Environmental RTDI Programme 2000–2006

CLIMATE CHANGE
Indicators for Ireland
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Final Report

Prepared for the Environmental Protection Agency

by

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Executive Summary

The Third Assessment Report of the Intergovernmental Panel on Climate Change represented a consensus among the world's leading climate scientists that rapid climate changes were occurring on a global scale. In particular, the marked warming that had occurred over the past half century was, they concluded, substantially caused by the build-up of greenhouse gases in the troposphere as a result of anthropogenic activities. Globally, 1998 was the warmest year of the warmest decade of the warmest century of at least the last millennium. Such fluctuations, the IPCC suggested, were already capable of being associated with changes in a diverse set of physical and biological indicators in many parts of the world.

Indicators of climate change are primarily used to simplify a complex reality and to communicate, more succinctly, critical information regarding climatic trends. They also provide an essential early warning system by making available information that may point to an environmental problem which is capable of being ameliorated before it becomes critical. In establishing indicators, a distinction can be made between primary indicators, based on analysis of directly observed meteorological data, and secondary indicators, based on the responses of the living world to climate changes which provoke a response in living organisms.

1 Primary Indicators

Potential primary indicators of climate change were investigated using the Irish meteorological monitoring network supported by Met Éireann. Although an extensive array of data sets was consulted in the exercise, the main focus was on the 14 synoptic stations located throughout Ireland. At these locations, observations of temperature, precipitation, wind, sunshine, cloud, visibility, pressure, humidity, and soil and grass temperatures are made by trained observers on an hourly basis. In most cases, the record extends from the 1940s and 1950s. However, some long-term records from locations such as Birr, Valentia and the Phoenix Park extend back to the 19th century.

1.1 Temperature

Temperature records indicate that global trends have been largely replicated in Ireland, albeit with an observed tendency for a lag of a few years. A warming episode from the first decade of the 20th century to the mid-1940s was followed by a cooling trend to the end of the 1970s. Thereafter, a rapid warming was apparent which continues to the present. A stronger warming trend was apparent in Ireland in the 1930s and 1940s than globally and this resulted in the warmest year of the last century being 1945 in Ireland. Similarly, mid-century cooling continued somewhat later in Ireland and only since the 1990s has warming ahead of the global mean resumed. The 1990s have been the warmest decade in the Irish instrumental record. This is consistent with the experience in the UK where the 1990s have been the warmest decade in records extending over 240 years.

The temperature observations indicate that most warming has occurred in the winter period. Maximum temperatures appear to be increasing more than minimum temperatures during this season. For summer and autumn, however, minimum temperatures are increasing more quickly than maxima. Stronger indicators of ongoing climate change are in evidence when the number of 'hot' and 'cold' days is examined. A 'hot' day is defined as one when the mean daily temperature exceeds 18°C whereas a 'cold' day had a mean below 0°C. A clear indication of a trend exists in both these parameters. In midland locations, such as Birr and Kilkenny, the number of cold days has halved over the past five decades while the number of hot days has roughly doubled.

A shortening of the frost season is also apparent at most locations, though the trend is not as consistent as might be expected. The first and last days of frost likewise do not display significant trends. The frequency of days with minima below 0°C is, however, a much more convincing indicator, with significant decreases of approximately 10 days per annum having occurred at some locations over the past four decades. The accumulation of evidence in the temperature records indicates a warming trend in

Ireland, particularly marked since the beginning of the 1980s. At present, Ireland appears to be warming by slightly over 0.25°C per decade.

1.2 Precipitation

Globally precipitation has been increasing by 0.5–1% per decade over the course of the 20th century and most global climate models predict winter increases and summer decreases for Britain and Ireland. This trend is not corroborated convincingly for Ireland though some aspects of precipitation change have been detected which support the hypothesis.

In the north, significant increases in annual rainfall have occurred in recent years. Malin Head has shown a 10-year moving average increase of over 40% during the 20th century, with 4 of its 5 wettest years occurring in the 1990s. In contrast to this, locations further south, such as Birr or Rosslare, show decreased receipt. A more pronounced precipitation gradient appears to be becoming established over Ireland.

Some of the changes in annual totals reflect divergences in seasonal precipitation receipt. Wetter winters in the west and north appear to contrast strongly with drier summers in the south and east. This was especially marked when Malin Head and Roche’s Point data were examined. The apparently growing divergence appears to be a good indicator of ongoing changes and appears also to corroborate global climate model predictions in this area.

The intensity of rainfall would be expected to increase as warmer temperatures enabled more water vapour to be held and ultimately released from the air. Indications of increases in average monthly rainfall amounts are particularly strong during the winter months of December and February. Equally, maximum 24-hourly receipts appear to be up in October and December at Malin Head and in March at Valentia. The number of ‘wet’ days has increased by 5 days in March and by 3 in October.

Much of the changes in temperature and precipitation appear related to the North Atlantic Oscillation (NAO), an index of the pressure difference between Iceland and Portugal. This index explains 50% of the Valentia winter temperature variance and 30% of that at Malin Head. The index has a cycle length of approximately 10 years. The close relationship between climate variables and the NAO suggests that quasi-cyclical changes in ‘westerliness’ still exert a dominant control on year-to-year variations in many climatic parameters in Ireland and these may be masking some of the forcing due to anthropogenic influences.

2 Secondary Indicators

Secondary indicators comprise phenomena, especially in the biological environment, which might be expected to show a response to changes in primary climatic parameters. As indicators, they will inherently be subject to a complex, multifactorial set of influences of which climate may be only one component. A wide range of possible indicators was examined and their potential utility assessed.

The problems of confounding factors were particularly evident in agricultural systems. Management practices, market forces, subsidy payments, genetically modified cultivars – all these made the isolation of climatic influences difficult. Some possible future indicators did emerge, most notably changes in the production area of warm weather crops such as forage maize and vines. However, it was concluded that more detailed phenological investigations would be desirable should agricultural indicators be employed.

Butterflies and bats were found to have more potential, especially since many species of butterfly are at their ecological limits in Ireland and would be highly sensitive to slight climate changes. While some data sources currently exist for butterflies, these are not adequate to serve as reliable indicators. Bats have received little attention.

Bird activity was found to provide one of the most successful secondary indicators. Reasonably good records exist and these have enabled the arrival of some new species to be recorded. The little egret, reed warbler, pied flycatcher, bearded tit, Mediterranean gull, goosander, lesser whitethroat and blackcap are just some of the new species which have arrived since 1980, possibly in response to warmer conditions. The displacement of some cold-tolerant species has been less dramatic, however, and more data are needed, especially on seabird population changes.

Arrival dates for migratory species have been meticulously recorded for some species such as the swallow and here a good indicator species seems to exist. It is not clear why such a strong response to temperature changes appears to be occurring and further work is also required to identify the role of climate change in the areas of origin or along the migratory route. Possibly, arrival dates are in response to previous year's experience in terms of food supply, especially earlier insect abundance. For every 1°C rise in March temperature, the swallow and house martin will arrive approximately 2 days and 1 day earlier, respectively.

The use of phenological indicators provided the main success of this part of the project. Data from the four phenological gardens in Ireland (Valentia Island, John F. Kennedy Arboretum, National Botanic Gardens and Johnstown Castle) were analysed. This indicated that the beginning of the growing season was occurring earlier at all locations for a number of the indicator tree species. An increase of temperature in spring of 1°C is associated with leaf unfolding occurring 5–8 days earlier. Leaf fall, on the other hand, has shown little change since 1970, except in the south-west where it has become significantly later. Accordingly, the length of the growing season has become longer, especially in the south-west. An extension of the growing season by 9 days for *Betula*, 3 days for *Fagus*,and 7 days for *Tilia* is indicated for every 1°C rise in annual temperature.

These data were seen to provide excellent indicators of climate change. It is, however, not collated or processed in Ireland at present and this should be considered a desirable objective to be attained for the future.

Palaeoecological records, such as dendrochronological data, pollen data and speleothem data, represent useful sources for placing present climate trends in a more long-term perspective. Recent advances in these areas permit greater temporal resolution to be obtained than previously and although these sources do not as yet offer good potential for indicators of very recent changes they do, nevertheless, merit continued support as potential future data sources.

Investigations of socio–economic data as indirect indicators of climate change were also undertaken. These sources included changes in energy consumption, insurance claims for weather-related damage and changes in domestic tourism. However, the appropriate data were not easily accessible and the problem of confounding factors, such as economic growth, restricts the usefulness of such approaches.

3 Conclusions and Recommendations

The research has assessed a very wide range of potential indicators and has established several potentially valuable data sources which satisfy or partially satisfy the requirements that a good indicator should have. Both the observational meteorological data and the careful surveillance and monitoring of ecosystems has been shown to provide useful information on sometimes quite subtle changes in Irish climate. These may, however, become more explicit in the future, and the value of indicators as early warning devices is clear.

The value of long-term monitoring has been demonstrated by this project. When the phenological gardens began collecting data in 1959 there was little awareness of issues related to climate change. But the importance of this dataset has now been realised. A network of long-term ecological monitoring sites across Ireland would enable trends to be more clearly identified and reduce the confounding effect of localised factors. Similarly the importance of continued support for the Met Éireann synoptic and climatological network is demonstrated in this work. It is of paramount importance for the charting of the course of future Irish climate that this be maintained at its present scale.

Clearly the Irish climate is changing, as it always has, and as it always will. However, the indicators examined in this study suggest that despite a maritime location buffered by the Atlantic from extremes of climate, Ireland is mirroring, albeit at a somewhat delayed rate, the trends apparent at a global scale. Its climate is also conforming, though the signal is as yet somewhat blurred, with projections for the future for this area being made by the climate modelling community.

1 Introduction

The work presented in this report is concerned with establishing indicators of climate change. The main focus of this study is to identify indicators that show a response to changes that have occurred in the recent past and that are continuing to occur today. These involve the detection of change in both meteorological and ecological systems; this study will not investigate the causes of these changes.

1.1 Climates of the Past

The Earth's climate has evolved and changed throughout its history. For approximately 94% of the past 850,000 years the earth's climate was colder than at present (Barry and Chorley, 1998). The last major glacial episode reached a maximum 25,000–18,000 years ago when sea surface temperatures in the vicinity of Ireland were probably 10°C below those of today. Sea levels were approximately 85 m below today's levels. Ireland was a part of continental Europe. Following deglaciation, migration routes for plants and animals were severed and the native flora and fauna of the island were determined. Since then, several notable fluctuations in climate have occurred, such as the cold Younger Dryas event (10,800–10,100 years ago). These events have been revealed from analysis of sources such as tree rings, lake sediments, ice/ocean cores, pollen deposits, corals and palaeosols. Post glacial warming peaked around 7,000–5,000 years ago when summer temperatures in Europe were probably 2–3°C warmer than today. As the present day is approached, a much richer source of climate information becomes available, ranging through documentary sources such as early newspapers, diaries, crop-yield data and culminating in the instrumental records which provide the most objective measures of recent events. In Ireland, these commenced in 1794 at Armagh Observatory and, in 1800, at the Botanic Gardens in Dublin and have left a valuable legacy of observational data with which to chart Ireland's climate.

Natural climate variability is not random but a function of complex atmospheric–ocean interactions, which produce marked oscillations (Daultrey, 1994). In addition, the characteristics of the geometry of the earth's orbit around the sun is now known to strongly influence long-term climate changes, such as the glacial–interglacial oscillations of the present Quaternary Period (Hays *et al.*, 1976). However, of growing concern is the likelihood that anthropogenically induced climate change may currently be occurring and, in the public perception, it is this aspect which looms largest when the subject is broached. The United Nations Framework Convention on Climate Change (1992) defines climate change

"*as a change of climate, which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods*".

More recently, the Intergovernmental Panel on Climate Change (2001) defined climate change as

"*any change in climate over time, whether due to natural variability or as a result of human activity*".

1.2 Climates of the Future

The Third Assessment Report of the IPCC (IPCC, 2001) represents the most authoritative contribution on the topic. Among the principal conclusions of the Third Assessment Report are the following:

- Global average temperature has increased by 0.6°C ± 0.2°C since the mid-19th century and the trend seems to have accelerated in the past three decades. A further increase of 1.5–6.0°C is projected for the period to 2100.
- The 20th century was the warmest century of the last millennium in the Northern Hemisphere. The 1990s was the warmest decade and 1998 was the warmest year.
- A widespread retreat of mountain glaciers outside the polar regions has taken place in recent decades and sea-ice thickness in the Arctic has decreased by 40% during late summer/early autumn.

- Sea level has risen by 10–20 cm since 1900, and a rise of approximately 0.5 m is considered likely during the period 1990–2100.
- Precipitation has increased over the land masses of the temperate regions by 0.5–1% per decade with some signs of increased intensities being measured. In the tropics, decreases in rainfall have been observed. The frequency of El Niño events appears to be increasing.
- No significant trends in tropical cyclone climatology have been detected.

