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The long-term temperature record from Markree Observatory, County Sligo, from 1842 to 2011

Michelle McKeown[a]*, Aaron P. Potito[a] and Kieran R. Hickey[b]

[a]*Palaeoenvironmental Research Unit, School of Geography and Archaeology, National University of Ireland Galway, Galway, Ireland;* [b]*School of Geography and Archaeology, National University of Ireland Galway, Galway, Ireland*

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This study analysed long-term temperature patterns in the north-west of Ireland using a previously unexplored data-set from Markree Observatory, County Sligo. The Markree series extends back to 1842, making it one of the longest instrumental temperature records in Ireland and is renowned for holding the lowest recorded temperature for the island of Ireland, −19°C on 16 January 1881. Despite its length, this record has been largely absent from past analyses of Ireland's long-term temperature trends, rendering spatial coverage for the extended Irish climate chronology incomplete. Daily data stored in a variety of the historical archives were gathered and digitised and monthly records created. Calibrations to account for instrumentation, time of reading and exposure were applied where possible in order to standardise the record. Trends were subsequently investigated for seasonal averages of daily minimum, maximum and mean temperatures, and a comparison with previously published long Irish temperature records was carried out to situate the Markree record among the existing long-term series. Although the Markree series follows similar patterns to the other long-term temperature records, it displays more decadal variability, particularly in its minimum values which show a higher rate of late twentieth-century warming compared to the other records. Due to its geographic location and surrounding topography shielding the site from direct ocean influences and prevailing south-westerly winds, Markree displays characteristic features of a more inland station (low minimum temperatures and large diurnal ranges) even though it is located only ∼7 km from the Atlantic Ocean. Such findings highlight the necessity of including the Markree data-set in future Irish climate change research.

Keywords: Markree; temperature; calibration; Ireland; climate change

Introduction

Reliable long-term instrumental records are globally quite rare, with only about 50 climate stations worldwide offering more than 200 years of temperature data (Bradley 1991). Of the climate records that extend into the nineteenth century, the vast majority are found in Europe (Butler *et al*. 2005). Consequently, for much of the globe, the spatially complete instrumental period is quite short (Klingbjer and Moberg 2003), limiting the time scale involved in climate research. Climate data in Ireland prior to the expansion of the station network, which followed the founding of

*Corresponding author. Email: m.mckeown1@nuigalway.ie

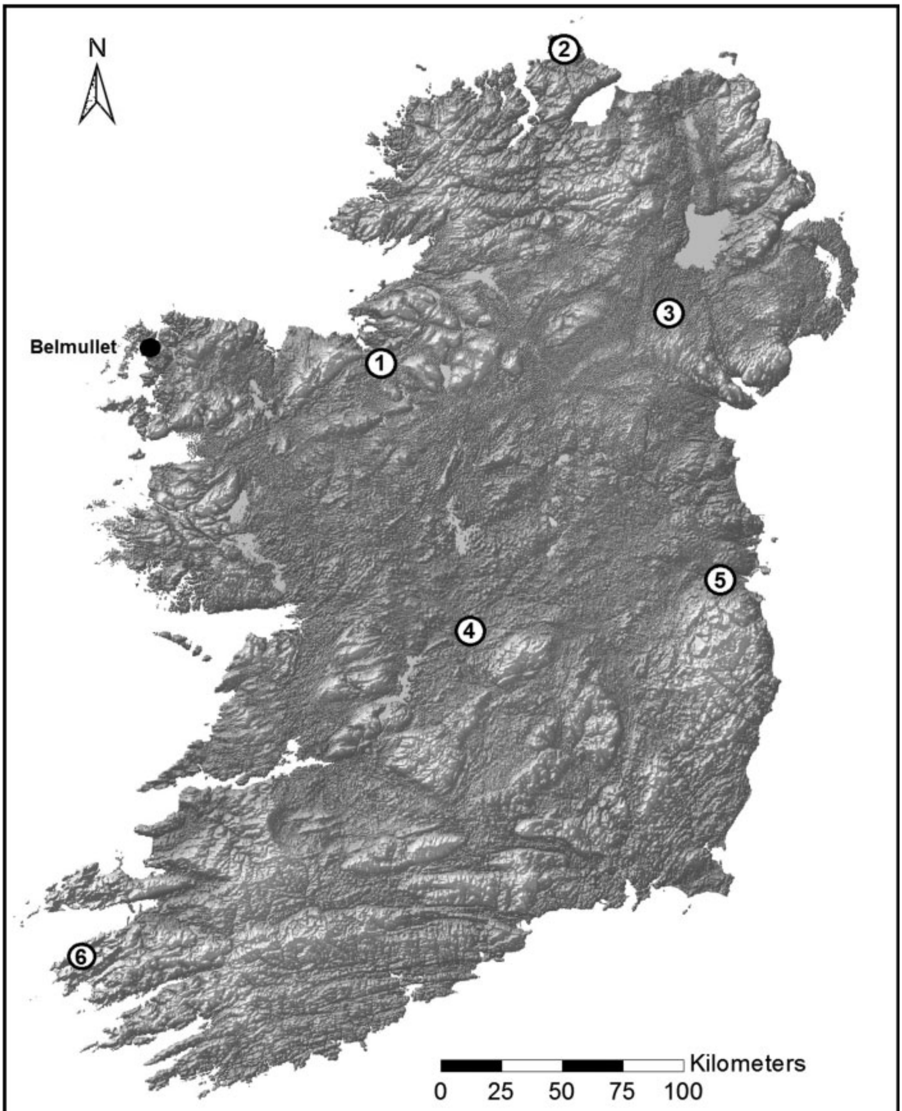
the Irish Meteorological Service from the British Meteorological Service in 1936, is largely dependent on the instrumental data collected by scientific institutions and private landowners. In Ireland a small number of stations actively recorded meteorological parameters prior to the twentieth century, and only one station (Armagh Observatory) has a record accurately extending back to the late eighteenth century. The majority of meteorological stations in Ireland only began recording continuously in the 1950s and 1960s (McElwain and Sweeney 2007), so the remaining long-term climate records provide an extended insight into climate trends in Ireland.

In recent studies of climate change in Ireland, it has been common practice to utilise data from the 1950s/1960s to the present as there is sufficient spatial coverage to implement a detailed study, particularly where climate modelling is used (Hulme *et al.* 1995, Kiely 1999, Charlton *et al.* 2006). This is a rather short observational time period, especially where climate forecasting is concerned. One way to overcome this problem is to examine longer climate records. A number of studies have created national- and continental-scale long-term data-sets by combining data from numerous stations to create composite records of climate change (Manley 1974, Klingbjer and Moberg 2003). While this is ideal for investigating climatic trends over large areas, details regarding more localised climate patterns, such as those exhibited in the longer Irish records, are lost. According to Donnelly *et al.* (2004), an understanding of climate at the regional and local scale is imperative to adequately examine potential impacts of future climate change. Although a number of studies have examined fluctuations at a regional Irish scale (Butler 1994, Sweeney *et al*. 2002, McElwain and Sweeney 2003, 2007, Butler *et al.* 2005), geographic coverage of Ireland is not complete. This paper presents an analysis of a previously unexplored temperature record from Markree Observatory located in County Sligo in the north-west of Ireland. Figure 1 displays the location of five existing long temperature records, as well as Markree Observatory. From this figure it is evident that a large portion of the island is not represented by existing long-term data. Furthermore, this study compares the temperature reconstruction from Markree Observatory to the existing records in order to situate temperature trends in the Sligo region within an island-wide context.

Although the introduction of a new long-term temperature series offers an extended regional chronology, most historic instrumental records do suffer from a degree of imperfection in portions of the series (Butler *et al.* 2005). Records must conform to a number of criteria in order to adequately narrate a climate story. These include: (1) continuity of data; (2) knowledge of instrumentation, exposure of instruments and time of observations; and (3) knowledge of site changes such as vegetation alterations and urban encroachment, which may affect microclimate. The majority of meteorological records lack one or more of these criteria, making the climate reconstruction inadequate. To date in Ireland only a small number of temperature series fill these absolute rules (Butler *et al.* 2005). Markree is one such record.

