, 2001). The mid-19th century warm period, which is also seen in the central England series, has received relatively little attention. It is important to establish the reality of such 19th century warmings, because that century is frequently used as a baseline for modelling the 20th century climate. A baseline at the end of the 19th century, when conditions were noticeably cooler, would exaggerate the subsequent warming in the 20th century.

Mean maximum and minimum temperatures show a consistent downward trend in the DTR at Armagh since readings began in 1843. This may be a result of the increased cloudiness previously inferred from bright sunshine data for Ireland.

Comparison of the Armagh temperature series with the central England and Swedish series shows good agreement in their general trends; however, temperatures in Sweden show significantly larger year-to-year variability. There is some evidence that the peaks in temperature in Armagh and central England occur a few years later than in Sweden.

A search for cyclic variability in the Armagh series identified a 7.8 year periodicity in winter and spring mean temperatures. This is undoubtedly due to the influence of the NAO, which contains power with the same periodicity. A similar periodicity was previously found in precipitation at Armagh.

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