The IPCC report asserts that the evidence for a human influence on global climate is now stronger than ever before and states that “increasing concentrations of anthropogenic greenhouse gases have contributed substantially to the observed warming over the last 50 years.”

The average atmospheric CO_2 concentration has increased from 280 ppm in 1850 to 365 ppm at present, and could exceed 700 ppm by the end of the present century if emissions continue to rise at current rates (IPCC, 2001). European annual mean temperatures have increased by 0.3–0.6ºC since 1900. A further increase of 2°C above the 1990 level is predicted for 2100 (EEA, 1998). This will have increasing impacts on natural and agri–ecosystems, human health, and water resources. Some of the climate driving forces may be sudden, having an immediate impact, while others may take much longer to be felt (Tyrrell, 1994).

1.3 Why do we Need Indicators?

The Organisation for Economic Co-operation and Development (OECD, 1993) defined an indicator as follows:

“*a parameter, or a value derived from parameters, which points to/provides information about/describes the state of a phenomenon/environment/area with a significance extending beyond that directly associated with a parameter value*.”

Indicators, therefore, provide information about phenomena that are regarded as typical for, and/or critical to, environmental quality. Indicators of climate change should give an overview of the climate and its development. Primary indicators are the instrumental observations of climate over time. Secondary indicators are systems/organisms the vitality and responses of which change in response to environmental conditions.

The OECD produces a core set of 33 indicators for environmental performance based on the Driver–Pressure–State–Impact–Response (DPSIR) framework (Fig. 1.1). Most national and international bodies base their sets of indicators on the DPSIR framework or a subset of it. According to this system, social and economic developments exert a *Pressure* on the Environment and, as a consequence, the *State* of the Environment changes. This leads to *Impacts* on human health, ecosystems and materials that may elicit societal *Response* that feeds back on the *Driving Forces*, or on the impacts directly, through adaptation or curative action.

The PSR framework is used to identify indicators of environmental pressures (P), conditions (S) and responses (R) (Figs 1.2 and 1.3) for use in the State of the Environment reports produced by each of the EU member states.

Indicators simplify a complex reality and communication is their major function (EEA, 1999). Indicators of climate change enable communication of critical information regarding climatic conditions. They also provide an essential early-warning system by making available observational data that may point to an environmental problem.

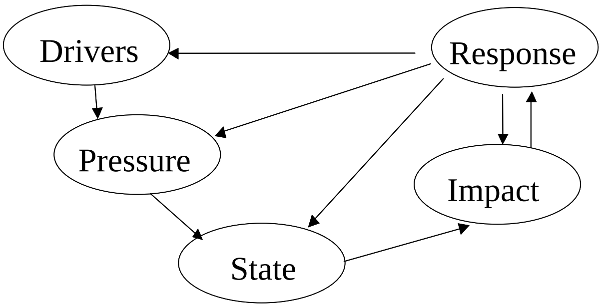

Figure 1.1. The Drivers–Pressures–State–Impacts–Responses framework. Source: EEA (1999).

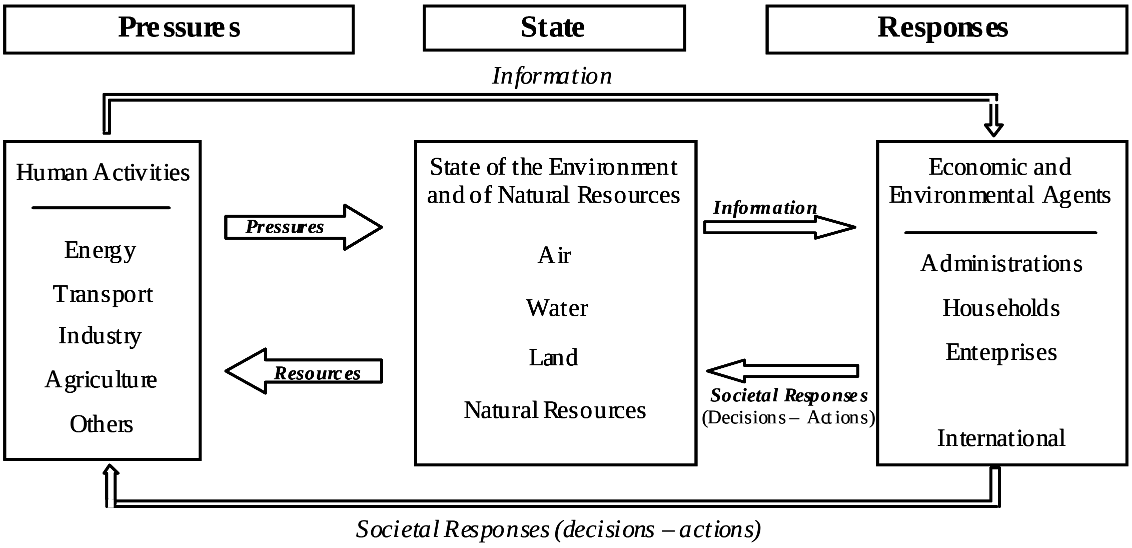

Figure 1.2. Pressure–State–Response framework.

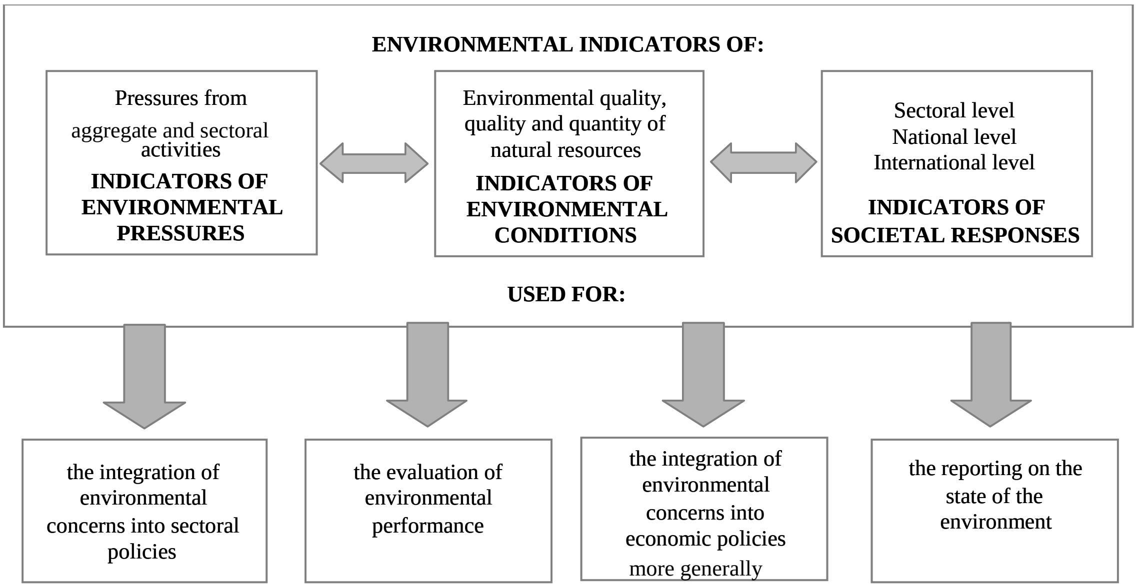

Figure 1.3. Nature and use of environmental indicators. Source: OECD (1993).

1.4 Criteria for Indicator Selection

The OECD (1993) established the following criteria for choosing environmental indicators.

An indicator should:

- provide a representative picture of environmental conditions
- show trends over time and be easily interpreted
- be responsive to change
- be comparable internationally
- be national in scope or applicable to regional environmental issues
- have a reference value against which comparisons can be made
- be well founded in technical and scientific terms

- be based on international standards
- be linked to forecasting and information models
- be of high quality, well documented and updated regularly
- be readily available at a reasonable cost.

Selecting indicators for Ireland, which fulfil all these criteria, presents great difficulties. The focus of this report is to select indicators that fit these criteria as far as possible.

1.5 Types of Indicators

In identifying indicators, a distinction is made between primary (climatological) and secondary (biological, sociological, economic) indicators. The Irish climate-monitoring network operated by Met Éireann is the source of primary data. This network comprises 14 synoptic stations, over 100 climatological stations and approximately 650 rainfall stations. An upper air station is also maintained at Valentia Observatory and several automatic weather stations are also supported. The synoptic stations, set up between 1940 and 1960, have the most comprehensive datasets, including temperature, precipitation, cloud cover, sunshine, wind, atmospheric pressure, and humidity. The measurements taken at the climatological stations are on a daily basis, and principally comprise only temperature and precipitation variables.

Secondary indicators are more problematic as the effects of climate change on natural flora and fauna are complex and multifaceted and subject to large uncertainty. There is limited availability of suitable long-term datasets of biological systems. Studies are normally short term, in a relatively local area and involve a small number of species, thus missing out on the processes that are taking place over many years, over a wide area and involving many species. It is not prudent, however, to wait for definite long-term trends to become apparent before processing whatever data are available in this field and making preliminary recommendations based on them.

1.6 Use of Indicators

This report focuses firstly on the primary meteorological indicators of climate change. Secondary indicators are then considered. Secondary indicators may be valuable in areas where direct meteorological measurements are not available to pinpoint vulnerable parts of the ecosystem. Finally, the main conclusions are discussed and recommendations for further work are made.

2 Primary indicators

2.1 Introduction

The primary purpose of this section is to assess whether primary indicators provide corroboration or otherwise as to whether Ireland is following the same climate trends as those apparent on a global scale.

2.2 The Irish Monitoring Network

Long-term observations of rainfall and temperature began in the 19th century, and some have continued right up to the present, e.g. Valentia Observatory and Birr. Early sites used a variety of instruments of varying accuracy and exposures. From about 1880 onwards, the records at these stations are considered fairly reliable. The oldest station in the country is the climatological station at Armagh Observatory, where records have been continued without interruption since 1794 (Sweeney, 1997).

Currently the Irish climate-monitoring network consists of both synoptic and climatological stations. Met Éireann operates 14 synoptic stations. These provide hourly observations of temperature, precipitation, wind speed and direction, sunshine, cloud cover, pressure, humidity, soil and grass temperatures (Fig. 2.1). Evapotranspiration and solar radiation are also measured at some of these stations. In addition, daily temperature and rainfall are monitored at over 100 climatological stations with sunshine, soil and earth temperatures being recorded at some of these (Keane, 1986). A further 650 stations measure daily rainfall. Most of these are operated by public bodies or by volunteers. All data are quality controlled by Met Éireann and held at their headquarters at Glasnevin in Dublin.

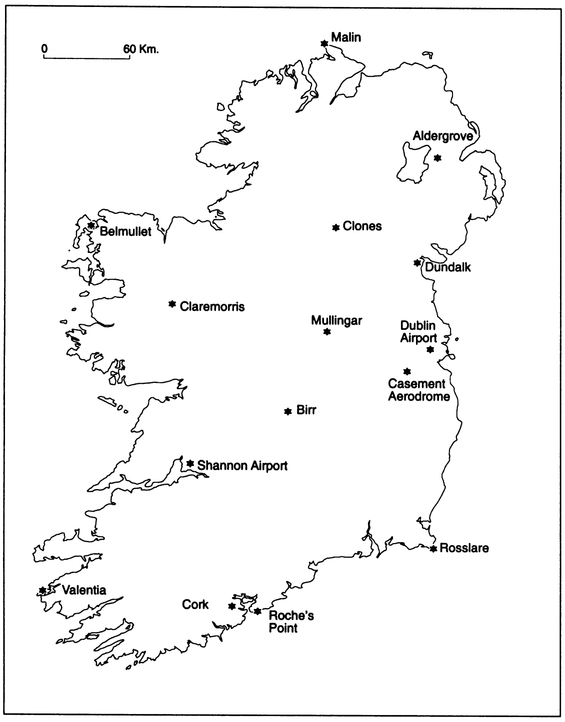

Figure 2.1. Location of 14 synoptic weather stations in Ireland.

