Tree Ring Chronology of Meteorological Extremes for Ireland, AD425-1650

by Dr Francis Ludlow, Harvard University and IMS member

Fludlow
@fas.harvard.edu

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"Sun Falls over the Lake"
Photograph taken by Ron Bending

"Stormy Waters"
Photograph taken by Richard Hatch

The Irish Dendrochronological Record

For over thirty years the study of Ireland's climate history has benefited from the availability of world class dendrochronological (tree ring) records, developed by Michael Baillie, David Brown and colleagues in Queen's University, Belfast, based upon the measurement of annual ring widths on oaks native to Ireland (i.e. the Sessile and Pedunculate Oak). Both species are suitable for the construction of long dendrochronological records because of their longevity, clear annual growth rings and a general absence of missing, partial or false rings that cause difficulties with the construction of chronologies from other species (Baillie, 1982, 1995). Living oaks and the availability of timbers from historic buildings and archaeological sites, and still older subfossil oaks preserved in peat bogs, lake margins and river gravels, means that overlapping chronologies of yearly ring widths from these sources can be successfully anchored to the present and extended into the past. Efforts in chronology construction culminated in 1984 in an unbroken 7,272-year oak chronology for Western Europe, incorporating chronologies from the North of Ireland, Britain and Germany (Pilcher et al., 1984).

A correlation between meteorological conditions and the growth of many tree species, as expressed in their annual ring widths, has long been recognised as a potential means of reconstructing climate before the era of instrumental meteorological records (Douglass, 1919). A landmark success in this field (dendroclimatology) involved an 1100 year climate reconstruction using the annual rings of Bristlecone Pines growing at high altitudes in the White Mountains, California (La Marche, 1974). In Ireland, the primary motivation for dendrochronology was not climate reconstruction, but rather the direct dating of archaeological sites from unearthed timbers, and the recalibration of the radiocarbon timescale, also for dating purposes (Pearson et al., 1984; Baillie, 1995). But the potential for quantitative reconstruction of annual temperature and precipitation from Irish oaks was recognised and investigated in the 1970s and 1980s (e.g. Hughes et al., 1978; Briffa et al., 1983) by comparing ring widths from oak chronologies to temperature and precipitation data from meteorological stations closest to the sites in which the trees forming the chronologies grew, for periods in which there were overlapping records.

A significant problem, however, with the use of Irish oak ring widths for climate reconstruction arises from Ireland's mild maritime climate. In La Marche's (1974) study, the Bristlecone Pines grew in a marginal high-altitude environment, where a clear stressor for the trees was temperature. But Ireland cannot be considered a marginal environment for oak, except in exceptional locations, and ring widths may vary ambiguously in response to a complex array of possible meteorological influences. One example of the complex relationship of oak growth to climate in Ireland is provided by an observed negative growth response to mild winters. A possible explanation is that continued biological activity promoted during mild winters (which are otherwise periods of dormancy) utilises stored energy usually reserved to fuel early growth during the next growing season (i.e. around April) (Pilcher and Gray, 1982). García-Suárez et al. (2009: 163) notes that *"around 20 years ago, dendroclimatic* *studies were discontinued using trees in the British Isles because it was believed that they were less sensitive to climate than those which live under more critical conditions."*

Recent work has shown that potential exists for climate reconstruction through a multi-species approach, combining oak, Scots pine, beech and ash, each of which exhibit different sensitivities to different aspects of climate (García-Suárez et al., 2009). Available chronologies for the latter species do not yet extend far into the past, but are the best prospect for quantitative annual climate reconstruction for Ireland before the instrumental period (which began most consistently in Ireland in the late eighteenth century with recording at Armagh Observatory (Butler et al., 2005)). It is hoped that these chronologies may be ultimately extended further.

Despite the limitations, it has been possible to use the available long Irish oak chronologies to identify years of dramatically reduced growth (Baillie and Munro, 1988; Baillie, 1999, 2006). Common years of poor growth identified in chronologies from dispersed locations across, and even beyond, Ireland, provide strong evidence of a climatic origin (Kelly et al., 1989), with climate being one of the only feasible mechanisms for inducing common growth signals over large geographical areas. Figure 1 (left) presents the annual average growth widths of Irish oaks from 1805-1825. This period is notable for the major explosive volcanic eruption in Tambora, Indonesia, in April 1815, which led to abnormally low temperatures across Europe and gave rise to the famous *"year without a summer"* in 1816 (Self, 2005). The impact of the eruption on Irish oaks is clearly visible in the pronounced decline in growth in 1816, continuing in 1817, with the low growth surpassed only once in the remainder of the record up to 1992.

