National Development Plan 2007 - 2013

Environmental Protection Agency
An Ghníomhaireacht um Chaomhnú Comhshaoil

Climate Change Research Programme (CCRP) 2007-2013
Report Series No. 5

Extreme Weather, Climate and Natural Disasters in Ireland

SSTI
Strategy for Science, Technology and Innovation

Comhshaol, Oidhreacht agus Rialtas Áitiúil
Environment, Heritage and Local Government

Environmental Protection Agency

The Environmental Protection Agency (EPA) is a statutory body responsible for protecting the environment in Ireland. We regulate and police activities that might otherwise cause pollution. We ensure there is solid information on environmental trends so that necessary actions are taken. Our priorities are protecting the Irish environment and ensuring that development is sustainable.

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EPA Climate Change Research Programme 2007–2013

Extreme Weather, Climate and Natural Disasters in Ireland

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The EPA CCRP programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to climate change. These reports are intended as contributions to the necessary debate on climate change as it relates to Ireland.

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Executive Summary

The aim of this project was to collate historical, proxy and observational (recent) records, and analyse the information within this variety of sources for incidences of extreme weather events and natural disasters, which may give insight into the variability of climate in Ireland, and its impact on human society. The study focused on extreme weather conditions: historical analysis from the fifth through to the seventeenth century AD was derived from the Gaelic Annals of Ireland[1] and also from local and regional proxy data (e.g. tree rings and ice-core data). Observational data from the nineteenth century onwards was analysed to identify extremes in rainfall, winds, storms, floods and droughts.

Modern instrumental records show that both maximum and minimum temperatures are increasing across the island. In addition, there has been approximately a 10% increase in annual rainfall over parts of Ireland since the 1970s. This is considered to reflect a climatic shift during the mid-1970s, and this shift is also evident in other records, such as river flow and evaporation. There has also been an increase in extreme rainfall events since the mid-1970s. Again, this change is observed in some river flow records. These findings suggest that the current practice of calculating return periods from the longest possible datasets (including pre- and post-1975 data) may result in underestimates of storm and flood magnitude. This observation also suggests that the assumption of stationarity[2] (with regard to rainfall) is now questioned.

More than 50 bog burst or 'landslides' in peatlands have occurred since the early 1900s. These appear to have been caused by extremes in rainfall following dry periods and possibly compounded at times by human activities.

The analysis also shows the localised nature of some extremes, in the variation between the west and east of Ireland, and illustrates the difficulty of extrapolation of local results to wider areas.

Ireland's location and geography on the Atlantic fringe of Europe means that is influenced more by the North Atlantic circulation than continental influences. European climatic reconstructions and projections may have less direct relevance for Ireland than continental European countries. Rainfall and river flow changes can be correlated to changes in the North Atlantic Oscillation.

The current study was carried out to determine if historical records from the Annals could support evidence from other sources of regional climate forcing events. For example, reported extremes of cold found in the Annals correlate with volcanic eruptions evident from the Greenland Ice Sheet Project 2 (GISP2) core analysis. This shows the important contribution of volcanic events made to regional short-term cooling, due to the emission of aerosols. The GISP2 record shows that aerosol sulfate levels increased during the twentieth century because of air pollution levels similar to those recorded during a number of smaller volcanic eruptions. The associated cooling is considered to have masked greenhouse warming.

Documentary sources, such as the Annals, provide evidence for extremes of climate down through the centuries. The low event counts in many cases make it difficult to derive robust statistical measures. However, some results emerge – such as a decrease in reported extremes of cold in the late fourteenth and early fifteenth centuries; a lack of reported dry episodes during the ninth and tenth centuries; and a relative infrequency of wet episodes reported during the interval 1250 AD–1450 AD. The data remain qualitative and it is not yet possible to ascribe return periods to extremes identified in these sources.

It is impossible to go back in time and make instrumental observations of past weather and climate. To learn about past climate, it is necessary to look to those processes in nature which are affected by climate, and which leave

1 Ireland holds one of the oldest bodies of written literature of any European country. The most important sources are the Gaelic Irish Annals. These represent the accumulation of an annual chronicling of major local, national and international events by the educated elite in Ireland.

2 Stationarity is a term used in statistical analysis to describe a variable whose properties such as mean and variance are constant over time. In this case, engineers have assumed that the risk of an occurrence of a flood events was constant with time.

the signature of past climate in their structure. These natural indicators of climate are known as ‘proxies’. For example, the growing conditions over time determine the pattern of tree-rings for a given tree. Temperature and water availability are key weather parameters that influence tree growth, although other confounding factors such as pests and other damage also feature. Tree-ring chronologies from multiple locations offer a means of overcoming the localised nature of individual proxies. The ‘Belfast’ oak chronology dates back more than 7,000 years, and is derived from oaks from most of Ireland. Unusual growth patterns within a tree-ring chronology can be evidence for an extreme event with regional impact. Many, but not all, low-growth years found through tree-ring chronologies correspond with episodes of cold reported in the Annals. The probabilities of other severe, non-climatic, global or local natural disasters, although uncertain (e.g. earthquakes) are extremely low compared to weather extremes, even though their probable impacts may be high. While these proxy records allow frequencies of extreme events to be estimated, it is not possible to quantify the magnitude of such events. This cross-referencing between sources allows us to be confident that the records of unusual or extreme weather in the Annals are reliable. Whilst many are due to regional impact of volcanic activity, other records may indicate the natural climate variability during this period.

In November 2009, widespread flooding occurred across Ireland. It was the wettest November on record at many locations, leading to saturated catchments throughout the country. Flooding followed a wet day (19 November, with approximately 50 mm or more of rain for the 24-hour period in the south-west). Three catchments (the Shannon, the Lee and the Liffey) were affected significantly. With climate change, extremes of flooding may become more frequent. The losses incurred in 2009 may be repeated, unless extensive flood alleviation is implemented along with significant improvements in flood monitoring, forecasting and warning.

The main recommendations from this study include:

1. The establishment of a national repository for all data with potential for palaeoenvironmental reconstruction;
2. An examination of further early texts for weather-related references (e.g. the Annals) and a comparison of wind reports in the Annals to other proxies of environmental and climatic information;
3. A reanalysis of the Belfast tree-ring chronologies with the specific purpose of palaeoenvironmental reconstruction;
4. The digitisation and web dissemination of the remaining undigitised meteorological records;
5. An effort to collate instrumental data from dispersed, fragmentary sources such as weather diaries;
6. A systematic homogenisation effort of the best available instrumental series;
7. An acute need for a single national authority to control all river monitoring functions and make data available on public websites.

1 Introduction

1.1 Project Aims

The aim of this project was to collate historical, proxy and observational (recent) records and analyse them for incidences of extreme weather events, climatic shifts, and natural disasters. This was to identify, where possible, event magnitudes and frequencies (return periods), probabilities of occurrence, and impacts on society. This analysis provides insight into the level of climate extremes that Ireland had to cope with in the past.

The definition of an extreme event depends on the local reference distribution. In other words, events that would be classified as 'extreme' in one location might not be considered unusual in another. Very often, the degree of risk associated with a given event is also dependent on the local expectation or degree of preparedness. Storms of magnitudes sufficient to cause widespread disruption in the east of Ireland may be much more commonplace in the west. For this reason, spatial shifts in weather patterns or storm tracks are of particular interest, as they may introduce unexpected events to new regions. Seasonality is a further consideration. An event that is unexpected for a season may be considered as extreme, even though events of similar or even larger magnitudes may not be uncommon in that region in general during other seasons. One prominent example is the series of storms of August and September 1588, which included the storm on 21 September which destroyed much of the Spanish Armada off the coast of Ireland (Forsythe et al., 2000; Lamb, 2005, 2nd edition). Similarly, there were two large storms in August 1986. The first on 5/6 August mainly affected the west and south. The second on 25/26 August (the remnants of Hurricane Charley) affected the east with severe flooding in areas such as Bray, Co, Wicklow.

By definition, extreme events are infrequent, but are recorded throughout human history and have resulted in environmental and economic damage as well as loss of life (Jentsch and Beierkuhnlein, 2008). Extreme events can be defined in terms of their return periods calculated over long intervals, i.e. 10-year, 50-year, 100-year returns, or, for continuous variables such as rainfall intensities or air temperatures (a percentile such as 99%). Thus, a severe 24-hour rainfall can be described by either its return period (e.g. 50 years) or as a percentile (2%).

The general expectation is that climate change occurs gradually over a long time frame. However, a climatic shift can be described as a relatively abrupt transition in climatic conditions. For instance, annual rainfall amounts may increase or decrease from the previous long-term averages. Similarly, temperature may undergo a climate shift – such as a warming in winter or a cooling in summer. For instance, for the northern hemisphere in recent decades, there are indications of a poleward shift of storm tracks and a strengthening of the storm tracks north of Britain and Ireland. The transition time depends on the overall timescale of interest, but is generally short, i.e. over a 2–5 year period. A shift in a climatic condition brings a change in climate parameters, which are reflected in the statistical properties of data series for these parameters. Rapid climatic shifts, as well as individual events, can result in stress for ecosystems, agricultural systems, infrastructure and societies (Budyko et al., 1988). A meteorological extreme event as distinct from a climate shift can occur during a stable climate. For instance, the floods in Ireland in November 2009 and the cold in January 2010 are regarded as extreme events.

People affected by an extreme weather event (e.g. extremely hot summer in Europe in 2003; Cork floods in 2009; cold spell in Ireland in December 2009 and January 2010, which delayed the start to the growing season in Ireland in Spring 2010) often ask whether human influences on the climate are responsible. A wider range of extreme weather events is expected with an unchanging climate, so it is difficult to attribute any individual event to a change in the climate. Several factors usually need to combine to produce an extreme event, so linking a particular extreme event to a single, specific cause is problematic. Simple statistical reasoning indicates that substantial changes in the frequency of extreme events can result from a relatively small shift of the distribution of a weather or climate

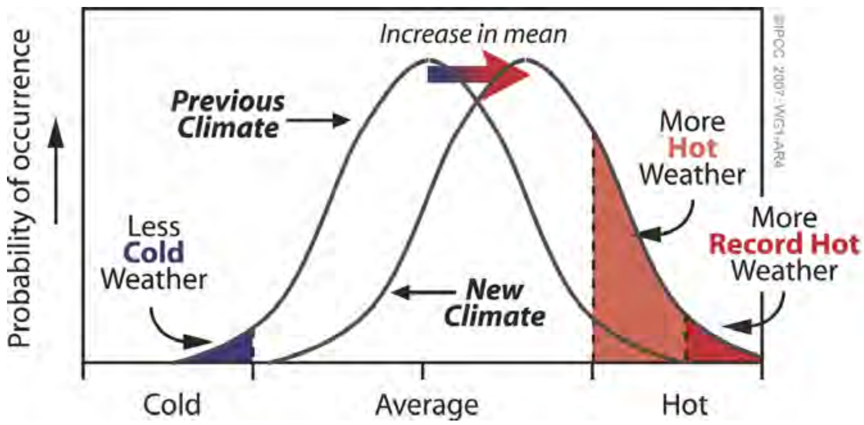

Figure 1.1. Schematic showing the effect on extreme temperatures when the mean temperature increases, for a normal distribution (Box TS.5, Intergovernmental Panel on Climate Change, Assessment Report 4: 53).

variable. Extremes are the infrequent events at the high and low end of the range of values of a particular variable. The probability of occurrence of values in this range is called a probability distribution function (PDF) that for some variables is shaped similar to a Normal distribution. Figure 1.1 is a schematic of such a PDF and illustrates the effect a small shift can have on the frequency of extremes at either end of the distribution. An increase in the frequency of one extreme (number of floods) will be accompanied by a decline in the opposite extreme (number of droughts) (Intergovernmental Panel on Climate Change [IPCC] Assessment Report 4 [AR4]).

A hazard is an event, or series of events, which has the potential to cause disruption, destruction, loss of life, loss of economic production and/or ecosystem function. The risk associated with such an event is often described as the product of the probability of occurrence of the event and the associated impact. High-impact low-probability events are the most damaging and difficult to deal with. In the context of this report, those extreme climate events that cause damaging impact on human society or activity are discussed. The term "natural hazards" encompasses a diverse range of phenomena associated with the natural environment, for example, floods, storms, landslides, tsunamis and earthquakes. The focus in this study is on climate-related hazards.

1.2 Approach

Three types of material were used in this study:

1. Historical records and literary references from approximately 400 AD (Chapter 2);
2. Proxy records from about 2500 BC (Chapter 3);
3. Observational records from 1800 to 2009 (Chapter 4).

These three categories possess very different temporal coverage, and resolution, and spatial resolution, density and reliability. The results are synthesised in Chapter 5.

Table 1.1. Date conventions.

Convention	Description	Main usage, notes.
BC/AD	Conventional Latin Anno Domini system	Instrumental, historical records
OS/NS	Old Style/New Style. Refers to variants of the BC/AD system caused by the change from the Julian to Gregorian calendar. NS is assumed unless otherwise indicated.	Historical records. In the OS, the new calendar year began on 25 March (this persisted until 1752 in England and her colonies). In NS the new calendar year begins on 1 January.
Years BP	(Uncalibrated) radiocarbon years before present	Palaeoenvironmental records. The reference year is 1950.
Cal years BP	Calibrated years before present	Palaeoenvironmental records. The reference year is 1950, and the raw radiocarbon age has been cross-calibrated by reference to independently dated sources.

1.2.1 Area and Time Period of Interest

This study is focused on the island of Ireland. The events themselves may be local to Ireland (e.g. floods, bog bursts, etc.); local to another region (e.g. volcanic eruptions) but with possible effects on Ireland; regional (e.g. large tsunamis); or global (e.g. changes in incoming global solar irradiance). The time frame is the period from about 2500 BC to the present. Table 1.1 summarises the standard dating convention.