2.3 Air Temperature Indicators in Ireland

2.3.1 Global and national air temperature anomaly

Long-term monthly records at a number of stations – Malin Head, Valentia, Birr and Armagh – extend back as far as 1890 (1865 for Armagh). These stations are considered representative for Ireland, as they cover the north-west, north-east, south-west and midlands–east regions. Figure 2.2 shows an 'air temperature anomaly for Ireland' based on data for these four stations. This is based on the calculation of an annual anomaly, from the 1961–1990 period, for each station. This is averaged to give an Irish anomaly, which has then been plotted alongside the global air temperature anomaly, obtained from the Climate Research Unit (CRU), University of East Anglia. The global trend shows decreasing negative anomalies from 1910 to 1940, slightly decreasing up to the mid-1970s and thereafter above average (in terms of the 1961–90 mean) warming continuing to the end of the series. Ireland however, experiences much greater interannual variability, with departures of over 1°C from the mean. While the Irish trend reveals much more variation, it also follows quite a similar pattern. Warming is apparent from 1910 to the mid-1940s; a general cooling occurred up to the start of the 1980s and rapid warming is apparent since the 1990s. The warmest year globally was

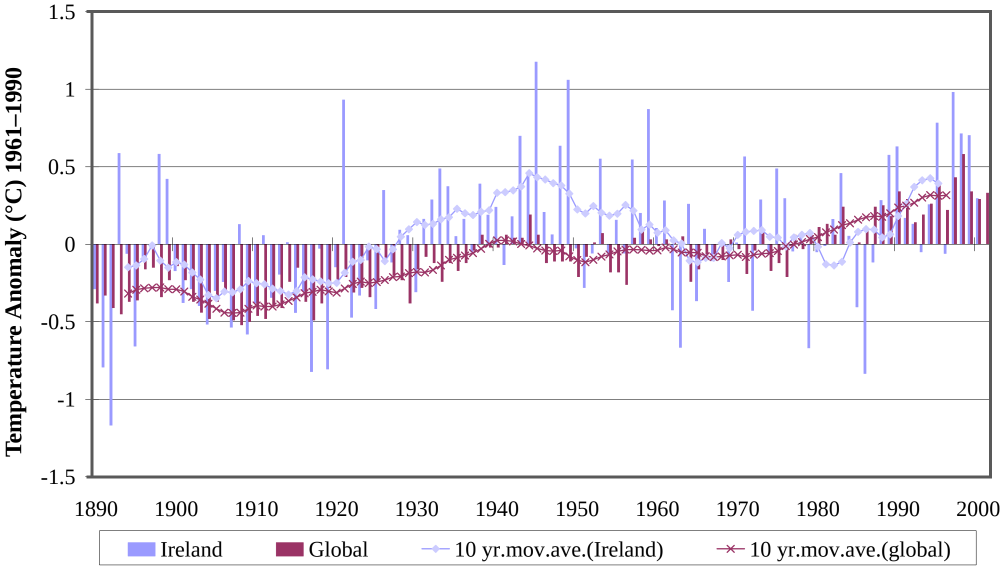

Figure 2.2. Global and national temperature anomaly, from 1961–1990 mean (10yr.mov.ave., 10-year moving average).

1998, which had a global anomaly of +0.58°C, whereas Ireland's warmest year of the past century on the index used was 1.18°C greater than normal, in 1945. There are a number of years between 1950 and 1980 when temperatures were both above and below normal for Ireland, but the general trend was gently decreasing. Rapid warming in the last two decades is quite significant.

2.3.2 *Long-term mean annual air temperature index*

The mean annual air temperature index has been derived from the average of the mean annual temperatures for the four long-term stations. Figure 2.3 illustrates the annual mean data and a 10-year moving average, plotted to show a clearer picture of decadal trends.

In this record, 5 of the 10 warmest years have occurred since 1990, with the warmest year within this period being 1997 (in contrast to the global year 1998). There have also been two distinct periods of warming, 1910–1950 and 1980–2000. The latter temperature increase, significant at the 99% level, has also occurred in a much shorter time scale and to a much greater magnitude. The decade beginning 1990 has been the warmest decade in the instrumental record for Ireland. Over the century,

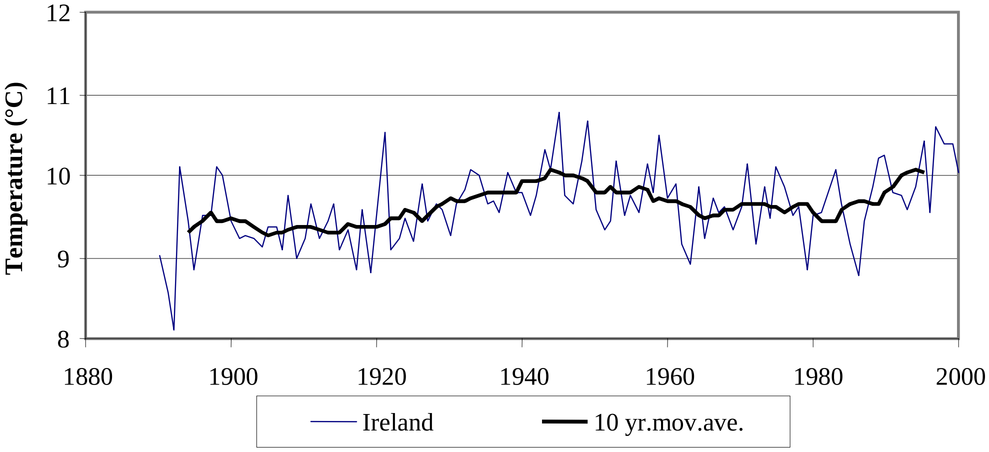

Figure 2.3. Mean annual air temperature index, 1890–2000 (10 yr.mov.ave., 10-year moving average).

there has been a mean linear increase of 0.51°C, significant at the 99% level. This is comparable to the global pattern, which revealed a 0.6°C increase.

2.3.3 Synoptic station air temperature index – 1950–2000

Figure 2.4 displays an index derived from the mean annual temperature for 11 synoptic stations averaged for each year, and also the 10-year moving average for these data. The index is considered representative as the stations are dispersed throughout the country (Fig. 2.1). Due to temporary data acquisition difficulties, Shannon Airport, Clones and Roche’s Point are not included.

Warming is significant (at the 99% level) for the whole period, with most of this occurring in the 1990s. This is consistent with UK trends where the 1990s has been the warmest decade in records extending over 240 years (Hulme and Jenkins, 1998). On a seasonal basis the greatest warming occurs in the period November to March, and the least warming with perhaps some cooling, occurs in the April to June, September and October months. This is similar to trends in other European countries (Balling *et al.*, 1998). The warmest month was August 1995, with a mean temperature of 18°C. July 1983 was the second warmest month. The coldest month in this period was January 1963 when mean temperatures were just below freezing. The highest maximum temperature recorded at a synoptic station was 31.5°C at Kilkenny in June 1976. Similar temperatures were recorded at other inland stations during this month and also in July 1983. The coldest minimum temperature, –14.9°C, was observed at Mullingar in January 1979. January 1982 also recorded very cold temperatures. The data trends from the synoptic stations mirror the global trend, and illustrate a significant increase in temperatures in Ireland in the 1990s.

2.3.4 Seasonal maximum and minimum air temperatures

Jones *et al.* (1999) in their analysis of the 240-year Central England Temperature (CET) record have found that the increase in temperature corresponds mainly to a reduced number of days with below-normal temperatures. The increase in days with temperatures above normal is not so evident. A global analysis of mean daily maximum and minimum temperatures point to an increase in minimum temperatures at a rate nearly twice that of maximum temperatures since approximately 1950 (Folland *et al.*, 2001). This may be associated with global changes in precipitation and cloud cover. Cloud cover in Ireland is dealt with in Section 2.5.

Figures 2.5 and 2.6 show the variations in summer and winter maximum and minimum temperatures for eight synoptic stations. The summer and winter seasons are regarded as 3-month periods: June–July–August, and December–January–February, respectively. For each

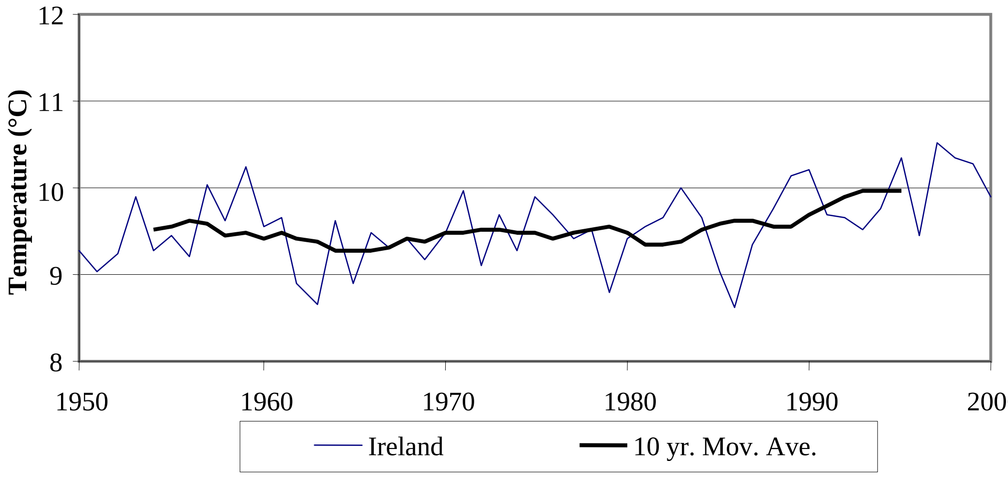

Figure 2.4. Synoptic station mean annual air temperature index, 1950–2000 (10 yr.Mov.Ave., 10-year moving average).

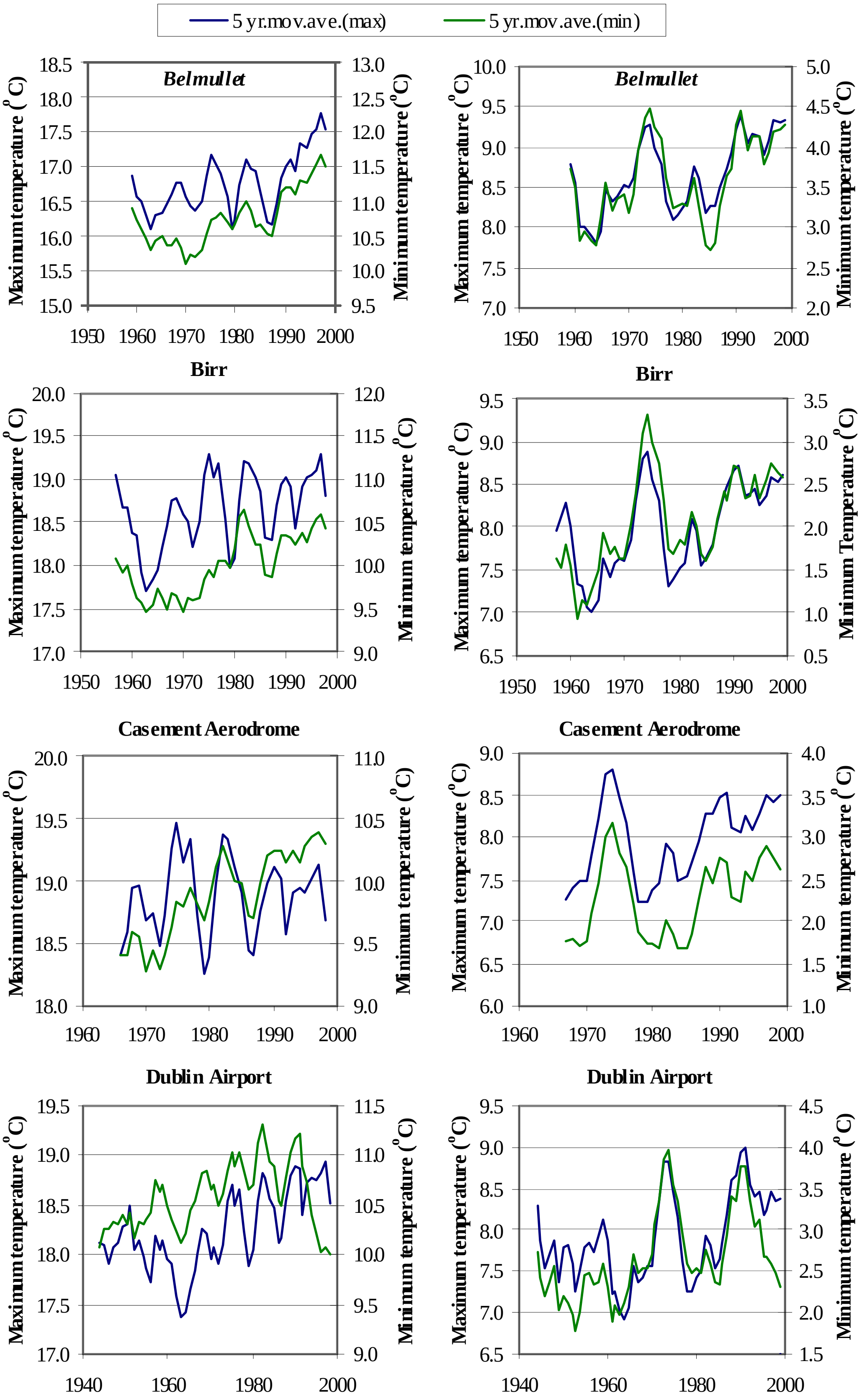

Figure 2.5. Summer (left-hand side) and winter (right-hand side) maximum and minimum temperatures at Belmullet, Birr, Casement Aerodrome and Dublin Airport (5 yr.mov.ave, 5-year moving average).

