Soil Temperatures at Armagh Observatory, N. Ireland, from 1904 to 2002

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Abstract

Soil temperatures at 30 and 100 cm depth from Armagh Observatory are presented covering the period 1904 to 2002. The series has been corrected for changes in depth and location of the thermometers and compared with data from two other sites in Ireland: Birr and Valentia.

Linear regressions of the soil temperatures over the past century for the three sites have positive slopes in all seasons which vary from 0.04 to 0.25 °C/decade, depending on the season, depth and location. There appear to be some geographical differences, with relatively shallow trends in winter in Armagh and Birr and steeper trends in Valentia.

Soil temperature variations at Armagh Observatory are intimately related to changes in the mean air temperature but are also influenced by changes in precipitation. We show that winter soil temperatures at Armagh can be successfully reconstructed from air temperature records.

Keywords: Temperature, Northern Ireland, climate change, soil temperature, soil moisture, earth temperature, rainfall, Palmer Drought Severity Index

1 Introduction

In the ongoing discussion of the causes and effects of *global warming*, the recent rise in tropospheric air temperatures has dominated the discussion. However, in the broader perspective of climate change, many other meteorological parameters will be involved, some of which may be expected to parallel atmospheric temperature. One such meteorological data set that has been routinely measured over the past century, but received little attention, is soil temperature which, though to some extent a derivative of atmospheric temperature, nonetheless represents an independent data set with its own peculiar instrumental and measurement problems.

Tang (1989) and Hu *et al.* (2002) have pointed out that the amplitude of the annual variation in heat storage of the top 5m of soil in mid-latitudes is similar in energy terms to that of the entire atmospheric column above. Thus the heat stored in the upper levels of the ground cannot be ignored in the study of the temporal variation of the atmosphere above. In addition, it is clearly evident, that soil temperature is an important parameter which directly affects the growth of plants and biological and physical processes occurring in the soil (Zhang *et al.* (2001) and Hu *et al.* (2002)).

Soil temperature depends on a variety of environmental factors including: the temperature of the air immediately above the surface, moisture content, evaporation rate, the energy received at the surface from the Sun, the albedo of the surface and the thermal conductivity of the soil. As a result, soil temperatures integrate the effects of other, more obvious, climatic factors such as sunshine, air temperature and precipitation (Zhang *et al.*, 2001; Marshall and Holmes, 1988; Hillel, 1982) and can also be used, instead of mean air temperature, to predict the phenological phases of plants, the length of the growing season and to study the evolution of permafrost in northern latitudes (Zhang *et al.*, 2001; McMaster and Wilhelm, 1998). Notwithstanding these more fundamental considerations, the motivation for this particular study arises from an ongoing programme to standardise the principal meteorological datasets from Armagh Observatory (Butler, 2001) and to use these in a subsequent study of the effects of meteorological variables on tree-rings of different species (García-Suárez *et al.* 2006).

In Ireland, soil temperatures have significant daily and annual variation depending on the time of the year and on cloudiness, with greater variations on days with a clear sky. The top 20 cms of soil show the greatest daily temperature variation, with coldest temperatures occurring in the morning. The annual cycle of soil temperature has a peak in June and a minimum between December and January for well-drained soils. Temperature changes at the surface propagate slowly downward into the ground at a rate which depends on the composition and cohesion of soil particles and moisture. These variations are progressively smoothed with increasing depth and a lag develops that depends on heat conductivity and thermal inertia. The land use and the nature of the vegetation covering the land are also important factors for soil temperatures (Collins and Cummins, 1996).

Soil temperature series are less common than air temperature series and, if available, they are usually of shorter duration. In Ireland, the longest soil temperature series, at 1 foot/30 cm and 4 foot/100 cm depth, are from Armagh Observatory where they commenced on 21 April 1904. Two other Irish stations, namely: Valentia and Birr have soil temperature records but they started later and are discontinuous.

2 The meteorological station and the data

The meteorological series maintained at Armagh Observatory ($6^\circ 39'.8$ W, $54^\circ 21'.2$ N, alt. 60m), which began in 1795, are the longest in Ireland and one of the longest in the British Isles from a single site (Butler *et al.*, 2005a). Daily observations of temperature and pressure began in 1795 and the recording of daily precipitation values commenced in January 1838 (García-Suárez *et al.*, 2002). From 1868 to 1883, an automatic self-recording meteorological station was built at Armagh which continuously monitored pressure, wind speed and direction, precipitation, and wet and dry temperatures. It was one of seven such stations erected and operated by the Board of Trade in various locations throughout the British Isles. From 1880, the hours of bright sunshine have been measured with a Campbell-Stokes sunshine recorder (Butler *et al.* 2005b and Pallé Bagó and Butler, 2001) and in 1885 a Stevenson Screen was introduced to house the air thermometers. Soil temperature readings were the last meteorological parameters to be included.

The meteorological station is situated close to the Observatory near the top of a drumlin of boulder clay. The top layer of soil ($\sim$40 cm), which is classified by Cruikshank (1997) and Collins and Cummins (1996) as *brown earth*, is composed of a mixture of sand and clay; below this is clay. As is common in the British Isles, the surface of the soil is covered by short grass.

The Symons-pattern thermometers used for soil temperatures are enclosed in glass tubes with their bulbs embedded in paraffin wax to reduce sensitivity to sudden changes in temperature. The thermometers which are suspended by chains inside an iron tube at the correct depth are lifted up for readings to be taken at 09:00 GMT each day. Note that, as the readings are made just once daily, the temperature recorded at 30cm depth is close to the minimum of its diurnal range, whereas, at 100cm, where there is no discernible diurnal variation, temperatures are representative of the daily mean.

The raw daily soil temperature data have been digitised as part of a project to place all of the meteorological data accumulated at Armagh Observatory over the past two centuries in the public domain. In the following sections we give details of the corrections made to the raw data for changes in the location and depth of the thermometers. Later we show the corrected mean monthly, seasonal and annual soil temperatures for this site. Further details, plus the tabulated corrected daily data are given in García-Suárez *et al.* (2005a) and *(http://climate.arm.ac.uk/calibrated/soil/).*

Regrettably, the soil temperature series from Armagh is not quite complete due to the breakage of the 1 foot instrument in July 1946 and a delay in its replacement. A new thermometer was received in January 1947 and readings resumed on 1 February of that year. There are no readings for the 4 foot/100 cm thermometers for the months of January 1947 or April 2000.

2.1 Calibration of soil temperature series

This paper summarises the work undertaken to homogenise the soil temperature records at Armagh Observatory. The process required corrections for the change from Imperial to Metric depths in 1971 and for location within the site. No correction for instrumental error of the thermometers has been made as none of the inspector's reports over the period 1904-2002 lists corrections for the relevant thermometers in excess of 0.1°C, their nominal reading accuracy.

2.1.1 Changes in the standard depths

Up until the end of 1970 the standard depth at which soil temperatures were measured at Armagh Observatory were 1 foot (304.8 mm) and 4 feet (1219.2 mm). From 1^{st} January 1971, following a proposal from the World Meteorological Organisation, the depths were redefined in metric units; namely at 30 cm and 100 cm. No overlap of readings between the old and new standard depths was made at that time which would have allowed a direct comparison to be made. As these changes might have led to a small systematic shift, especially with the change from 4-ft to 1 metre, it was decided to measure temperature profiles versus depth over a period of a year to confirm whether or not a correction was needed.