1.3 Climate Forcing

Extreme events occur because of the natural variability within the climate system. The global climate system also responds to forcings that alter the planet's energy balance (Budyko et al., 1988; Kondratyev and Galindo, 1997). This includes natural forcing such as the long-term solar cycles (Milancovich cycles) which have caused major changes to the Earth's climate, such as Ice Ages. More recent climate forcing is linked to enhanced levels of atmospheric greenhouse gases such as carbon dioxide and particulate pollutants know as aerosols. These forcings are of concern because of both long-term shifts in climate and changes to the frequency and characteristics of extreme climate events, and their implications for ecosystems and socio-economic systems. Radiative forcing (RF) is a measure of the influence that a parameter has in altering the balance of incoming and outgoing energy in the Earth's atmosphere system, and is an index of the importance of the parameter as a potential climate change mechanism. Positive forcing warms the surface while negative cools the surface. Figure 1.2 compares the RF values for 2005 to pre-industrial time (1750). The combined RF from increases in CO_2, CH_4, and N_2O is +2.3 W m^{-2} and its rate of increases during the industrial era is very likely to have been unprecedented in more than 10,000 years. The CO_2 radiative forcing increased by 20% from 1995 to 2005, the largest change in any decade in at least 200 years. (IPCC, 2007)

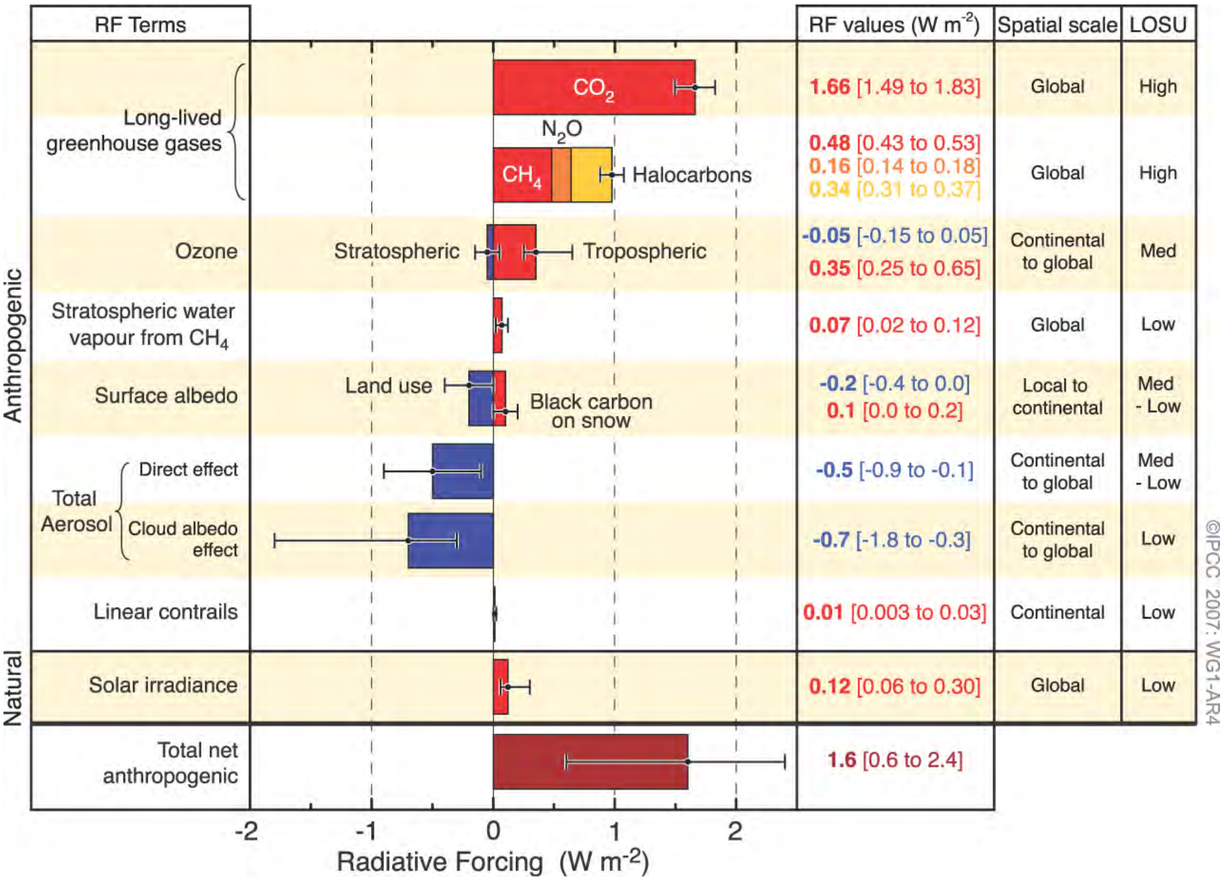

Figure 1.2. Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic CO_2, CH_4, and N_2O and other important agents and mechanisms, together with the spatial extent and associated level of scientific understanding (LOSU) (Figure SPM.2, Intergovernmental Panel on Climate Change, (IPCC, 2007). Summary for Policymakers: 4).

2 Historical Review of Extreme Weather

The potential for the reconstruction of past climatic conditions and weather extremes from the longest continuous written body of literature from Ireland, the Irish Annals, was investigated.[3] Direct references to episodes of extremes of cold, wind, precipitation and temperature were extracted. Indirect weather records or parameteorological phenomena such as floods and droughts in the Annals were also noted. Other than the Annals, other indigenous Irish sources with the potential for describing past climatic conditions and extremes of weather are limited. Newspaper articles have been also used to construct a storm chronology for Dublin (Sweeney, 2000). The use of documentary evidence, for the period prior to systematic observations of climate/weather parameters, requires careful consideration of contemporaneous factors and reports as well as the established provenance and critical reviews of the reliability of the record.

2.1 Historical Documentary Evidence of Extreme Weather

2.1.1 Available Historical Sources

Ireland holds one of the oldest bodies of written literature of any European country. The most important sources are the Gaelic Irish Annals. These represent the accumulation of an annual chronicling of major local, national and international events by the educated elite in Ireland. Recording was initially undertaken in monastic settings after the establishment of Christianity, but largely moved to secular schools of learning from the thirteenth century, with events recorded by professional hereditary historians (Mac Niocaill, 1975; Dumville, 1999; McCarthy, 2008). This move was precipitated in part by the twelfth-century church reform (O'Dwyer, 1972; Gwynn, 1992).

The most recent and extensive study of the Annals (McCarthy, 2008: 161) argues that 'a capacity for accurate chronicling in the most difficult of circumstances existed in an Irish monastic context by 538 AD and possibly before'. McCarthy bases this assessment upon a comparison of evidence from the Annals of major societal stresses (implied food shortage and disease) and coincident severe downturn in northern hemisphere tree-ring growth in the sixth century. The general reliability of later events recorded in the Annals can be determined by comparing them to major events and dates known from independent documentary sources within and external to Ireland (e.g. Byrne, 1967; McCarthy, 2000). This is further confirmed by the accurate recording of astronomical phenomena, such as solar and lunar eclipses, the dates of which can be reconstructed independently.

2.1.2 Past Investigations of the Annals

Numerous authors have reported records of weather extremes, related phenomena and associated societal impacts in the Annals (e.g. Meaden, 1975; Dixon, 1987; Mallory and Baillie, 1988; Rowe, 1989; Baillie, 1994, 1995, 1999, 2006; Kelly, 1997; McCarthy and Breen, 1997a, b; Sweeney, 2000; Pfister et al., 1998; Hall and Mauqouy, 2005; McCafferty and Baillie, 2005; National Research Council, 2006; McCormick et al., 2007; Down, 2008; McCarthy, 2008). As part of the *Census of Ireland, 1851*, Wilde's survey included records of weather extremes and unusual meteorological and natural phenomena. In 1878, a survey of relevant material in the Annals was published by Walford in the *Journal of the Statistical Society of London*, entitled 'The famines of the world: past and present'. The next major attempt to compile material from the Annals was by Britton, published in *Geophysical Memoirs* in 1937. Britton's main focus was on British and Irish sources and he adopts a critical stance in citing dates and sources. The next notable assessment of weather extremes in the Annals is by Dixon (1953, 1959). Rather than presenting a compilation of transcripts from the Annals, a more traditional essay is presented in which major extremes (e.g. storms) are listed by date, with some representative examples quoted. The most recent published catalogue of extremes and related phenomena in the Annals is by Lyons (1989). Table 2.1 gives examples that recognise a broad division between records of *direct* meteorological phenomena

3 See Appendix.

(e.g. rain, wind) or conditions (e.g. dry weather) and *indirect or proxy* phenomena, from which underlying meteorological conditions may be inferred (e.g. drought, frost, flooding, and, more indirectly, harvest yields and failures, fruit yields, scarcity, famine).

Table 2.1. Examples and categories of relevant records in the Annals (Four Masters).

Example text	Categories and dates (Corrected, Julian Calendar)
There was great frost in this year, so that the lakes and rivers of Ireland were frozen …	*Indirect (parameteorological) phenomena (frost and frozen water bodies). 700 AD.*
There was unusual ice and great snow in this year, from Christmas to Shrovetide.	*Direct (snow) and indirect (parameteorological) phenomenon (ice). Christmas is 25 December 817 AD. Shrovetide falls in January of 818 AD.*
A great wind on the festival of St Martin … caused great destruction of the woods in Ireland, and swept oratories … from their respective sites.	*Direct weather phenomenon (wind) with associated impacts (destruction of trees and buildings). The Feast of Martin is 11 November. 892 AD.*
The cornfields remained unreaped throughout Ireland until after Michaelmas, in consequence of the wet weather.	*Indirect (phenological) phenomena (delayed harvest) associated with a direct weather phenomenon (wet weather). Michaelmas is St. Michael's Day, 29 September. 1329 AD.*
Great dearth in this year, so that sixpence of the old money were given for a cake of bread in Connaught, or six white pence in Meath.	*Economic information associated with indirect phenomenon (dearth) subcategorised under famine and scarcity. 1545 AD.*
Intense heat and extreme drought in the summer of this year; there was no rain for one hour, by night or day, from Bealtaine to Lammas.	*Direct observations of meteorological conditions (heat, no rain) and indirect phenomenon (drought). Bealtaine is 1 May and Lammas is 1 August. 1575 AD.*

2.1.3 *Reliability of Evidence*

Even records contemporary to the events and phenomena they purport to describe must be assessed for reliability, in the context that other material supports the description. The interpretation of natural events and phenomena before the modern period generally employed explanatory frameworks based upon myth, folklore and religion, which, in the case of Christianity, described the origins and operation of the natural world. Studies of the perception of weather extremes and other natural hazards in the pre- and early-Modern periods are scarce (e.g. Janković, 2000; Kempe, 2003; Kempe and Rohr, 2003; Rohr, 2003, 2005; Given-Wilson, 2004). McCarthy and Breen (1997a, b) and Ludlow (2005a) have shown that many unusual events recorded in the Annals are explained by reference to modern knowledge of rare physical phenomena. This is not to imply that every record in the Annals is reliable. Some may be exaggerated, manipulated or fabricated according to the motives of scribes (or later copyists). Understanding the motives for the recording of natural phenomena can aid in identifying instances of potential unreliability. Based upon assessments of the astronomical records in the Annals, McCarthy and Breen (1997a, b) suggest that a primary motive for recording arose from the interpretation of astronomical phenomena (e.g. eclipses) as portents foretelling the coming of the Biblical Last Days. However, Ludlow (2005b) suggests that the desire to document weather extremes arose because, unlike the majority of astronomical phenomena, extremes often had an impact upon society (e.g. damage to crops, mortality of humans and animals).

Of concern in investigating changes in the frequency of extremes recorded in historical sources is the representivity of derived trends. For example, it may be that a period, in which fewer extremes are recorded, reflects not an actual decrease in the occurrence of extremes, but a decrease in available records of extremes. This might arise from the destruction of sources or a lack of interest in recording the information at that time. What is commonly observed is a decrease in the frequencies of extremes in earlier portions of reconstructions. This may reflect a paucity of available records as much as any real decrease in extremes.

Such issues may be investigated for the Annals once the digitisation of major texts by the CELT (Corpus of Electronic Texts)[4] project, University College Cork, is complete. This will allow a quantification of the number of entries (of all types, e.g. obituaries of important personages). This data is given in Figure 2.1, showing the combined number of entries available per year in

4 CELT, Ireland's longest running Humanities Computing project, brings Irish literary and historical culture onto the Internet. It includes a searchable online textbase consisting of 13.6 million words, in over 1100 contemporary and historical documents from many areas, including literature and the other arts.

seven major texts from 431 AD to 1649 AD.[5] The thick line is the 10-year moving average: each text ends on a different year and final pages are often lost to decay or interference, whilst in other cases scattered entries have been added through time. Though many entries are duplicated between the texts, each provides different densities of coverage in entries per year. The mean value for Fig. 2.1 is 29.5 entries per year (median 27, standard deviation 18.9). Because the available entries are not distributed through time evenly, the mean, median and standard deviation are unrepresentative for many periods. It is tempting to interpret the variation in Fig. 2.1 as reflecting the level of recording undertaken through time, with marked trends corresponding to known phases of Irish history (e.g. low but increasing numbers from 431 AD might represent the progressive establishment of Christianity and the spread of literacy among monasteries). This is, however, speculative as the seven texts from which the data is drawn have often abbreviated (or incorporated already abbreviated versions of) earlier texts, while material in unknown texts may not be incorporated in the surviving Annals. Because duplicates are not removed, a proportion of the variation in Fig. 2.1 is controlled by the number of texts providing coverage for given periods rather than the absolute number of records surviving for those periods.

5 (i) Annals of the Four Masters; (ii) Annals of Ulster; (iii) Annals of Inisfallen; (iv) Carew Fragment; (v) Annals of Tigernach; (vi) Annals of Loch Ce; (vii) Annals of Connaught.

2.2 Chronologies of Extremes from the Annals

It is possible to obtain chronologies of the combined records of extremes of wind, precipitation and temperature from the Annals. As noted above, these are derived from the seven major texts. Relevant records have been taken from the respective texts from about 431 AD to the date of their cessation around 1600. The differing meteorological origin and spatial extent of certain extremes also necessitates the exclusion of some records to allow a comparison of like with like (e.g. in the frequency of extremes per 50-year period). This means that the derived chronologies are likely to describe trends in events or episodes across Ireland rather than local events, for example in Munster. It is acknowledged that even large-scale synoptic systems (e.g. storms) may have a variable impact across relatively small geographical areas. This is highlighted by major storms such as the great 1703 AD storm that severely affected England (Wheeler, 2003) being felt only moderately in Ireland, while the 'night of the big

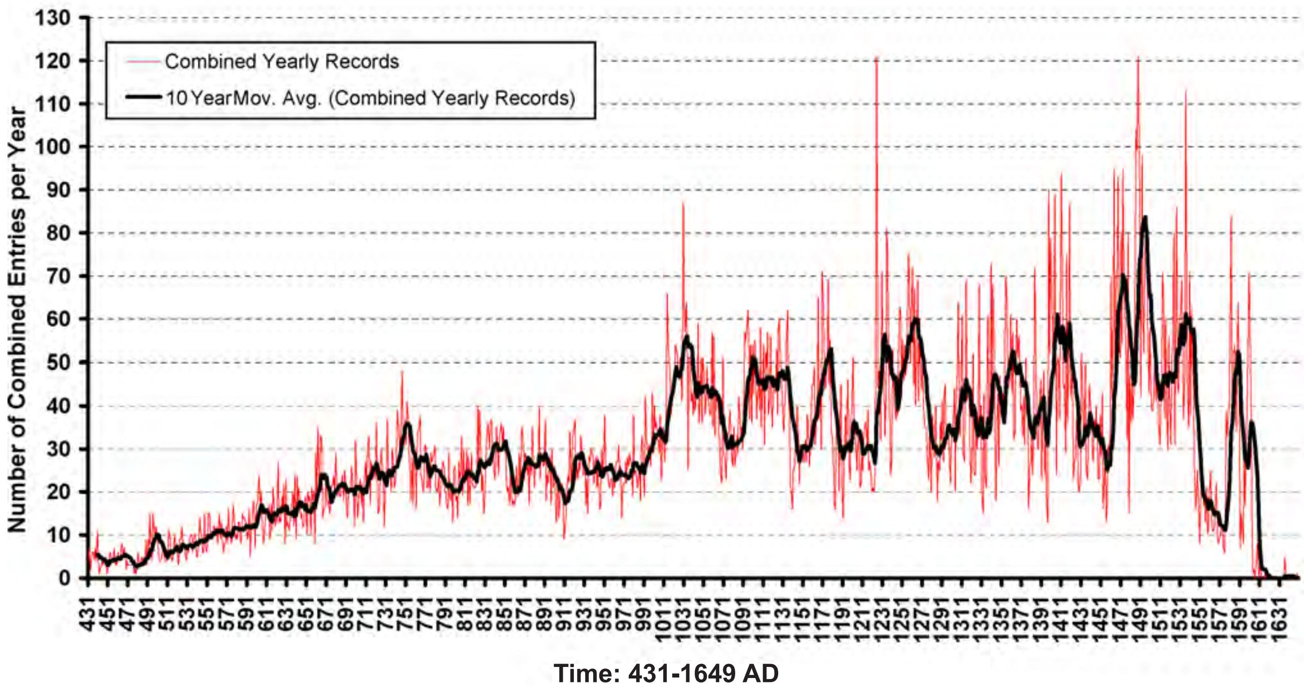

Figure 2.1. Combined available yearly records.

wind' in 1839 AD that strongly affected Ireland (Shields and Fitzgerald, 1989; Hickey, 2008) was felt with much less force in England (Lamb and Frydendahl, 1991).