Temperature context for Ireland

Mean global surface temperature has increased by 0.76°C from the mid-nineteenth century until 2005 (IPCC 2007). Current trends in Irish temperature closely follow



No.	Meteorological Station	Lat/Long	Elevation (m a. s. l.)	Years of Record
1.	Markree	54° 10' 19'' N, 08° 28' 41'' W	35	1842 - 2011
2.	Malin Head	55° 21' 09'' N, 07° 19' 55'' W	22	1890 - 2011
3.	Armagh	54° 21' 09'' N, 06° 38' 59'' W	57	1884 - 2011
4.	Birr	53° 05' 47'' N, 07° 54' 50'' W	73	1873 - 2009
5.	Phoenix Park	53° 21' 09'' N, 06° 20' 17'' W	48	1875 - 2011
6.	Valentia	51° 56' 20'' N, 10° 14' 33'' W	25	1871 - 2011

Figure 1. Names and locations of the six long-term meteorological stations in Ireland. Elevation in metres above sea level (m a.s.l.).

global patterns, with numerous studies having focused on climate amelioration at the beginning of the twentieth century and the accelerated warming since the 1990s (Vincent and Gullet 1999, Zhai and Ren 1999, McElwain and Sweeney 2003, 2007). Two main warm intervals have been widely acknowledged in Irish climate literature: 1910–1945 and 1978–present (McElwain and Sweeney 2003). A cool period in the late nineteenth century is evident from a small number of available long instrumental records. However, these records show that, despite low temperatures in the 1880s, a general warming trend takes place leading up to the twentieth century. As the late nineteenth century warming has received little attention, it is important to establish a longer baseline against which present and future warming can be compared (Butler *et al*. 2005). To date, studies have shown that winter warming accounts for most of the recent Irish warming (Jones and Moberg 2003), with maximum temperatures accounting for the majority of this change (Sweeney *et al.* 2002, McElwain and Sweeney 2003). However, it has also been widely confirmed that the majority of warming in the other three seasons is driven by minimum temperatures increasing at around twice the rate of maximum temperatures (Vincent and Gullet 1999, Zhai and Ren 1999, McElwain and Sweeney 2007), possibly due to increasing cloud cover (Kiely *et al.* 2007).

The climate of Ireland is dominated by the Atlantic Ocean and notable long-term periodicities are related to the North Atlantic Oscillation (NAO). It has been shown that air temperature, precipitation, cloud cover, wind velocity and relative humidity are all positively correlated to NAO index values (Jennings *et al.* 2000). This mode of natural variability is most prevalent during the winter months (McElwain and Sweeney 2003), and inter-decadal change is exhibited on irregular timescales (Hurrell 1995, Hurrell and Deser 2009). NAO variability and its influence on winter climate in Irish long-term records have been previously investigated (McElwain and Sweeney 2007, Galvin *et al*. 2011). Despite the small geographical area of Ireland, regional temperature differences are evident. Due to the moderating influence of the Atlantic Ocean, coastal sites, especially in the west, experience more equable temperature regimes than inland localities (Smith 1976), including suppressed diurnal ranges. In the middle and east of the island, temperatures tend to be somewhat more extreme. It has been suggested that within 50 km of the coastline the mean daily range of temperature is likely to be at least 1°C less than that of an inland location (Smith 1976). However, topography also exerts a strong influence on local and regional climate. The complex interplay between topography and airstreams within the island results in some regions being more sheltered from the Atlantic Ocean while others are exposed to its full effects (Sweeney 1997). Regional climate histories become important in order to understand the distinctive coastal-versus-interior climate character of Ireland (Sweeney 1997).

Data and methods

Markree Observatory

Markree Observatory is located 54°10′19″N, 8°28′41″W, approximately 1.5 km south-east of the town of Collooney in County Sligo and approximately 7.3 km south-east of the coastline. The station is positioned on slightly higher ground than the surrounding terrain (35 m above sea level) and 125 m north-west of a meander of the River Unshin. Sparse vegetation dots the country landscape, yet no trees are located close to the observatory itself. Situated on a private estate, 200 m to the side of a castle which has been recently renovated into a hotel, the grounds resemble those which existed in 1831 when the observatory was first established. Thus no microclimate effects from urban encroachment have been created over time.

Historically, the Royal Irish Academy has supported meteorological research in Ireland and Britain. This organisation accepted meteorological handbooks from individual stations for review in the London head office. It was the first attempt to formalise a nationwide network of meteorology in the British Isles in the late nineteenth century. Standard forms were issued to stations regulated by the Academy, and in Markree from 1874 onwards the handwritten recordings were scribed in such forms. Consequently, private meteorological stations in Ireland (including the Markree and the other long-term records in Figure 1) were monitored in the same way as the official stations. The Academy provided support to members and put in place a monitoring system for ensuring that instruments were not only used properly but were also checked for errors. This was implemented by employing a member of the Academy to travel Britain and Ireland inspecting stations, their instruments and the approach observers used to record weather data. Any systematic errors were then noted on the monthly weather documents. Despite the invaluable effort made by this organisation, the data still require a degree of standardisation in order to make it comparable to modern data.

Temperature data

The principal data for this paper are daily maximum, minimum and mean temperature values. Markree Observatory began recording meteorological information in January 1842 using self-registering thermometers. Initial readings were taken in the morning from 1842 until 1862. From December 1863 until November 1874, recordings ceased when the founding observer, Edward Synge Cooper, passed away (Doberck 1884). For 11 years the observatory lay inactive and it was not until a qualified Dutch astronomer, William Doberck, was employed at Markree by Edward Cooper's successor that meteorological data continued to be monitored and recorded again. Various qualified observers from Europe were successively appointed at Markree which ensured the quality and consistency of the recorded information into the twentieth century (MacKeown 2011, Treanor 2012). Maximum and minimum temperature values continued to be documented continuously until October 1998, when a break in the modern portion of the record unfortunately occurred as a result of the switch from manual to automated recording. Readings were not resumed until June 2008. Fortunately, as this gap is located in the modern recording era, maximum and minimum temperature data from Belmullet were available to supplement the Markree data.

In order to explore the data comprehensively, the Markree temperature series was subdivided into three independent time series. Series I consists of the initial maximum and minimum temperature recordings from January 1842 to December 1863. This information was discovered within a paper published in the nineteenth century by one of the observers (Doberck 1884). The original documents have never been discovered and it is thought that the observer, William Doberck, may have taken the original handwritten records with him when he moved to Hong Kong with his sister, Anna, in 1876. It was Anna Doberck who actually recorded the meteorological data at Markree; she has only recently received recognition for her keen interest in climatology (MacKeown 2011). As Doberck was established at the Hong Kong Observatory when the 1884 paper was written, it is highly likely that the documents, should they survive, are located there. Series I differs from Series II due to deviations in instrumentation and exposure. Caution must be taken when analysing Series I as the data is secondary, solely taken from a paper containing monthly mean maximum and minimum values. Series II is the longest series, comprising data from January 1875 to October 1998. These data were transferred from the original observers' documents, stored in the Met Éireann library. Daily maximum and minimum values recorded in these original documents were calculated into mean maximum and mean minimum monthly values. Metadata relating to instrumentation and exposure have been extracted from the vast amount of additional handwritten remarks on the datasheets. Finally, Series III is the automated weather data which span the period June 2008 to December 2011. This information was available in digital format from Met Éireann. No calibration was performed for the Series III data.

Data calibration

Series I and Series II are of primary concern in this calibration. Instrumentation and exposure were investigated thoroughly and, where possible, corrections were made. This required knowledge of specific thermometers and exposure of instruments throughout the record. Knowledge of such changes, and the specific time of any change, is essential in order to standardise the entire series accurately. Even though the instrumentation was monitored closely in Ireland by the Royal Irish Academy, a meticulous exploration of the handwritten weather documents was carried out in order to find remarks made by visiting inspectors. Such comments refer to, for example, changes of thermometer models, methods of recording and even exposure modifications. This information is crucial in order to comprehensively calibrate the data for both minor and substantial errors. Exposure is the most difficult category for which to calibrate, as information regarding exact locations of thermometers is required, something that was often not noted in the observers' handbook and therefore lost (Butler *et al.* 2005). This is a frequent problem for the earliest data in many temperature reconstructions.

Series I

Instrumental calibration. Early thermometers were not as accurate as those used today; therefore, knowledge of instrumentation is required for calibration purposes. Unfortunately the thermometer model for this series is not known. Doberck (1884) simply states that the thermometers were hung on the wall of the observatory. No evidence is available to determine the exact location of the thermometer, its height above ground, or whether it was on a north-facing wall. Evidence from this era suggests that two thermometers were universally in use in the first half of the nineteenth century for collecting maximum and minimum values – the Rutherford model and Six's model (Symons 1897). The Rutherford model was usually hung on the wall of an observatory as the Six's model was too large. Therefore, it is likely that the Rutherford model was the self-registering thermometer in use at this time.

Unfortunately, as there is no overlapping time period with another independent thermometer or even spot readings registered over this series, a suitable correction cannot be performed. Therefore, no adjustments were made due to instrumentation in this series.