Figure 1 shows the temperature profiles against time and depth for Armagh Observatory. The left panel shows the temperatures at the standard depths (both Imperial and Metric) throughout the year, the middle panel shows the mean monthly temperature at 100cm/4-foot for the years 2002-2005 and the right panel shows the temperature depth-profiles at different dates approximately evenly spaced throughout the year. These profiles correspond to a well drained soil. Wetter soils give flatter peaks and maximum and minimum temperatures are delayed (Collins and Cummins, 1996).

No temperature profiles with depth were previously available for Armagh; indeed, the nearest data of this type we have found was reported by Collins and Cummins (1996) for Kilkenny ($52^{\circ}39'$ N and $7^{\circ}15'$ W) where significant differences were found between soil temperatures at 100 cm and 120 cm.

Figure 1 (left) shows that the temperatures for 30 cm and 30.5 cm (~1ft) were identical for the period studied (March 2002 to Feb 2003) and no correction is required for this change. This was not the case for the temperatures at 100 cm and 122 cm (~4ft); during spring and summer months significant differences appear and, in some cases, those differences can be greater than 0.2°C. A correction for the change from Imperial to Metric depths (4 feet-to-100cm) of +0.1 °C was applied from 15 May to 15 October in each year over the period 1904-1970. This correction is the mean of the difference between the temperature recorded by the thermometers at 4ft and at 1 m depth during that period of the year. Although this correction has been determined from data for just three years (2002-2004), significant changes from year-to-year are not expected. Nevertheless, it has been decided to continue the temperature measurements at 122 cm and 100 cm for a further period. These 122 cm soil temperature measurements take place every Monday. Note that this correction is valid for monthly soil temperatures, but may not be applicable for the correction of daily data on days with heavy rain. In principle, it would also be possible to correct the daily data using the thermal conductivity model proposed by Hu *et al.* (2002) and Hu and Feng (2003).

2.1.2 Thermometer location

Following the commencement of soil temperature readings, the thermometers have changed location three times, though they have always remained within the South Lawn of the Observatory (see Fig. 4 in García-Suárez et al., 2005a), and therefore refer to the same soil type.

The calibration of the soil temperature readings for exposure effects associated with their location is complicated by the fact that, for a period from the 1930s to the mid-1960s, the thermometers were in close proximity to a gravel and, from 1949 to a tarmac, path. From readings made during 1966-68, at these locations and others more properly positioned, we have been able to derive corrections which have been applied from January 1949 to January 1968. These corrections have a well defined seasonal variation and reach a maximum amplitude of 1 deg C in mid-summer for the 4-foot and 0.7 degs C in winter for the 1-foot thermometers. Details of the corrections and how they have been applied are given by García-Suárez *al.* (2005a).

2.2 Comparison of the raw and corrected data

In Figures 2 and 3 we plot the corrected seasonal and annual mean soil temperature series (thick lines) together with the raw data (thin lines) for 30 cm and 100 cm series respectively. Note that for the 1949-1968 period, two corrections have been applied to the 100 cm soil temperature series: firstly, for location with respect to the path and, secondly, for the change in depth from four feet to one metre. The 30 cm soil temperature series was corrected only for location.

3 Comparison of the seasonal mean soil temperature at different depths

In Figure 4 we compare the corrected seasonal and annual means for the 30 cm and 100 cm soil temperature series in a single diagram. The behaviour of the seasonal and annual mean curves is closely similar for both series with rises and falls in the 30 cm data mirrored at 100 cm. This close similarity in behaviour results in parallel temperature curves at the two depths in each season. However, in summer and spring, 30 cm temperatures are higher than at 100 cm depth, whereas in autumn and winter, the situation is reversed. This results in approximately equal values for the mean annual temperature at 30 cm and 100 cm (bottom panel, Figure 4). The almost identical curves for the annual mean temperatures at the two depths gives us added confidence that the corrections made for depth and location changes have been successful and that the calibrated series are reliable.

Over the long term, we note that soil temperatures at Armagh have risen in spring, summer and autumn whereas, in winter, the temperature time profile is relatively flat. Annually, the rise in spring, summer and autumn dominates to give a steady rise in ground temperatures at both depths throughout the 20th century. A linear regression of 30 cm soil temperatures gives an average rise of ~0.16 °C/decade in spring, summer and autumn and 0.04 in winter (see Table 1). Decadal trends in 100 cm temperatures are practically identical. Annual trends for both depths are 0.13 °C/decade.

Apart from these broad trends, it is noticeable that summer soil temperatures since the late 1980s have dropped compared to the 1970s to mid-1980s. This could either be due to the shift in the site in 1988 or to a true climatic change. Regrettably, due to earth works that have taken place in the Observatory grounds (see García-Suárez, 2005a), it is no longer possible to reproduce measurements at locations South Lawn A and B to check this possibility.

3.1 Soil temperatures from Armagh Observatory compared with other Irish sites

Although the soil temperature records from Armagh Observatory are the longest from the island of Ireland, there are some comparable records from stations in the Republic of Ireland operated by Met Éireann, namely at Valentia, Co Kerry and Birr, Co Offaly. Both have made soil temperature records at 30 cm and 100 cm depth although the records are less complete than at Armagh.

Valentia Observatory (10°14′.7 W, 51° 56′.4 N, alt. 11m), originally founded on Valentia Island in 1860, moved to its current site on the mainland, one kilometre west of the town of Cahirciveen, in 1892. The soil temperature records for this site, which have been kindly made available by Met Éireann, include: mean monthly data from January 1931 to December 1936 and daily data from October 1939 to present. In February 1999, the soil thermometers were moved to a new site about 350 m SW of their former position. A 2-year comparison between the old and the new sites was made from March 1999 to February 2001 (pers. comm. J. O'Sullivan, see ARM/MET/000632 in García-Suárez *et al.*, 2005b). The mean temperatures at 30 cm were 12.5 °C for the old site and 11.8 °C for the new (new site colder by 0.7 °C) whereas at 100 cm the mean temperature was 12.7 °C and 12.5 °C for the old and the new site, respectively (new site colder by 0.2 °C).

The meteorological station at Birr, established in the grounds of Birr Castle in 1862, was moved, first in 1939 to St John's Mall (about 1.3 Km from the original location), and again in October 1954 to its current site at Syngfield (7°53′.5 W, 53°05′.5 N, alt. 73 m), 1.5 Km ESE of the town of Birr and 1.2 Km from St John's Mall (Lynch, 2004, priv. comm.). For Birr, the soil temperature records cover the periods from January 1912 to October 1941 and from October 1954 to the present. The gap in the Birr records is believed to be due to a missing record book.

Due to the changes in location that have occurred at both sites and the uncertainties involved, we have not made any attempt to correct the Valentia and Birr soil temperature data here and have used the raw data as provided. This limits the value of the Birr and Valentia series in comparison with Armagh where an extensive amount of metadata is available and has been employed in assessing corrections. It seems likely that soil temperature data from Valentia could be standardised satisfactorily, however a careful study of metadata relevant to the site would be required. Standardisation of the Birr soil temperature series would be more difficult in the absence of appropriate information.