2.2.1 Extremes of Wind

A composite chronology of extremes of wind derived from the seven major annalistic texts over the period 431 to 1649 is presented in Fig. 2.2. The frequency of extremes is provided per 50-year period in Fig. 2.2a and the deviation from the average in Fig. 2.2b. The median frequency of extremes of wind per 50-year period is 3. The problematic nature of averages derived from such time series is noted, with a low number of cases (i.e. low number of 50-year periods, with only 20 from 600–1599 AD) and the low number of extremes recorded per period (ranging from 0 to a maximum of 6). The averages may thus be sensitive to small changes in the number of recorded extremes and the selection time increment (e.g. 50- vs. 20-year periods).

2.2.2 Extremes of Precipitation

A composite chronology of extremes of precipitation from the seven major Annals, arranged in 50-year periods, is presented in Fig. 2.3. The frequency is shown of recorded wet events/episodes (in blue) versus the number of dry events/episodes (in orange). On four occasions, records included as dry events/episodes may be considered as indicating actual conditions of drought, while on one occasion a similar consideration applies to wet events/episodes. In the chronology of dry events/episodes, these four involve large rivers drying out for a specific period, namely, the Galway river (Corrib) on three occasions (i.e. 1178 AD, 1191 AD, 1462 AD) and once the River Liffey in Dublin (i.e. 1152 AD). However, the records do not include descriptions of drought to support a definite meteorological contribution. Several records describing notably hot summers are included, though these do not automatically equate with drought.

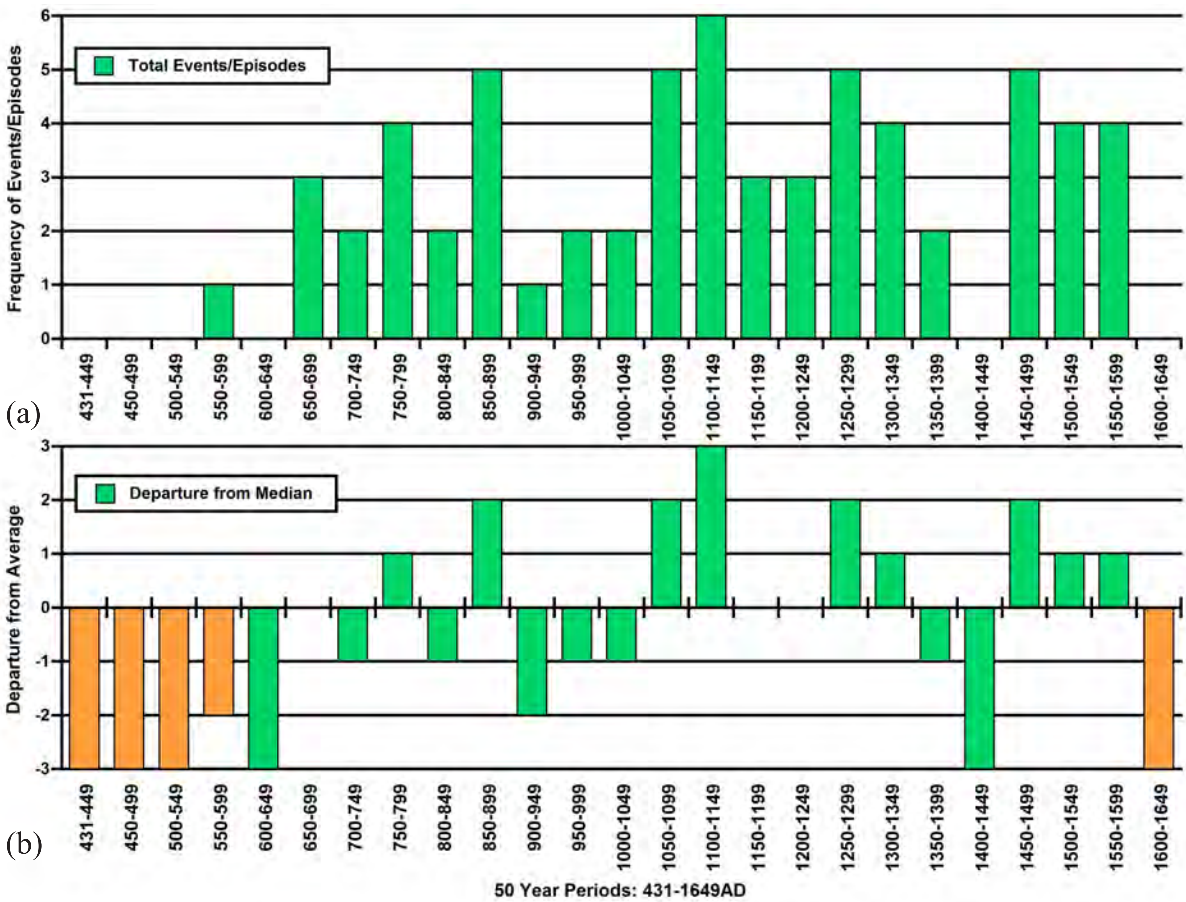

Figure 2.2. Frequency of wind events, 431–1649 AD . (a) total number of events per 50-year period with a median of 3 and (b) the deviation from the average.

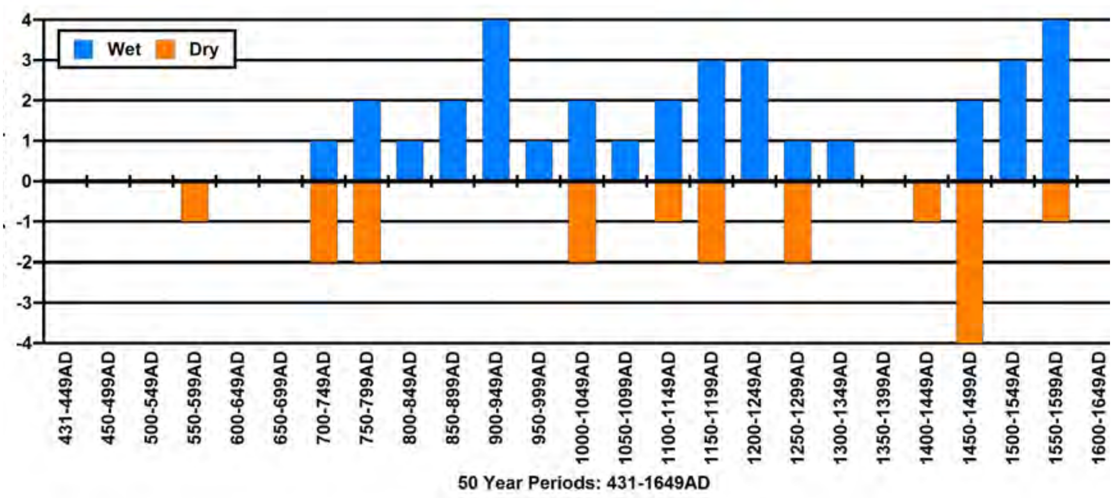

Figure 2.3. Frequency of wet/dry events/episodes, 431–1649 AD.

The frequency of wet events/episodes per period ranged from 0 to 4, with an average of approximately 2. The first reliably recorded extreme occurs in 700–749 AD and the number of recorded extremes varies from 1 to 2 per period until 900–949 AD, for which 4 extremes are noted. This is one of the highest observed values, matched only by one later period (1550–1599). The frequency continues to vary between 1 and 2 from 950–1149 AD, before increasing to 3 events/episodes per period from 1150–1249 AD. A notable aspect of the series is only 1 record for 1250–1349 AD and none from 1350–1449 AD. This marks one of the most sustained periods of below-average records. A steady increase in the number of events follows from 1450 AD, reaching a peak of 4 in the 1550–1599 AD period. This final peak corresponds to a period known for its series of cold and wet years across much of Europe owing to persistent low pressure centred over Scandinavia and much of North West Europe (Pfister, 2007). No event/episode is recorded for 1600–1649 AD, likely reflecting the fall in records generally available in this period.

2.2.3 Extremes of Temperature

For extremes of temperature (e.g. low temperatures, Fig. 2.4), the chronology comprises records from the Annals and several lesser texts and one non-annalistic source for 1601 AD (Stafford, 1633). A more extensive search for recorded extremes of cold can be found in the proxy Greenland Ice Sheet Project 2 (GISP2) ice core record of past volcanism and the Irish oak tree-ring record. The chronologies are broadly representative of the trends that would be apparent were all relevant records in the lesser remaining Annals included. This may be inferred from the relatively few additions to the chronology of extremes of cold from the lesser texts and the general small volume of these texts in comparison to the seven major texts.

Very few extremes of heat are recorded in the Annals. Cold events/episodes are well represented and more likely reflect the actual frequency of extremes of cold experienced through time, so a chronology derived from these has potential for further investigation in terms of statistical analysis. Extremes of cold are under-investigated in an Irish context; however, the Annals can afford the opportunity to test the response of biologically environmental proxies such as tree-rings to known extremes of cold. Spatial patterns of temperature also tend to vary less across larger geographical areas than do patterns of precipitation that are more prone to variation from local orographic influences (Croxton et al., 2006). Thus, recorded cold may be more representative of extremes experienced across Ireland as a whole. Figure 2.4 depicts 83 recorded direct and indirect proxy phenomena and observations from which low temperatures may be inferred for Ireland, arranged in 50-year periods from 431–1649 AD. Of the 83 recorded cold events, 47 (or 56.6%) are records of snowfall (often with descriptions of unusual depth, widespread geographical extent, and/or duration of snow cover). Twenty-seven (or 32.5%) are records of frost or ice on water bodies, while 9 (or 10.8%) are observations of generally cold conditions. Figure 2.4 shows significant variation in the frequency of extremes involving low temperatures through time. Figure 2.4

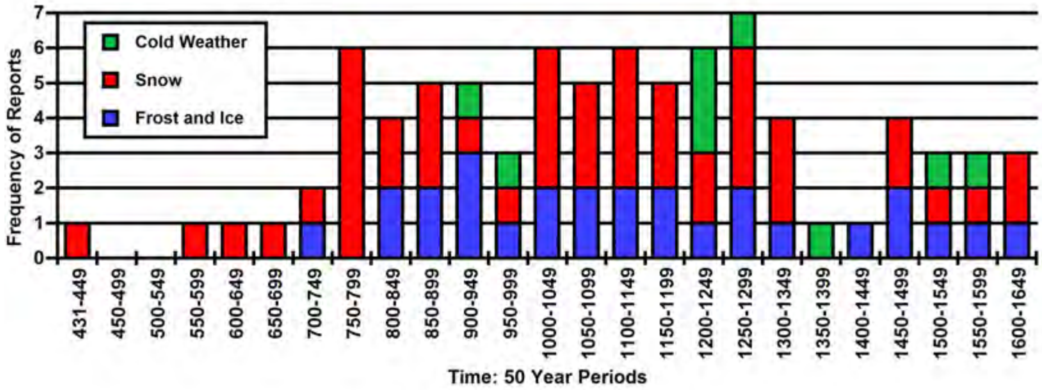

Figure 2.4. Recorded information from which low temperatures may be inferred.

therefore presents the frequency of individual episodes of cold (whether each involves several phenomena or only one). Chapter 5 presents an investigation of the relationship between extremes of cold reported in the Annals and Irish oak dendrochronological records, and a comparison of extremes of cold in the Annals to the record of Northern Hemisphere volcanic eruptions in the GISP2 ice core.

2.3 Conclusions

The Annals provide a unique and valuable record of the climate between 400 AD and 1649. Information from the Annals on extremes may offer more potential for understanding the nature of the climate signal in other proxies than a definitive record of climate. It can advance investigating the relationship between the incidence of extremes and the mean state of climate variables (i.e. precipitation) should an appropriate and sufficiently high-resolution record be developed as discussed in Chapter 5. The trends in extremes of wind, precipitation and temperature reveal potentially significant variations in Ireland's weather. Evidence from the Annals may be compared to or combined with information from proxies to improve understanding. It is recommended that a systematic review of the Annals and other sources be undertaken for extreme event related material.

3 Proxy Records

3.1 Introduction

Climate reconstructions are in part based on climate proxy data. Climate proxies are measured variables that can be used to infer climate attributes such as temperature, precipitation or storminess. Some proxy records, like oxygen isotopes in lake/cave deposits describe long-term trends in climate change, while others like tree rings and shipwrecks may represent single extreme events. Ireland's climate is strongly influenced by the Atlantic ocean. This creates markedly different climatic conditions to other European (continental) regions and makes the use of palaeo-climate data from outside Ireland unsuitable. The literature on Irish proxy data is reviewed under the headings: (i) temperature proxies; (ii) hydrological proxies; and (iii) landslides proxies. Shipwrecks as a proxy for storminess are also examined briefly.

3.1.1 Temperature Proxies

Biotic proxies include tree rings, sub-fossil insects and pollen. Sub-fossil insects have been used in palaeo-temperature reconstruction, especially to identify the late glacial/early post-glacial transition (i.e the end of the last Ice Age, and the beginning of the present period, e.g. Brooks and Birks, 2000; Coope and Lemdahl, 1995). Pollen data have also been used in several investigations of early Holocene environments in Ireland. For instance, Haslett et al. (2006) used pollen data from Glendalough, Co. Wicklow to calibrate a temperature reconstruction model based on Bayesian statistics.

Tree-ring widths have been variously used as a proxy to reconstruct past precipitation levels, temperature, volcanic activity and meteor impacts (Briffa et al., 1983; Baillie and Munro, 1988; Baillie et al., 2000). Tree-ring widths often correlate with both precipitation and temperature, but the correlation with precipitation appears more significant (García-Suárez, 2005). Isotopic measurements on tree cellulose generally reflect climate parameters more closely than ring width and may be more specific in its application (Loader et al., 1995). In locations such as Ireland, there is a very clear climate signal from tree-ring widths in stressed environments (high altitudes, northern forest margins, etc.) (Baillie, 1995). Some of the Irish temperature proxy records show a detailed picture, particularly of the step-wise progress of post-glacial warming. Among the Holocene temperature proxies, several records stand out for their accuracy, resolution and dating. Given the number of potentially excellent lake, cave and tree-ring-based archives available in Ireland, it should be possible in the future to produce enough well-dated, high-resolution temperature proxy records to achieve a comprehensive understanding of Holocene temperature change in Ireland.

3.1.2 Hydrological Proxies

In this context, 'hydrological proxy' is used to include palaeo-precipitation, surface water, water-table depth and flood indicators. In Ireland few natural archives have been identified that store palaeo-precipitation proxy data. Most Irish surface water proxy records have been generated through macrofossil, testate amoebae, humification, sub-fossil insect and peat stratigraphic analyses of raised bog sediments. Most of these proxies are thought to reflect the climate patterns of a number of years or decades rather than of a single growing season. This can be due to several factors, such as a lag time between climate and vegetation change or the structure and growth of raised bog systems, which accumulate plant material first in the 'acrotelm' (the aerated top layer of the bog above the water table). After some decades this material is incorporated into the permanently waterlogged substructure of the bog (the 'catotelm') where it is subject to much slower decay rates and is thus less influenced by later climate regimes. Most of the proxy records described here point to climate trends rather than specific extreme weather events.

Bog bursts, which may be caused by a combination of internal stress on the peat and high precipitation, have been separated successfully from climate signals (Bermingham and Delaney, 2005; Casparie, 2005; Geary and Caseldine, 2006). In two studies, in Derryville Bog, Co. Tipperary and Tumbeagh Bog, Co. Offaly, beetles produced important evidence for catastrophic bog bursts (Gowen et al., 2005; Bermingham and

Delaney, 2005). In both cases, the response of beetles to changes in the hydrology of the bog could be identified in changes in the composition of water beetle assemblages before and after the dated bog bursts (Reilly, 2005; 2006). However, the sample resolution of the insect assemblages was coarse so the changes observed might not have been recognisable specifically as bog bursts.