Time of reading. The advantage of maximum and minimum thermometers arises from their ability to be insensitive to the time of reading (Butler *et al.* 2005). Originally readings were taken at 8 am until June 1846, then at 10 am until 1862. No correction was made due to the negligible difference in observation times over such a short series.

Exposure. According to Doberck (1884) extreme air temperatures were not correctly registered in Markree over this period. Thermometers were hung on the wall of the observatory, but no information was provided relating to their exposure. Before the introduction of Stevenson Screens in the late nineteenth century, thermometers were usually placed on north-facing walls. Thermometers placed in such locations, and thus shielded from direct solar influences, have been found to be in close agreement with Stevenson Screen readings (Butler *et al.* 2005). However, no evidence is available to suggest that the thermometers in Series I were housed in a screen of any kind, and the instruments could have been exposed to direct sunlight. Unfortunately, the lack of metadata means that no calibration can be applied to this series to adjust for errors in exposure.

Series II

Instrumental calibration. Maximum and minimum self-registering thermometers were often broken easily due to the disturbance to which instruments were subjected when resetting. Additionally, maximum thermometers were known to endure more occasional problems due to detachments of mercury from the main column (Butler *et al.* 2005). Over time these minor errors could become more substantial, introducing systematic errors in the time series. Three maximum thermometers from Series II have been adjusted for such instrumental errors. From November 1874 until December 1883, a maximum thermometer of the Casella type 11395 was employed. An overlap between this thermometer model and the newer Negretti and Zambia model 55207, which eventually replaced the Casella type 11395, was assessed by meteorologists in Markree between January 1884 and December 1884. The Casella type 11395 thermometer found to have an error of +0.5°F. Thus 0.5°F (0.28°C) was subtracted from the maximum data over this period. The Negretti and Zambia model 55207 was solely used to record maximum temperatures from January 1885. This thermometer model was found to have a lower-than-normal average reading. Again the data were adjusted by +0.8°F (0.44°C) following suggestions outlined in the documents from 1884 to 1893. On 13 January 1894 this model was found to be broken and was substituted with the previous Casella 11395 until 1897. The previous correction of +0.5°F was made to the data over this interim period. The final maximum thermometer by Negretti and Zambra 94861 was in operation from 1898 to 1954. It is widely accepted that these thermometers leading into the twentieth century are accurate to within 0.2°F; therefore, no correction was made (Butler *et al.* 2005). The thermometers used after 1954 have not been referred to in the documents. However, it is known that a new maximum and minimum thermometer was purchased along with a new Stevenson Screen. This was likely part of the wide-scale national expansion of the Irish meteorological network. The correction made for the data at this interim period will be discussed in the correction for exposure section.

With regard to the minimum thermometer only one model appears to have been employed from 1874 onwards – Casella minimum model 10458. In the documents, one exclusive calibration is specifically referred to which states that this thermometer had an error of $-0.5°$F from 1874 to 1883; therefore, the readings were increased by 0.5°F (0.28°C) to standardise the data. Despite the fact that this thermometer was used throughout the historical time series, no further errors were remarked; therefore, no other corrections were made.

Time of reading. Although it has been noted that maximum and minimum thermometers are generally insensitive to the time of reading (Butler *et al.* 2005), considerable changes in observation times can have an effect on the data by introducing minor errors over long timescales. Originally, readings at Markree were taken in the morning, until March 1918 when thermometers were read at 9 pm. This was the practice until May 1963 when readings were reverted back to 9 am. According to Butler *et al.* (2005) this has a minor effect on the data. An empirically determined amendment was made to the record for the 12-hour effect using methods outlined in Coughlin (1998). The data were calibrated as follows: $+0.08°$F (0.044°C) was applied to the monthly maximum readings and $+0.19°$F (0.11°C) to the monthly minimum readings over the period March 1918 to May 1963 (Coughlin 1998).

Exposure. Maximum and minimum thermometers were moved into a Stevenson Screen by 1875. Thus, for Series II, exposure changes were minor. In November 1954 a new Stevenson Screen was installed at the site. A historic photo of the observatory that includes a Stevenson Screen (photo taken in 1880, Figure 2) confirms that its modern location is only metres from its nineteenth-century placement. The Markree

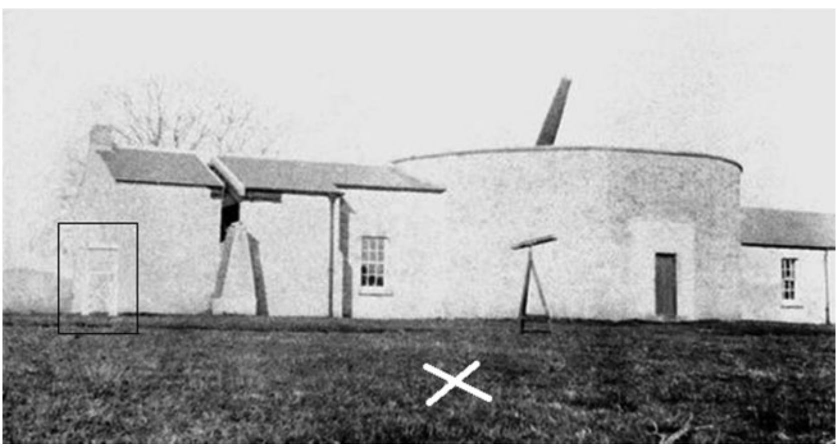


Figure 2. Photo of Markree Observatory taken in 1880 AD. Stevenson Screen located outside the building on the left (within the rectangle). The location of the modern Stevenson Screen is indicated by the white x. Picture sourced from The Royal Astronomical Society, London, UK.

record states that the nineteenth-century screen continued to be operated for one year, in line with the new screen in 1954–1955. This suggests that not only was the Stevenson Screen changed, but new instruments were also installed in the new screen. Due to this overlapping period, a correction was easily calculated. A seasonal correction of −0.1°F (0.056°C) for winter, −0.07°F (0.039°C) for spring, −0.27°F (0.15°C) for summer and −0.1°F (0.056°C) for autumn was made for Series II maximum values from 1874 to 1954. No correction was required for the minimum values.

The Belmullet patch

Recordings ceased for a short time in the modern portion of the time series, 1998–2007. Fortunately, as this gap is located in the modern recording era, maximum and minimum data from Belmullet (54°13′40″N, 10°0′25″W, 11 m a.s.l.) were used to supplement the missing Markree patch. The data from Belmullet were transformed to that of Markree using an overlapping period of 41 years from both stations. The adjustment was calculated using monthly maximum and minimum values from 1957 to 1997. The mean difference between the two sites over this period was calculated for each month and used to patch the Markree series. A greater difference between the minimum values was noted, since Belmullet lies close to an open ocean, exposed to the west, while Markree is close to a sheltered inlet. Table 1 reports the corrections made for each month.

Markree master series

Annual averages for daily maximum, minimum and mean temperatures from Series I, Series II and Series III along with the Belmullet patch are presented in Figure 3. Series I appears to be inconsistent with the other series as maximum and minimum values appear far too extreme. The reason for such a disparity lies in the unreliability of early instrumentation and lack of knowledge regarding the effects of exposure. A greater understanding of observation procedures, instrumentation and exposure during this series may allow the data to be standardised. However, this would require the discovery of further metadata for Markree covering this initial recording period. To date, such information is unavailable and consequently no calibrations were performed for Series I, meaning the data remain in its original raw format. Although Series I could not be calibrated as part of a longer chronology, relative temperature changes such as the colder conditions of the mid-1850s, which coincide with a solar minimum in December 1855 (Hickey 2012), can be observed. The gap between Series I and Series II marks a period of inactivity in the observatory from December 1863 until November 1874. Throughout Series II, data were recorded almost continuously with only minor breaks in recording occurring from September to November 1898 and May to November 1969. This series has been comprehensively calibrated, and is therefore comparable to modern data. The converted Belmullet data filling the Markree gap have sufficiently connected Series II and Series III, allowing a continuous series from 1875 to present.

From an examination of all temperature categories, a number of warming and cooling periods can be identified. The maximum values display a minor rate of temperature increase from the onset of the record in 1875 and continue this trend until the mid-twentieth century before dipping into a cooler period over the 1960s.

Table 1. Monthly corrections (°C) applied to Belmullet data from 1998 to 2007 in order to reconstruct Markree patch.