Figure 1 (right) shows a sample taken from a living oak on the grounds of Shane's Castle, Co. Antrim, which highlights a period of very small ring growth beginning in 1740, a time before consistent instrumental meteorological record keeping in Ireland. This low growth, culminating in 1742, corresponds clearly with a very severe and prolonged frost (associated with conditions of famine) recorded widely in contemporary Irish historical records, and written about most extensively by David Dickson (1997) in *Arctic Ireland: The Extraordinary Story of the Great Frost and Forgotten Famine of 1740-41*. Examining the records of known episodes of major explosive volcanism (Zielinski et al. (1994) and Zielinski (1995)) reveals a major volcanic eruption in Tarumai, Japan, in 1739. It seems likely that this eruption played some part in inducing the cold spell of 1740-41, with the initial impediment to oak growth possibly being defoliation by frost.

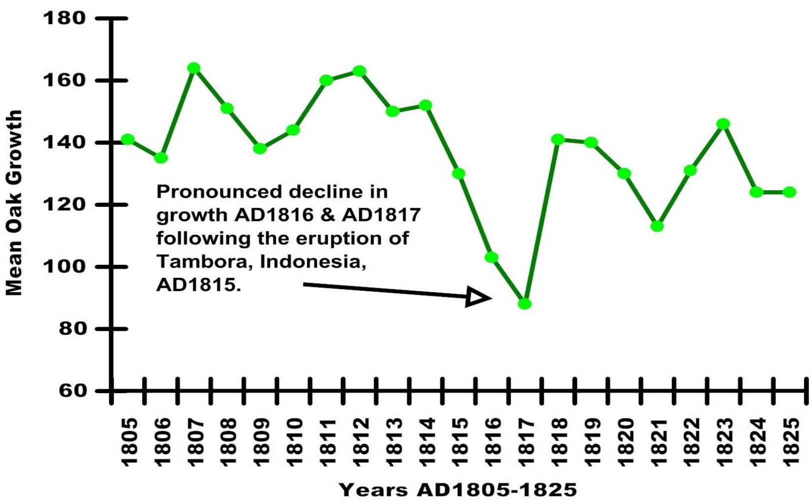

Figure 1. (left) Annual mean tree ring width of Irish oaks, between the years 1805 and 1825. **(right)** Oak sample from Shane's Castle, Co. Antrim. Image courtesy of M. Baillie.

The Irish Annalistic Record

Carefully examining the Irish dendrochronological record can thus provide a precisely-dated chronology of years of very adverse growing conditions for Irish oaks. When combined with evidence of human activities from archaeological, palaeoecological and historical sources, this can be valuable in exploring the socio-economic impacts of episodes of inclement or extreme weather and abrupt climate changes in Ireland before the era of modern instrumental record keeping. The influence of non-climatic factors, such as disease and pest outbreaks, or the coppicing and pollarding of oaks in deliberately managed woodlands that might lead to non-climatic variations in ring growth (Bridge et al., 1986; Baillie, 1993), can be largely excluded by identifying years of poor growth common to different regions. But even when a climatic cause is most likely, the problem of interpreting the exact conditions underlying any particular episode of notably reduced growth remains. An episode of prolonged summer drought may have significantly different impacts upon pre-Modern Irish society than the occurrence of severe and persistent winter frost. But if these conditions are registered in the Irish oak record, it is uncertain how they may be expressed, or if it is possible to clearly tell one from the other. Matters may, however, be clarified by reference to the long tradition of annual chronicling in Ireland, which has left a large corpus of documentary records known collectively as the Irish Annals.

The Irish Annals are yearly listings of major events maintained at first in monastic foundations across Ireland, and from roughly the thirteenth century AD, in the secular schools of learning run by hereditary historians employed by the Gaelic aristocracy (McCarthy, 2008). This transition from monastic to secular recording was due, in large part, to twelfth century reform of the Irish church, which saw a move away from secular involvements (of which the chronicling of secular events was seen as part) and the destabilising impacts of the twelfth century Anglo-Norman invasion and colonisation. The early content of many surviving manuscripts (most preserved on vellum) stretches back centuries before the arrival of Christianity to Ireland in the fifth century. It represents a mixture of events borrowed from Biblical chronology, world history from continental chronicles, integrated with events from Irish mythology. The date at which the surviving manuscripts begin to report genuine contemporary events in Ireland is long debated, with dates given in the sixth, seventh and later centuries (Kelleher, 1963; Hughes, 1972; Smyth, 1972). More recent work provides strong evidence for a date as early as ~425 (McCarthy, 2008; Ludlow, 2010). Chronicling of events in Ireland effectively ceased by the mid-seventeenth century when the spread of English custom and colonial rule resulted in the disruption of the old Gaelic order.