Tree-ring width, large-scale dying and germination events in oaks and the number of oaks found in lake and bog archives have been used as proxies for adverse and favourable hydrology affecting tree growth (Leuschner et al., 2002; Turney et al., 2005, 2006). Furthermore, runoff and erosion, as measured by magnetic susceptibility and other lake level indicators, may have been due to increased precipitation. However, runoff could also have followed from catchment deforestation and may thus be an ambiguous proxy signal. In the An Loch Mor and Lough Maumeen cores, climate change evidence could be separated from deforestation signals since landscape change was recorded independently through pollen analysis (Holmes et al., 2007; Huang, 2002). The first record shows low lake levels around 8300, 7500 and 7000 cal BP and rising lake levels from 6400 until *ca.* 5200 cal BP while the second indicates wetter conditions between 6250 and 6000 cal BP, as well as during the Little Ice Age.

3.1.3 Landslide Proxies

The destabilisation of sediments in mountainous areas may be caused by either extreme weather events or land-use changes. For example, it often occurs in the wake of human-induced deforestation. Ancient debris sometimes encases one or several lenses of peat that accumulated while there was no geomorphic impact on the find site. These peat lenses can be used to infer palaeo-environmental information. Macrofossils or bulk samples of extracted peat from such lenses provide a dating tool while pollen may inform on land use at the time of peat growth. The publications reviewed identify times with increased debris aggradation as coincident with cultural periods and deforestation. From the pollen records, it appears that the aggradation followed on from increasing intensive land use of the catchment, including deforestation. Changes in land use are shown by pastoral and in some cases arable indicator pollen. The authors of publications on geomorphic activity speculate that an interplay between land-use changes and extreme weather events such as big storms lead to downslope movement of destabilised sediments (Creighton et al., 2006). The periods of debris aggradation in the Macgillycuddy Reeks are partly based on the Gaddagh Valley record (Anderson et al., 2004) and partly on the Hags Glen, Glen Coomloughra and Curraghmore records (Anderson et al., 2000). Both these sources rely on only a few dates while the Mount Brandon record is based on 26 dates and the Upper Liffey Valley record on 18 dates. Conclusions overall must remain general as there are neither enough examined sites nor well-constrained dates to provide a firm link between sites, proxy climate and land-use evidence.

3.2 General Conclusions

While Ireland has many useful, high-resolution archives that have generated important proxy data of past climate trends and single extreme events, significant gaps – particularly in temperature proxy records – remain. While proxy records may record a single extreme event, such as a major storm or volcanic eruption, they seldom give an accurate picture of the amplitude of the event. Other proxy records may be useful to infer general trends of temperature and hydrology but their applicability may be limited in geographical and chronological terms.

Climate proxy research in Ireland is relatively new. Improvements in dating and analytical techniques help to develop the potential of such studies. Ireland's position on the Atlantic fringe of Europe makes it an important stage for climate research as both ocean and solar-mediated climate change hypotheses can potentially be tested. It is therefore important that the existing gaps in our proxy records are filled and the potential offered by tree rings, tephra and accelerated mass spectrometry (AMS), and wiggle-matched dating techniques, to produce high-resolution chronologies for multi-proxy climate records, are fully exploited. The current investigation of proxies notes that:

- There is a lack of temporally well-resolved, temperature proxy records (apart from tree rings, see Chapter 5). However, general early Holocene warming, subsequent cooling and variable temperature conditions in recent millennia may be inferred from existing records;

- There are common indications of wet periods from multiple hydrological proxies from multiple sites in some instances, including the periods 4450–4300 cal BP; 3500–3000 cal BP; 2800–2500 cal BP; 2000–1800 cal BP and 1600–1050 cal BP. Conditions appeared to be dry thereafter, followed by wetter periods around 850 cal BP and 200 cal BP. The 3500–3000 BP wet period coincides with an upsurge in the construction of wooden trackways in the midlands and with an increase in hillfort settlements, which may be due to the wetter conditions, although cultural influences cannot be ruled out;
- Analyses of other indicators such as documentary shipwreck records and aggraded sediments are complicated by strong confounding, non-climatic influences. For example, a large surge in reported incidence of shipwrecks in the second half of the nineteenth century is probably due to increased reporting frequency and may be unrelated to an independent record of storminess. In the case of sediments, shifts in cultivation practices (possibly in response to climatic influences) may be the strongest influence.

4 Observational Records

4.1 Introduction

Precipitation, temperature and wind speed records are available at 13 stations in the Republic of Ireland. Records date back to 1794 at Armagh. Other climatic variables – including radiation, soil temperature and barometric pressure, and, at some locations, evaporation – are more recently available at the synoptic stations. In the 1990s many of the stations were automated with new instrumentation. At that time, there were as many as 2000 daily rain stations around the country, although the number has been decreasing over the last two decades. River records at flow stations around the country do not have the same longevity as many of the rain stations, The river flow stations are managed by multiple agencies including: the Office of Public Works (OPW), the Environmental Protection Agency (EPA), the Electricity Supply Board (ESB), the county councils and others. Some are managed for flood flows while others for low flows.

4.2 The Era of Instrumental Weather Observations in Ireland

The era of regular, instrumental, meteorological observations in Ireland started in Armagh in 1794 with barometric pressure and wind direction (Hickey, 2003). Records commenced in Dunsink, near Dublin, around the same time (Butler et al., 2005). Various other meteorological quantities (e.g. soil temperature; García-Suárez and Butler, 2005) have been added since the commencement of the Armagh record. More stations began recording during the nineteenth century (Table 4.1), for example, the Botanic Gardens, Dublin in 1801, Valentia in 1860 and Birr in 1872 (Shields, 1987; Rohan, 1986). Not all the early records are digitised, which makes them difficult or impossible to analyse. Locations of stations are shown in Fig. 4.1 with details in Table 4.1.

4.3 Air Temperature

The regional patterns of increasing air temperatures during the twentieth century have also been noted in records from various stations in Scotland and Ireland. A combined Scottish–Northern Irish temperature time series found that 23 of the warmest months, seasons and years (out of a total of 51 series: 17 time series and 3 locations) in the period 1861–2002 have occurred after 1988. Wavelet analysis has shown that the temperature time series has a periodic component of a period of 7.8 years, corresponding to the period of the North Atlantic Oscillation (NAO) (Butler et al., 2005). Statistically significant increasing trends have been noted for twentieth-century annual and particularly March–May temperatures at Valentia, and annual and all seasonal temperatures, except December–February at Armagh.

The annual 99th percentiles of daily maximum and minimum temperatures for four Irish stations since the 1950s are shown in Fig. 4.2. There are clear increasing trends for maxima and minima. The rate of increase of the minima range is between 0.27 and 0.42 °C /10-year while the rate of increase of the maxima range is from 0.04 to 0.33 °C /10-year. The increasing trends were generally stronger for daily minimum temperatures

Table 4.1. List of selected continuous, long-term meteorological records in Ireland.

Location	Station type 2008	Current operator	Start date	End date	Values measured
Armagh	Automated	Armagh Obs.	1794	present	P, WD, Ts, SD, M
Birr	Synoptic	Met ÉÉireann	1872	present	P, Pr, Ta, SD, M
Galway	Daily	Met Éireann	1861	present	Pr, Ta, M
Dublin(Botanic Gardens)	Daily	Met Éireann	1801	present	Pr, Ta, M
Dublin (Phoenix Park)	Daily	Met Éireann	1829	present	Pr, Ta, SD, M
Valentia	Synoptic	Met Éireann	1860	present	Pr, Ta, P

P = Pressure; WD = Wind Direction; Pr = Precipitation; Ta = Air Temperature; Ts = Soil Temperature; SD = Sunshine Duration; M = More. See the Armagh Observatory website (http://climate.arm.ac.uk/) for a full description and Met Éireann's website (http://www.met.ie/) for the station names, types and records.

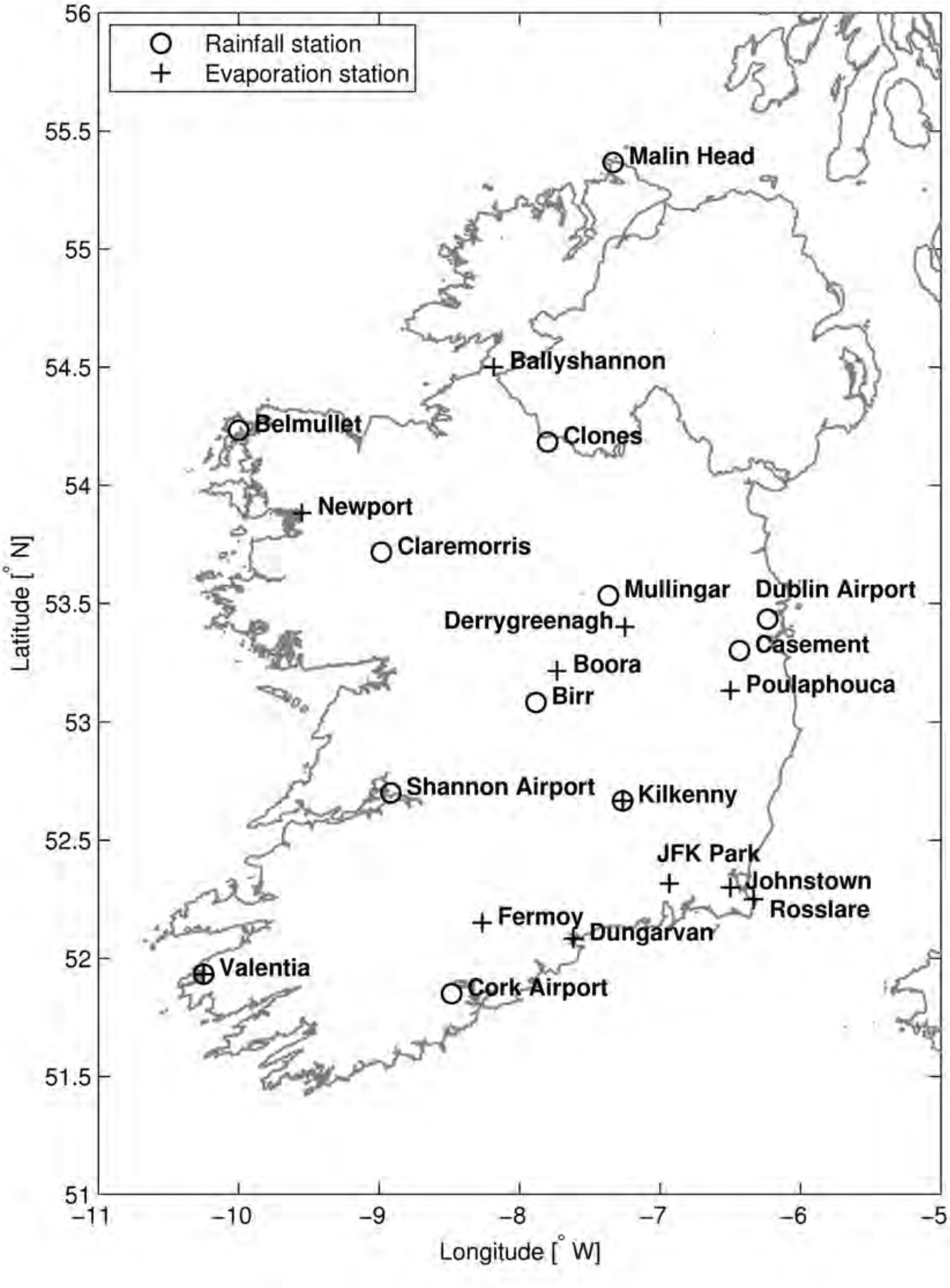

Figure 4.1. Locations of hourly synoptic (temperature, rainfall etc) stations and pan-evaporation used (from Met Éireann).

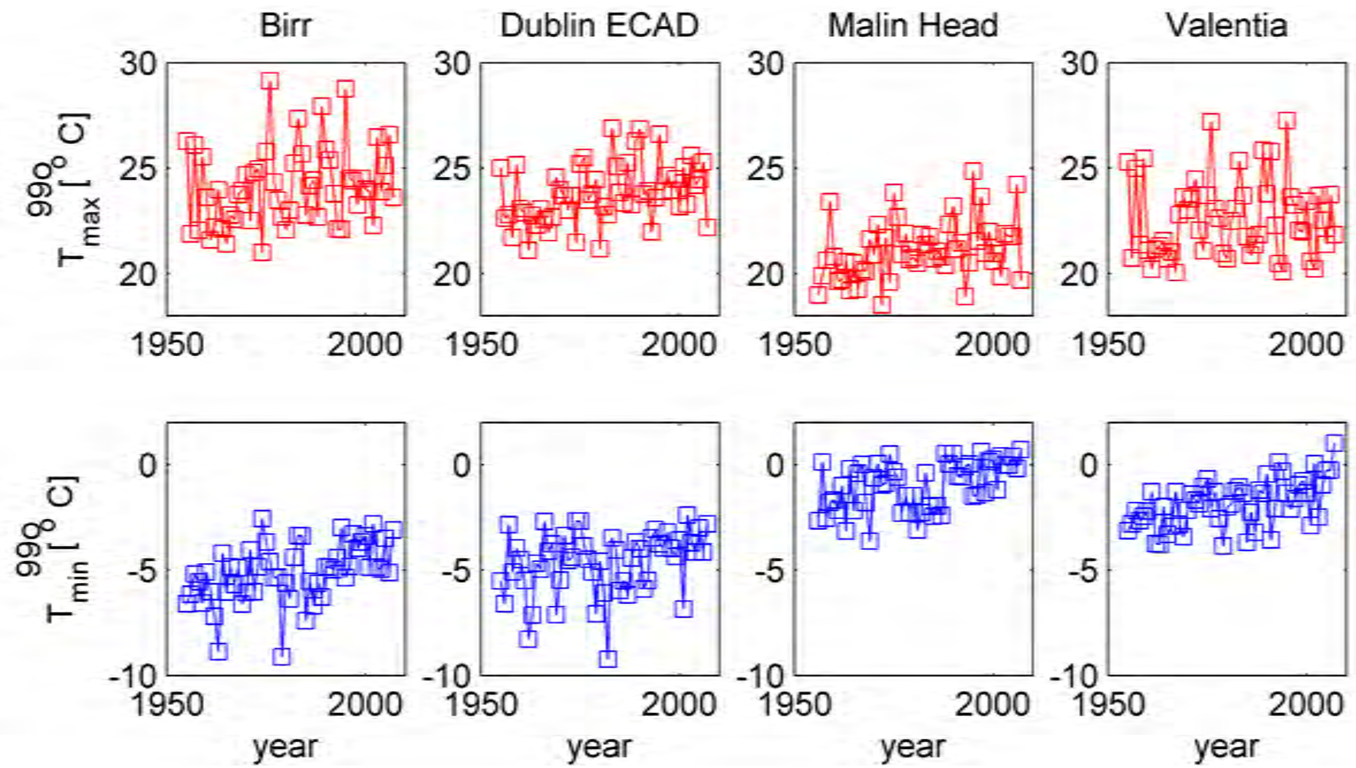

Figure 4.2. Annual 99th percentiles of daily maximum and minimum air temperatures from Birr, Dublin, Malin Head and Valentia.

(both means and extrema) than for daily maximum temperatures. This indicates a narrowing of the mean daily temperature range. Comparing the trends in annual means of daily minimum temperature and the 99th percentiles of daily minimum temperatures, it is noted that the increasing trends of the 99th percentiles exceed those of the annual means. This suggests a decrease in the likelihood of extremes of cold. The rate of increase of both the maxima and minima exceeds the rate of increase of the means, suggesting that the extremes are becoming more extreme.