Valentia suffers from wetter conditions than the other two stations. The driest months occur in spring for all three stations, the rainiest season at Valentia is winter, whereas for Armagh and Birr the months from July to January are the wettest.

Figures 5 and 6 compare the soil temperature series for Armagh, Birr and Valentia at 30 cm and 100 cm depths respectively. The year-to-year variations for all series are very similar, although the mean temperatures differ significantly, as expected. Valentia, due to its proximity to the Atlantic seaboard, has higher winter (Dec-Feb) and annual mean temperatures than the other two stations. In summer (Jun-Aug), the soil temperatures are similar for the three stations. However, unexpectedly, for periods lasting a decade or so in the second half of the twentieth century, the soil temperatures in summer for Armagh Observatory are higher than for the other two stations. This occurs between 1960 and 1975 in the 30 cm readings and between 1970 and 1985 in the 1m readings. Whilst there remains a possibility that this is due to exposure and location, there is strong evidence that it arises from changes in summer rainfall and therefore reflects a true climatic change. This will be discussed in a later section.

The mean summer and the annual soil temperature has increased for all three stations over the last century. The increase is larger in summer and most clearly evident in the longer Armagh Observatory series (see also Figure 4 and Table 1). A linear regression of the seasonal and annual soil temperature series for all three sites gave the trends (°C/decade) listed in Table 1. The regression coefficients were computed for all available data and therefore cover a rather shorter period for Birr and Valentia than Armagh. We note that the trends in all seasons and all sites are positive, with good agreement between trends at 30 cm and 100 cm depths.

The good agreement in the behaviour of the three series gives us added confidence that the variations seen are real and of value in the ongoing discussion of climate change. On the other hand, there appear to be significant differences between the trends in winter soil temperatures at Armagh, Birr and Valentia. For Armagh (30 and 100 cm) and Birr (30 cm), the winter temperatures curves are almost flat over the 20^{th} century, whereas winter soil temperatures at both depths in Valentia show an upward trend similar to other seasons. Whilst this difference may be due to unresolved exposure corrections at any of the stations there is evidence from other data that they may be climatic (see Section 5).

4 Comparison of trends in soil temperature and other climatic parameters from Armagh

As previously mentioned, soil temperatures are influenced by a number of meteorological parameters. In this section, we show how some of these parameters have varied over the past two centuries at Armagh and discuss their relevance to soil temperatures. Figures 7-9 show the annual and seasonal variations of (from top to bottom): (1) Air temperatures. (2) Soil temperatures at 30 cm. (3) Soil temperatures at 100 cm. (4) Rainfall totals. (5) Palmer Drought Severity Index (PDSI) which is a standard index quantifying the severity of drought conditions compared to normal soil moisture conditions (for further details see Dai *et al.*, 2004). Note that the longer term variations are shown with a smoothed curve whereas the annual means are shown by histograms. In addition to these commonly measured meteorological indices, the total daily solar energy received on a horizontal surface would be expected to influence soil temperatures, particularly close to the surface. Unfortunately, data of this type is not available for this site. In principle, it might prove possible to reconstruct this parameter from more detailed measurements of the record cards for the Campbell-Stokes instrument, however this would be a tedious undertaking that has not so far been attempted. Therefore we restrict our discussion to the influence of air temperature, rainfall and PDSI.

(1) Air temperatures. Over the past 207 years, the air temperatures in Armagh show an overall trend upwards, consistent with other northwest European series such as Central England, Uppsala and Stockholm, (Butler *et al.*, 2005a). However, this apparent trend is not uniform for there were warm periods in the mid-19th century, in the mid-20th century and at the end of the 20th century, interspersed by relatively cool periods in the early 19th century, in the 1880s and the 1970s.

(2 and 3) Soil temperatures. As with air temperatures, the soil temperatures at Armagh Observatory have increased over the past century. Both 30 cm and 100 cm annual means were approximately 10 ^{o}C at the beginning of the 20^{th} century, whereas at present the annual means are around 10.5 ^{o}C.

Figure 4 compares the corrected seasonal and annual means for the 30 cm and 100 cm soil temperature series. The most striking feature of Figure 4 is the gradual increase of summer, autumn and spring soil temperatures. The enhancement is most significant for the summer mean in which temperatures have risen more that one degree Celsius. The winter means for both 30 cm and 100 cm series are much flatter with a marginally significant fall in the 1950s and 1960s. This behaviour is similar to that of seasonal mean air temperatures for this site over the same interval.

(4) Rainfall. The total annual rainfall series does not have a clear trend. There are periods of reduced precipitation with respect to the mean of the series after the 1970s to the present and before the 1900s. At Armagh the rainfall is well distributed throughout the year, though spring months are drier and August to October wetter, than average. Butler *et al.* (1998) found a significant decrease in summer rainfall from the 1960s whereas winter rainfall has increased from the beginning of the 20^{th} century.

(5) PDSI. The average PDSI for the whole series is 0.15 which is considered normal for the soil moisture conditions at Armagh. Years with high soil moisture such as 1877, 1882, 1883 and 1966 and years with low soil moisture such as 1934, 1996 and 1997 do not always coincide with unusually wet or dry years. Note a decline in the soil moisture, particularly in summer and autumn, from the 1970s.

4.1 The influence of air temperature and soil moisture on soil temperatures

If there is no internal heat source in the soil, within the depth of interest, the heat or energy affecting soil temperatures will originate either from the atmosphere or from the Sun. In these circumstances, soil temperature will vary in response to changes in the radiant, thermal and latent heat exchange processes which take place through the soil surface (Hillel, 1982). The transport processes most relevant in soils are radiation and conduction. The transfer of heat by radiation will differ during day and night. Similarly, conduction is affected by the composition of the soil. For instance, air contained in soil is a poor conductor compared to the solid and denser components. In turn, water in soil can vary the energy transport because water replaces air in the soil, thus increasing conductivity. Thus, whilst the physical processes involved are well understood (see Hillel, 1982 and Marshall and Holmes, 1988), in order to construct realistic models of the soil heat budget, the values of many physical parameters must be known as well as how they vary with depth in the soil. For these reasons, we consider detailed modelling of how various physical parameters affect soil temperatures to be beyond the scope of this study. In this section we adopt an empirical approach to identify which climate parameters influence soil temperatures, when and how strongly.

Figures 7-9 show that the soil temperature year-to-year variations are similar to those for the air temperature. However, the amplitude of the changes and trends may be different. For example, in the annual means, soil temperature has increased in the last century more than air temperature. The year-to-year variations are similar, but rises and falls do not occur at the same time. This implies that changes in soil temperature are not solely dependent on, or directly proportional to, changes in air temperature.

With respect to the influence of precipitation on soil temperatures, we note the following: (1) In summer, the difference in patterns of change for soil and air temperature are more accentuated than in winter and often coincide with rainfall variations. (2) In the 1970s, the annual air temperature was stable for several years while the rainfall decreased which produced an increase in the annual soil temperatures. (3) In the 1970s and 1980s there is similar occurrence for the summer temperatures. (4)

In the 1990s, the mean annual air temperature increased whereas the PDSI passed through a minimum. This has led to an increase in the soil temperature above that registered by the air temperature, particularly at 100 cm depth.