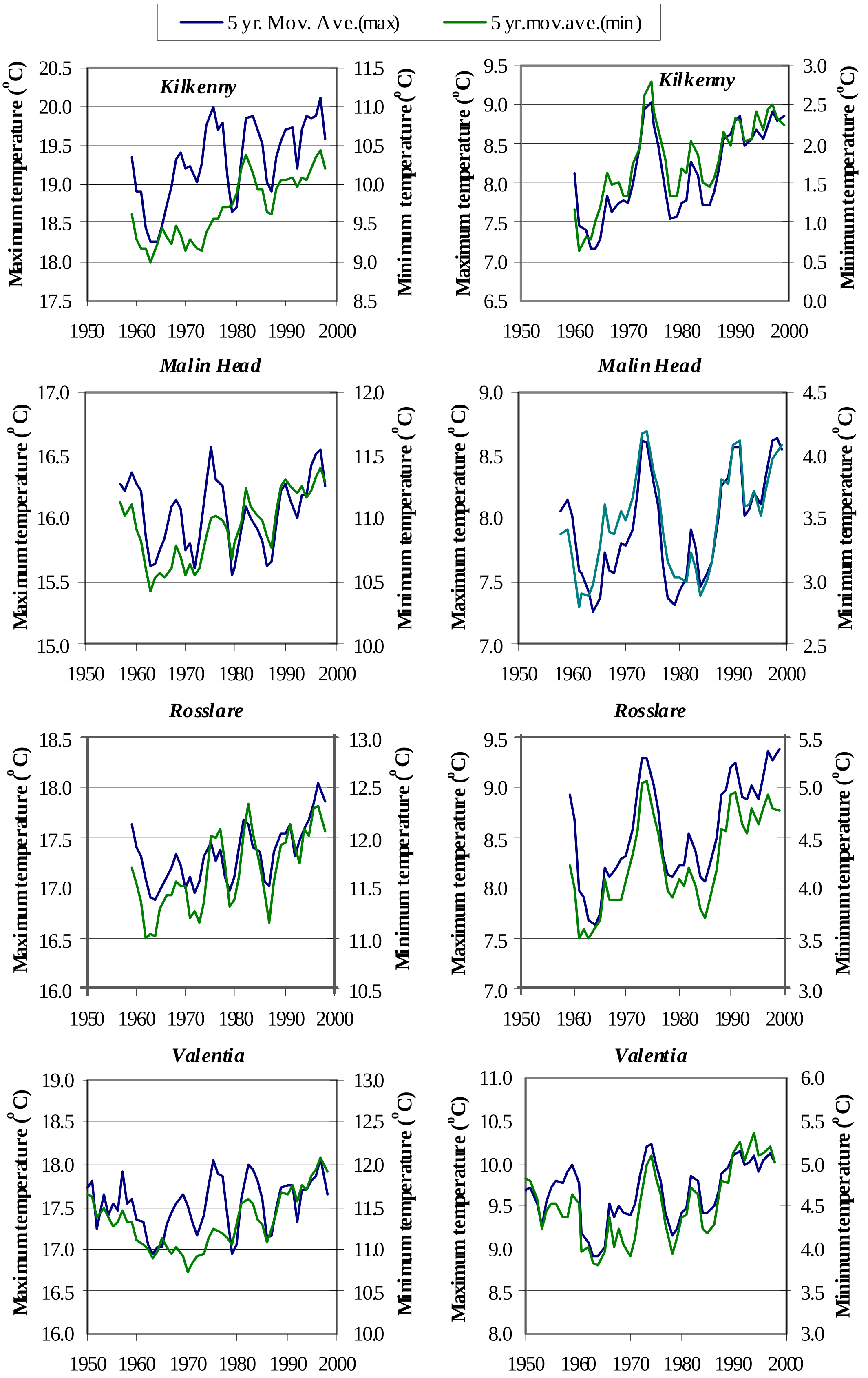

Figure 2.6. Summer (left-hand side) and winter (right-hand side) maximum and minimum temperatures at Kilkenny, Malin Head, Rosslare and Valentia (5 yr.mov.ave, 5-year moving average).

station, daily maximum and minimum temperatures were averaged for the 3-month period and their 5-year moving averages plotted. The variations in maximum and minimum temperature trends are generally the same at all stations.

Summer minimum temperatures increase more than maximum for six stations. The increases were significant at the 95% significance level for Malin Head and at the 99% level for Belmullet, Birr, Kilkenny, Rosslare and Casement Aerodrome. Summer maximum temperatures increased more than minimum at Valentia and Dublin Airport. The reasons for the difference with the rest of the synoptic stations are not clear.

Winter minimum temperatures increased more at Birr, Kilkenny and Malin Head than at the other sites. This increase is significant at the 95% significance level. Maximum temperatures increased more at Belmullet and Rosslare (95% significance level), Dublin Airport, Valentia and Casement Aerodrome. In spring, minimum temperatures increased more than maximum at Birr, Casement Aerodrome, Malin Head and Rosslare, but were significant only at Casement (99% significance level). Maximum temperatures increased more at Belmullet, Dublin Airport and at Kilkenny (95% significance level), while they decreased at both Malin Head and Valentia. These are the only stations, and spring is the only season, where a temperature decrease is recorded. Apart from the Kilkenny minimum temperature, changes in autumn maximum and minimum temperatures are not significant.

On a global level, the greatest seasonal warming has occurred during the Northern Hemisphere winter and spring. As a result, the disparity between summer and winter has decreased (Folland *et al*., 2001). In Ireland, trends in seasonal averages from 1960 to 2000 for all stations taken together indicate minimum temperatures warming more than the maximum during summer (99% significance level) and autumn, while maximum temperatures in winter and spring (95% significance level) increase more than the minimum. It is, however, winter warming which accounts for most of the annual warming, with winter maximum temperatures accounting for the greatest proportion of this. Autumn temperatures contribute the least to overall annual warming. Table 2.1 shows the change in temperature over the full length of record available at each station and at all stations for the period 1960–2000 calculated by linear regressions using the least squares method.

2.3.5 Annual frequency of ‘hot’ and ‘cold’ days

Temperature extremes are rare in Ireland. For the purposes of this analysis, a ‘hot’ day is defined as a day when the mean temperature is greater than 18°C, a ‘cold’ day is defined as a day when the mean temperature is less

Table 2.1. Increases in maximum and minimum temperatures (°C) by season The figures in bold are significant at either the 95% or 99% level, while those that are underlined point to the seasonal value which has increased the most at that station.

	Spring Max	Spring Min	Summer Max	Summer Min	Autumn Max	Autumn Min	Winter Max	Winter Min
Belmullet	0.621+	0.558+	**0.876***	**1.021+****	0.484+	0.031+	**0.887+***	0.770+
Birr	0.275+	0.522+	0.513+	**0.851+****	0.054+	0.202+	**0.968+***	**1.139+***
Casement	**0.809+***	**1.201+****	0.299+	**1.088+****	0.152+	0.759+	0.929+	0.648+
Dublin AP	0.168+	0.042+	**0.767+***	0.372+	0.313+	0.041+	0.762+	0.654+
Kilkenny	**0.862+***	**0.796+***	0.911+	**1.091+****	0.352+	**0.933+***	**1.184+***	**1.236+***
Malin Head	0.037–	0.469+	0.161+	**0.598+***	0.009+	0.092+	0.644+	0.649+
Rosslare	0.436+	0.517+	0.598+	**0.897+****	0.242+	0.501+	**0.888+***	**0.853+***
Valentia	0.366–	0.156–	0.276+	0.174+	0.144+	0.198+	0.582+	0.276+
All Stations	0.677+*	0.644+	0.722+	0.804+**	0.488+	0.533+	1.160+*	0.988+

**Correlation is significant at the 0.01 level (2-tailed).

*Correlation is significant at the 0.05 level (2-tailed).

than 0°C. Air temperature is rarely greater than 30°C or less than –10°C, and rarely remains below 0°C for more than 24 h (Rohan, 1986). Maximum temperatures above 30°C have a once in a century return period at coastal locations and once every 50 years inland. Temperatures of less than –7°C occur every second year inland, while only once every 100 years at Valentia (Sweeney, 1997).

The frequency of 'hot' and 'cold' days per year at Birr and Kilkenny, in the midlands and at Dublin Airport, on the east coast are shown in Figures 2.7–2.9. The figures show the actual number of days and 5-year moving average values for these. To illustrate the general trends, a linear regression line, calculated by least squares fitting, is also shown. The number of 'hot' days have increased

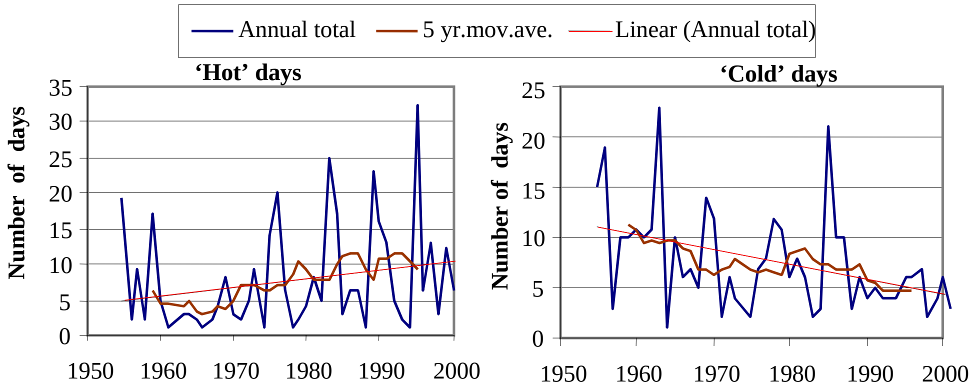

Figure 2.7. Frequency of 'hot' and 'cold' days per year for Birr.

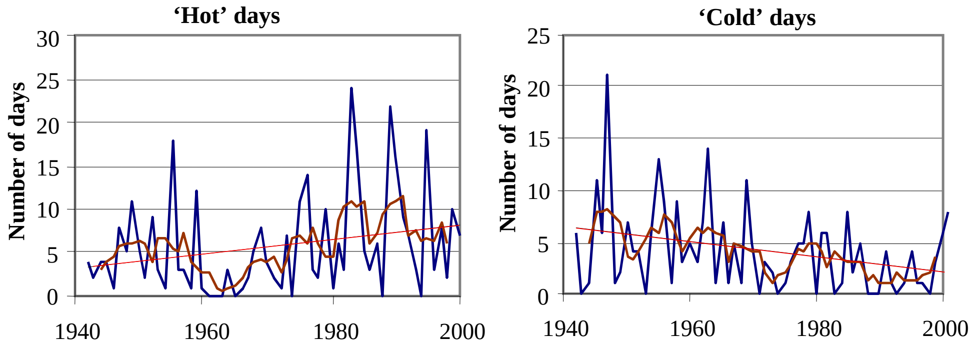

Figure 2.8. Frequency of 'hot' and 'cold' days per year for Dublin Airport.

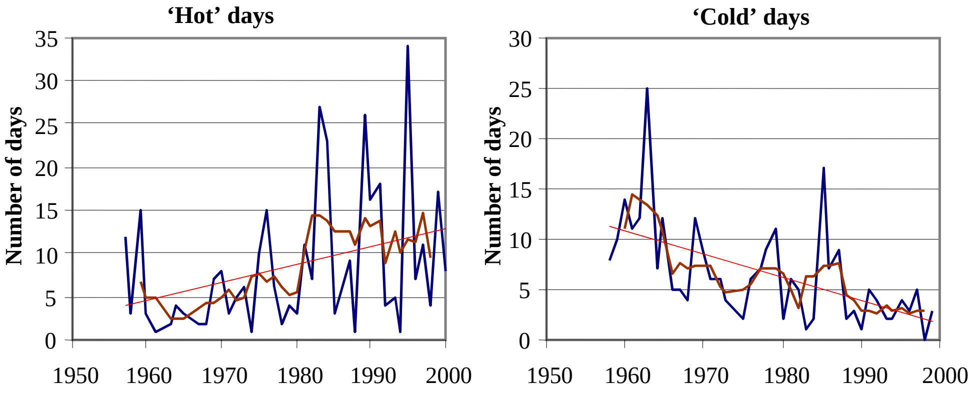

Figure 2.9. Frequency of 'hot' and 'cold' days per year for Kilkenny.

at Birr, Dublin Airport and Kilkenny. In the case of Dublin and Kilkenny, this increase is significant at the 95% significance level.

The number of ‘cold’ days has decreased at Birr (99% significance level), Kilkenny (95% significance level) and Dublin (90% significance level). Over the 1961–1990 period, there were 7 ‘hot’ summer days and 7 ‘cold’ winter days recorded per year on average at Birr and Kilkenny. In 1995, Kilkenny experienced 34 such days, and Birr 32. In 1998, Kilkenny had no ‘cold’ days while Birr had only 2 such days. Dublin had an average of 6 ‘hot’ and 4 ‘cold’ days over the 1961–1990 period. However, there were 19 hot days in 1995 and only 1 cold day in 1992, 1994, 1996 and 1997.