4.4 Rainfall

The locations of hourly rainfall stations and pan-evaporation stations operated by Met Éireann are shown in Fig. 4.1. Hourly precipitation from the 13 synoptic stations were examined for: (a) interannual variability of total precipitation; (b) interannual variability of seasonal distribution; (c) hourly intensity; (d) frequency of wet hours; (e) intensity-duration-frequency (IDF) relationships. Significant increasing trends in total annual precipitation were found for the west coast stations of Belmullet (42.1 mm decade^{-1}), Valentia (48.2 mm decade^{-1}) and Malin Head (23.6 mm decade^{-1}) for the period 1957–2006. The year 2008 experienced the breaking of many rainfall records throughout the country (Lennon and Walsh, 2008). Met Éireann's 2008 annual weather summary stated: 'Annual rainfall totals were above normal everywhere and it was the wettest year for between six and 22 years generally, while Shannon Airport's total of 1270 mm was the highest at the station since it opened in 1945' (Met Éireann, 2009).

Met Éireann noted that 2009 was wetter than normal everywhere – annual rainfall totals were well above normal for the second successive year. They ranged from 981 mm at Dublin Airport to 2175 mm at Valentia (between 12% and 55% higher than the 30-year annual average amounts respectively). November was the wettest November since records began at most stations and the wettest of any month on record in several places. Annual totals were highest in over 50 years at Mullingar and Wexford, while at Valentia it was the highest since records began in 1866. The annual number of wet days (>1 mm per day) was above normal everywhere by between 10 and 20% generally, with 145 wet days in Dublin and 231 wet days at Valentia (Met Éireann, 2010; Smith, 2010). While the rainfall for the month of November 2009 was extreme, the 24-hour and 48-hour rainfalls immediately prior to the flooding of 19/20 November were not extreme.

Figure 4.3 shows the average precipitation anomaly over all Irish synoptic stations (from the 1961–1990 mean). An increasing trend line in the series can be seen. Annual rainfall series were analysed for change points, and there is strong statistical evidence (P >0.95) that change points in the annual total precipitation occurred for stations near the west coast: Belmullet, Claremorris, Malin Head and Valentia, with a transition to increased rainfall levels being evident. The change points were

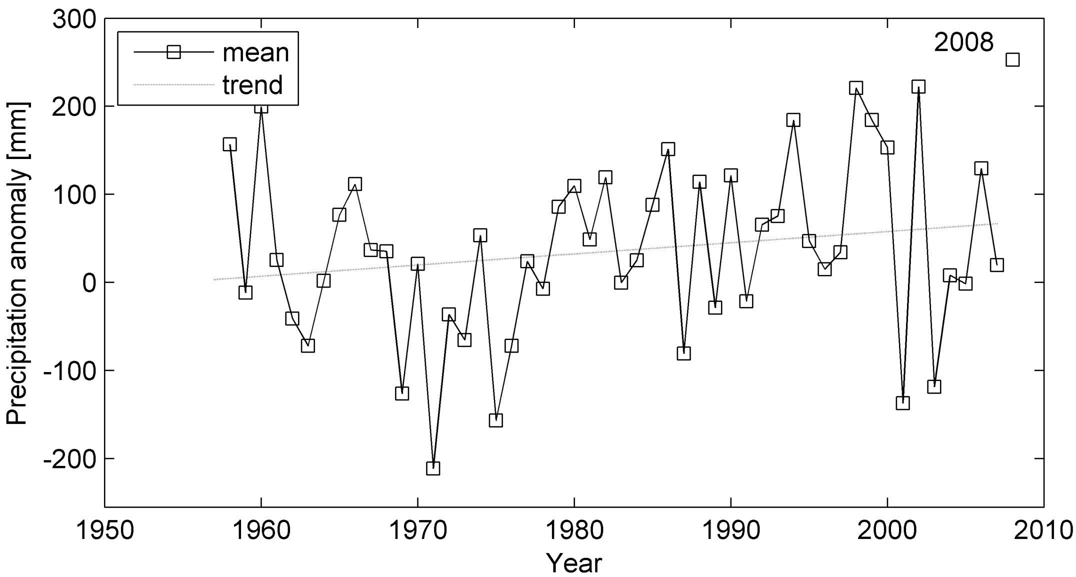

Figure 4.3. Total annual precipitation anomaly, arithmetic average over all stations.

shown to have occurred between 1975 and 1978, with the exception of Belmullet, where the change point was estimated to be 1983. A very high (*P* >0.99) probability was associated with the Belmullet and Valentia change points. No significant change points were detected for stations in the remainder of the country, nor for the Shannon station despite its proximity to the west coast. In general, most stations, particularly those in the east and south-east showed decreases in July rainfall after 1975, and all stations showed increases in the March and October rainfall.

This analysis extends that of Kiely (1999), who used rainfall data from synoptic stations up to 1995. It confirms an increase in annual precipitation amounts and in the occurrence of extreme precipitation events in Ireland, particularly in the west of the country, post-1975. The change to wetter conditions was coincident with a change in the seasonal pattern of the NAO. The change in the seasonal pattern of the NAO has also been noted by others (Werner et al., 2000; Visbeck et al., 2001). Most of the increase in annual precipitation was observed during the two months of March and October. Storm events at the Valentia station that had a 30-year return period before 1975 were estimated to have a 10-year return period after 1975. Furthermore, in a ranking exercise, it was found the seven highest annual Valentia precipitation totals for the entire record occurred after 1975, and the five lowest annual totals occurred before 1975.

Increasing rainfall amounts post-1975 suggest that the rainfall amounts are non-stationary. This is relevant as it suggests that the traditional methodology of analysing rainfall data based on the assumption of stationarity may no longer be valid. It is suggested that in determining rainfall amounts for particular return periods that the shorter post-1975 data set be considered rather than the longer datasets.

4.4.1 Storminess and Rainfall

To examine the variation in rainstorm magnitudes over the second half of the twentieth century, rain-event intensities were calculated over 1-, 3-, 4-, 6-, 8-, 12-, 18- and 24-hour intervals. For each duration, only unique (i.e. completely non-overlapping) events were considered. Following the approach of Willems (2000), in the cases of events of less than 12-hour duration, only events separated by a minimum of 12 hours were considered in order to ensure statistical independence. The top 20 events of each duration category were then selected and ranked by intensity. The total number of events falling into each time range (full time range, pre-1975 and post-1975) was tabulated. Intensity-duration-frequency curves were computed for several locations and compared across the three time ranges: (i) the full extent of the record; (ii) up to 1975; and (iii) after 1975. The IDF relations were then calculated for return periods of 10 years and 30 years. The partial duration series (PDS) approach was used to calculate event magnitudes for several return periods (Madsen et al., 1997). A generalised Pareto (GP) distribution was fitted to the observed distribution of extreme values over a defined threshold, I_0. The threshold was determined by sorting the partial series in descending order by magnitude, and by truncating the partial series at 2.7 times the number of years in the series of observations under consideration. The threshold value is the final value in the truncated series (Kiely 1999). The method of moments was used to estimate the GP distribution parameters. The IDF analyses showed an increase in storm event magnitude for return periods of 10 and 30 years at many, but not all, stations after 1975, when compared to pre-1975 (Figure 4.4). However, for many stations these increases were small (<5 mm) at all durations.

The IDF analysis of the Valentia observations shows that storm events (of 12-hour duration or longer) with a 10-year return period in the post-1975 record are of similar magnitude to events with a 30-year return period in the record up to 1975. A similar change is evident at Dublin Airport after 1975. By contrast, the IDF relationships for Malin Head remain almost unchanged after 1975 and there is little change in the Belmullet or Casement IDFs, despite the latter station's proximity to Dublin Airport. Rainfall in the north-west of the country is the most strongly influenced by the pattern of the NAO.

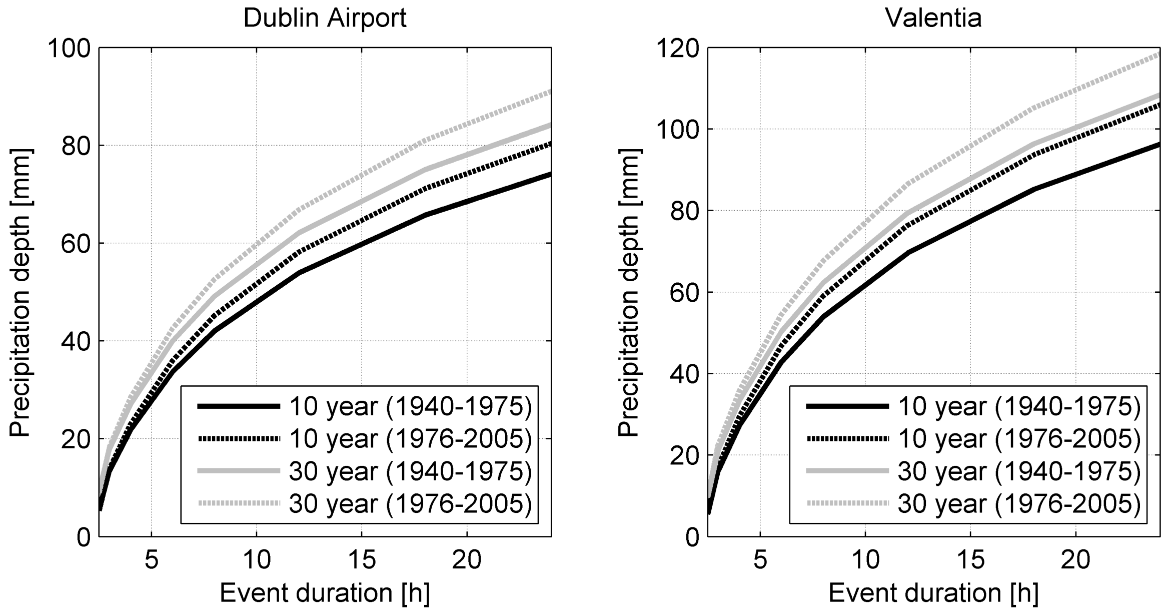

Figure 4.4. 10-year and 30-year intensity-duration-frequency (IDF) relationships for Dublin Airport and Valentia before and after 1975. It is noted that for the higher storm durations (>12 h) the precipitation depth for the 30-year storm (pre-1975) is similar to the precipitation depth for the 10-year storm (post-1975).

4.5 Evaporation

Stanhill and Moller (2008) recently reported evidence for the enhancement of the hydrologic cycle over Britain and Ireland with the general increase in pan-evaporation since the mid-twentieth century. Findings from the current research confirm this result, and also investigate these trends on a seasonal basis and examine the spatial variability. Pan-evaporation is a reasonable approximation of actual evapotranspiration, as surface moisture availability is rarely a limiting factor in the Irish climate. Total annual evaporation, averaged over all stations that satisfied data-coverage requirements (Ballyshannon, Boora, Fermoy, Johnstown, Poulaphouca, Rosslare and Valentia), shows a significant negative trend of -14.6 mm decade^{-1} between 1967 and 2006. Statistically significant positive linear trends, indicated by the F-test of the fitted trend line, were found for two stations in the south-east: Johnstown (35.0 mm decade^{-1}) and Rosslare (32.9 mm decade^{-1}). Significant negative trends were found for the Ballyshannon (-14.4 mm decade^{-1}) and Poulaphouca (-33.1 mm decade^{-1}) stations. Change point tests of the annual evaporation time series from Valentia revealed change points at the end of 1974 and 1976 respectively, with a probability greater than 0.99. This change point is coincident with the change point in the Valentia annual precipitation series. The evaporation change points were more spatially heterogeneous than the precipitation change points, revealing different change points in annual totals in different parts of the country. In general, stations far from the west coast such as Boora, Derrygreenagh, Dungarvan, John F. Kennedy Park, Poulaphouca and Kilkenny, all displayed significant change points from either or both tests. Most of these change points were detected around 1990. However, it should be noted that the relatively short evaporation records, most of which date back only to the 1960s, make it more difficult to detect a change point in the mid-1970s reliably. Statistically significant trends were observed in the annual series of monthly pan-evaporation from several stations.

4.6 Droughts

Low rainfalls in 1976 and 1995 in particular produced droughts in Ireland (MacCarthaigh, 1996). During the 1976 drought, most stations recorded negligible rainfall for 60 consecutive days up to early September. Although an examination of the rainfall records shows that the 1976 drought was more prolonged than that of 1995 in most of the country, river flows at the end of the 1995 drought were comparable to those measured at the end of the 1976 drought. MacCarthaigh (1996) noted that groundwater generally begins to recede in early Spring and the trend of the recession is largely unaffected by subsequent rainfall in late Spring and Summer. A subsequent long period of negligible rainfall, ending in September, produced exceptionally low river flows.

4.7 River Flows

River flows for the three rivers (The Suir, The Nore, The Fergus) were examined with results for The Suir shown in Fig. 4.5. It was found that the annual, March and October means all showed an increase particularly after the change point years of around 1976. The trends coincide with the increases in precipitation over the latter quarter of the twentieth century.

4.8 Winds

In Ireland, extreme winds are generally caused by large-scale mid-latitude depressions. These typically pass to the west or north of the country, tracking easterly or north-easterly (Logue, 1989). Surface wind speeds are usually measured close to 10 m height and thus the long-term records may be unaffected by changes in the surface roughness from development or tree growth. Two studies combining observational and instrumental records of high wind events in Ireland showed an increase in storm occurrence in Dublin and Armagh during the 1970s and 1980s, and a decrease thereafter (Sweeney, 2000; Hickey, 2003). These studies also noted that trends of storminess in the last three decades of the twentieth century were spatially variable, with locations in the north-west of the country (Belmullet and Malin Head) registering an increase, and stations in the north-east and south-west (Armagh and Valentia) registering a decrease. In an analysis of wind data from 1953–1987, a fall-off in extreme winds in the period after 1975 was observed, which was ascribed to a decrease in the occurrence of extreme windstorms (Logue, 1989). Bengtsson et al. (2006) noted that there are indications of a poleward shift of storm tracks – a reduced frequency of Mediterranean storm tracks and a strengthening of the Atlantic storm tracks north of Britain and Ireland – which is consistent with the trends noted in local precipitation time series (e.g. Kiely, 1999; Serrano et al., 1999). However, the impact of this poleward shift has yet to be studied for Ireland.

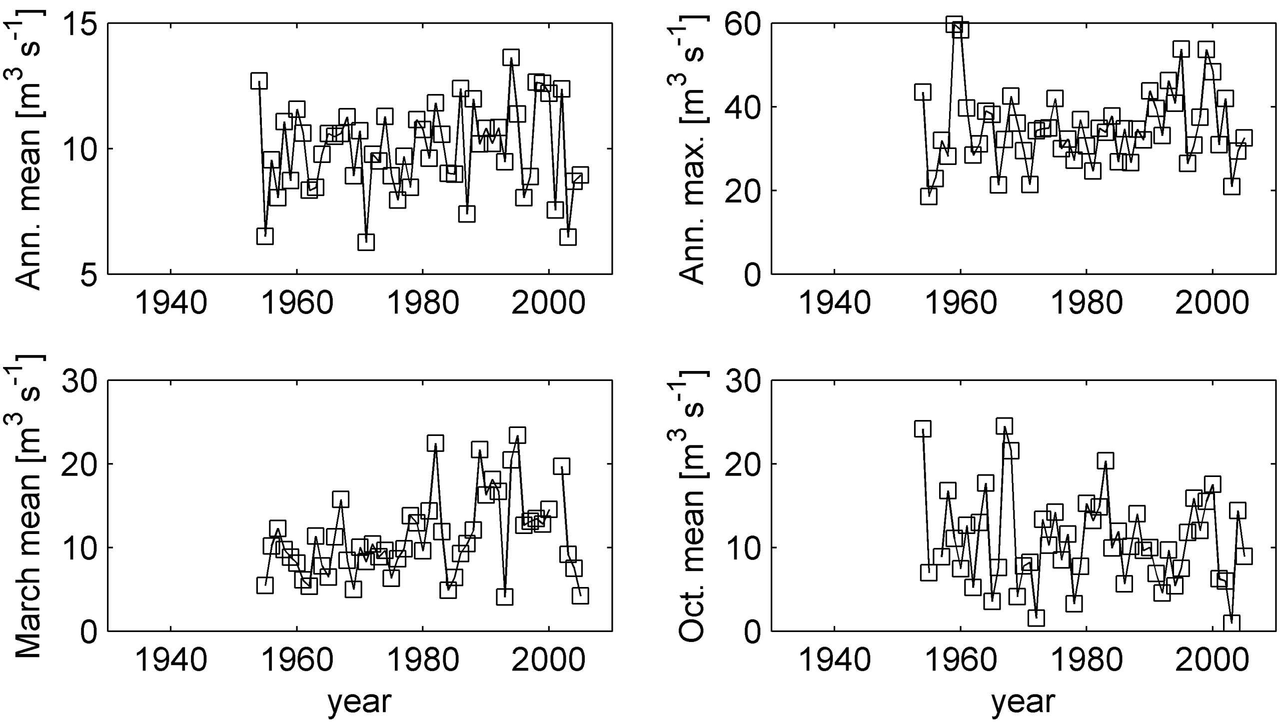

Figure 4.5. Annual mean, maximum, March mean and October mean flow for The Suir at Newbridge.