Table 2 lists the correlation coefficients between soil temperatures and air temperature, rainfall and PDSI. This Table shows that the correlation between soil and air temperatures is strongest in winter. The correlation coefficients between the soil temperatures and rainfall are significant only in summer and marginally so in spring and for the annual means. Note that the correlation coefficients between soil temperatures and rainfall are poorer than for the PDSI. This is not unexpected since the PDSI depends on both air temperature and rainfall and thus is not completely independent. If the relationship between soil temperature and rainfall is weak but strong with air temperature, the PDSI will reflect both, leading to a higher correlation than for rainfall alone. Note also that the influence of air temperature is more important for the soil temperature at 30 cm than at 100 cm depth whereas the effect of rainfall is more important at a greater depth.

Due to the thermal inertia of soil, there will be a delay in soil temperature changes compared to the air temperature. In Figure 10 we show the time profiles of the soil temperature at Armagh at 100cm depth together with the air temperature time profile. We note a roughly ten day delay in the peak soil temperature at 100cm compared to the peak air temperature and a somewhat longer delay of around 30 days at minimum. This compares with a delay of 1 or two months found by Hu and Feng (2004) in North America. No significant delay has been found for the temperature at 30cm compared to air temperatures.

The above patterns and trends indicate that the soil temperature variations are enhanced by rainfall or soil moisture. Rainfall and PDSI have declined in the summer, autumn and annual means at Armagh from the 1970s. This has produced a decrease in the soil moisture accompanied by a reduction in energy consumption by evaporation. Thus, in the 1970-1980s, for the summer, the increase in soil temperatures is larger than for the air temperatures.

A similar example of the effect of moisture on soil temperature was found by Zhang *et al.* (2001) for the summer months at Irkutsk station (Russia) where summer rainfall accounts for 84% of the annual precipitation. The increase in moisture in the summer months resulted in an increase in the evaporation rate which extracted energy from the soil leading to a drop in soil temperature even though summer air temperatures were rising at that station at that time. This effect is called the negative soil moisture feedback mechanism (Zhang *et al.*, 2001) in which the soil moisture may play an important role in influencing soil temperature. At that site, and in cold regions in general, the snow cover thickness, its timing and duration may also influence the soil temperature due to its insulation properties (Chen *et al.*, 2003). As discussed later, we have found no evidence of a similar effect on Armagh soil temperatures on seasonal or annual timescales.

4.2 Reconstruction of soil temperatures from air temperature and rainfall

The good correlation between soil and air temperatures in winter suggests that soil temperatures could be successfully reconstructed from mean air temperature readings. In Figure 11 (second and fourth panel down), we show the winter soil temperature anomalies predicted from a simple linear regression on air temperature. From Figure 11, it is evident that reconstructions at both depths are very successful in predicting both year-to-year and gradual changes in winter soil temperature, particularly at 30 cm.

For summer, we have seen that rainfall is likely to be an additional factor. In Figure 11 (first and third panel) we show reconstructions of the summer soil temperature anomalies at both depths derived from a multiple regression of soil temperature with air temperature and rainfall. Though the reconstructed summer soil temperatures do not fit the observed data as well as in winter, some of the principal features of the variability are present.

According to these reconstructions, the soil temperatures at the beginning of the 19^{th} century were lower than current values. In winter the reconstructed soil temperature curves remain quite flat whereas the summer curves have a minimum in the first two decades of the 20^{th} century.

Reconstructions of soil temperatures in winter, using statistical methods as above, could be erroneous if there were extensive and prolonged snow coverage. In fact, due to the mild winters in Armagh, days with 24-hour coverage of snow are relatively rare for this latitude. Over recent decades, the total number of days in the period November to March with 24-hour snow cover has varied from 39 in the exceptionally cold winter of 1962/1963 down to zero in 1999/2000, with the average in single figures. Even for the exceptional winter of 1962/1963, we note that the winter soil temperature reconstructed from air temperature shown in Figure 11 is very close to that actually measured, both at 30 cm and 100 cm depths. Nonetheless, daily soil temperature values may be affected by snow cover at shallow depths.

5 Summary and conclusions

Compared to the number of mean air temperature series, there is a lack of long-term soil temperature data available. We have corrected the Armagh Observatory series for changes in both depth and location and compared them with similar, but uncorrected, records from Birr and Valentia.

We find broad agreement in the mean annual soil temperature trends from Armagh with those from the other two sites, with a steady rise throughout the 20^{th} century. However, seasonally, there are differences. In spring, summer and autumn, all three sites show a similar upward trend which is evident in both 30 cm and 100 cm depths.

In winter, on the other hand, only Valentia has a strong upward trend; for both Armagh and Birr, soil temperatures in winter have risen only slightly over the past century. The seasonal difference in the trends of soil temperatures at Armagh are similar to those of mean air temperature over the same period.

The question arises as to whether this geographical difference in the trends of seasonal mean soil temperature is real. One piece of evidence that suggests that it may be can be found in the difference between the length of the growing season in Valentia on the west coast of Ireland and Dublin and Wexford, both of which lie close to the east coast. These results, which are based on phenological observations of Lime (*Tilia Cordata*) from the International Phenology Gardens at Valentia, the National Botanic Gardens, Dublin, Johnstown Castle and the JFK Arboretum, Co Wexford, over the period 1970-2001, show a trend towards a longer growing season in the west of Ireland compared to the east where it is roughly constant (Donnelly *et al.* 2004). This behaviour, is consistent with our findings on the geographical variation of soil temperatures.

The second part of this work seeks to understand how soil temperatures at Armagh are influenced by air temperature and soil moisture. Our study indicates that soil temperature is mainly controlled by the surface boundary conditions, principally air temperature. We have found that air temperature strongly influences soil temperature in all seasons, however, the impact of changes in precipitation is seasonal and more complicated. This has been previously reported by Zhang *et al.* (2001) but for a colder climate. It appears that the increase in summer soil temperatures in the last century at Armagh is evidence, not only of warming, but also of drier conditions in summer.

We have shown that soil temperatures in winter can be reconstructed from air temperature, however, even with the addition of precipitation data, reconstructions of soil temperatures in summer are less successful.

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Table 1. The slope (°C/decade) of a linear fit to the seasonal and annual soil temperature series from Armagh, Birr and Valentia.

	30 cm/1-ft depth		
	Armagh	**Valentia**	**Birr**
Spring	0.16±0.02	0.15±0.04	0.23±0.04
Summer	0.15±0.02	0.08±0.04	0.22±0.04
Autumn	0.16±0.02	0.12±0.04	0.21±0.04
Winter	0.04±0.03	0.25±0.04	0.05±0.04
Annual	0.13±0.01	0.17±0.03	0.15±0.02
	100 cm/4-ft depth		
	Armagh	**Valentia**	**Birr**
Spring	0.15±0.02	0.08±0.03	0.27±0.03
Summer	0.19±0.02	0.07±0.04	0.26±0.03
Autumn	0.16±0.02	0.12±0.03	0.12±0.02
Winter	0.04±0.02	0.19±0.03	0.13±0.03
Annual	0.13±0.01	0.12±0.02	0.19±0.01

Table 2. Seasonal and annual correlation coefficients between the soil temperatures and mean air temperature, PDSI and rainfall over the period 1905-2002. Superscript ‘1’ stands for significant at 99% and ‘2’ at 95%.