	January	February	March	April	May	June	July	August	September	October	November	December
Max	−1	−0.6	0.1	0.2	1	1.6	1.7	1.2	0.6	0	−0.8	−1.2
Min	−2.4	−2.3	−2.3	−2	−1.7	−1.5	−0.9	−1.5	−2	−2.2	−2.5	−2.4

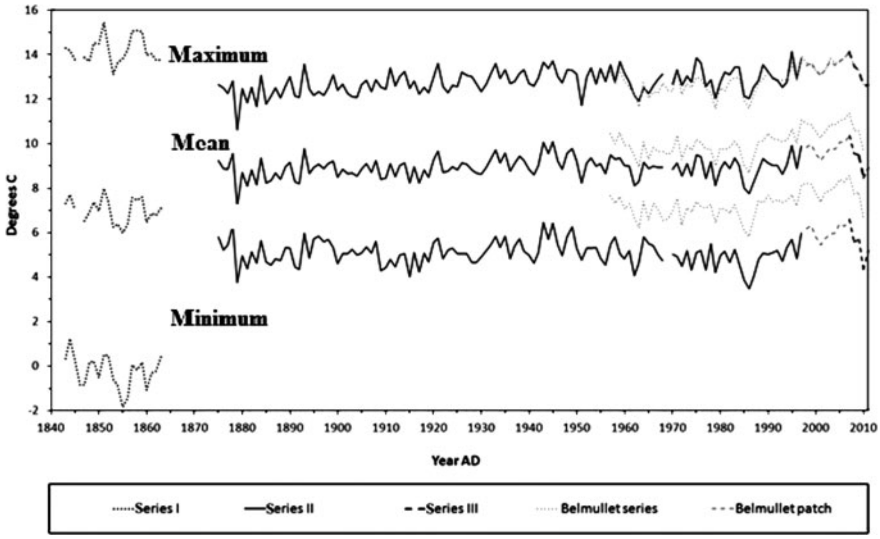


Figure 3. Fully corrected annual time series for average daily maximum, mean and minimum temperatures from Markree Observatory, 1842–2011.

Following this downturn, maximum temperatures continue to increase steadily into the twenty-first century. The years 2010 and 2011 showed cooler maximum temperatures than have been experienced in the previous 20 years. Minimum temperatures appear to be following a slightly different pattern, and a Pearson correlation between the maximum and same day minimum temperatures showed a weak relationship ($r = 0.41$, $p < 0.05$). This weak correlation is likely to signify less cloud cover/radiation at night, where the minimum temperatures display more year-to-year variability in comparison with the mean and maximum values. From 1875, the minimum series displays a declining trend until 1880 before a return to warmer conditions from the mid-1880s to the beginning of the twentieth century. Cooler temperatures are again experienced from ~1910–1917 before a return to warmer conditions until the mid-twentieth century. A temperature trough from the mid-1940s until the mid-1980s is a distinct feature of the minimum series. From the late 1980s until 2009, the fastest and most substantial rate of minimum warming is evident (0.85°C per decade). Again, 2010 and 2011 mark considerably cold years, the coldest experienced in the minimum record for 20 years.

Figure 4 displays the mean seasonal trends at Markree Observatory from 1875 to 2011. Eleven-year running means were used to investigate long-term trends. This graph displays a number of important results: (1) winter shows more year-to-year and decadal variability when compared to the other three seasons, with summer and autumn showing the least variability; (2) all seasons exhibit a gradual warming at the end of the nineteenth century; (3) winter displays a slightly different trend to the other three seasons, with a substantial drop in annual mean temperature from the mid-1920s to the 1960s before a short warming phase until the early 1970s. From the mid-1970s until the mid-1980s winter temperatures drop briefly until warming commences again until 2009. The other three seasons experience warming from the 1920s until the mid-1940s, before temperatures slowly begin to decline until the

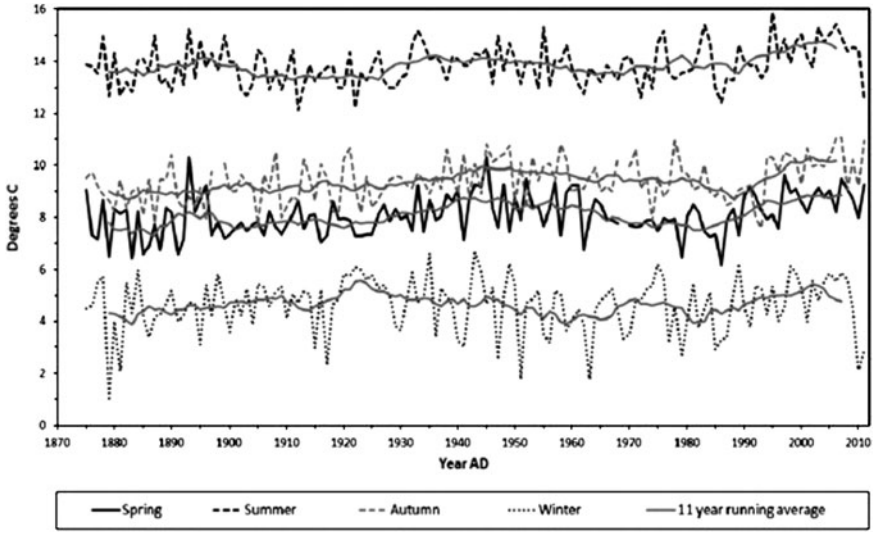


Figure 4. Mean seasonal temperatures from Markree Observatory, 1875–2011.

1980s. (4) All seasons show accelerated warming from the mid-1980s until 2011. The fastest rate of temperature increase (0.53°C per decade) occurs in autumn. The anomalous cold spells in 2010 and 2011 have broken a 30-year trend of winter warming. Summer and autumn temperatures also display a considerable downturn during these years. Spring temperatures remain similar to previous years, although in 2011 spring temperatures exhibited a minor drop.

Comparison with other long-term Irish records

In order to situate the Markree reconstruction with existing Irish records, a comparison was carried out between the Markree series and the five other long-term temperature records: Armagh, Birr, Malin Head, Phoenix Park and Valentia. All information was extracted from original observers' handbooks, stored in the Met Éireann library in Dublin city and digitised for this analysis. Daily mean values for each month are available in digital format throughout the length of each record; however, the maximum and minimum data are only available post-1950 in this format. Therefore, monthly average maximum and minimum data pre-1950 needed to be manually transferred for this study. Figures 5, 7, 8 and 9 display the 11-year running means for seasonal daily maximum, minimum and mean temperatures for each of the six temperature records. With the inclusion of Markree, the geographical spread of the six stations allows for a comparison of the various regional temperature regimes of Ireland, including the south-west (Valentia), north (Malin Head), west/north-west (Markree), midlands (Birr), north-eastern midlands (Armagh) and east (Phoenix Park). Each record extends back into the nineteenth century, allowing comparison of long-term trends. In addition to a graphical comparison of trends, Pearson correlations were used to compare the Markree seasonal daily maximum, mean and minimum records with the other five data-sets (Table 2). As the NAO has been shown to exhibit a strong control on winter

Table 2. Pearson's correlations between Makree and five other long-term stations in Ireland, 1875–2011.

	Winter			Spring			Summer			Autumn		
Temperature series	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean
Valentia	0.913	0.850	0.900	0.803	0.813	0.878	0.874	0.687	0.879	0.809	0.825	0.870
Malin Head	0.826	0.799	0.870	0.819	0.707	0.837	0.874	0.668	0.820	0.834	0.767	0.860
Birr	0.884	0.816	0.912	0.899	0.795	0.837	0.875	0.726	0.820	0.910	0.877	0.940
Armagh	0.913	0.850	0.900	0.881	0.808	0.903	0.920	0.649	0.888	0.895	0.866	0.906
Phoenix Park	0.896	0.835	0.917	0.904	0.746	0.837	0.832	0.660	0.868	0.869	0.833	0.882

All correlations significant at $p < 0.01$.

temperatures in Ireland (McElwain and Sweeney 2007), winter temperatures from each station were correlated with winter NAO (Hurrell 1995) to examine any geographical trends in the NAO–temperature relationship (Table 3). As prolonged positive phases of the NAO generates stronger westerly wind regimes across Ireland, the frequency of westerly wind regimes were also examined for each season (Figures 5, 7, 8 and 9).