4.9 Landslides and Bog Movements

Shallow landslides occur relatively infrequently in upland areas and can have long-lived geomorphological effects and shorter-lived, local environmental impacts (Dykes and Warburton, 2008). Work has recently been undertaken to catalogue known incidences of landslides in Ireland (Creighton et al., 2006). Almost 50% of landslides in Ireland occur in peatland areas, and such events typically occur in the months of July and August, in areas between 300 and 500 metres in elevation and of 4–10 degrees in slope (Fleming, 2009). Bog slides of upland blanket peat are of particular interest in Ireland, given the extent of surface peat cover in these areas, and the potential for human fatality, fish kills and damage to infrastructure. Extreme rainfalls, particularly following relatively dry periods, and human disturbance such as cutting, digging of drainage channels or construction activity are often cited as contributing factors (Creighton et al., 2006; Dykes and Warburton, 2008). Past bog movements can be inferred from presently visible surface geomorphological features (Feehan and O'Donovan, 1996) or may occur as dating anomalies in other palaeoenvironmental studies due to lateral transportation of material resulting in older material overlying new (Caseldine and Gearey, 2005). 'Dry shifts' in hydrological proxies in peat may be the result of bog bursts rather than shifts in environmental conditions (Stefanini, 2008). Intact peatland margins provide the structural integrity of peatlands against failure as the margins contain peat of higher density and lower hydraulic conductivity than peatland central areas.

4.10 Conclusions

An increasing trend in annual minimum temperatures since the second half of the twentieth century was indicated by the 99th percentile of daily minimum values suggesting reduced frequencies of cold episodes. Two stations in the east and midlands also exhibit increasing annual maximum temperatures over the same period. An increased annual and seasonal rainfall (particularly March and October) since 1975 was observed in the instrumental record. Precipitation IDF analysis shows that at several recording stations there has been an increase in extreme rainfall events since the mid-1970s, with the 30-year rainfall event pre-1975 similar in magnitude to a 10-year event post-1975 at some locations. Corresponding trends were found for some river flows. These changes in winter precipitation receipt and storminess are correlated with large-scale changes in the NAO. Increasing and spatially variable trends in pan-evaporation have also been observed in the records from the second half of the twentieth century, with stations in the south-east recording strong positive trends in pan-evaporation during the summer months. Given the conditions of the 1976 drought, the combination of increased evaporation and reduced precipitation in the south-east during the summer is a cause for concern.

5 Synthesis

This chapter combines documentary (Annals) with proxy (GISP2 ice core and Irish oaks tree-ring) analysis. Firstly, spatial correlations in instrumental data are examined to determine the spatial extent of events.

5.1 Global and Regional Extremes Trends in Meteorological Time Series

Trends in globally averaged climatic values are not always reflected at the regional scales. Shifts or trends in mean conditions do not imply corresponding changes in extremes.

5.1.1 Temperatures

The global average air temperature increased for most of the twentieth century. The series of record-breaking mean surface air temperatures in the period 1990 to 2009 is unprecedented in the modern, instrumental era and is unlikely (P <0.001) to occur by chance in the climate system. This result can be derived from several different reanalysis datasets and is consistent across global and regional (including European) scales (Zorita et al., 2008).

5.1.2 Precipitation

In Europe, the last 50 years have been the wettest of the last 500 years, in terms of total annual precipitation (TAP) (Pauling and Paeth, 2007). Annual precipitation totals in the Northern hemisphere midlatitudes showed an increasing trend in the twentieth century. In a recent reanalysis of records of rainfall records from 689 stations in the United Kingdom, Maraun et al. (2008) found positive trends in the occurrence of heavy precipitation in winter and spring storminess. Lamb (2005, 2nd edn) noted an increase in the frequency of large storms and low pressure systems over Ireland and Britain since 1950 and suggested a link with trends in sea surface temperature. Lozano et al. (2004) noted a shift in the seasonal wind climate around the same time, with a regional pattern of more severe winters and calmer summers emerging in the middle to late twentieth century, apparently linked to a poleward shift in the trajectories of North Atlantic cyclones. Recent work using regional climate models (RCMs) has shown that the development of extratropical cyclones in the North Atlantic in the future may be influenced by changes in atmospheric stability in the region, and that changes in sea surface temperature (SST), a control on cyclone intensity, may be moderated by a weakening of the thermohaline circulation (Semmler et al., 2008).

5.2 Comparison of Annals Information with Proxy Data

An important step in making use of the weather and related information from the Annals is its comparison to other environmental and climatic proxies. It is worth determining whether other proxies corroborate the Annals. In combination with other sources, the annalistic record has the potential to advance understanding of Ireland's weather and climatic extremes. This may be particularly useful for biological proxies that respond to a number of interacting environmental influences, including weather and climate. This section presents a preliminary comparison of the Annals record of cold episodes to the GISP2 ice core record of volcanism and the Irish oak dendrochronological record.

5.2.1 Core Records of Volcanic Forcing

An association between volcanic eruptions and unusual weather has long been considered. Volcanic eruptions have been confirmed as a source of climatic perturbations. Some eruptions have only minimal, localised or short-term climatic effects, a recent example being the 1980 AD Mount St Helen's eruption in the western USA (Robock, 1983). Others have significantly larger (e.g. hemispheric or global) impacts upon climate, with up to three years being the most commonly cited duration. An historic example is the 1815 AD Tambora eruption in Indonesia that caused the European 'year without a summer' in 1816 AD. Records of atmospheric sulphate deposition (as SO_4) in high resolution and precisely dated ice cores can extend the known record of historic volcanism millennia into the past (Zielinski, 2000). One of the most important ice cores for the Northern Hemisphere is the GISP2 ice core, completed on 1 July, 1993. The record of SO_4 deposited in annual layers of ice is available at a biannual resolution for the GISP2 across the period matching the Annals. Work has shown that the SO_4 record in the GISP2 is

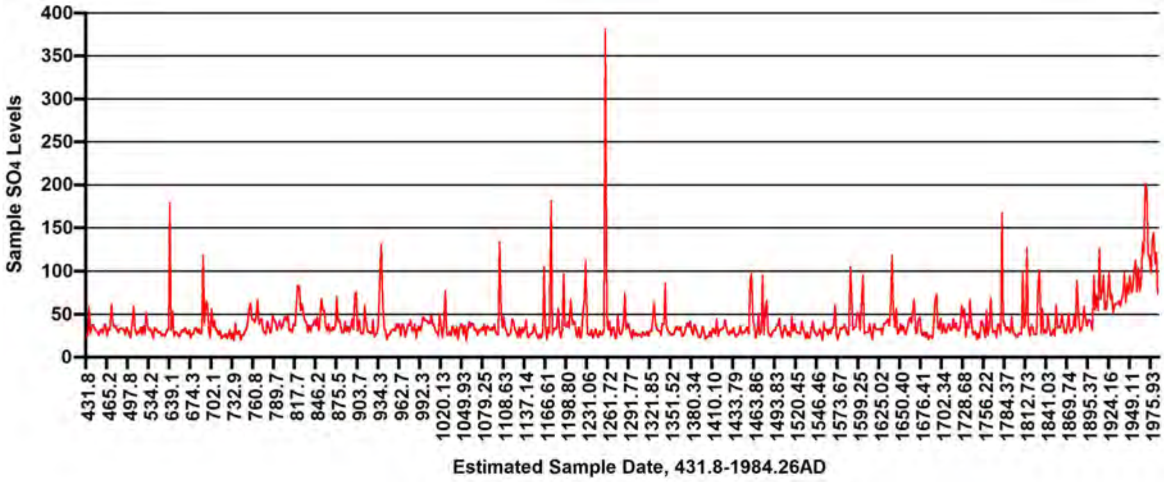

Figure 5.1. Greenland Ice Sheet Project 2 (GISP2) sample SO4 levels, 431–1984 AD.

representative of a background of sulphate (e.g. from continental dust sources, Legrand, 1997) and also from equatorial and Northern Hemisphere volcanic emissions (Zielinski et al. 1994; 1996).

The SO_4 record from the GISP2 core is presented in Fig. 5.1 for the period 431 AD to 1984 AD along with its distribution in Fig. 5.2. The core is of sufficient resolution and accuracy to compare to the Annals. Background SO_4 levels above zero may be observed in all cases, along with significant spikes indicative of volcanic eruptions. The largest visible spike, dated to 1257 AD, reaches an SO_4 level of 380.6 ppb, the highest value observed for several millennia. Ironically, the location and identity of this volcano remains unknown (Stothers, 2000; 2003), but other known eruptions such as the Laki fissure eruption (1783–1874 AD) in Iceland are clearly identifiable in the core (Zielinski et al., 1994). The trend towards increased SO_4 concentrations seen to begin shortly before the twentieth century is attributed to anthropogenic activity (Mayewski et al., 1993) and is clearly visible and can disguise volcanic signals. An association between eruptions registered in the GISP2 and several episodes of cold recorded in Ireland has been recognised by McCormick et al. (2007) in the eight, ninth and tenth centuries AD. Here, a simple approach was adopted. The sample SO_4 levels >45ppb are taken as potentially representing deposition from explosive (and hence more likely climatically effective) volcanism. The mean SO_4 level for 431–1648 AD is 36.9

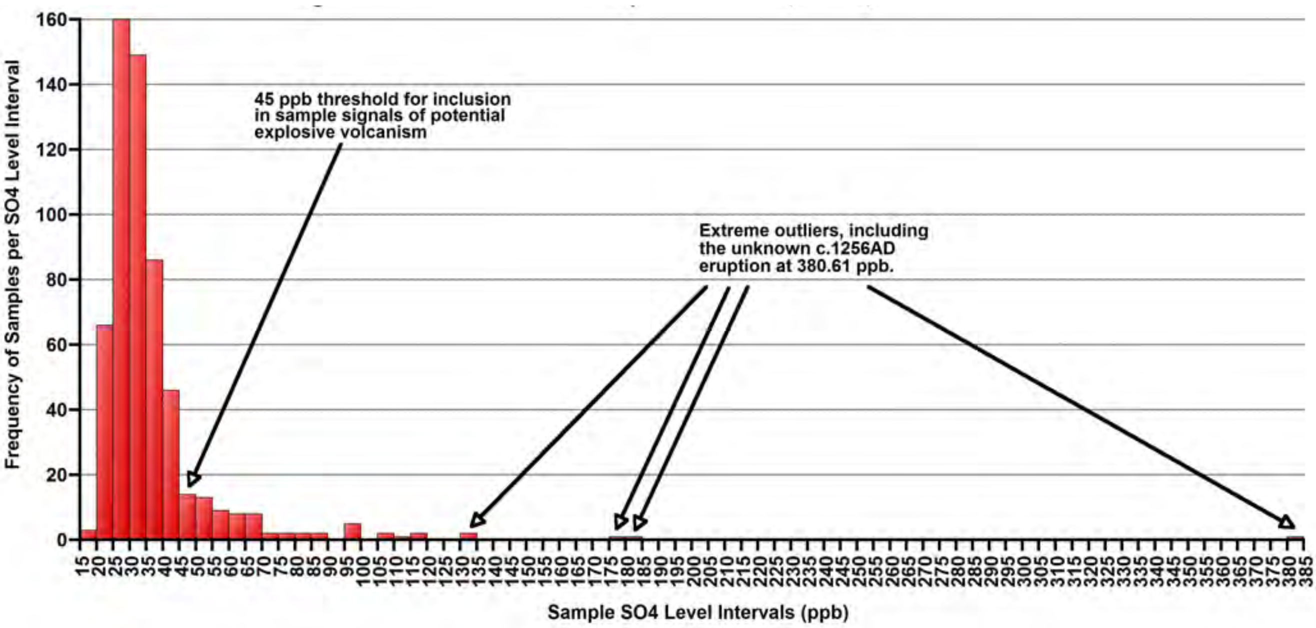

Figure 5.2. Distribution of sample SO_4 levels, Greenland Ice Sheet Project 2 (GISP2), 431.8–1648.3 AD.

ppb and the standard deviation is 22.4 ppb. However, the distribution of SO_4 levels shown in Fig. 5.2 is skewed by the presence of relatively few very large values (most likely resulting from major explosive eruptions).

A 45 ppb threshold is chosen in light of the skewed character of the distribution and to avoid omission of signals representing eruptions that may have been climatically effective in the Northern Hemisphere. This threshold distinguishes 75 samples from the 585 available for 431–1648 AD and discards 87.2% of the available samples. The value of 75 is comparable to the 65 recorded cold episodes in the Annals over the same period.

The SO_4 dates are taken as indicating a potential correspondence between an explosive eruption and an unusually severe cold in Ireland. In Fig. 5.3, of the 75 relevant GISP2 SO_4 samples, 29 (or 38.7%) correspond to 1 or more dated episodes of cold in Ireland. Conversely, of the 65 episodes of cold, 26 (or 40%) correspond to 1 or more of the 75 relevant GISP2 samples. This is a significant observation and highlights the role of volcanism in forcing episodes of extreme cold (and associated phenomena, such as heavy snow and prolonged frost) in Ireland.

5.2.2 *Irish Oak Dendrochronological Records*

5.2.2.1 Background

Investigation of the potential for dendrochronology on the island of Ireland began in a concerted manner in the 1970s with Baillie in Queen's University, Belfast (e.g. Baillie, 1988) focusing on the tree-ring widths of sessile and pedunculate oaks (*Quercus Petraea* and *Quercus Robur*, respectively). Both species are native to Ireland and were found to be suitable for the construction of long dendrochronological records because of their longevity, clear annual rings and a general absence of problems with missing, partial or false rings that caused difficulties with the construction of long tree-ring width series from other species. The availability of modern living oaks, timbers from historic buildings and archaeological sites, and still older preserved sub-fossil oaks from peat bogs, lake margins and river gravels meant that overlapping chronologies of ring widths could be anchored in time to the present and extended into the prehistoric period. Efforts in chronology construction culminated in the creation of an unbroken 7,272-year oak tree-ring chronology for Western Europe, comprising a series from the North of Ireland, Britain and Germany, complementing each other (Pilcher et al., 1984). For dendroclimatic studies attempting to utilise tree-ring chronologies to infer past climate conditions, or reconstruct annual temperatures or precipitation, very high levels of replication are required to minimise local climatic or non-climatic influences (Jones et al., 2009). The possibility for oak chronologies in Ireland and Europe to allow quantitative reconstruction of annual temperature and precipitation was investigated in the 1970s and 1980s (e.g. Briffa et al., 1983a, b). A significant problem with the use of Irish oak ring widths relates to Ireland's maritime climate. An example of the complex relationship of oak growth to climate is provided by an observed strong negative growth response to warm Irish winters.