	Air Temp	**PDSI**	**Rainfall**
	Soil 30		
Dec-Feb	$.861^{1}$	$-.327^{1}$	.028
Jun-Aug	$.704^{1}$	$-.353^{1}$	$-.377^{1}$
Sep-Nov	$.817^{1}$	$-.378^{1}$	.067
Mar-May	$.886^{1}$	$-.288^{1}$	$-.220^{2}$
Annual	$.791^{1}$	$-.419^{1}$	-.153
	Soil 100		
Dec-Feb	$.772^{1}$	$-.348^{1}$	.079
Jun-Aug	$.639^{1}$	$-.391^{1}$	$-.454^{1}$
Sep-Nov	$.661^{1}$	$-.483^{1}$	.001
Mar-May	$.729^{1}$	$-.341^{1}$	-.187
Annual	$.684^{1}$	$-.495^{1}$	$-.247^{2}$

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Figure 1. Left panel - Soil temperature at standard depths throughout the year at Armagh Observatory, 2002-2003. Middle panel - Soil temperature at 100 cm (continuous lines) and 122 cm (discontinuous lines) depth for 2002-2005. Right panel - Soil temperature versus depth for various dates from 14 March 2002 to 13 February 2003.

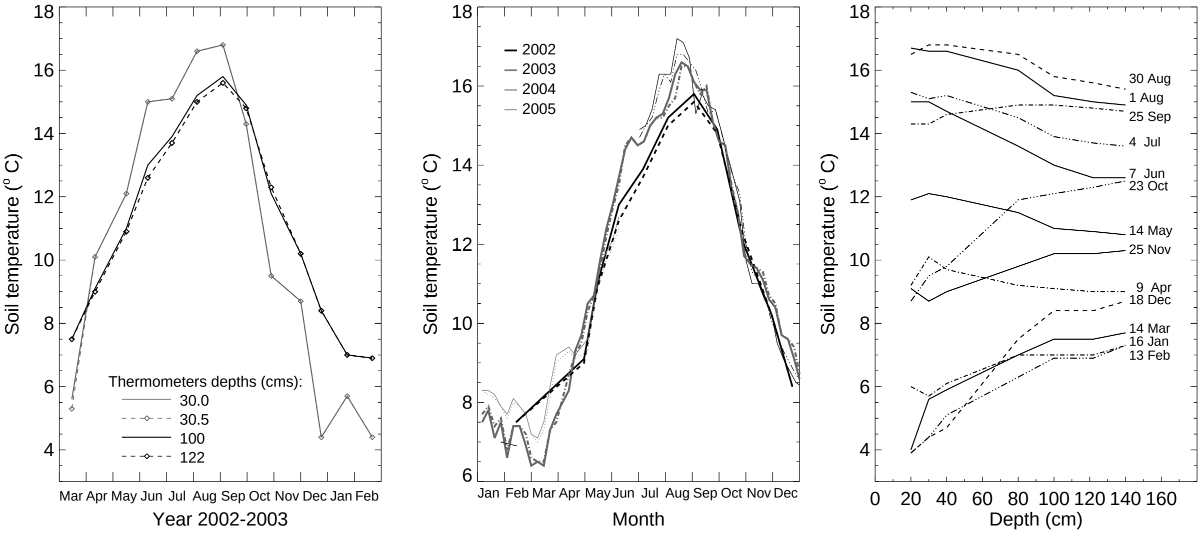

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Figure 2. Comparison of seasonal and annual corrected (thick) and uncorrected (thin) soil temperatures at 30 cms.

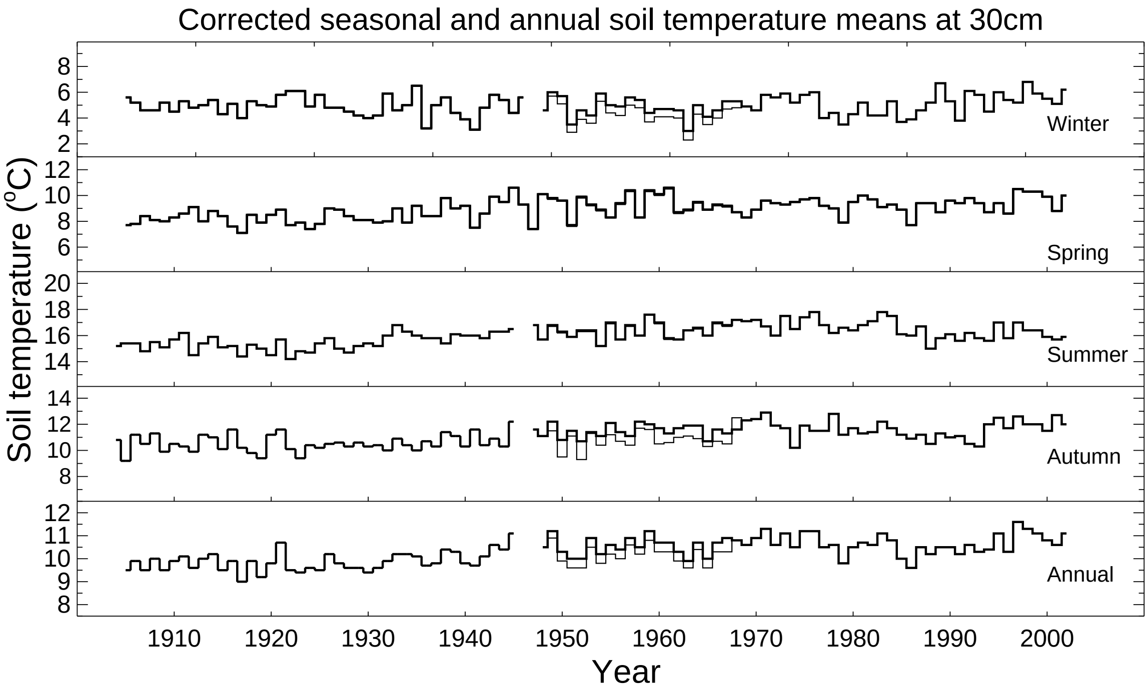

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Figure 3. Comparison of seasonal and annual corrected (thick) and uncorrected (thin) soil temperatures at 100cms.