In addition to recording events such as the founding and sacking of ecclesiastical settlements, major battles and the obituaries of important persons, the Irish Annals preserve unique and abundant records of adverse meteorological conditions and extremes, as well as descriptions of their impacts upon society and the biosphere. An example is a report of *"very severe weather, frost and snow, from the fifteenth of the kalends of January [i.e. 15 days before the 1st of January] to the fifteenth of the kalends of March [i.e. 15 days before the 1st of March], or longer, which made great havoc of birds, cattle and people; and from which arose great scarcity throughout all Ireland, and Leinster especially"* recorded in the *Annals of Loch Cé* for 1115. A further example, from the *Annals of the Four Masters* for 892, reports *"a great wind on the festival of St. Martin this year [i.e. 11 November, Julian Calendar]; and it prostrated many trees, and caused great destruction of the woods in Ireland, and swept oratories and other houses from their respective sites."* A final example from the *Annals of Connacht* for 1252 reports *"great heat and drought in the summer… so that folk used to walk across the Shannon dryshod. The wheat was reaped three weeks before Lammas [i.e. 1 August, Julian Calendar], and indeed all corn-crops were reaped then. The trees were burned by the sun."* Although the records are not always as detailed, these examples demonstrate the advantages of documentary meteorological information. It is phenomena-specific, clearly identifying the meteorological conditions and phenomena experienced, it is precisely dated, even specifying within-year durations, it provides valuable geographical information on the locations or spatial extent of conditions, and gives unique secondary information about the impacts upon society and the biosphere.

Unsurprisingly, historical documentary records are now recognised as valuable sources for climate history, with their use in climate reconstruction the concern of historical climatology (Brázdil et al., 2005). The USA's *National Research Council* (NRC) (2006: 40) notes that *"documentary evidence is one of the few kinds available that can register severe floods… and other natural disasters. Consequently, their analysis enables an investigation of the relationship between variations in climate and the frequency and severity of extreme events, a subject that is of major societal concern in relation to projected global warming".*

Extreme events are, by definition, rare, and long records are required to reliably characterise their likelihood of occurrence. The long record of the Irish Annals, spanning up to twelve centuries, can play an important role in determining if past changes in long-term climatic averages (e.g. of temperature and precipitation) were accompanied by changes in the frequency and severity of extreme events. Exploring the socio-economic responses to historic extremes and abrupt climate changes is similarly important, given the prospect of changes in the frequency and severity of extremes under future climate change (McBean, 2004; Skinner, 2008). Comparing the rich record of social stresses preserved in the Irish Annals (e.g. conditions of scarcity and famine) to the chronology of major growth downturns registered in the Irish oaks may show that past experiences hold valuable lessons for the future (Campbell, 2010).

In 1975 the eminent Irish historian F. X. Martin remarked that *"the quantity and quality of the [Irish] Annals are formidable… as far as annals are concerned Ireland has an embarras de richesse. Few European countries, if any, can claim a similar body of literature on a national scale"* (Martin, 1975: 5). Of immense value is the fact that the Irish Annals provide detailed coverage during the "Dark Ages" of the first millennium for which comparable information is extremely scarce in Europe (Lamb, 1995; Pfister et al., 1998). Yet the meteorological content of the Irish Annals has been largely ignored, or used only anecdotally, with few exceptions (to varying degrees including, Dixon (1953, 1959), Mallory and Baillie (1988), Ludlow (2005), McCormick et al. (2007), Hickey (2008), Kerr et al. (2009) and Kiely et al. (2010)). This is despite the extensive use of similar sources in palaeoclimatology in Europe and Asia (e.g. Chu et al., 2002; Brázdil et al., 2005; Ge et al., 2008). Indeed, misconceptions exist regarding the meteorological content of the Irish Annals. In commenting upon the scarcity of early medieval documentary data for Europe, the NRC (2006: 40) state that *"there are… weather records preserved in Irish and Norse annals back to the middle of the first millennium A.D., but their dating is imprecise and descriptions of weather and climate are often exaggerated."* This statement reflects real, but also perceived, barriers to using the meteorological content of the Irish Annals, and helps to explain its neglect.