There is evidence that Irish oaks reflect, via notably depressed growth, many environmental and climatic disturbances such as the reputedly volcanically induced 'year without a summer' of 1816 AD (Baillie, 1995). Whether oaks consistently register similar responses to cold episodes as recorded in the Annals (many also probably induced by volcanic eruptions), is unknown. Although severe cold and frost are known to stress oaks (e.g. Thomas et al., 2002), for these to have a notable effect, it is probable that they must occur during the growing season (i.e. April to September/October).

5.2.2.2 Comparison with Documentary Sources

Here, a simple comparison of the Irish dendrochroniligical oak research and studies of the Annals is presented, with a focus on recorded cold episodes. The oak record used for comparison is a standardised index chronology provided by Baillie, Queen's University, Belfast. This chronology comprises multiple-site chronologies from Ireland, in which mean tree-ring widths are smoothed statistically by application of a 30-year tapered cubic spline, and vary about a long-term mean of 100. This removes long-term trends of non-climatic origin, arising, for example, where the chronology comprises young trees tending to exhibit wider (i.e. early growth) rings. Two periods for which episodes of recorded cold are pronounced (i.e. 750–799 AD and 1250–1299 AD, each with six episodes)

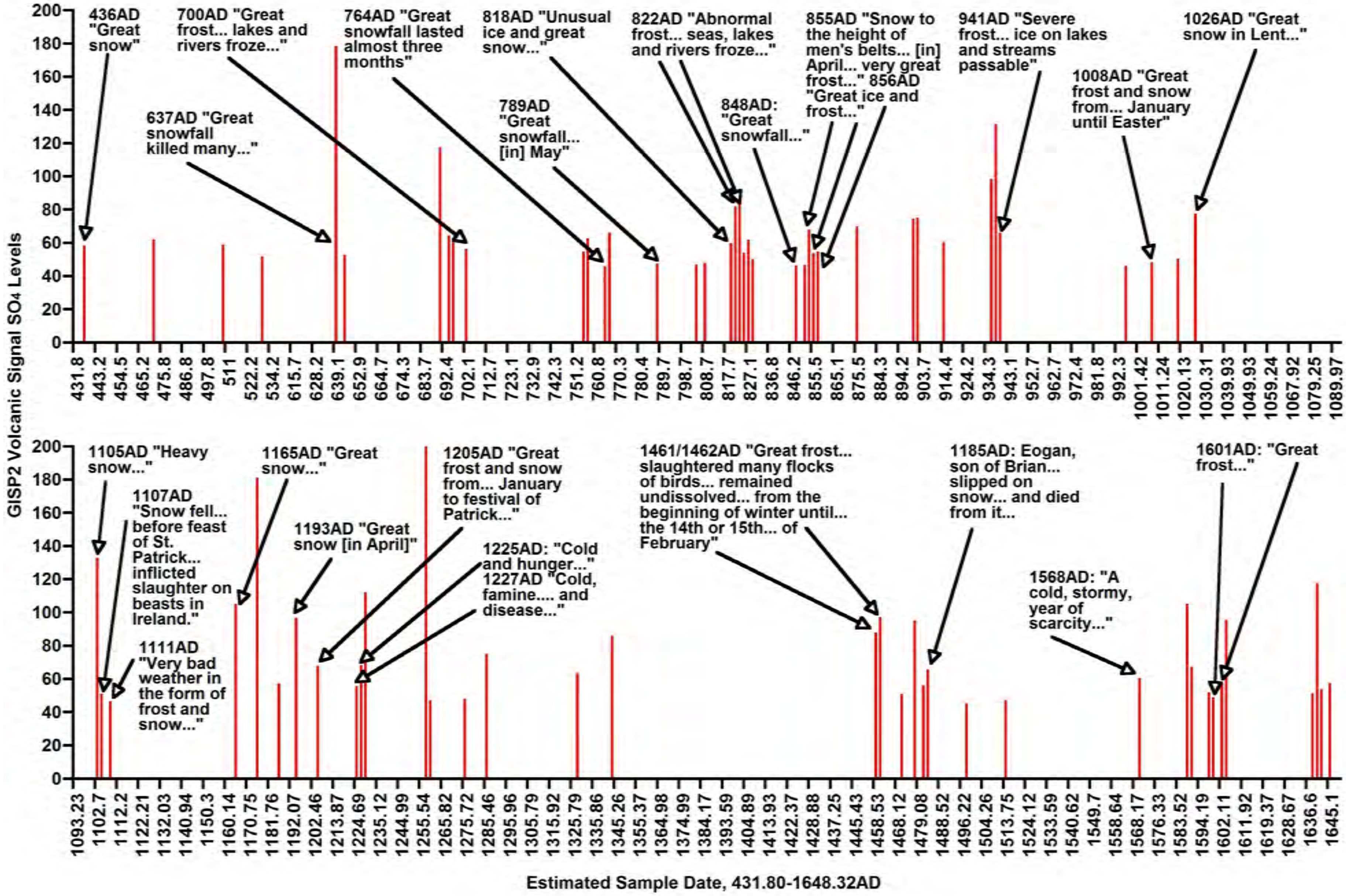

Figure 5.3. Greenland Ice Sheet Project 2 (GISP2) sample SO4 volcanic signals and associated cold episodes, 431–1648 AD

are extracted from the overall index chronology. For 750–799 AD, the mean of the extracted index values is 101.5, standard deviation 9.9, minimum value 83.0. For 1250–1299 AD, the mean is 99.8, standard deviation 8.9, minimum value 80.0. Figure 5.4 presents each indexed ring width value per period as a departure from the respective mean, with horizontal lines marking departures equalling or exceeding 0.5 and 1 standard deviation below the mean.

For 750–799 AD, 25 of the 50 indexed ring width values are below the mean. Eight (16%) are 1 standard deviation (SD) or further below the mean. Allowing a margin of 3 years following the date of recorded cold, wherein any growth below the average is deemed a potential match, then all 6 dates of cold in the first period (760, 762, 764, 780, 789, 799 AD) correspond to observed index values below the mean. Of the 18 years for which growth is at least 0.5 SD below average, 7 (38.9%) correspond to recorded cold within the margin set out above. The relevant years of cold are 760, 764, 780, 789 and 799 (or 5 of 6 years with recorded cold episodes for the period). Of the 7 years for which growth is at least 1 SD below the average, 2 (28.6%) correspond to recorded cold within the allowed margin (the relevant years of cold being 780 and 789 AD). Similar results are observed for the 1250–1299 AD period. All 6 recorded cold episodes (1251, 1270, 1271, 1280, 1281/1282, 1296 AD) correspond to years of below average ring growth.

Of the 14 years for which growth is at least 0.5 SD below average, 28.6% correspond to a date of cold (1251, 1270, 1271, 1280 and 1281/1282 AD, 5 of the 6 recorded dates of cold in the Annals). Of the 8 years where growth is at least 1 SD below average, 37.5% correspond to recorded cold for 1251, 1271, 1280 and 1281/1282 AD. From this simple analysis, it may be tentatively proposed that episodes of cold may be registered by the Irish oaks by decreased averaged growth of at least 0.5 SD below the average. It is also clear that more years of notably depressed growth exist than there are recorded episodes of cold. This may imply that not all such episodes are recorded in

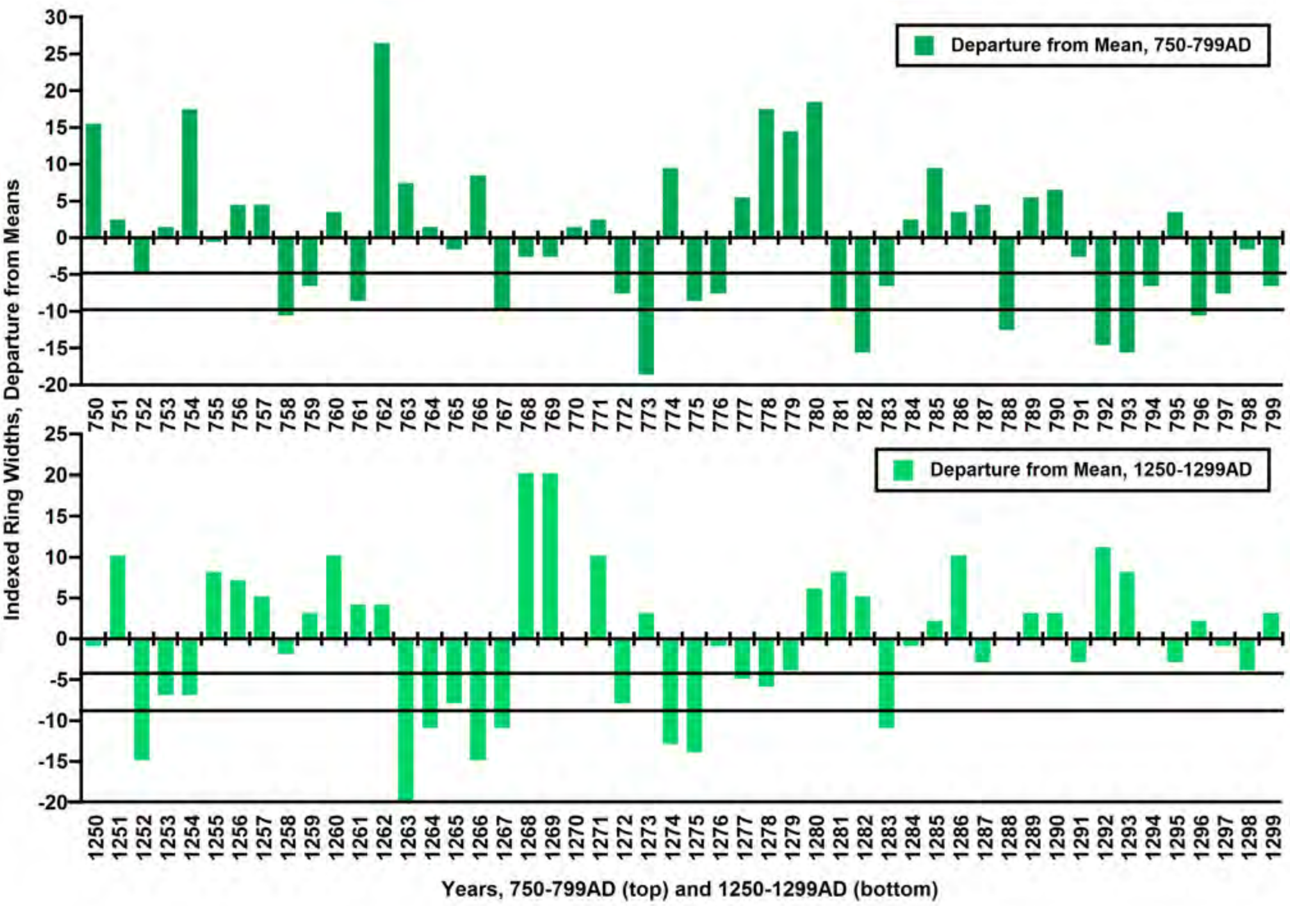

Figure 5.4. Indexed ring widths, departures from means, 750–799 AD and 1250–1299 AD.

the Annals. However, numerous other factors may be proposed to explain reduced oak growth, some of which are non-climatic, such as pest outbreaks or the deliberate coppicing of trees for human consumption of oak timbers, known to produce reduced tree-ring widths in many species in following years (Rackham, 1990). Of the potential additional climatic factors, extremes of precipitation (wet and dry) are a further potential influence, as are storm events where branches are torn from trees, potentially inducing growth decreases as seen after coppicing.

5.3 Conclusions

- Annual rainfall extremes, extracted from multi-year series as 99th percentile amounts are far more spatially variable than daily precipitation amounts. While the 50% decorrelation distance for annual rainfall in Ireland and Britain is approximately 240 km, the annual 99th percentiles of daily rainfall are correlated by less than 50% over all distances. This illustrates the localised nature of extremes, and the benefit of considering multiple, spatially distributed proxies when possible.
- There is a correspondence between incidents of reported cold in the documentary evidence (Annals) and the record of explosive volcanism (with consequent cooling effects) from the GISP2 ice core.
- Tree-ring chronologies from multiple locations offer a means of overcoming the localised nature of individual proxies. Many, but not all, low-growth years from the ‘Belfast’ oak chronology, derived from oaks from most of Ireland, correspond with episodes of cold reported in the Annals.
- More than 50 bog burst or ‘landslides’ in peatlands have occurred in the past century. They are the results of extremes in rainfall following dry periods (sometimes associated with human activities) and have led to loss of human life as well as extensive ecosystem degradation.

6 Conclusions

6.1 Summary Conclusions

While this study has used a comprehensive reference list of over 70 published and unpublished proxy climate indicators for Ireland, it is still apparent that because of the localised nature of most of the indicators, extrapolation to regional scales is difficult. ‘Colder’ or ‘wetter’ periods may be identifiable from the known records, but individual events are harder to discern, and ascribing magnitudes to either events or climatic shifts is not currently possible. However, some overall conclusions can be made from the proxy sources, particularly with respect to hydrological changes. Nevertheless, there are enough well-dated records in the dataset to gain an impression of past hydrological conditions in Ireland. Periods of increased wetness emerge from records between 4450 and 4300 cal BP, between *ca.* 3500 and 3000 cal BP, between 2800 and 2500 cal BP, around 2000 and 1800 cal BP and between 1600 and 1050 cal BP, particularly around 1400 cal BP. After a drier interval, conditions become wet again around 1100 cal BP, and again at 850 and 200 cal BP. The temperature proxies hint at warming in the early to mid-Holocene and some cooling and more unsettled conditions in recent millennia, but they have insufficient temporal resolution to cross-check records against each other or to provide information on changes at the decadal or even centennial scale. However, the ‘Belfast’ tree-ring chronology does provide an opportunity to examine summers of lower than average temperatures, several of which have been observed to correspond with episodes of reported cold in the documentary evidence, as well as the ‘year without a summer’ following the Tambora eruption in 1815.

Documentary sources offer the potential for isolating individual extreme events, particularly cold episodes, but long-term trends or patterns may be difficult to isolate because of changes in record density over time. From a statistical comparison of documentary evidence of cold events in the Annals and the record of volcanic events from the Greenland GISP2 core, of 65 reported independent cold episodes, 40% correspond to large volcanic signals in the GISP2 ice core. This result, combined with the widely reported ‘year without a summer’ in 1816, following the Tambora eruption illustrates the influence of remote volcanic events on summertime temperatures, and consequently on agricultural productivity in Ireland. As noted above, the Annals suggest evidence of dry events/episodes involving the drying of large rivers, namely, the Galway river (the Corrib) on three occasions (i.e. 1178 AD, 1191 AD, 1462 AD) and once the River Liffey in Dublin (i.e. 1152 AD).

Results from a comparison of the documentary and dendrochronological evidence are less conclusive. Several years of reduced oak growth correspond with recorded cold episodes in the Annals, but any relationship may be at least partly disguised by autocorrelation in the oak chronologies. To improve confidence between the records, more robust methods of comparison should be sought and over longer time scales.