Winter

In winter, three periods of warming are evident (Figure 5). The initial warming phase spans the 1880s to the 1920s, the second is from the 1960s to the 1970s and the final phase occurs from the mid-1980s to 2009. The only exception to this pattern occurs in maximum values for Valentia from 1880 to 1920, where temperatures decrease into the 1900s before a sharp increase in temperature until 1920. Valentia, located in the south-west of the country, is the only record that acts like a typical coastal station according to the classification by Smith (1976), where mean winter temperatures are on average above 6°C, and the minimum values are above 4°C. Malin Head and Markree are also located in close proximity to the coast. Malin Head, at the northernmost point of the island, has slightly cooler winter minimums ranging between 3 and 4°C (Figure 5c). Markree has the lowest minimum temperatures, ranging between 0.5°C and 2°C throughout its recording history. With the site located ~7 km from the coast, local topography and geographic location must either be sheltering Markree from direct oceanic influences and prevailing south-westerly winds and/or causing cold air drainage from the surrounding mountains. Armagh, Phoenix Park and Birr display similar minimum temperature ranges to Markree over their respective records. Markree displays more variability in minimum temperatures compared to all other stations, particularly in the first half of the twentieth century. In the late nineteenth century, Markree, Birr, Armagh and Phoenix Park have similar minimum values. However, throughout the twentieth century they increasingly deviate from one another. It is only in recent years that temperature values in these stations are once again becoming similar.

The maximum winter temperatures exhibit a similar trajectory in all stations apart from Valentia (Figure 5a). Temperatures in south-western Ireland fall from the 1880s into the early twentieth century. However, a gradual rise is detected in all other

Table 3. Pearson correlations between winter NAO and winter temperatures for all long-term stations between 1875 and 2011.

	Markree	Valentia	Malin Head	Birr	Armagh	Phoenix Park
Maximum temperature vs. winter NAO	0.602	0.611	0.471	0.601	0.611	**0.641**
Mean temperature vs. winter NAO	**0.617**	0.611	0.441	0.587	0.611	0.593
Minimum temperature vs. winter NAO	0.569	**0.587**	0.441	0.536	**0.587**	0.508

All Pearson correlations coefficients at $p < 0.01$.
Highest correlations in each row indicated in bold; lowest correlations indicated in grey.

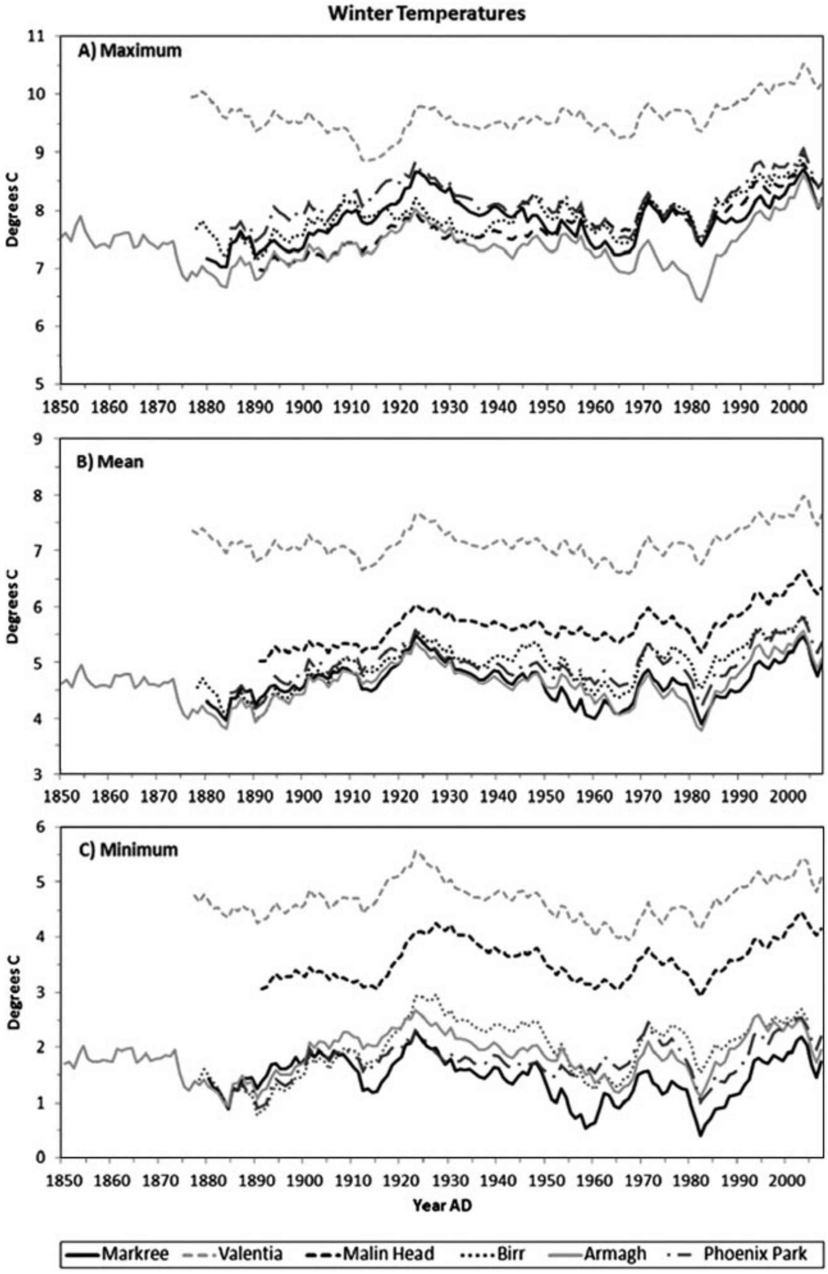


Figure 5. Eleven-year running means for winter daily maximum (a), mean (b) and minimum (c) temperatures for each of the six long-term meteorological stations in Ireland.

stations from the 1880s to the 1920s. Apart from Valentia, temperatures cool in all other stations from the 1920s to the 1960s. Armagh shows the greatest rate of maximum temperature increase from the 1980s to present, with Valentia showing the smallest increase. Mean temperature patterns in all regions are quite similar

(Figure 5b). Valentia displays the highest winter temperatures followed by Malin Head. The remaining regions are clustered together closely. From the 1920 to the 1960s, temperature decline is greater at Markree, Birr, Phoenix Park and Armagh in comparison with those at Malin Head and Valentia, and Valentia displays the most subdued mean temperature rise from the mid-1980s to present. From the early 1940s until the early 1970s, when the NAO exhibited continuing downward trend, maximum and minimum temperatures in Armagh, Phoenix Park, Birr and Markree decreased. However, maximum temperatures for the coastal locations of Valentia and Malin Head do not display this falling trend. As the NAO was in decline between 1940 and 1970s, the frequencies of westerly winds were also in decline for much of this period (Figure 6a). As westerly winds carry warmer conditions to Ireland, a fall in the frequency of westerlies will bring about cooler winter conditions. These cooler conditions are more pronounced in inland sites, but Markree displays the greatest decrease during this time. Maximum temperatures at coastal locations such as Valentia and Malin Head are more subdued due to oceanic influences (Sweeney 1997).

The values in Table 2 show the strength of the relationship between Markree and the other five stations in winter. Valentia and Armagh display the strongest relationship to the Markree maximum ($r = 0.913$) and minimum ($r = 0.850$). Birr ($r = 0.912$) and Phoenix Park ($r = 0.917$) show the greatest mean correlation to Markree. Malin Head shows the least significant relationship for the maximum ($r = 0.826$), minimum ($r = 0.799$) and mean ($r = 0.870$) for Markree. The relationship between NAO and winter temperatures for each record is presented in Table 3. Markree displays a similar strong correlation with the winter NAO when compared to the other stations, with the exception of Malin Head which shows the overall weakest NAO relationship (maximum $r = 0.471$; mean $r = 0.441$; minimum $r = 0.441$). Markree illustrates the strongest affiliation with the NAO in the mean values ($r = 0.617$), slightly higher than Armagh ($r = 0.611$), Valentia ($r = 0.611$), Phoenix Park (0.593) and Birr ($r = 0.587$). The strongest NAO correlation with minimum values was shown in Valentia ($r = 0.587$) and Armagh ($r = 0.587$), with Markree following closely with $r = 0.569$. Finally, Phoenix Park displayed the strongest relationship for maximum values with $r = 0.641$.