Most of these barriers have now been removed or shown to be overstated. The pioneering work of McCarthy (1998, 2001, 2005) in correcting and calibrating the chronology of the Irish Annals against independent evidence, including precisely calculable dates of solar and lunar eclipses, has provided coherent and more reliable dating for events in the Annals. Although the NRC (2006) provide no citation or evidence to support an exaggeration of information in the Irish Annals, the reliability of information in documentary sources is a legitimate concern (Brázdil et al., 2005). Ludlow (2010) has conducted a detailed examination of the reliability of the meteorological content in the Irish Annals, founded upon an investigation of the perception of rare natural phenomena and meteorological extremes in medieval Ireland. For example, scribes based in monastic institutions largely wrote from a religious perspective and employed Biblical allusions in describing natural phenomena (McCarthy and Breen, 1997). An example from the *Annals of Ulster* for 772 relates the occurrence of *"lightning and thunder like the Day of Judgement… which was called fire from heaven… the Irish fasted two periods of three days, with a single meal between them, through fear of the fire."* Knowledge of how meteorological extremes were perceived, and what significance was attached to them, in turn tells us about the varying motives for their recording. Some motives promote recording of lesser reliability than others, but the results of this assessment suggest that less than 10% of all meteorological records should be considered completely unreliable.

Other barriers have also been largely resolved, such as the widespread duplication of recorded meteorological extremes between surviving manuscripts of the Irish Annals, arising due to shared ancestry. Most manuscripts contain unique material, but also a large body of duplicated material that exists due to the copying of a common earlier manuscript (e.g. most surviving manuscripts contain material from older annual records originally compiled in the monastic centre at Clonmacnoise, Co. Offaly, up to the thirteenth century). When scribes were copying from earlier sources, they might accidentally change the text and enter records under incorrect years. This helps to disguise the fact that a given record is a duplicate also found in other manuscripts. *The Annals of Clonmacnoise*, which is a translation to Elizabethan English in 1627 from a lost Irish manuscript, reports for 819 that *"there was such froste this yeare [that] all the Laughes, pooles and rivers of Ireland were soe dryed upp and frozen, [that] steed and all manner of cattle might pass on them without Danger."* In contrast, two years later (in 821) the *Annals of Ulster* report in Irish: *"aigh anaicenta: ru -reset inna muire & inna locha & inna aibni co ructha* graige & eti & fedman iarmaibh". This is translated by Mac Airt and Mac Niocaill (1983) as *"abnormal ice; the seas, lakes and rivers* *froze and herds of horses and cattle, and loads, were brought across them."* Investigating errors in the chronologies of these manuscripts suggests that both records should, in fact, refer to the year 822, so that instead of two distinct episodes of cold, the conditions described are the same. And despite apparent textual differences, there are enough similarities in the description to suggest that these are duplicates of a single original account of conditions for 822. This is further supported by the knowledge that both these sources contain material from a common, but now lost manuscript, likely to have been originally compiled in Clonmacnoise (McCarthy, 2008).

All instances of duplication must be found and accounted for, otherwise the result will be an artificial inflation of the number of extreme events that appear to have happened through time. This issue was tackled by Ludlow (2010), who systematically surveyed the surviving manuscripts, categorising and quantifying their relevant content. Even when duplication is accounted for, the occurrence of some 585 extreme meteorological conditions and related phenomena are recorded in the Irish Annals, the majority of which can be considered historically reliable, along with unique descriptions of the impact of these conditions on society and the biosphere. The aim of Ludlow's (2010) work is to provide a secure foundation for the systematic, and long overdue, use of the remarkable meteorological records preserved for posterity by the Irish medieval scribes.

Combining the Record of the Irish Annals and Irish Oaks

We can learn most about our climate history through the comparison and combination of diverse lines of evidence (Mann, 2002), as with the Irish dendrochronological record and the Irish Annals. Although the Irish oak record may not clearly mirror annual variations in temperature and precipitation in Ireland's mild maritime climate, the clear response of the trees to exceptional events such as the *"year without a summer"* in 1816 suggests that similar growth impacts may be observed during or after years with extremes recorded in the Irish Annals. This may help to determine if different types of extreme conditions leave distinct signatures on the Irish oaks (e.g. frosts *vs* droughts). Figure 2 shows the mean annual growth widths for the Irish oaks for the period 770-800. Years of reported extremes in the Irish Annals are indicated by arrows.