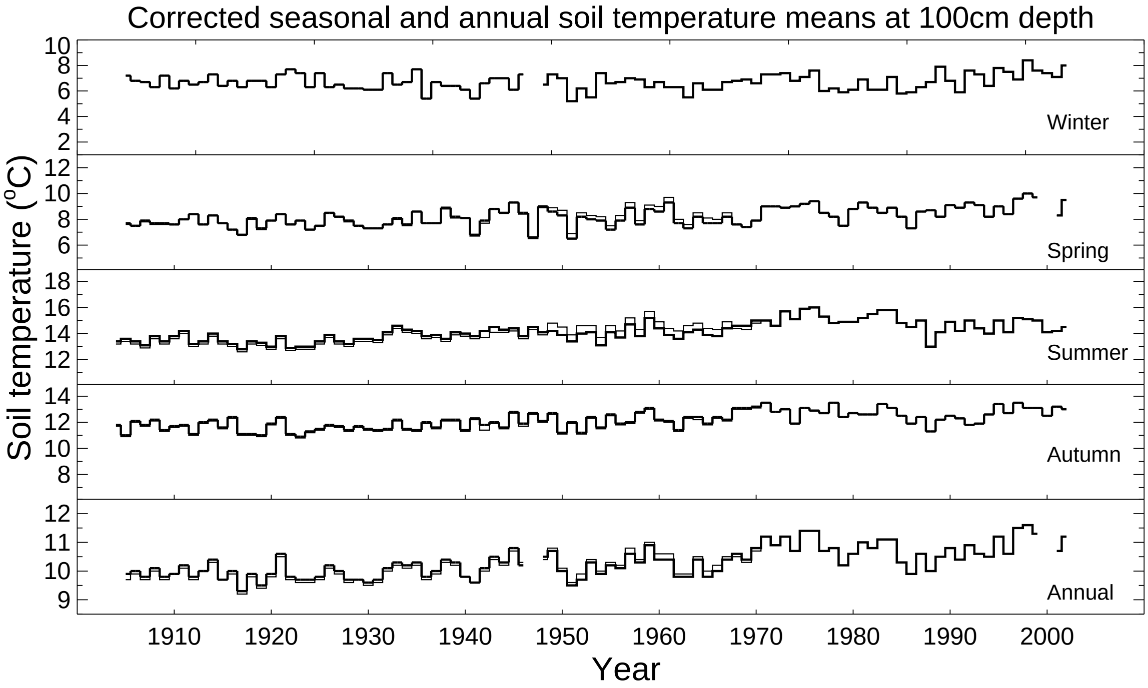

Figure 4. Comparison of 100 cm (thin) and 30 cm (thick) seasonal and annual mean soil temperatures at Armagh.

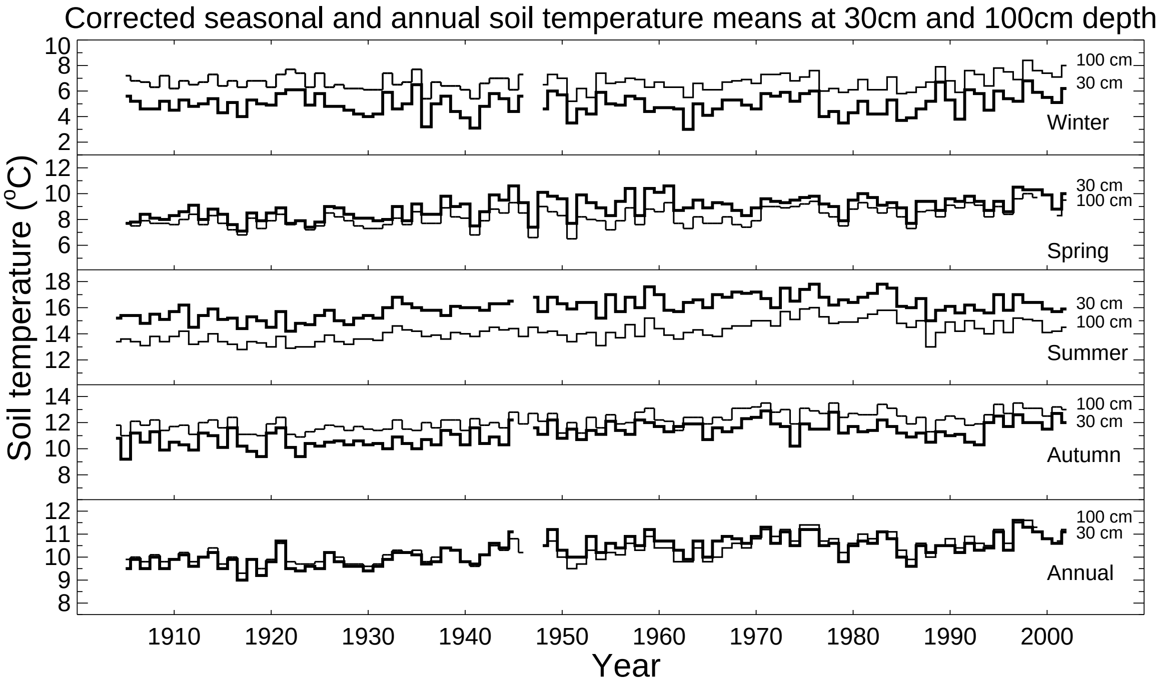

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Figure 5. Comparison of summer, winter and annual mean soil temperatures at 30 cm for Armagh (thick black), Valentia (grey) and Birr (thin black).

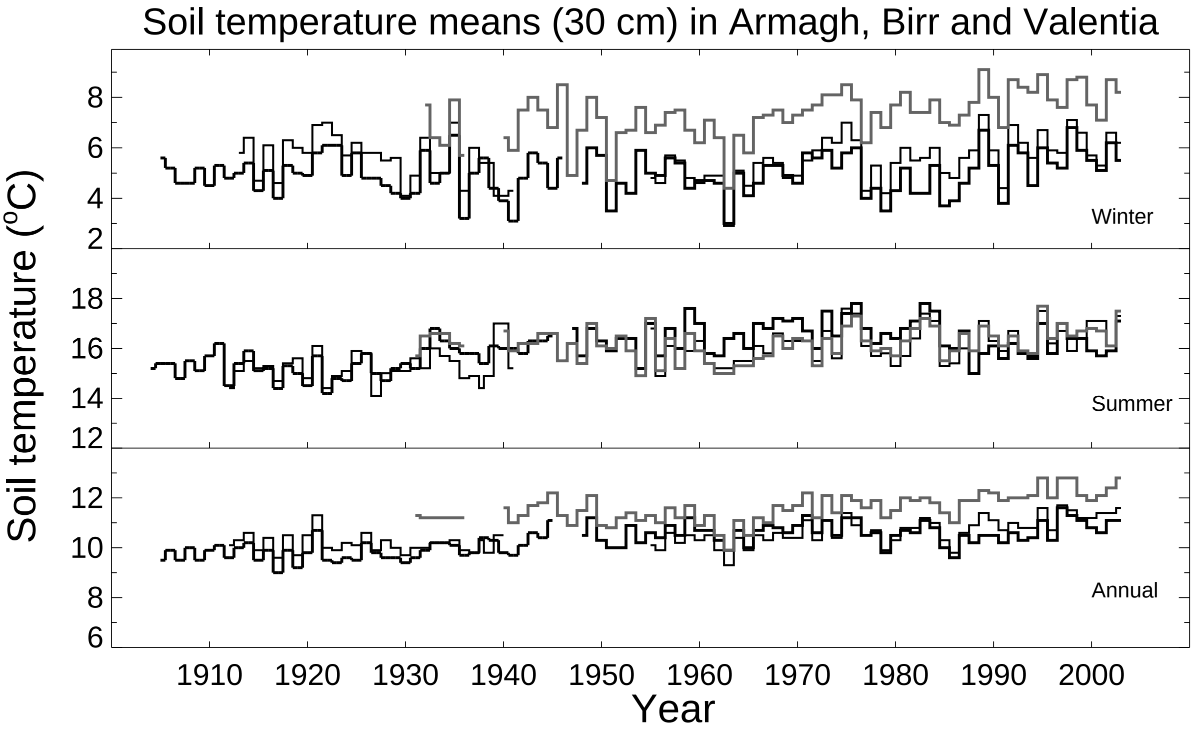

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Figure 6. Comparison of summer, winter and annual mean soil temperatures at 100 cm for Armagh (thick black), Valentia (grey) and Birr (thin black).