Spring

Three periods of warming are evident in the spring records (Figure 7). The first phase commences in the 1880s into the twentieth century. The next warming stage occurs from mid-1910s until the 1940s. The final and most recent rapid warming occurred from the mid-1980s until present. The most substantial spring warming in all records is experienced in the maximum values. The minimum values show more decadal variability than maximum values throughout the records. In the 1880s, Markree, Birr, Armagh and Phoenix Park had almost identical minimum temperatures ranging from 3°C to 5°C (Figure 7c). Valentia experienced the highest minimum temperatures (between 5.5°C and 7.0°C), followed by Malin Head (4.8–6.3°C). Throughout the record, Markree displays the most variability, with a significant decline in minimum temperature spanning the 1940s to the mid-1980s. This cooling was less severe in the other records, and as a result Markree experienced the lowest minimum temperatures from the 1960s until present. Although Markree displays the lowest

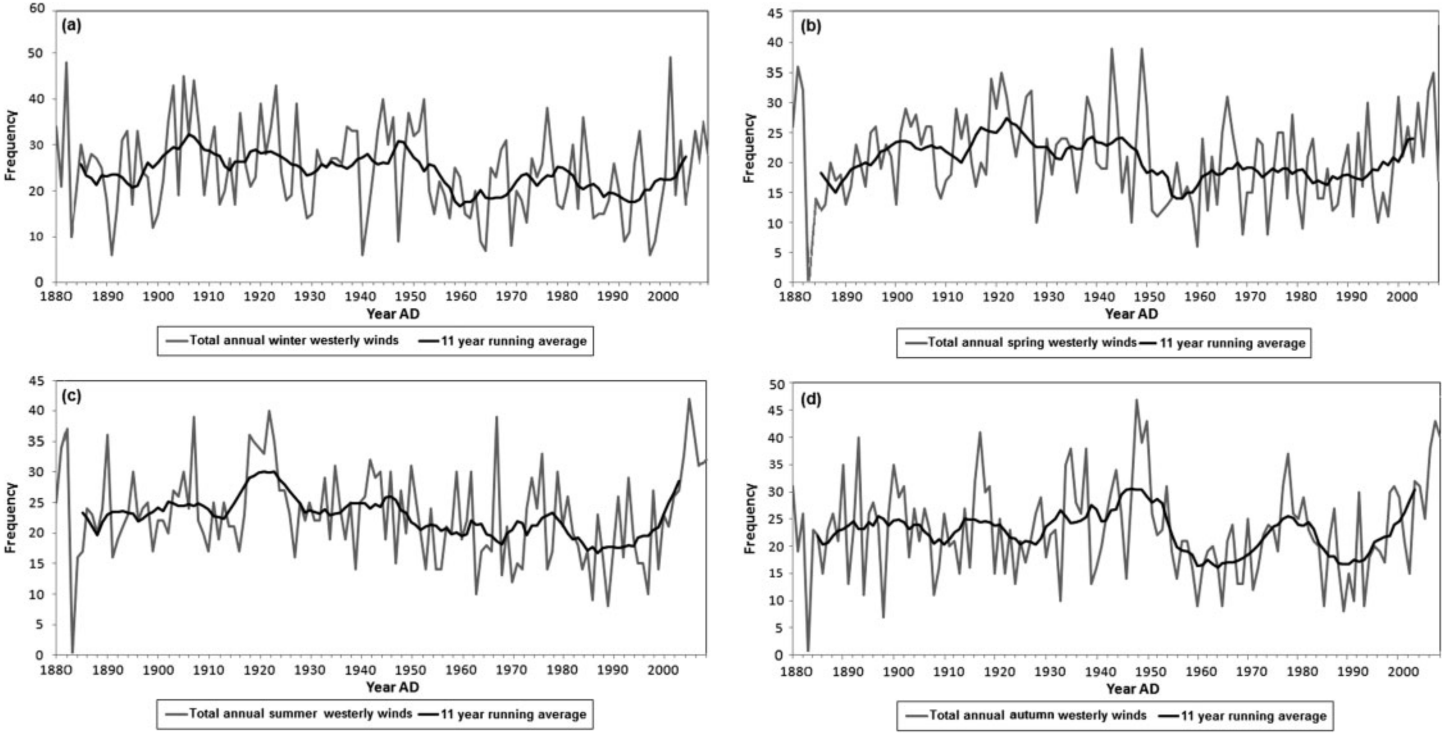


Figure 6. The number of days in which westerly winds were recorded in Ireland, 1880–2008, for each season: (a) winter, (b) spring, (c) summer and (d) autumn.

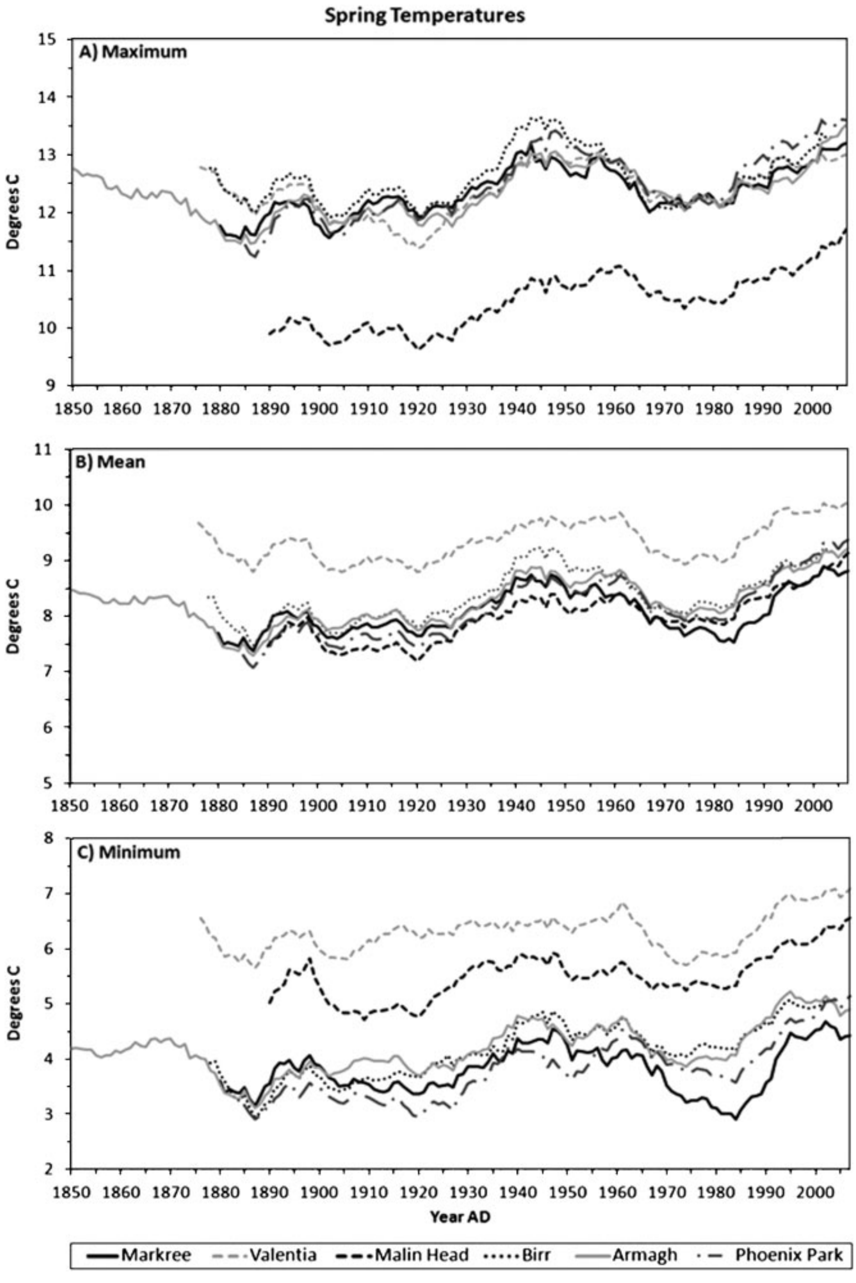


Figure 7. Eleven-year running means for spring daily maximum (a), mean (b) and minimum (c) temperatures for each of the six long-term meteorological stations in Ireland.

minimum temperature values, it has the greatest rate of minimum warming from 1980 to 1990 (1.5°C per decade).

The maximum spring temperatures show a general increase through time in each data-set (Figure 7a). Malin Head displays the lowest maximum temperatures compared to the other regions, which are clustered together around a similar temperature range of 11.5–13.5°C. From 1880 to 2009, Phoenix Park and Armagh show the greatest warming of ∼2°C, followed by Markree and Birr, while Valentia and Malin Head experiences the lowest rate of temperature increase over the entire record. Valentia and Malin Head display more muted changes in maximum temperatures over the length of the record compared to the more inland locations and Markree (Figure 7a). The more extreme sub-decadal temperature range evident at inland locations can be linked to the westerly wind regimes, with an increased frequency of westerlies corresponding with higher temperatures (Figure 6b).