Some clear correspondences are observed, such as that between the 773 report from the *Annals of Ulster* of *"unaccustomed drought and heat of the sun so that nearly all bread-[grain] failed"* and the very low ring growth for the same year. The low value for this year is surpassed only by the low growth in 782, which can be seen as a continuation of the low growth in 781. These years of poor growth may correspond to the *"great snowfall in April"* reported in the *Annals of Ulster* for 780. This event is particularly notable for its lateness in the year, which may have magnified its impact by being coincident with the start of the growing season for the oaks. The fact that it is

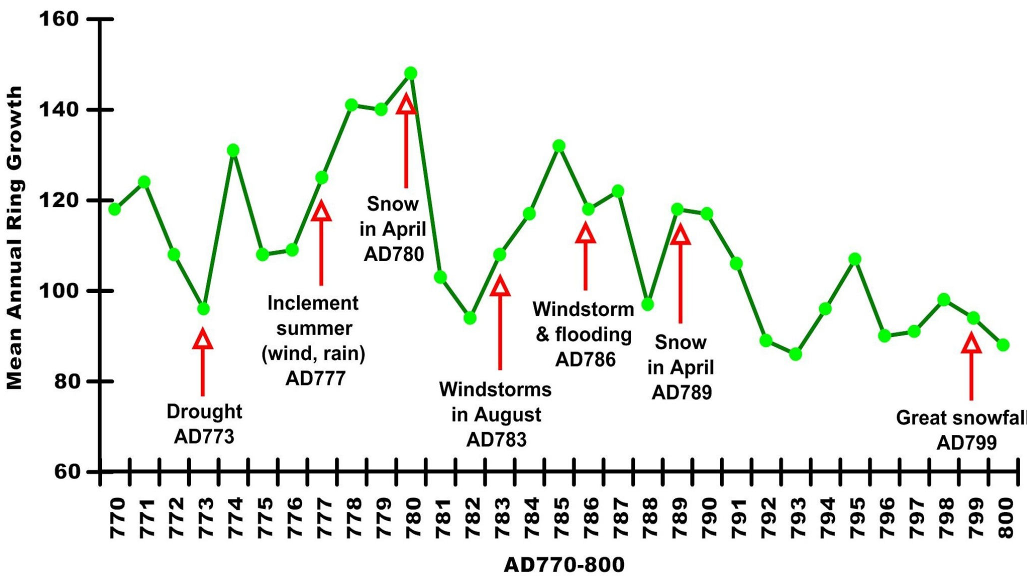

Figure 2. Annual mean tree ring width of Irish oaks between the years 770 and 800.

recorded as occurring a year before the pronounced drop in ring growth may be a reflection on the mechanism described by Baillie (1993) in which energy reserves can sustain growth during the year of the occurrence of adverse growing conditions, with the greatest visible impact occurring only in the following years. Alternatively, despite the great advances in our understanding of the chronology of the Irish Annals from the work of Daniel McCarthy, and the resulting corrections to the chronology based upon this understanding, it is still possible that small dating errors may remain. This example provides a glimpse of the biological and chronological complexities that are quickly encountered upon comparing historically recorded extremes to the record from the Irish oaks.

These complexities can be further observed with the example of the *"great snowfall on the third of the Kalends of May"* (i.e. three days before the 1st of May, Julian Calendar) recorded in the *Annals of Ulster* for 789. Ring growth is, however, not remarkably low in 789, but is notably low in 788, implying either that the date assigned to this event is marginally in error, or that there was no clear impact on the trees. It is interesting to note that the Greenland Ice Sheet Project 2 (GISP2) ice-core registers elevated sulphate deposition levels for the year 788 (with +/- a 2.5 year uncertainty). Elevated sulphate levels in the GISP2 are a reliable indicator of the occurrence of explosive volcanism (Zielinski et al., 1994) and explosive volcanism is in turn known to induce episodes of extreme cold. This occurs because the presence of volcanic sulphate aerosol injected into the stratosphere effectively backscatters incoming direct solar (shortwave) radiation to space, and thereby cools the Earth's surface (Robock, 2000). The resultant reduced temperatures are known to effect tree growth in marginal environments, such as the high latitudes of the Northern Hemisphere (e.g. Briffa et al., 1998). But the effects of low temperatures may be reduced, perhaps particularly in non-marginal growth settings such as Ireland, because the same volcanic aerosols that reduce incoming direct solar radiation also act to increase the levels of diffuse (scattered) radiation reaching the Earth's surface. Robock (2005) has shown that diffuse radiation can be more effectively used in photosynthesis than direct radiation, thereby acting to enhance tree growth. It can be speculated, therefore, that extremes of cold recorded in the Irish Annals may be less likely to affect tree ring width if the cold extreme was as a result of a volcanic event. In this respect, it is worth noting that the snowfall in the year 780 (see figure 2), which appears to have occurred, is not associated with any volcanic event registered in the GISP2.