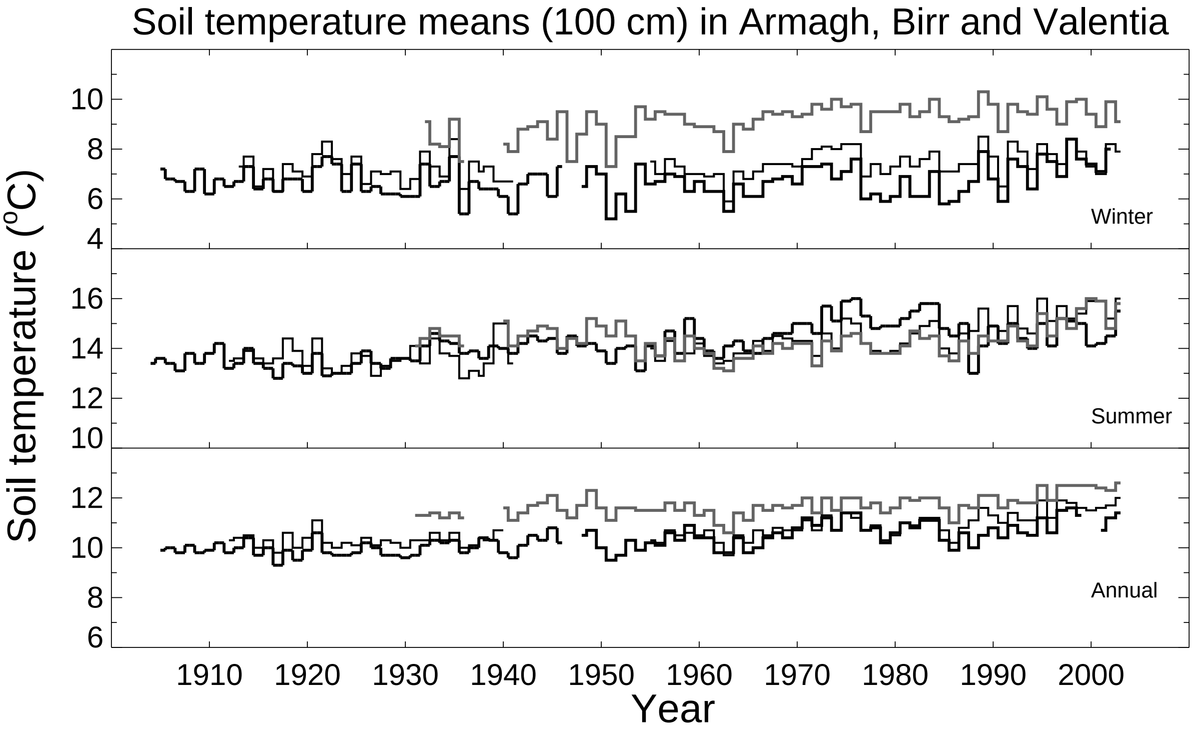

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Figure 7. Annual variations of several climate variables. Panels in descending order show: (1) Air temperatures. (2 and 3) Soil mean temperatures at 30 and at 100 cm, respectively. (4) Rainfall. (5) PDSI.

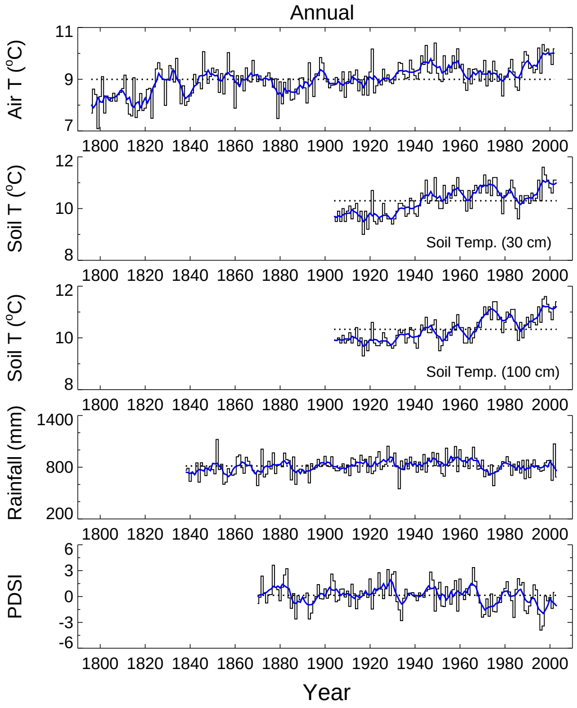

Figure 8. Variations of several climate parameters in Winter (left) and Spring (right). Panels in descending order show: (1) Air temperatures. (2 and 3) Soil mean temperatures at 30 and at 100 cm, respectively. (4) Rainfall. (5) PDSI.

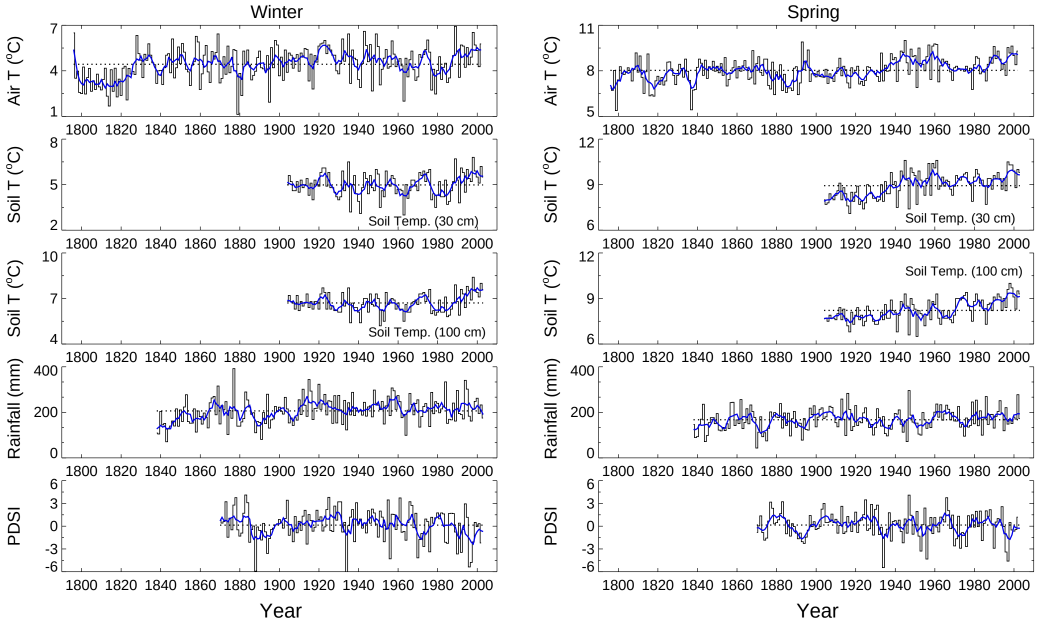

Figure 9. Summer(left) and Autumn (right) variations of several climate variables. Panels in descending order show: (1) Air temperatures. (2 and 3) Soil mean temperatures at 30 and at 100 cm, respectively. (4) Rainfall. (5) PDSI.