These trends, showing recent increases in the number of hot days and decreasing cold days, are similar to those observed by Hulme (1999a) in the CET record, although there has been little long-term trend in the number of cold days. The estimated return period of temperatures similar to those of 1995 in England is at present 90 years, but expected to be once every 3 years by 2050 (Raper *et al.*, 1997). Obviously if this was the case in Ireland also, it would have severe implications for a variety of sectors including agriculture and water resources. In response to global warming and increases in mean temperature, it may be expected that there will be a continued increase in the frequency of hot days and a decrease in the frequency of cold days in the future.

As indicators of a changing climate these changing frequencies will be expected to show more sensitivity than more conservatively changing parameters such as mean temperature.

2.3.6 First and last day of frost season

Due to the increase in minimum temperatures in spring and autumn, a shorter frost season may be expected, with a reduced number of frost days. This season extends from 1st August to 31st July and is measured when minimum temperatures fall below 0°C. Four representative stations – Dublin Airport, Valentia, Birr and Malin Head – were chosen to examine the changes in date of first and last frost (Figs 2.10–2.13). Different trends were found at these stations. None of these trends are statistically significant. In two stations, Birr and Malin Head, the frost season appears to be shorter, whereas it is getting longer at Dublin Airport and Valentia. In both Malin Head and Birr, the trend is towards an earlier last frost. The last frost at Birr seems to have shifted from the first week in May to the last week of April. At Malin Head, the first frost is approximately 10 days earlier and the last frost is over 2 weeks earlier (changing from mid-March to the beginning of the month). Valentia’s frost season is slightly longer as the last frost is 9–10 days later, and Dublin Airport is also longer because the first frost is approximately 4 days earlier and the last frost is 4 days later.

The occurrence of air frosts can have important consequences for farmers and it is useful to be able to indicate the possible dates of first and last frosts for the purpose of growing frost-sensitive crops. However, continued monitoring should take place with a view to detecting any long-term changes in these data.

2.3.7 Frequency of frost days

The frequency of frost days is likely to be a more sensitive climate change indicator. The recorded sea temperature around the coasts has never fallen to 0°C, and air frost is infrequent at coastal locations. The number of days reporting air frosts from stations on the south and north-west coasts of Ireland are only about 10 per year (Rohan, 1986). Moving inland, however, the number of days with frost increases rapidly, and there can be 50–60 days with air frosts per year in the midlands.

The frequency of frost days at two inland and two coastal stations is shown in Figures 2.14–2.17. There are significant decreases in frost at all four stations, at the 95% level for Birr (Fig. 2.14), Valentia (Fig. 2.15) and Kilkenny (Fig. 2.16), while Rosslare (Fig. 2.17) shows significant decreases in the frequency of frost days at the 99% level. The decline in the actual number of frost days is related to the decline in the number of ‘cold’ days and the general increase in seasonal minimum temperatures.

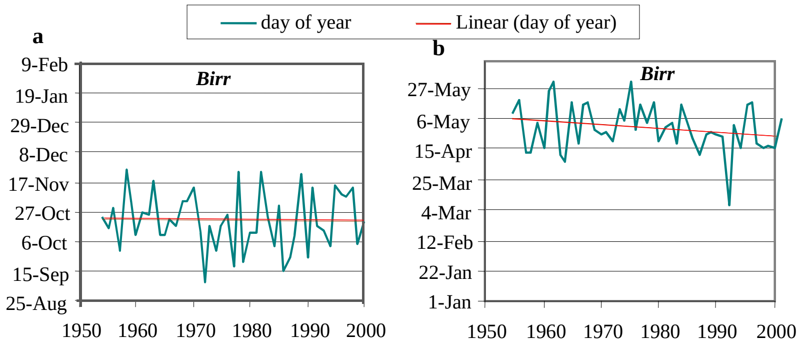

Figure 2.10. Date of (a) first and (b) last frost at Birr.

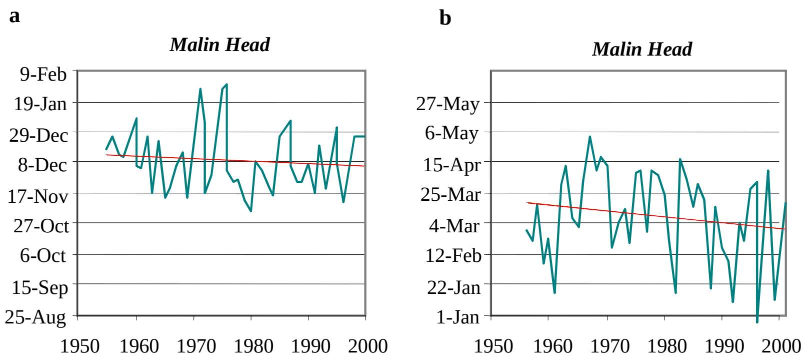

Figure 2.11. Date of (a) first and (b) last frost at Malin Head.

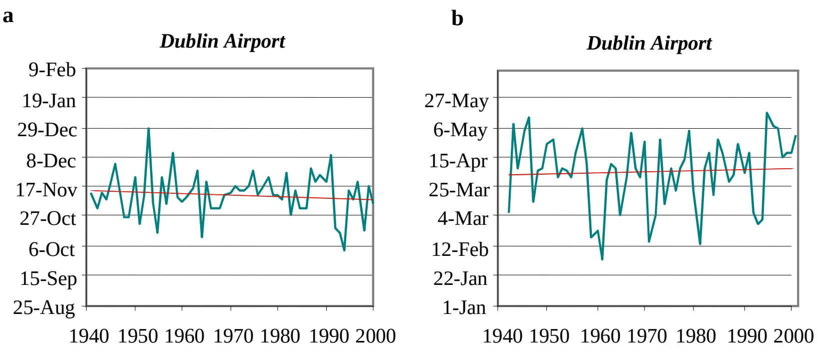

Figure 2.12. Date of (a) first and (b) last frost at Dublin Airport.

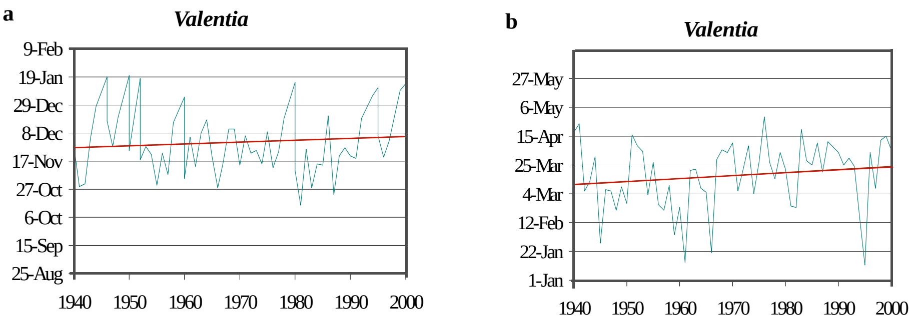

Figure 2.13. Date of (a) first and (b) last frost at Valentia.

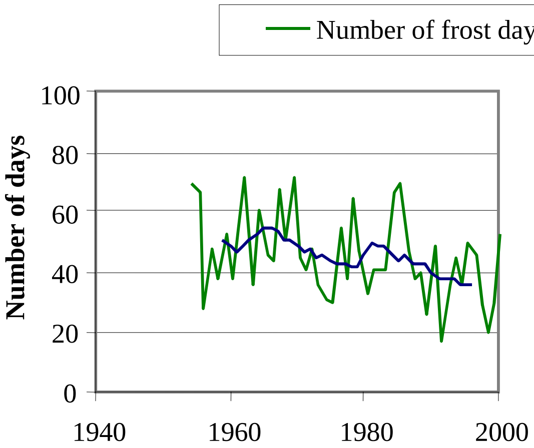

Figure 2.14. Number of frost days per year at Birr.

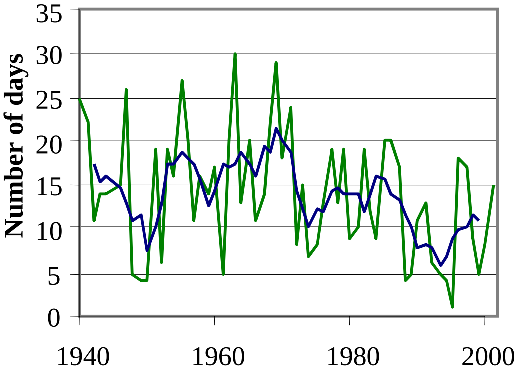

Figure 2.15. Number of frost days per year at Valentia.

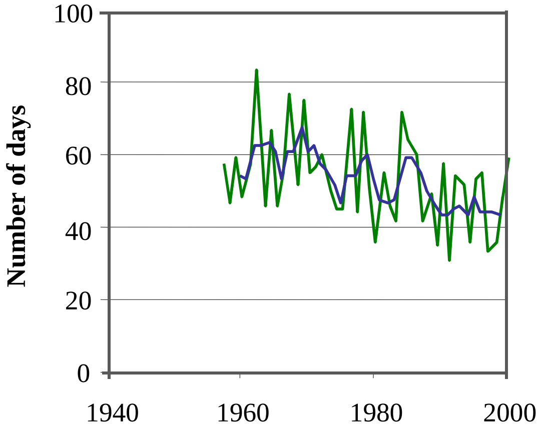

Figure 2.16. Number of frost days per year at Kilkenny.

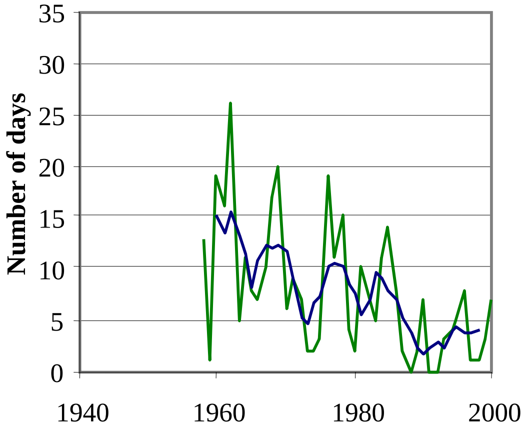

Figure 2.17. Number of frost days per year at Rosslare.

2.4 Precipitation Indicators in Ireland

2.4.1 Long-term precipitation series

Warming of the atmosphere will inevitably cause changes in precipitation due to an intensified hydrological cycle. It is likely that this will have more important impacts on human and environmental systems than any change in temperature. Precipitation has increased by 0.5–1% per decade in the 20th century over most mid and high latitudes. It is also likely that that there has been a 2–4% increase in the frequency of heavy precipitation events (Folland *et al.*, 2001). It is the magnitude and frequency of heavy precipitation that has the most severe consequences, and it is necessary to understand the distribution of these events.

Precipitation in Ireland is generally in the form of rain or drizzle, with hail and snow accounting for only very small percentages of annual totals. In examining precipitation trends, three long-term stations – Malin Head, Birr and Roche’s Point/Rosslare – are considered. The Roche’s Point data end in 1990. This series is supplemented by data for Rosslare for which rainfall amounts were quite similar and follow generally the same trend.

At Malin Head (Fig. 2.18), there is a significant increase in total annual rainfall amounts (at the 99% level). The 10-year moving average shows that rainfall amounts increased from 800 mm in the 1890s to 1150 mm in the 1990s, i.e. an increase of 350 mm over 100 years. Four of the five wettest years at Malin Head occurred in the

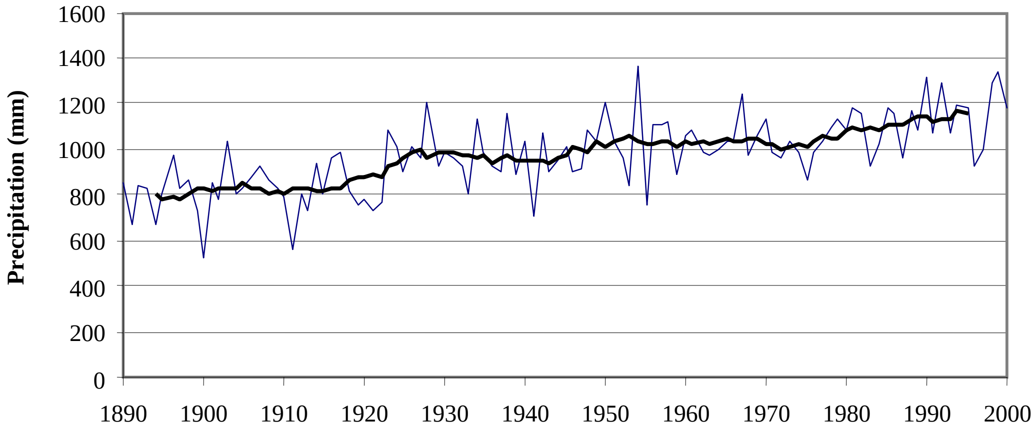

Figure 2.18. Total annual precipitation at Malin Head (thin line) with 10-year moving average (thick line).

1990s. The 1961–1990 mean rainfall total is 1060 mm. This value has been exceeded in most years since the mid-1970s.