6.2 Key Findings

- From the documentary sources (the Gaelic Annals) there is much evidence for extremes of climate through the centuries. The data is qualitative and it is not yet possible to ascribe return periods to extremes events. A proportion of cold events in the Annals is linked to volcanic events.
- From proxy records (e.g. Belfast tree rings, GISP2 ice core record) frequencies of extreme events can be ascribed, but it is not possible to quantify the magnitude of events.
- The instrumental record since about 1950 (e.g. temperature, rainfall, wind), which is extensive and of high quality, is our best quantitative source and is managed by Met Éireann. Very few digitised data sets exist prior to 1950. River records prior to 1980 are sparse and in the case of many rivers, the data is of questionable quality. From the instrumental record it can be noted that:
    - ◊ The annual 99th percentiles of daily maximum and minimum temperatures show clear increasing trends for maxima and minima. The rates of increase of the minima range between 0.27 and 0.42 °C /10-year while the rate of

increase of the maxima is lower and range from 0.04 to 0.33 °C /10-year. The increasing trends were generally stronger for daily minimum temperatures (both means and extrema) than for daily maximum temperatures. This indicates a narrowing of the mean daily temperature range. Comparing the trends in annual means of daily minimum temperature and the 99th percentiles of daily minimum temperatures, it is noted that the increasing trends of the 99th percentiles exceed those of the annual means, suggesting a decrease in the likelihood of extremes of cold. The rate of increase of both the maxima and minima exceeds the rate of increase of the means, suggesting that the extremes are becoming more extreme;

- ◊ There was a shift in rainfall patterns of the post-mid 1970s record by comparison with the pre-1975 record. The post-1975 record shows that the annual rainfall amounts have increased by approximately 10% over the pre-1975 amounts in the western half of Ireland. Most of the 10% annual increase was found in the two months of March and October, with the increase being in the number of wet hours/days rather than in rainfall intensities;
- ◊ Analysed in terms of return periods, what was deemed a 30-year storm (rainfall amount) prior to 1975 is now closer to a 10-year return period for storm durations >12 hours. This has implications for engineering design (e.g. bridge structures, flood magnitude etc.) where it is now more conservative (safer) to use the shorter post-1975 record to estimate the particular return period rain amounts rather than the longer observations record (in some cases back to 1940). This change is also observed in some river flow records;
- ◊ The rainfall changes correspond to changes in the NOA;
- ◊ Summer increases in evaporation and decreases in precipitation in the south-east result in reduced available water and may exert seasonal pressure on water resources.

- More than 50 bog burst or 'landslides' in peatlands have occurred in the past century. They are the result of extremes in rainfall following dry periods and sometimes compounded by human activities and have led to loss of human life as well as extensive ecosystem degradation. Intact peatland margins (e.g. near streams) provide the structural integrity of peatlands against failure as the margins contain peat of higher density and lower hydraulic conductivity than peatland central areas.

6.3 Recommendations

1 The establishment of a national repository for all data with potential for palaeoenvironmental reconstruction. Site investigators should be required to notify such a repository of their findings, cores retrieved, and so on. There is excellent potential in lake, cave and tree ring-based archives to produce enough well-dated, high-resolution temperature proxy record of Holocene temperatures in Ireland.

2 An examination of further early texts for weather-related references (e.g. the Annals); comparison of wind reports in the Annals to other proxies of environmental and climatic information (e.g. reflecting the state of the NAO) will be important in further understanding of Ireland's past wind regime. Evidence of impacts (famine, infrastructural damage, disease) in the texts may also be a suitable area for further study.

3 A reanalysis of the Belfast tree-ring chronologies with the specific purpose of palaeoenvironmental reconstruction. Secondary information can be used in addition to tree-ring widths to infer additional climatic information.

4 Digitisation and web dissemination of the remaining undigitised meteorological records, following the example of Armagh Observatory is desirable.

5 An effort to collate instrumental data from dispersed, fragmentary sources such as weather diaries.

6 A systematic homogenisation effort of the best available instrumental series, drawing on the full network of daily rain gauges.

7 The lack of adequate river data for monitoring/analysis/research purposes is due to the multiplicity of authorities with overlapping briefs involved in river monitoring. There is an acute need for a single national authority control all river monitoring functions and make data available on public websites.

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Acronyms and Annotations

AD	Anno Domino
AMS	Accelerated mass spectrometry
AR4	Assessment Report 4 (IPPC)
BC	Before Christ
CAL	Calibrated years before present
GISP2	Greenland Ice Sheet Project 2
GP	Generalised Pareto
IDF	Intensity-duration-frequency
IPPC	Intergovernmental Panel on Climate Change
NAO	North Atlantic Oscillation
PDF	Probability distribution function
PDS	Partial duration series
RCMs	Regional climate models
RF	Radiative forcing
SST	Sea surface temperature
TAP	Total annual precipitation

Appendix: Gaelic Irish Annals

- Annals of the Four Masters (O'Donovan, 1848–1851);
- Annals of Ulster (Mac Airt and Mac Niocaill, 1983; Hennessy and MacCarthy, 1887–1901);
- Annals of Loch Cé (Hennessy, 1871);
- Annals of Connacht (Freeman, 1944);
- Annals of Inisfallen (Mac Airt, 1944);
- Annals of Tigernach (Wilde, 1851; Stokes, 1895, 1896, 1897a,b);
- Annals of Ireland: Three Fragments/Fragmentary Annals of Ireland (O'Donovan, 1860; Radner, 1978);
- Mac Carthaigh's Book – Fragment 1 (Ó hInnse, 1947);
- Annals of Boyle (Freeman, 1924, 1925, 1926, 1927);
- Egerton Annals (O'Grady, 1892); Fragment 2 (Ó hInnse, 1947);
- Annals of Oileán Na Naomh – Fragment 3 (Ó hInnse, 1947);
- Mageoghagan's Book (Murphy, 1896);
- Annals from the Book of Leinster (Stokes, 1887);
- The Annals of Ireland, from the Year 1443 to 1468 (O'Donovan, 1845);
- Memoranda Gadelica (Breathnach, 1931);
- Short Annals of Tirconaill (Breathnach, 1934);
- Short Annals of Fir Manach (Breathnach, 1935);
- Short Annals of Leinster (Breathnach, 1936);
- Annala Gearra as Proibhinse Ard Macha (Mac Niocaill, 1958–9);
- Carew Fragment (Ó Cuív, 1981).

An Ghníomhaireacht um Chaomhnú Comhshaoil

Is í an Gníomhaireacht um Chaomhnú Comhshaoil (EPA) comhlachta reachtúil a chosnaíonn an comhshaol do mhuintir na tíre go léir. Rialaímid agus déanaimid maoirsiú ar ghníomhaíochtaí a d'fhéadfadh truailliú a chruthú murach sin. Cinntímid go bhfuil eolas cruinn ann ar threochtaí comhshaoil ionas go nglactar aon chéim is gá. Is iad na príomh-nithe a bhfuilimid gníomhach leo ná comhshaol na hÉireann a chosaint agus cinntiú go bhfuil forbairt inbhuanaithe.

Is comhlacht poiblí neamhspleách í an Ghníomhaireacht um Chaomhnú Comhshaoil (EPA) a bunaíodh i mí Iúil 1993 faoin Acht fán nGníomhaireacht um Chaomhnú Comhshaoil 1992. Ó thaobh an Rialtais, is í an Roinn Comhshaoil agus Rialtais Áitiúil a dhéanann urraíocht uirthi.

ÁR bhFREAGRACHTAÍ

CEADÚNÚ

Bíonn ceadúnais á n-eisiúint againn i gcomhair na nithe seo a leanas chun a chinntiú nach mbíonn astuithe uathu ag cur sláinte an phobail ná an comhshaol i mbaol:

- áiseanna dramhaíola (m.sh., líonadh talún, loisceoirí, stáisiúin aistrithe dramhaíola);
- gníomhaíochtaí tionsclaíocha ar scála mór (m.sh., déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta);
- diantalmhaíocht;
- úsáid faoi shrian agus scaoileadh smachtaithe Orgánach Géinathraithe (GMO);
- mór-áiseanna stórais peitreail.
- Scardadh dramhuisce

FEIDHMIÚ COMHSHAOIL NÁISIÚNTA

- Stiúradh os cionn 2,000 iniúchadh agus cigireacht de áiseanna a fuair ceadúnas ón nGníomhaireacht gach bliain.
- Maoirsiú freagrachtaí cosanta comhshaoil údarás áitiúla thar sé earnáil - aer, fuaim, dramhaíl, dramhuisce agus caighdeán uisce.
- Obair le húdaráis áitiúla agus leis na Gardaí chun stop a chur le gníomhaíocht mhídhleathach dramhaíola trí comhordú a dhéanamh ar líonra forfheidhmithe náisiúnta, díriú isteach ar chiontóirí, stiúradh fiosrúcháin agus maoirsiú leigheas na bhfadhbanna.
- An dlí a chur orthu siúd a bhriseann dlí comhshaoil agus a dhéanann dochar don chomhshaol mar thoradh ar a ngníomhaíochtaí.

MONATÓIREACHT, ANAILÍS AGUS TUAIRISCIÚ AR AN GCOMHSHAOL

- Monatóireacht ar chaighdeán aeir agus caighdeáin aibhneacha, locha, uiscí taoide agus uiscí talaimh; leibhéil agus sruth aibhneacha a thomhas.
- Tuairisciú neamhspleách chun cabhrú le rialtais náisiúnta agus áitiúla cinntí a dhéanamh.

RIALÚ ASTUITHE GÁIS CEAPTHA TEASA NA HÉIREANN

- Cainníochtú astuithe gáis ceaptha teasa na hÉireann i gcomhthéacs ár dtiomantas Kyoto.
- Cur i bhfeidhm na Treorach um Thrádáil Astuithe, a bhfuil baint aige le hos cionn 100 cuideachta atá ina mór-ghineadóirí dé-ocsaíd charbóin in Éirinn.

TAIGHDE AGUS FORBAIRT COMHSHAOIL

- Taighde ar shaincheisteanna comhshaoil a chomhordú (cosúil le caighdéan aeir agus uisce, athrú aeráide, bithéagsúlacht, teicneolaíochtaí comhshaoil).

MEASÚNÚ STRAITÉISEACH COMHSHAOIL

- Ag déanamh measúnú ar thionchar phleananna agus chláracha ar chomhshaol na hÉireann (cosúil le pleananna bainistíochta dramhaíola agus forbartha).

PLEANÁIL, OIDEACHAS AGUS TREOIR CHOMHSHAOIL

- Treoir a thabhairt don phobal agus do thionscal ar cheisteanna comhshaoil éagsúla (m.sh., iarratais ar cheadúnais, seachaint dramhaíola agus rialacháin chomhshaoil).
- Eolas níos fearr ar an gcomhshaol a scaipeadh (trí cláracha teilifíse comhshaoil agus pacáistí acmhainne do bhunscoileanna agus do mheánscoileanna).

BAINISTÍOCHT DRAMHAÍOLA FHORGHNÍOMHACH

- Cur chun cinn seachaint agus laghdú dramhaíola trí chomhordú An Chláir Náisiúnta um Chosc Dramhaíola, lena n-áirítear cur i bhfeidhm na dTionscnamh Freagrachta Táirgeoirí.
- Cur i bhfeidhm Rialachán ar nós na treoracha maidir le Trealamh Leictreach agus Leictreonach Caite agus le Srianadh Substaintí Guaiseacha agus substaintí a dhéanann ídiú ar an gcrios ózóin.
- Plean Náisiúnta Bainistíochta um Dramhaíl Ghuaiseach a fhorbairt chun dramhaíl ghuaiseach a sheachaint agus a bhainistiú.

STRUCHTÚR NA GNÍOMHAIREACHTA

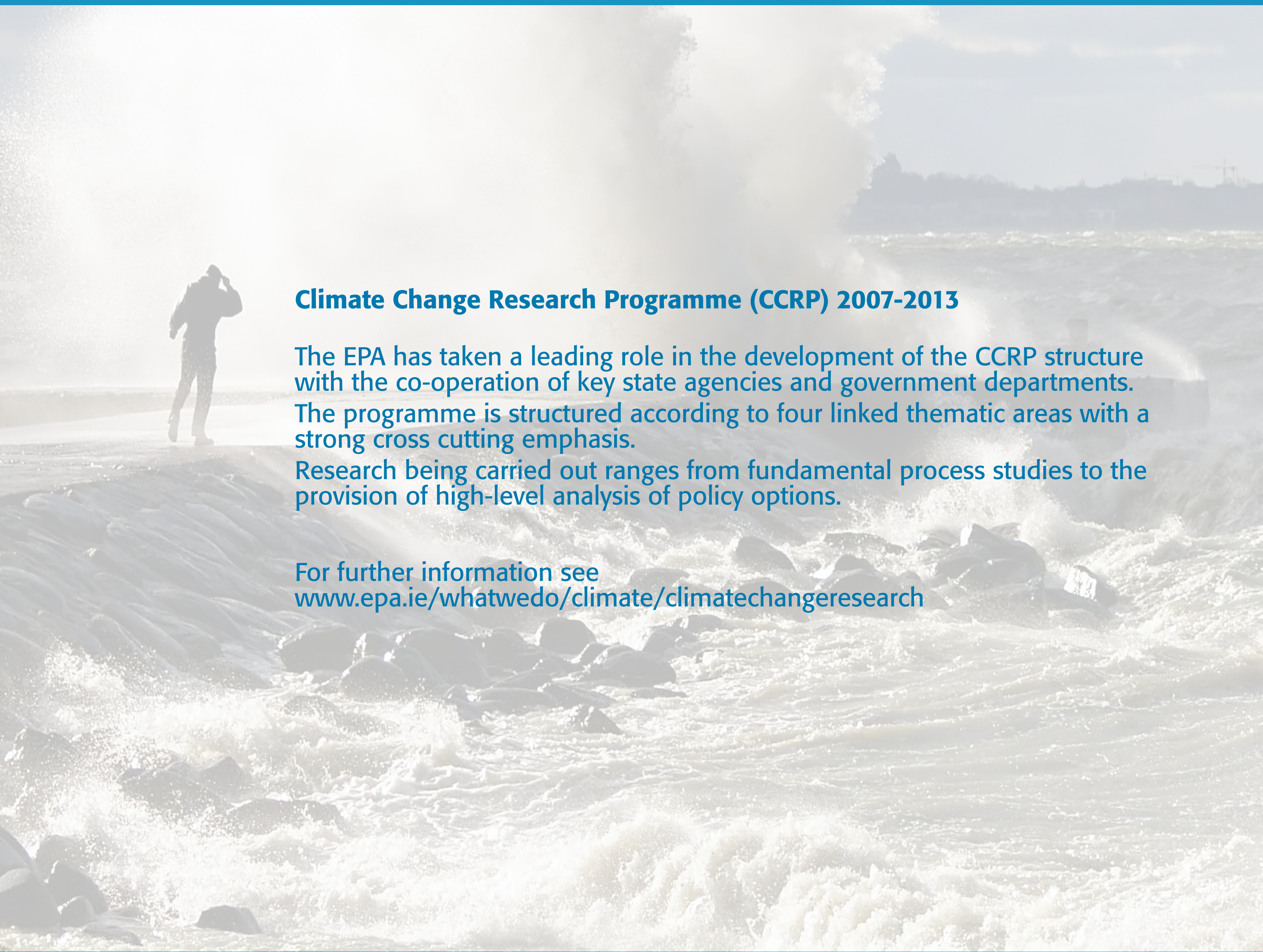
Bunaíodh an Ghníomhaireacht i 1993 chun comhshaol na hÉireann a chosaint. Tá an eagraíocht á bhainistiú ag Bord lánaimseartha, ar a bhfuil Príomhstiúrthóir agus ceithre Stiúrthóir.

Tá obair na Gníomhaireachta ar siúl trí ceithre Oifig:

- An Oifig Aeráide, Ceadúnaithe agus Úsáide Acmhainní
- An Oifig um Fhorfheidhmiúchán Comhshaoil
- An Oifig um Measúnacht Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáide

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag ball air agus tagann siad le chéile cúpla uair in aghaidh na bliana le plé a dhéanamh ar cheisteanna ar ábhar imní iad agus le comhairle a thabhairt don Bhord.

National Development Plan 2007 - 2013



Climate Change Research Programme (CCRP) 2007-2013

The EPA has taken a leading role in the development of the CCRP structure with the co-operation of key state agencies and government departments.
The programme is structured according to four linked thematic areas with a strong cross cutting emphasis.
Research being carried out ranges from fundamental process studies to the provision of high-level analysis of policy options.

For further information see
www.epa.ie/whatwedo/climate/climatechangeresearch

Environmental Protection Agency
An Ghníomhaireacht um Chaomhnú Comhshaoil

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SSTI Strategy for Science, Technology and Innovation

Comhshaol, Oidhreacht agus Rialtas Áitiúil
Environment, Heritage and Local Government