The mean temperature record observed as in Figure 7b shows Valentia experiencing warmer conditions compared to the other regions. All areas show increasing temperatures, with Markree displaying the greatest variability over the record. Decreasing temperatures from the 1940s to the mid-1980s and rapid increase into the twenty-first century characterise Markree's variable nature. The greatest mean temperature increases in the most recent warming period were experienced in Markree, Armagh and Phoenix Park. Spring correlations displayed in Table 2 show mixed results. Valentia displays the strongest minimum ($r = 0.813$) relationship with Markree and the weakest maximum ($r = 0.803$) correlation. Malin Head shows the weakest relationship for the minimum ($r = 0.707$) and mean ($r = 0.837$) temperatures. Birr and Phoenix Park display the strongest maximum relationship with $r = 0.899$ and $r = 0.904$, respectively. Finally, Armagh shows the strongest relationship with Markree for the minimum ($r = 0.808$) and mean ($r = 0.903$) series. Again minimum values from the other records show the lowest correlations with Markree.

Summer

Warming over the length of each record for summer is not as substantial when compared to other seasons (Figure 8). Despite this, slight increases in temperature are still apparent in each region. Again three stages of warming are evident, with the rise from mid-1880 to 1900 marking the first significant phase. A short but considerable increase is evident from the late 1920s to the late 1930s. From the 1970s until the 1990s, temperatures in the maximum values display greater inter-decadal variability compared to the minimum values. Finally, modern accelerated warming begins in the 1990s in the maximum, minimum and mean values.

Valentia again displays higher minimum temperatures than the other stations, followed by Malin Head (Figure 8c). Markree presents the greatest variability over the length of its record including the highest rate of warming post-1990. Markree again displays the lowest minimum temperatures from the 1940s until the 1970s. Warming in all regions is evident in the maximum temperature record (Figure 8a). From the 1960s, temperatures generally rise with a number of peaks emerging in the record over this period. Temperatures in all regions apart from Valentia show late twentieth-century warming. Valentia and Malin Head follow similar rates of sub-decadal maximum temperature variability compared to all other station locations, with the exception of the most recent warming from the mid-1980s into the twenty-first century. The frequency of westerlies increases from the mid-1980s to 2008 (Figure 6c). This increase corresponds with greater warming in more inland (and Markree) locations compared to the coastal areas of Malin Head and Valentia.

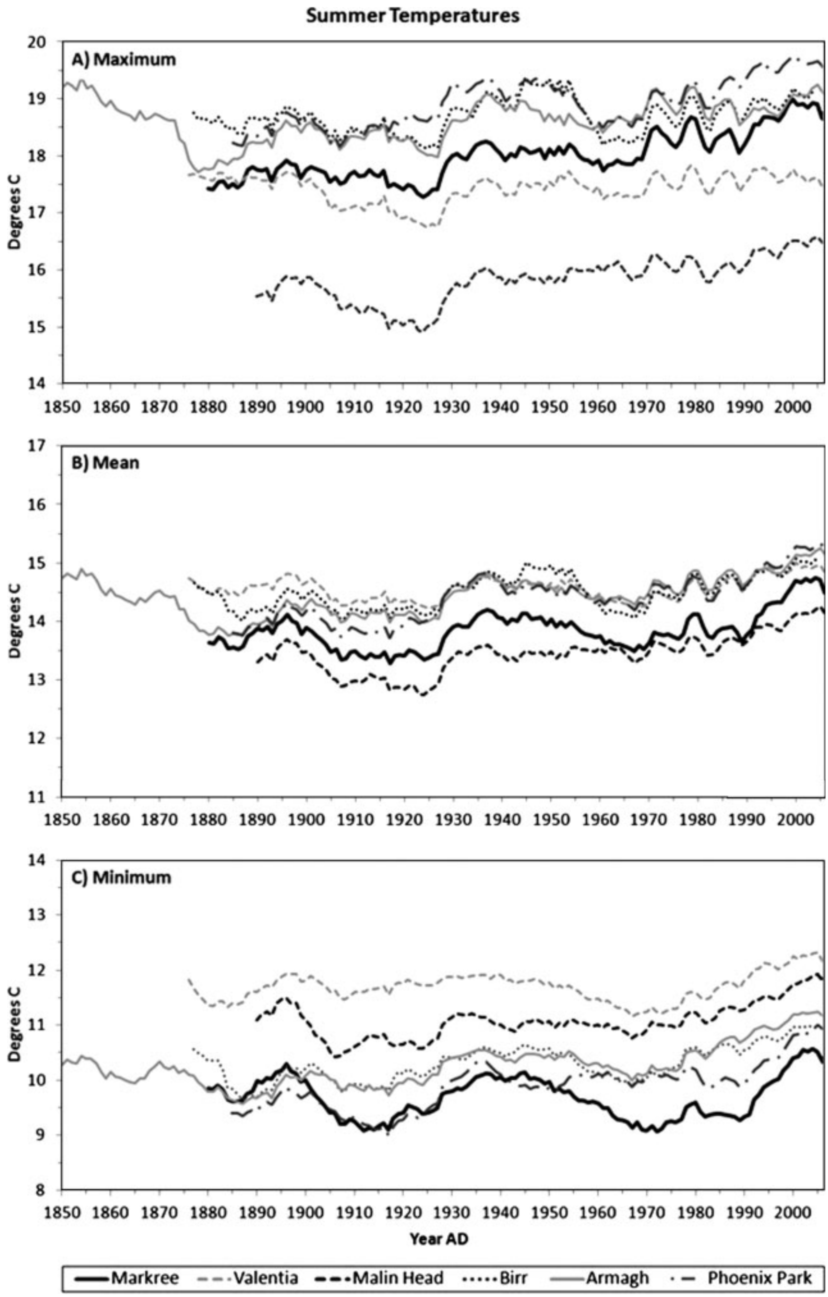


Figure 8. Eleven-year running means for summer daily maximum (a), mean (b) and minimum (c) temperatures for each of the six long-term meteorological stations in Ireland.

Therefore, more inland or sheltered locations tend to exhibit a greater range in maximum temperatures through time compared to coastal regions. Once more, this emphasises the ability of oceanic influences to overwhelm the modulating control of westerly wind regimes at coastal location in Ireland. Finally, mean summer values illustrate similar temperature ranges and patterns for each region (Figure 8b). Markree and Malin Head show cooler temperatures than the other regions, which are clustered together around the 14–15°C range. Markree again shows the greatest decadal variability, with more substantial cooling in the 1940s until the late 1960s and the most rapid warming from the mid-1980s into the twenty-first century. Malin Head and Valentia display more a subtle mean temperature increase from the mid-1980s to 2011, due to the muted increase in maximum temperatures over this time period.

The lowest correlations for all five stations to Markree are again seen in the minimum values. Birr has the highest correlation with the minimum ($r = 0.726$) and mean ($r = 0.892$) series. Armagh shows the second highest correlation after Birr in the mean ($r = 0.888$) series and the highest maximum correlation ($r = 0.920$). Armagh has the lowest minimum correlation with Markree ($r = 0.649$). Malin Head has the lowest mean ($r = 0.820$) correlation, and Phoenix Park has the lowest maximum ($r = 0.832$) correlation. Summer displays lower minimum correlations between Markree and the other five stations than any other season.

Autumn

The greatest warming for each region over the entire chronology occurs in autumn (Figure 9). Two substantial warming phases are apparent. The first takes place from the 1880s until the 1940s, with the second extending from the 1990s into the twenty-first century. This latter period marks the fastest rate of temperature increase for any of the seasons – Markree warms at 0.11°C per decade in the maximum series and 1°C per decade in the minimum series. From Figure 9c it is apparent that the minimum temperatures are driving the mean values, particularly from 1990 to present. Maximum temperatures from Markree, Malin Head, Birr, Armagh and Phoenix Park show notable warming from 1880 to present, while Valentia displays a slightly more muted temperature increase (Figure 9a). This more subtle temperature increase evident in Valentia over the length of the record may again be due to the modulating oceanic influence at this coastal location overwhelming the control of westerly wind regimes. The frequency of westerly winds in autumn appear more variable than other three seasons with a general increase from 1880s until the mid-twentieth century, followed by a sharp decline from 1950 to mid-1960 (Figure 6d). The frequency of westerly winds increases once more from the mid-1960s to 1980, followed by a brief but notable decline until 1990; a final sharp incline in westerly winds spans the early 1990s to 2008. From the 1990s, although warming is evident in the maximum values (particularly at Armagh and Birr), the minimum record shows greater rates of temperature change. Interestingly, Valentia and Malin Head display less minimum temperature warming than other locations. It is likely that autumn westerly winds subdue the minima in exposed coastal locations. The autumn series is defined by less decadal variability and a temperature incline that includes significant modern warming over all records apart from Valentia.