No significant trends are found in annual precipitation levels for the Birr (Fig. 2.19) or Roche's Point/Rosslare data (Fig. 2.20). At Birr there was a decrease of 150 mm in the 1960s followed by a steady increase up to 2000. The Roche's Point/Rosslare graph illustrates a general decline in precipitation over the century, although neither Birr nor Roche's Point/Rosslare display any significant trends.

European annual precipitation trends display general wetting in Northern Europe, with increases of between 10 and 40% in the 20th century, and little change or drying in Southern Europe (Parry, 2000). This would appear to match what is happening in Ireland, with increases in the north of the country, and decreases in the south. Climate modelling studies suggest that stronger precipitation gradients from NW to SE are expected to occur in the future (Hulme, 1999b).

2.4.2 Seasonal and geographical distribution of precipitation

Significant seasonal changes in precipitation levels may be masked in annual data. Ten-year moving averages of winter (December, January and February) precipitation totals for Malin Head and summer (June, July and August) precipitation totals for Roche's Point/ Rosslare are shown in Figure 2.21. This indicator was chosen as a measure of the seasonal and geographical distribution of rainfall. There is a clear differentiation between winter and summer precipitation in the North and South of the country, as a result of increasing winter rainfall at Malin Head and decreasing summer rainfall at Roche's Point and Rosslare. At Malin Head, winter precipitation is significantly increasing more than summer precipitation, while at Roche's Point and Birr summer precipitation is

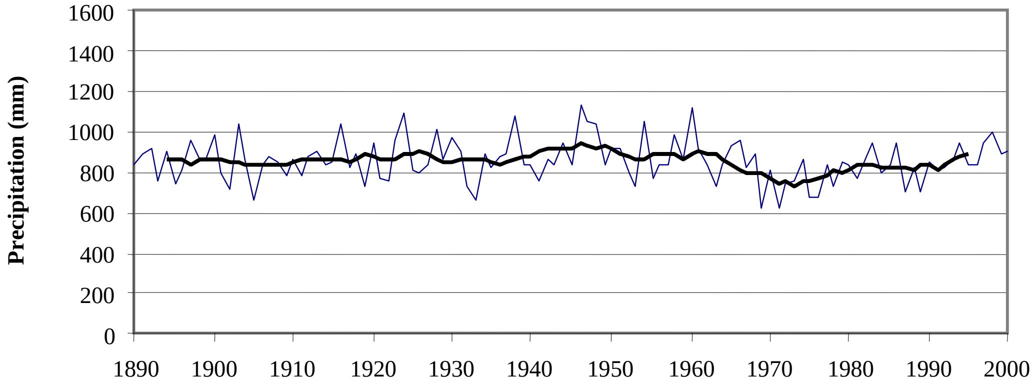

Figure 2.19. Annual precipitation at Birr (thin line) with 10-year moving average (thick line).

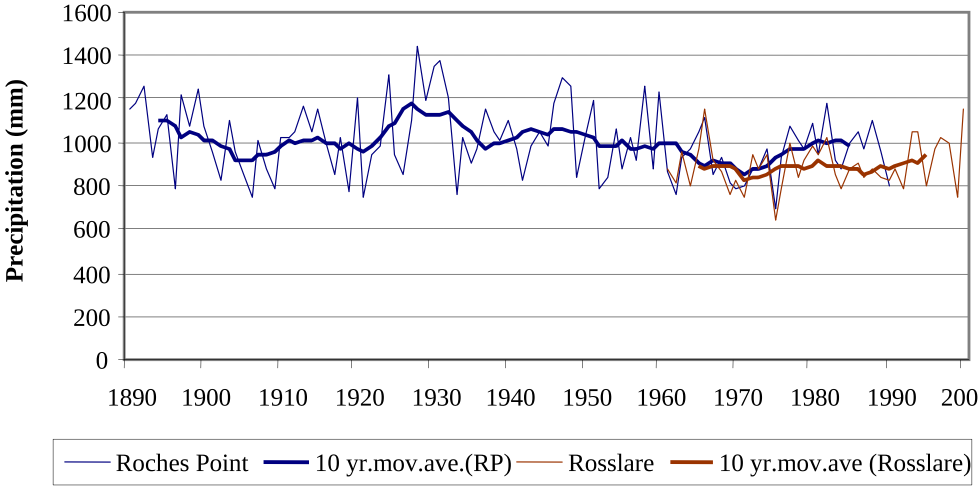

Figure 2.20. Total annual precipitation at Roche's Point (RP) and Rosslare.

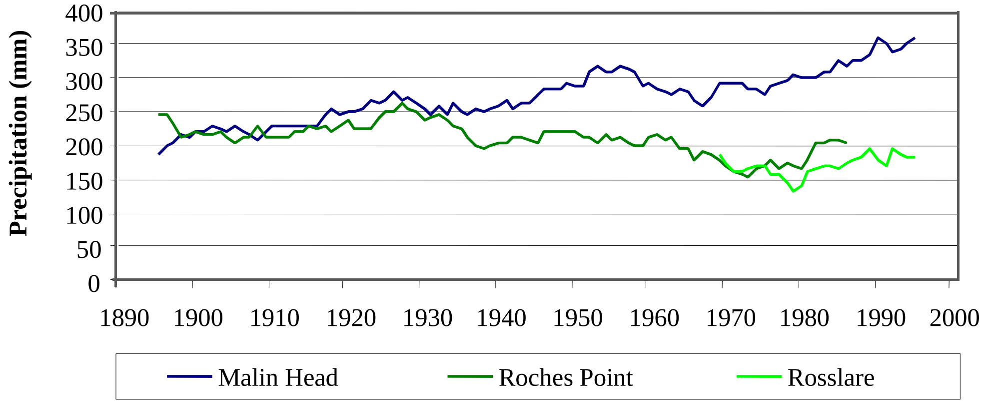

Figure 2.21. 10-year moving averages of Malin Head winter (December, January and February) precipitation, and Roche's Point and Rosslare summer (June, July and August) precipitation.

significantly decreasing more than winter precipitation (at the 95% significance level for Roche's Point, and at the 99% level for Birr and Malin Head). This is similar to an index chosen by Hulme (1999b) which demonstrated increased winter precipitation in Scotland and decreasing summer precipitation in south-east England. The growing disparity between the two rainfall trends may be considered indicative of the climate predictions of global climate models being realised in the Irish rainfall pattern.

2.4.3 Synoptic station precipitation

An index of total annual precipitation for Ireland, based on averaging 11 of 14 synoptic stations, was derived for the period 1960–2000. The selection of stations was based on the completeness of datasets and the length of record available. Figure 2.22 shows a general trend (5-year moving average) of increasing precipitation over the 40-year period, with notable increases especially since the 1970s; 1998 was the wettest year in the synoptic station record, with average precipitation for the country of 1164 mm.

Seasonal averages for precipitation amounts are given in Table 2.2. These figures show that the winter of 1994/1995 was the wettest on record, with a total rainfall receipt of 451 mm. Spring 1981, summer 1985 and autumn 2000 also had high precipitation amounts. Analysis of monthly records indicates that August, October, December and January recorded the highest monthly precipitation amounts – in January 1974, 345

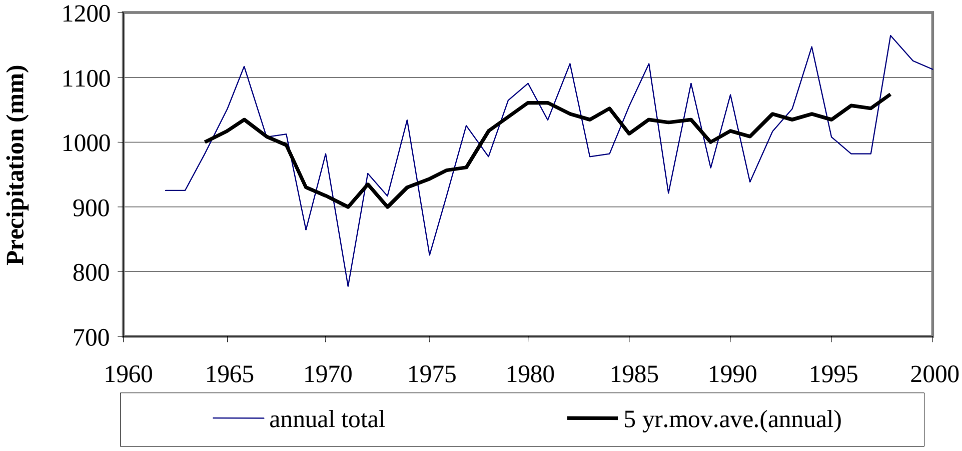

Figure 2.22. Total annual precipitation for 11 synoptic stations.

Table 2.2. Highest total rainfall amounts by season.

Season	Year	Total rainfall amount (mm)
Winter	1994/1995	451
	1993/1994	438
	1989/1990	421
Spring	1981	295
	1986	293
	1994	272
Summer	1985	352
	1997	301
	1998	300
Autumn	2000	430
	1982	378
	1980	373

mm of rain were recorded in Cork, while in October 1977, 322 mm were measured at Valentia. August is the month demonstrating greatest year-to-year variability, especially since 1975/1976. However, there is no long-term trend in rainfall amounts during this month (Fig. 2.23). The highest increase in average precipitation levels occurred in December and February. May and September show the greatest decrease in average precipitation levels.

Analysis of daily records shows that the largest daily rainfall was 116 mm, which was recorded at Valentia on 1st November 1980. However, events such as Hurricane Charley which produced 24-hour falls of up to 280 mm in the Wicklow Mountains on 26th August 1986, and the Mount Merrion thunderstorm on 11th June 1963 which saw 184 mm fall in a 24-h period, with up to 75 mm falling in 1 hour, can occur at more localised stations (Sweeney, 1997).

2.4.4 Annual frequency of ‘rain’ and ‘wet’ days

Variation in precipitation totals can be caused by changes in the frequency of precipitation events or changes in the intensity of rainfall events. A ‘rain’ day is defined as a day of not less than 0.2 mm of precipitation, while a ‘wet’ day is a day having greater than or equal to 1.0 mm. (The use of ‘rain days’ poses some difficulties because of the significant errors associated with detecting and measuring small precipitation amounts due to wetting problems and the relatively large effects of local obstacles and wind speeds on readings at the lower end of the scale.) Daily precipitation data for eight stations for the period from 1940/1950 to 2000 were used to examine whether indicative changes were occurring. Figures 2.24 and 2.25 show that there is an increase in the frequency of ‘rain’ and ‘wet’ days in March and October for all stations, with linear trends indicating increases of 6 and 5 days, respectively, in March, and increases of 3 ‘rain’ and 3 ‘wet’ days in October. There has been a general increase in ‘rain’ and ‘wet’ days in January–April and October and November, with decreases in the May to September period and December. With the exception of March and October, these trends are poorly defined and are not statistically significant.

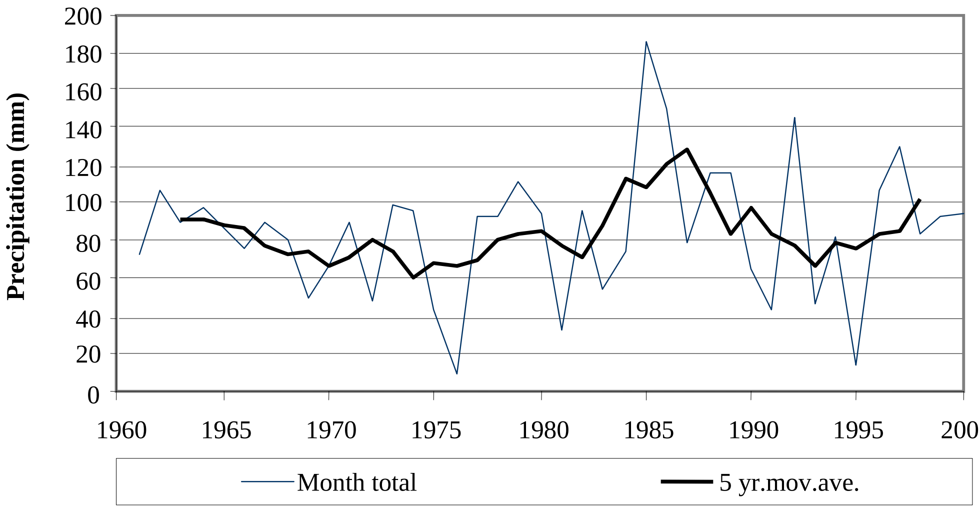

Figure 2.23. Total August precipitation averaged for 11 stations.