It is clear that a systematic comparison of the record of the Irish oaks to that of the Irish Annals, making use of the full span of reliable historical recordings from the fifth to the seventeenth centuries, is needed to establish if the Irish oaks tree ring widths consistently register the conditions that have been deemed sufficiently extreme to merit recording by human observers. By comparing both records, it may be possible to determine the conditions to which the trees are most sensitive, and those to which they are not, which would help to shed light on the origins of many dramatic growth downturns that currently do not have a clear interpretation. Attention must also be paid to hidden properties of the Irish dendrochronological record. It is easy to treat the record as a single monolithic entity, with unchanging properties through time. But, in fact, the record is comprised of numerous overlapping chronologies that can be untangled from each another. Each has different levels of replication (i.e. more replication equates to more trees, making up a chronology which should equate to a more reliable climatic signal). The chronologies can also originate from widely dispersed sites throughout Ireland (Baillie, 1982), incorporating trees that grew in very different contexts with an array of variable local environmental influences (e.g. elevation, aspect). In essence, the trees from some sites and some periods may prove more sensitive to climate than others.

Conclusion

The existence of the excellent Irish dendrochronological record and the long and abundant record of weather extremes in the Irish Annals offers the prospect of significantly improving our knowledge of Ireland's climate history. Our island is a key region for the study of past climatic conditions, occupying a climatically sensitive northeast Atlantic location. Our climate is sensitive to the influence of major atmospheric modes of variability, such as the North Atlantic Oscillation, and to ocean circulation changes (Sweeney, 1997; Turney et al., 2005). And now, more than ever, an improved understanding of our climate history is needed to distinguish climate change, as influenced solely by natural factors in the past (e.g. volcanism or solar variability), from that caused by human activities in the future.

References Cited

Baillie, M. G. L. and Munro, M. A. R. (1988) Irish Tree Rings, Santorini and Volcanic Dust Veils, *Nature*, 332, 344-346.

Baillie, M. G. L. (1982) *Tree-Ring Dating and Archaeology*. London: The University of Chicago Press, Ltd.

- (1993) Great Oaks from Little Acorns…: Precision and Accuracy in Irish Dendrochronology, In: Chambers, F. M. (ed.), *Climate Change and Human Impact on the Landscape*. London: Chapman & Hall, 33-46.

- (1995) *A Slice Through Time: Dendrochronology and Precision Dating*. London: B.T. Batsford.

- (1994) Dendrochronology Raises Questions About the Nature of the AD 536 Dust-Veil Event, *The Holocene*, 4, 212-217.

- (1999) *Exodus to Arthur: Catastrophic Encounters With Comets*. London: B.T. Batsford.

- (2006) *New Light on the Black Death*. Stroud: Tempus.

Brázdil, R., Pfister, C., Wanner, H., Von Storch, H. and Luterbacher, J. (2005) Historical Climatology in Europe – The State of the Art, *Climatic Change*, 70, 363-430.

Bridge, M. C., Hibbert, F. A. and Rackham, O. (1986) Effects of Coppicing on the Growth of Oak Timber Trees in the Bradfield Woods, Suffolk, *The Journal of Ecology*, 74 (4), 1095-1102.

Briffa, K. R., Jones, P. D., Schweingruber, F. H. and Osborn, T. J. (1998) Influence of volcanic eruptions on Northern Hemisphere summer temperature over the past 600 years, *Nature*, 393, 450-455.

Briffa, K. R., Jones, P. D., Wigley, T. M. L., Pilcher, J. R. and Baillie, M. G. L. (1983) Climate Reconstruction from Tree Rings: Part 1, Basic Methodology and Preliminary Results for England, *Journal of Climatology*, 3, 233-242.