The results from Table 2 show that the highest correlation with Markree is from Birr and Armagh, and the lowest correlations are from Valentia and Malin Head. Birr has a slightly higher correlation than Armagh for maximum, minimum and

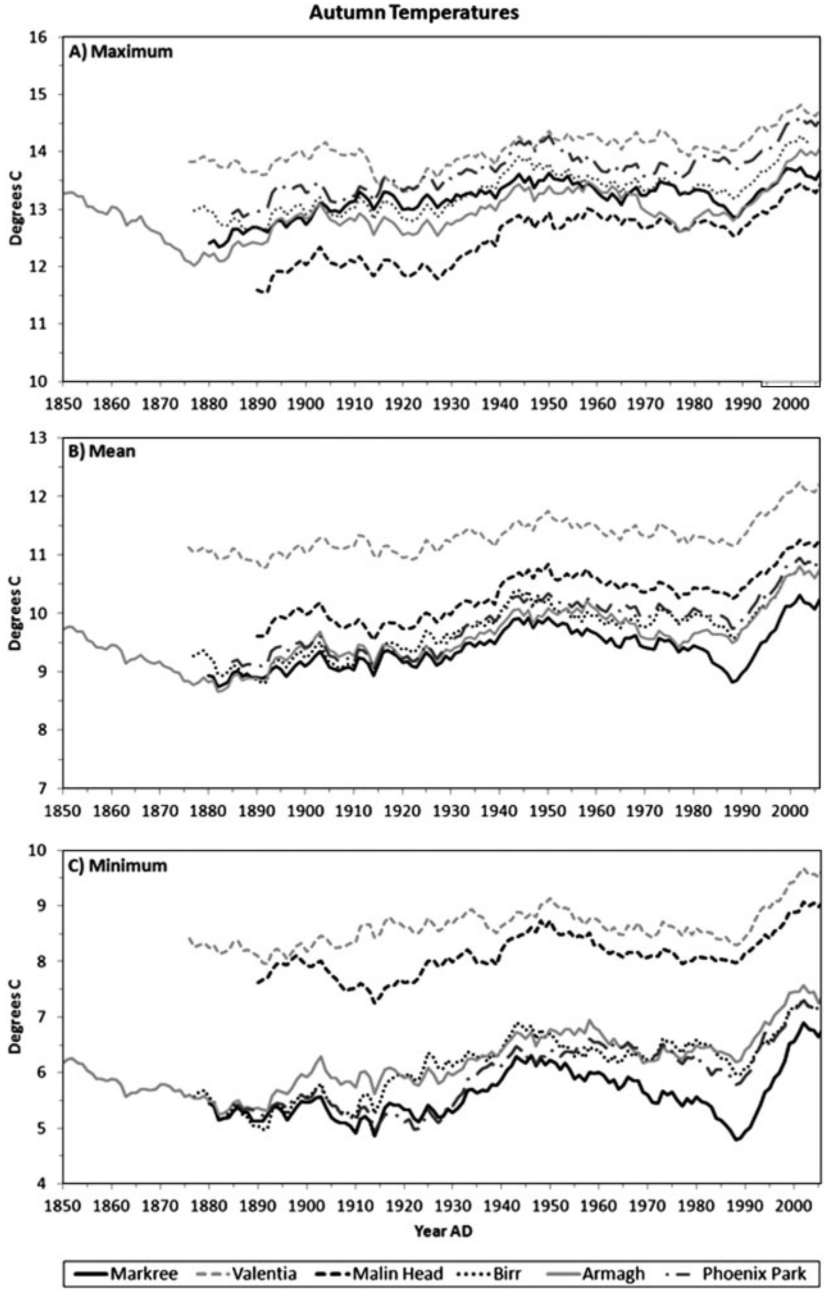


Figure 9. Eleven-year running means for autumn daily maximum (a), mean (b) and minimum (c) temperatures for each of the six long-term meteorological stations in Ireland.

mean with $r = 0.910$, $r = 0.877$ and $r = 0.940$, respectively. Valentia shows the lowest correlation with maximum values ($r = 0.809$). Malin Head displays the lowest correlation for the minimum and mean series with $r = 0.767$ and $r = 0.860$, respectively.

Discussion

In the Markree data-set all seasons show a gradual warming trend at the end of the nineteenth century. Despite this warming trend, temperatures in the late 1880s were still lower than those at present. In winter, spring and summer this late nineteenth-century warming is greatest in minimum values. However, in autumn this temperature increase is more substantial in the maximum data. Apart from Valentia in winter (which has a decreasing trend) and Armagh in autumn (where minimum values display the greatest rate of warming), the rest of the stations follow quite similar patterns and rates of increase in this late nineteenth-century data. A short cooling period in the early twentieth century is evident in all records in the minimum data, and this temperature decline is strongest in Markree.

Markree displays the greatest minimum warming since the mid-1980s in all seasons, particularly spring and autumn. This highlights the importance of the region in future climate change scenarios, particularly as it has been shown that recent minimum temperatures in Ireland are increasing at around twice the rate of the maximums (Vincent and Gullet 1999, Zhai and Ren 1999, McElwain and Sweeney 2003, 2007). The most recent patterns in temperature from 2010 and 2011 show a notable drop in winter temperatures. This cold spell highlights that despite a recent warming trend, extreme events can still occur. Similar cold spells are displayed over the Markree reconstruction, the coldest taking place in 1879 when the average winter daily minimum value was -2.28°C. This exceptionally cold year has been linked to volcanic activity in Iceland and a solar minimum in December 1878 (Hickey 2012). The year 2010 was the 6th coldest year on record, with a winter mean minimum value of -1.20°C, and 2011 was the 13th coldest year with a seasonal winter mean minimum of -0.42°C. This places the recent cold anomaly in a greater context and emphasises the need for this longer-term record to be included in future climate research, especially in a region that experiences such low minimum temperatures.

The Markree record displays many characteristics of an inland locality, despite its close proximity to the coast. Markree's low minimum temperatures and large diurnal range are similar to inland and eastern sites such as Birr, Phoenix Park and Armagh. Furthermore, seasonal correlations between Markree and the other stations are often strongest with Birr and Armagh and weakest with Malin Head and Valentia. This suggests that the Sligo region in the north-west of Ireland is somewhat sheltered from direct oceanic influences. The mountains surrounding the northern and western areas of Sligo Bay (Figure 1), along with Markree's geographic location adjacent to the shallow Ballysadare estuary, place it well 'inland' from a south-westerly direction, and is likely providing shelter from the moderating westerly/south-westerly wind regimes that dominate the Irish climate. Evidence for this is seen in all seasonal minimum long-term temperature records, where Markree consistently exhibits the lowest or among the lowest values, and Valentia and Malin Head display the highest seasonal minimum temperatures. Valentia and Malin Head are also characterised by more subdued sub-decadal maximum warming and cooling throughout the record in all seasons compared to more 'inland' stations, including Markree. The Markree record consistently exhibits greater maximum and minimum temperature variability than the other five records over the past 135 years. It could be argued that the variability in the early portion of the Markree record is noise within the data-set as a result of instrumentation and exposure defects. However, as the same variability is evident in the record post-1950, when recording measures were standardised across the country, it is highly likely that the large range in sub-decadal temperatures evident in the Markree record is due to the observatory's sheltered location, which buffers this site from the full effects of the Atlantic Ocean.

Interestingly, Valentia is the only location in the available long-term climate series that typically displays a regional coastal climate according to the classification by Smith (1976). Malin Head displays the lowest spring, summer and autumn maximum values; however, the minimum values are more closely related to Valentia. Thus, the three coastal stations located in the north, south-west and north-west of the island (Malin Head, Valentia and Markree, respectively) all display different seasonal temperature trends, highlighting the unique regional climate regimes that exist in western Ireland. Finally, although the NAO predictably showed a strong relationship with winter temperatures from all stations (McElwain and Sweeney 2003), there was no discernible geographical trend except that Malin Head (on the north coast) consistently displayed the weakest relationship with winter NAO.

Conclusions

The primary purpose of this study was to provide a new data-set that will increase the spatial coverage of the long-term instrumental temperature record in Ireland. To date, only five regions in Ireland are represented in the long-term temperature record, as shown in Figure 1. Results from the Markree reconstruction and comparisons with other long-term records show the unique temperature regime for the Sligo region and highlight that the Markree record should be included in future climate change research in Ireland. Furthermore, the large diurnal ranges and low minimum temperatures show the potential influence of surrounding topography on seasonal temperatures, as well as the importance of prevailing winds' direction when considering coastal influences. As this record has been largely absent from past analyses of Ireland's long-term temperature trends, it offers more complete spatial coverage for the extended Irish climate chronology, especially for the western portion of the island. Further climate reconstructions can be carried out using the Markree historical data on precipitation, relative humidity and wind regimes to create a comprehensive climate history for this region of Ireland.

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