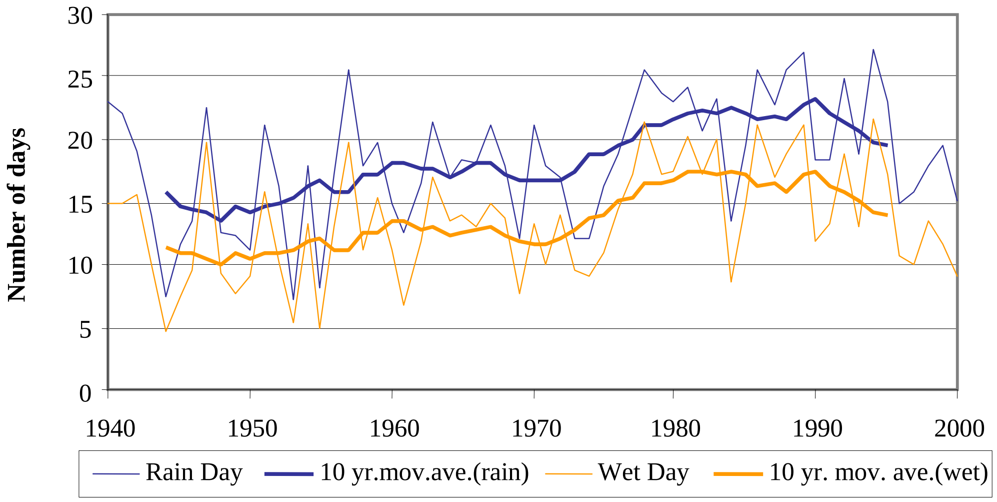

Figure 2.24. Frequency of 'rain' and 'wet' days in March (10yr.mov.ave., 10-year moving average).

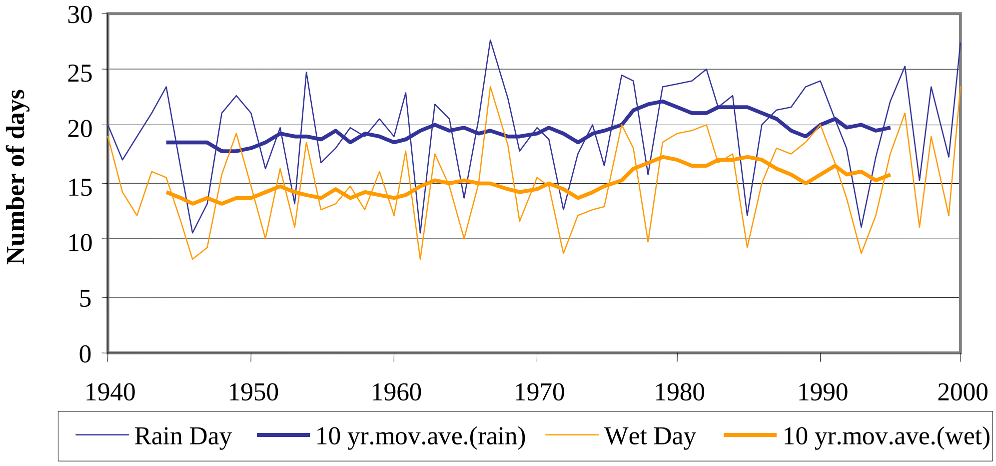

Figure 2.25. Frequency of 'rain' and 'wet' days in October (10yr.mov.ave., 10-year moving average).

2.4.5 Maximum 1-day precipitation events

Changes in maximum 1-day precipitation may indicate an increase in rainfall intensity. Along with increases in intensity, there is also a change in variability. An analysis of data for four stations, which are spread throughout Ireland, indicates the following. The greatest increase in 1-day rainfall intensities and variability occurred at Malin Head during October and December (Fig. 2.26), at Birr during June (Fig. 2.27), at Dublin Airport during October and at Valentia in March (Fig. 2.28). The greatest decrease in rainfall was at Valentia in May (Fig. 2.29) and Dublin in September, where there are decreases of up to 10 mm.

There are large local differences between heavy rainfall events. As a result, it is difficult to ascertain whether the observed changes are the result of climate change. Studies in other countries show that a significant increase or decrease in monthly and seasonal precipitation is directly related to a change in heavy and extreme events (Easterling *et al*., 2000). In the UK, increases in heavy winter rainfall events and decreases in heavy summer rainfall events have been found (Osborne *et al*., 2000), which would seem to correlate with increases in winter precipitation and decreases in summer precipitation.

2.5 Cloud Cover Indicators in Ireland

2.5.1 Global trends

The IPCC Third Assessment Report (2001) concluded that increases in total cloud amount over the Northern Hemisphere mid- and high-latitude continental regions

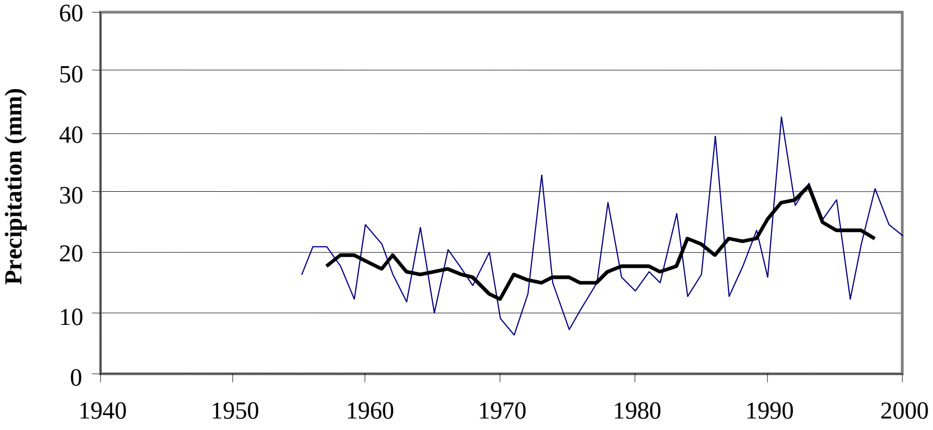

Figure 2.26. Malin Head – maximum 1-day precipitation event (thin line) in December with corresponding 5-year moving average (thick line).

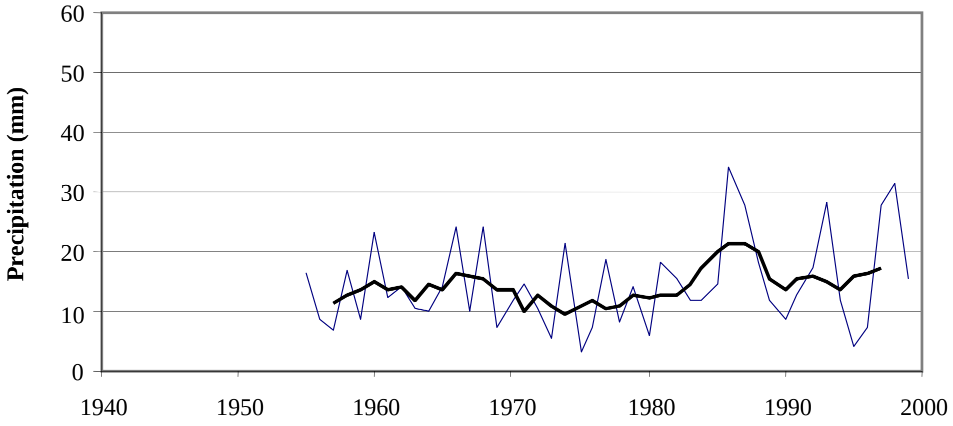

Figure 2.27. Birr – maximum 1-day precipitation event (thin line) in June with corresponding 5-year moving average (thick line).

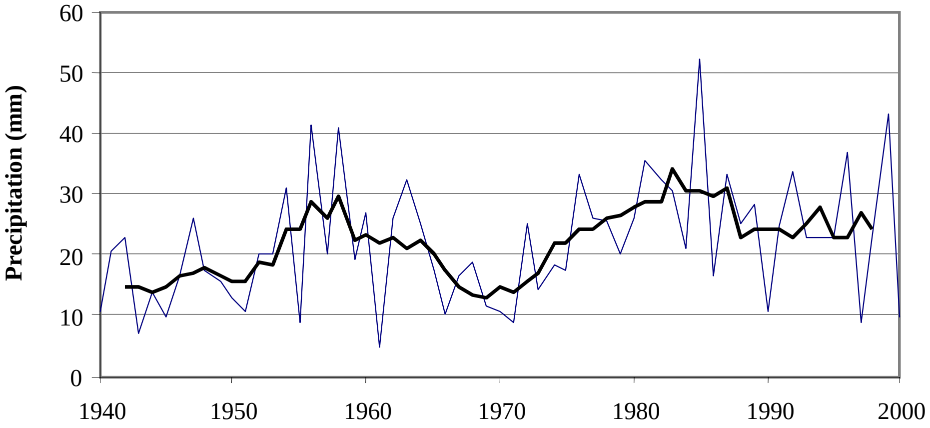

Figure 2.28. Valentia – maximum 1-day precipitation event (thin line) in March with corresponding 5-year moving average (thick line).

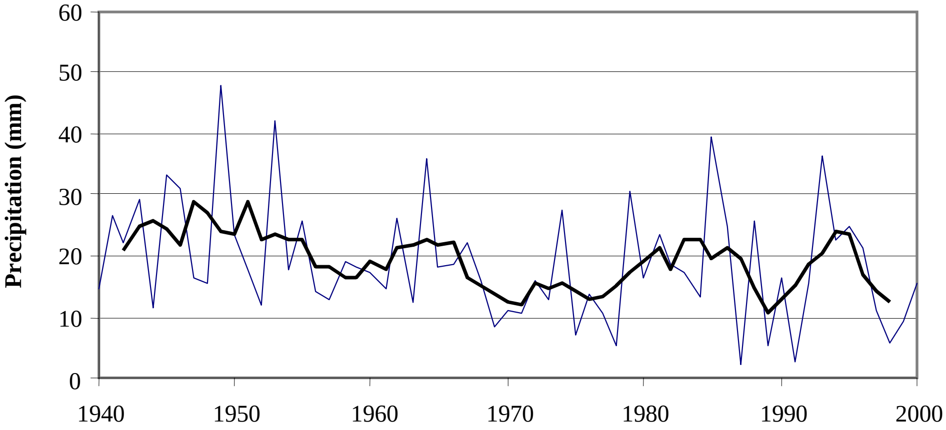

Figure 2.29. Valentia – maximum 1-day precipitation event (thin line) in May with corresponding 5-year moving average (thick line).

had occurred at a rate of 2% since the beginning of the 20th century. These increases have been positively correlated with decreases in the diurnal temperature range and increases in precipitation (Folland *et al*., 2001).

In Ireland, Stanhill (1998) analysed long-term trends in solar radiation and found a significant decrease in the insolation level at Valentia. The decrease in this variable could not be attributed to changes in the extent of cloud cover, as changes in cloud amount were small and insignificant. Analyses of annual cloud amount at Valentia and Malin Head (Figs 2.30 and 2.31) are in agreement with Stanhill's results. At Valentia, there has been a 1% (0.06 okta) increase in cloud amount since 1940, while at Malin Head there has been an increase of 0.8% (0.35 okta) since 1956. Neither of these trends is significant. However, a decrease of 12% in the incident global solar radiation level, measured at Valentia between 1955 and 1991, is considered to reflect important changes in this parameter which warrant further study.

2.6 Irish Climate and Macro-Scale Circulation Indices

2.6.1 North Atlantic Oscillation (NAO)

The North Atlantic Oscillation is based on the difference of normalised sea level pressure between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland (Hurrell, 1995). The index has been calculated for the period since

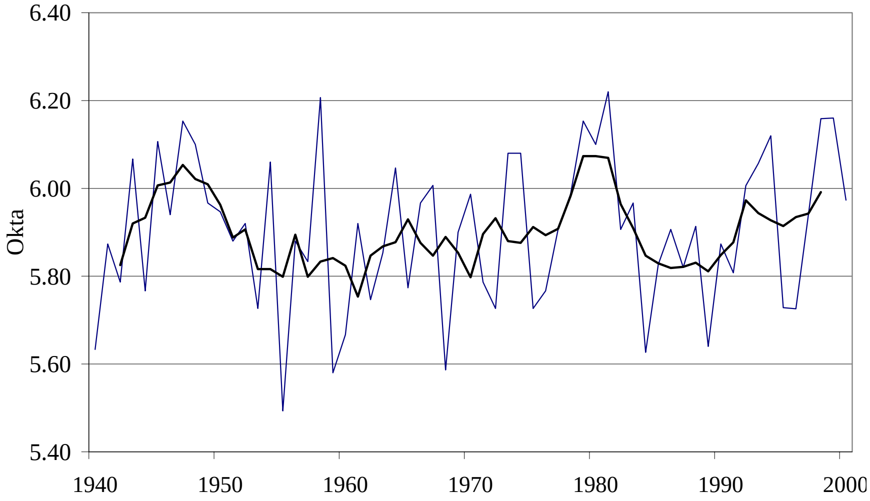

Figure 2.30. Annual cloud amount at Valentia (blue line) with corresponding 5-year moving average (black line).