Butler, C. J., García-Suárez, A. M., Coughlin, A. D. S. and Morrell, C. (2005) Air Temperatures at Armagh Observatory, Northern Ireland, *International Journal of Climatology*, 25, 1055-1079.

Campbell, B. M. S. (2010) Nature as Historical Protagonist: Environment and Society in Preindustrial England, *Economic History Review*, 63 (2), 281-314.

Chu, G., Liu, J., Sun, Q., Lu, H., Gu, Z., Wang, W. and Liu, T. (2002) The 'Mediaeval Warm Period' Drought Recorded in Lake Huguangyan, Tropical South China, *The Holocene*, 12, 511-516.

Dickson, D. (1997) *Arctic Ireland: The Extraordinary Story of the Great Frost and Forgotten Famine of 1740-41*. Belfast: White Row Press Ltd.

Dixon, F. E. (1953) Weather in Old Dublin – Part 1, *Dublin Historical Record*, 13, 94-107.

- (1959) Weather in Old Dublin – Part 2, *Dublin Historical Record*, 15, 65-73.

Douglass, A. E. (1919) *Climate Cycles and Tree Growth: A Study of the Annual Rings of Trees in Relation to Climate and Solar Activity*. Volume 1. Washington: Carnegie Institution of Washington.

García-Suárez, A. M., Butler, C. J. and Baillie, M. G. L. (2009) Climate Signal in Tree-Ring Chronologies in a Temperate Climate: A Multi-Species Approach, *Dendrochronologia*, 27, 183-198.

Ge, Q., Zheng, J., Tian, Y., Wu, W., Fang, X. and Wang, W. (2008) Coherence of climatic reconstruction from historical documents in China by different studies, *International Journal of Climatology*, 28, 1007-1024.

Hickey, K. (2008) *Five Minutes to Midnight? Ireland and Climate Change*. Belfast: The White Row Press.

Hughes, K. (1972) *Early Christian Ireland: Introduction to the Sources*. London: Hodder and Stoughton.

Hughes, M. K., Gray, B., Pilcher, J., Baillie, M. G. L. and Leggett, P. (1978) Climatic Signals in British Isles Tree-Ring Chronologies, *Nature*, 272, 605-606.

Kelleher, J. V. (1963) Early Irish History and Pseudo-History, *Studia Hibernica*, 3, 113-127.

Kelly, P. M., Munro, M. A. R., Hughes, M. K. and Goodess, C. M. (1989) Climate and Signature Years in West European Oaks, *Nature*, 340, 57-60.

Kerr, T. R., Swindles, G. T., Plunkett, G. (2009) Making Hay while the Sun Shines? Socio-Economic Change, Cereal Production and Climatic Deterioration in Early Medieval Ireland, *Journal of Archaeological Science*, 36, 2868-2874.

Kiely, G., Leahy, P., Ludlow, F., Stefanini, B., Reilly, E., Monk, M. and Harris, J. (2010) *Extreme Weather, Climate and Natural Disasters in Ireland*. Synthesis Report. Johnstown Castle: Environmental Protection Agency.

La Marche, V. C. (1974) Palaeoclimatic Inferences From Long Tree-Ring Records, *Science*, 183, 1043-1048.

Lamb, H. H. (1995) *Climate, History and the Modern World.* 2nd edition. London: Routledge.

Ludlow, F. (2005) A Surprisingly Useful Source of Information about Ireland's Past Climate: The Irish Annals, *Geographical Viewpoint*, 33, 26-33.

- (2010) *The Utility of the Irish Annals as a Source for the Reconstruction of Climate*. 2 Vols. Unpublished PhD Thesis, Department of Geography, University of Dublin, Trinity College.

Lyons, M. C. (1989) Weather, Famine, Pestilence and Plague in Ireland, 900-1500, In: Crawford, E. M. (ed.), *Famine: The Irish Experience 900-1900: Subsistence Crises and Famines in Ireland.* Edinburgh: John Donald, 31-74.

Mac Airt, S. and Mac Niocaill, G. (eds.) (1983) *The Annals of Ulster to A.D. 1131*. Dublin: Dublin Institute for Advanced Studies.

Mallory, J. P. and Baillie, M. G. L. (1988) *Tech ndaruch:* The Fall of the House of Oak, *Emania: Bulletin of the Navan Research Group*, 5, 27-33.