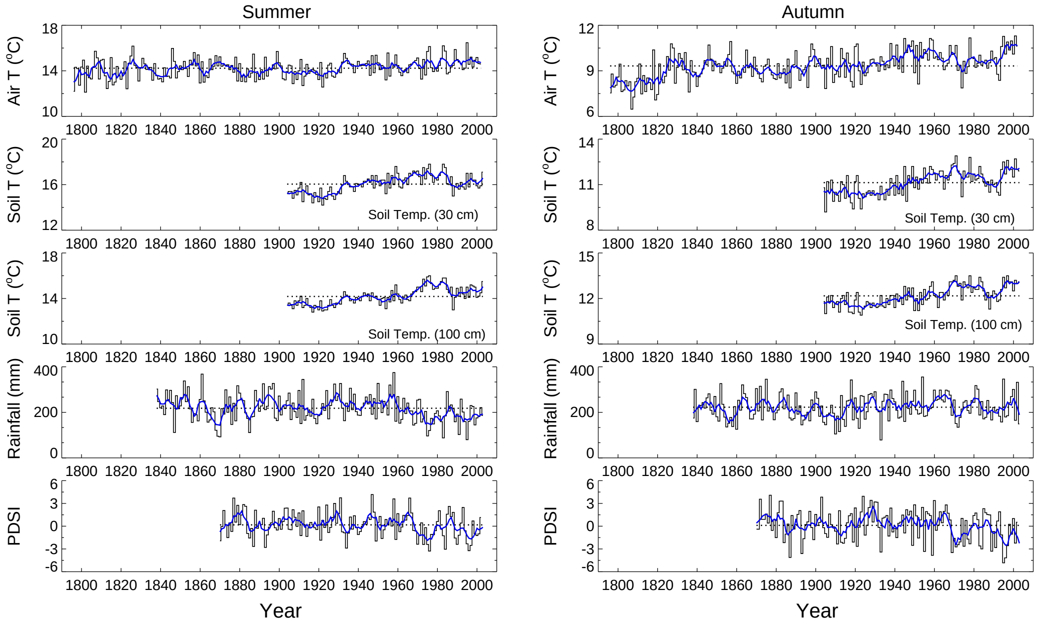

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Figure 10. Soil temperature at 100 cm (thin) and mean air temperature (thick) versus day number.

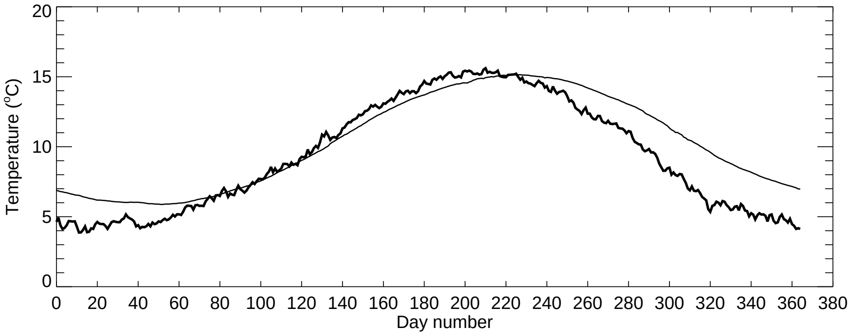
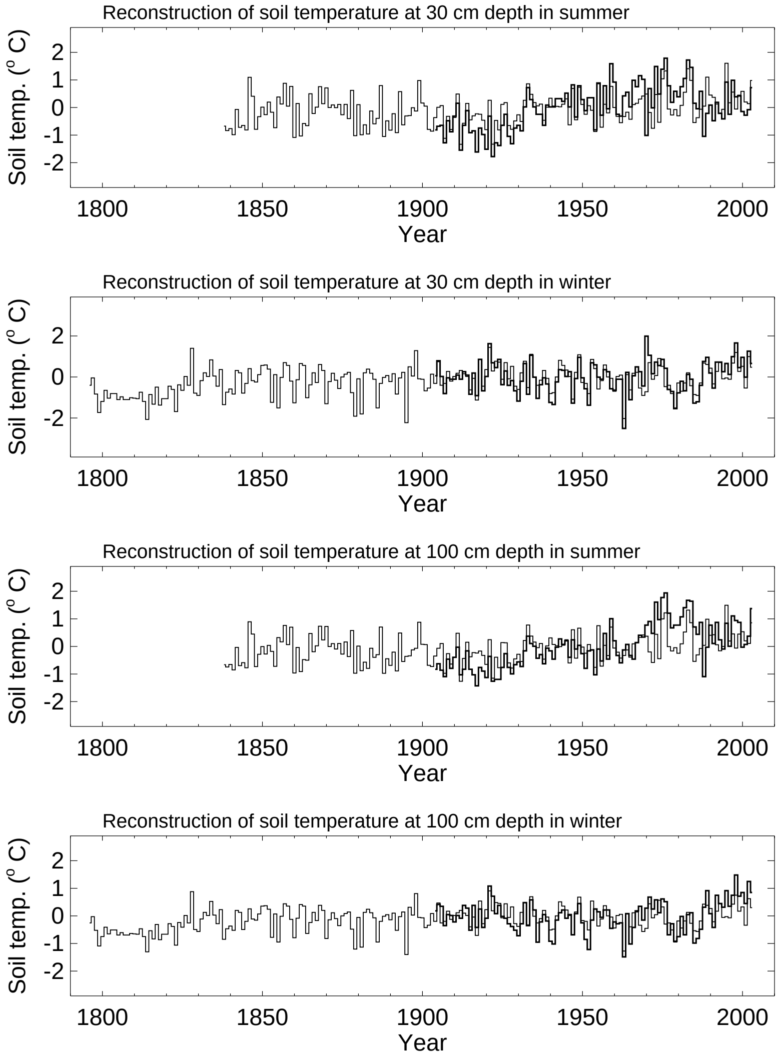


Figure 11. Reconstructions of soil temperature anomalies (in descending order): (1) 30 cm in summer, (2) 30 cm in winter, (3) 100 cm in summer and (4) 100 cm in winter. The estimated values are shown by the thin black histogram and the observed values by the thick black histogram.



Reconstruction of soil temperature at 30 cm depth in summer

Reconstruction of soil temperature at 30 cm depth in winter

Reconstruction of soil temperature at 100 cm depth in summer

Reconstruction of soil temperature at 100 cm depth in winter