Mann, M. E. (2002) The Value of Multiple Proxies, *Science*, 297, 1481-1482.

Martin, F. X. (1975) Foreword, In: Mac Niocaill, G., *The Medieval Irish Annals*. Dublin: Dublin Historical Association, 5-10.

McBean, G. (2004) Climate Change and Extreme Weather: A Basis for Action, *Natural Hazards*, 31, 177-190.

McCarthy, D. and Breen, A. (1997) An Evaluation of Astronomical Observations in the Irish Annals, *Vistas in Astronomy*, 41, 117-138.

McCarthy, D. (1998) The Chronology of the Irish Annals, *Proceedings of the Royal Irish Academy*, 98C, 203-255.

- (2001) The Chronology and Sources of the Early Irish Annals, *Early Medieval Europe*, 10, 323-341.

- (2005) Irish Chronicles and their Chronology. 4th edition. Last updated: 21/03/05. www.cs.tcd.ie/Dan.McCarthy/chronology/synchronisms/Irish Annals-chron.htm

- (2008) *The Irish Annals: Their Genesis, Evolution and History*. Dublin: Four Courts Press.

McCormick, M., Dutton, P. E. and Mayewski, P. A. (2007) Volcanoes and the Climate Forcing of Carolingian Europe, A.D. 750-950, *Speculum*, 82, 865-895.

NRC – National Research Council (2006) *Surface Temperature Reconstructions for the Last 2,000 Years*. Washington, D.C.: National Academies Press.

Pearson, G. W., Pilcher, J. R., Baillie, M. G. L., Corbett, D. M., Qua, F. (1986) High-precision ^{14}C measurements of Irish oaks to show the natural ^{14}C variations from AD 1840 to 5210 BC, *Radiocarbon* 28 (2B), 911–934.

Pfister, C., Luterbacher, J., Schwarz-Zanetti, C. and Wegmann, M. (1998) Winter Air Temperature Variations in Western Europe During the Early and High Middle Ages (AD 750-1300), *The Holocene*, 8, 535-552.

Pilcher, J. R. and Gray, B. (1982) The Relationships between Oak Tree Growth and Climate in Britain, *Journal of Ecology*, 70, 279-304.

Pilcher, J. R., Baillie, M. G. L., Schmidt, B. and Becker, B. (1984) A 7,272-year Tree-Ring Chronology for Western Europe, *Nature*, 312, 150-152.

Robock, A. (2000) Volcanic Eruptions and Climate, *Reviews of Geophysics*, 38, 191-219.

- (2005) Cooling Following Large Volcanic Eruptions Corrected for the Effect of Diffuse Radiation on Tree Rings, *Geophysical Research Letters*, 32, L06702, doi:10.1029/2004GL022116.

Self, S. (2005) Effects of Volcanic Eruptions on the Atmosphere and Climate, In: Martí, J. and Ernst, G. G. J. (eds.), *Volcanoes and the Environment*. Cambridge: Cambridge University Press, 152-174.

Skinner, L. (2008) Facing Future Climate Change: is the Past Relevant? *Philosophical Transactions of the Royal Society*, 366A, 4627-4645.

Smyth, A. P. (1972) The Earliest Irish Annals: Their First Contemporary Entries and Earliest Centres of Recording, *Proceedings of the Royal Irish Academy*, 72C, 1-48.

Sweeney, J. (1997) Ireland, In: Mayes, J. and Wheeler, D. (eds.), *Regional Climates of the British Isles*. London and New York: Routledge, 254-275.

Turney, C., Baillie, M. G. L., Clemens, S., Brown, D., Palmer, J., Pilcher, J., Reimer, P. and Leuschner, H. H. (2005) Testing Solar Forcing of Pervasive Holocene Climate Cycles, *Journal of Quaternary Science*, 20, 511-518.

Zielinski, G. A., Mayewski, P. A., Meeker, L. D., Whitlow, S., Twickler, M. S., Morrison, M., Meese, D. A., Gow, A. J. and Alley, R. B. (1994) Record of Volcanism Since 7000 B.C. from the GISP2 Greenland Ice Core and Implications for the Volcano-Climate System, *Science*, 264, 948-952.

Zielinski, G. A. (1995) Stratospheric Loading and Optical Depth Estimates of Explosive Volcanism over the Last 2100 Years Derived from the Greenland Ice Sheet Project 2 ice Core, *Journal of Geophysical Research*, 100 (D10), 20,937-20,955.