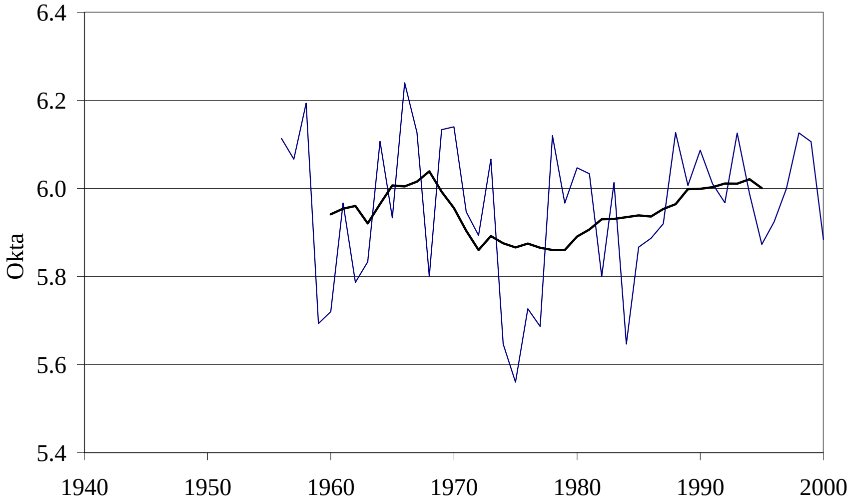

Figure 2.31. Annual cloud amount at Malin Head (blue line) with corresponding 5-year moving average (black line).

1864 and appears to peak every 6–10 years. When the pressure difference is large, with a deep Icelandic low and a strong Azores high, the NAO is said to be in a positive phase, and is negative when the opposite occurs. When in a positive phase, the storm tracks moving across the North Atlantic Ocean are stronger, bringing depressions north-eastward into Europe. A positive NAO index is, therefore, associated with an increase in wind speeds from the west, together with an increase in temperature and rainfall in Northern Europe in winter (Jennings *et al*., 2001). The index is most relevant in winter when the pressure gradients are at their strongest. The wintertime NAO exhibits significant interannual and interdecadal variability (Hurrell, 1995), although it demonstrated a markedly positive phase at the beginning of the century, and again from the mid-1970s until 1990 (Jennings *et al*., 2001). Superimposed on this, however, is high year-to-year variability.

The NAO explains about 30% of the variance of mean winter Northern Hemisphere temperatures (Hurrell, 1996). Strong positive phases are associated with stronger westerly and south-westerly flow and, therefore, milder, wetter weather conditions for Northern Europe and low temperatures in Greenland and south-eastern Europe (Perry, 2000). On the other hand, a negative index points to colder continental conditions in north-west Europe. The index used in this report has been acquired from the Climate Research Unit at the University of East Anglia.

2.6.2 *NAO Index in relation to maximum and minimum winter temperatures at Valentia*

As is evident from Figure 2.32, there is a general agreement between winter maximum and minimum temperatures and the NAO, with the three datasets sharing the same basic variations. The NAO is positively correlated with maximum, minimum and mean temperatures, significant at the 99% level.

2.6.3 *NAO Index in relation to winter temperatures at Malin Head and Valentia*

Wilby *et al.* (1997) found significant positive correlations between the NAO and the Central England Temperature in all seasons except summer and also a positive correlation with the Lamb westerly weather type. In Ireland, there is a positive correlation between the winter NAO index and winter temperatures at both of the long-term west-coast stations, Malin Head and Valentia. Ten-year moving averages of both series plotted alongside each other indicate a clear pattern, with positive phases of the NAO associated with higher temperatures. Figures 2.33 and 2.34 show the relationship between Malin Head winter temperatures and the NAO, while Figures 2.35 and 2.36 show Valentia winter temperatures with the NAO Index. The variation in temperatures at Malin Head and Valentia that is explained by the NAO index is approximately 30% and 50%, respectively.

2.6.4 *NAO Index in relation to total winter precipitation*

Above-normal precipitation occurs in Northern Europe when the NAO is in a positive phase, while the opposite occurs when it is in a negative phase. In western Scotland, flooding has increased in frequency during high NAO winters (Mansell, 1997; Perry, 2000). In Ireland, there is also a significant correlation between winter precipitation and the winter NAO index. Figure 2.37 illustrates the relationship between Malin Head winter rainfall and the NAO index, while Figure 2.38 shows the linear regression by the least squares fitting method.

The NAO is an important mode of natural variability, but it is still uncertain whether this is random or if there are other forces driving it. However, the NAO only explains about 30% of the variation in temperature and precipitation globally so there are still some other elements causing this change. Future research will be needed, therefore, to detect if human-induced global warming is driving the NAO, or whether the NAO and other factors are forcing the warming.

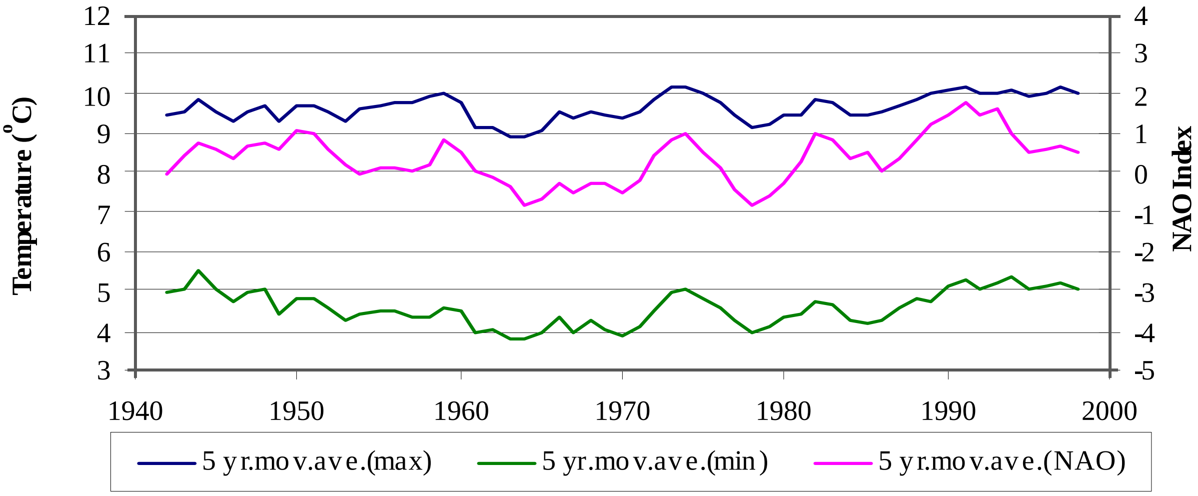

Figure 2.32. Valentia winter mean maximum and mean minimum temperatures in relation to the North Atlantic Oscillation Index. Each trend is a 5-year moving average.

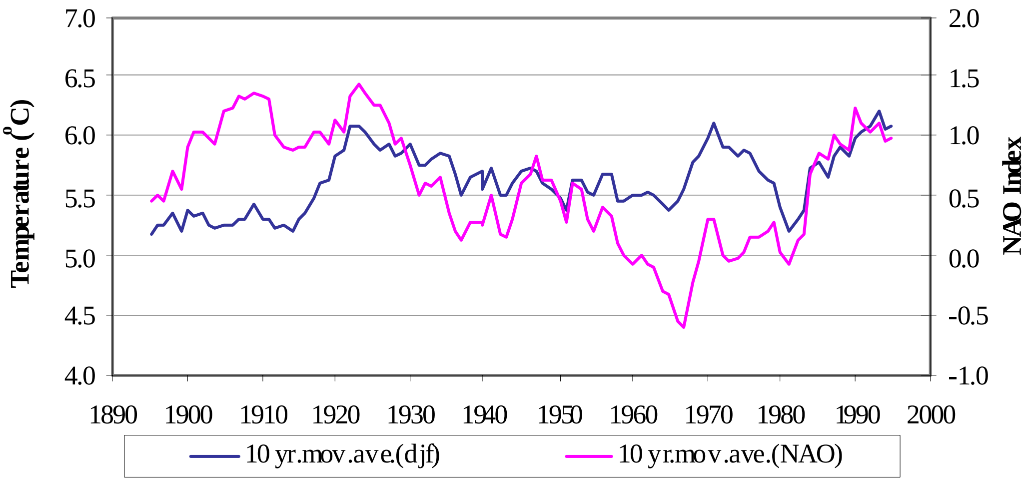

Figure 2.33. Malin Head winter temperature in relation to the North Atlantic Oscillation (NAO) Index (10yr.mov.ave., 10-year moving average; djf, December, January and February).

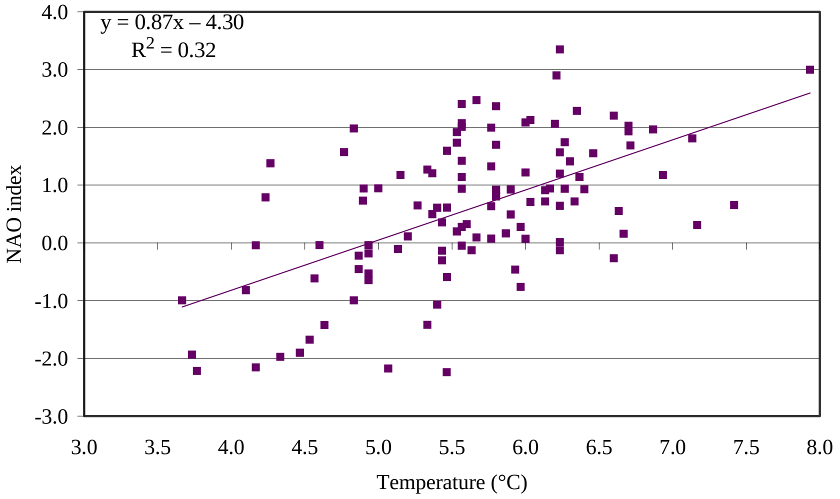

Figure 2.34. Linear regression by least squares fitting – Malin Head in relation to the NAO index.

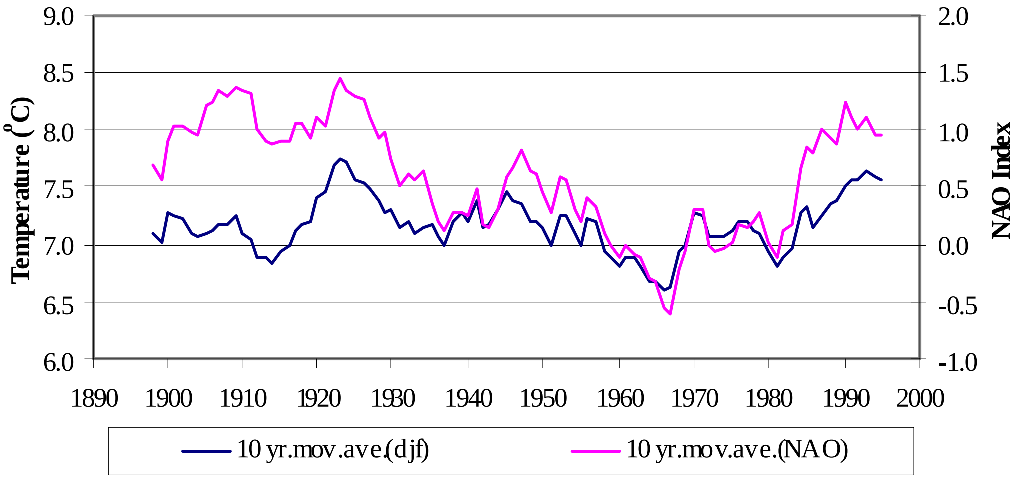

Figure 2.35. Valentia winter temperatures in relation to the North Atlantic Oscillation (NAO) Index (10yr.mov.ave., 10-year moving average; djf, December, January and February).

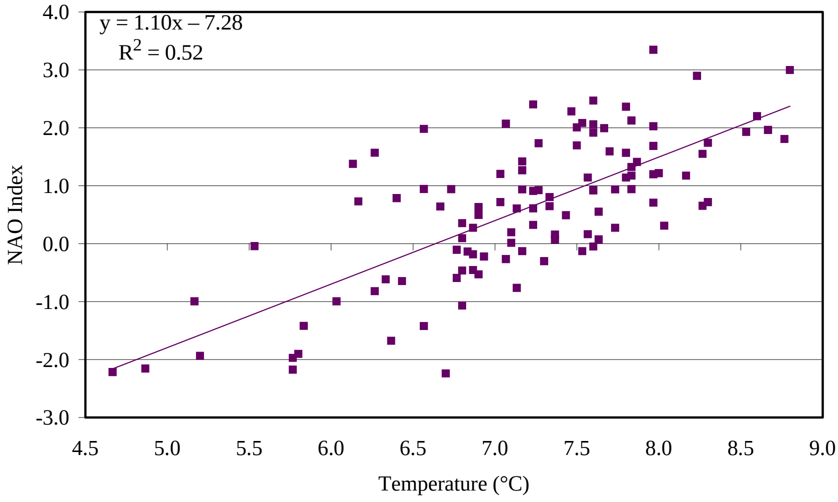

Figure 2.36. Linear regression by least squares fitting – Valentia temperature data in relation to the NAO Index.

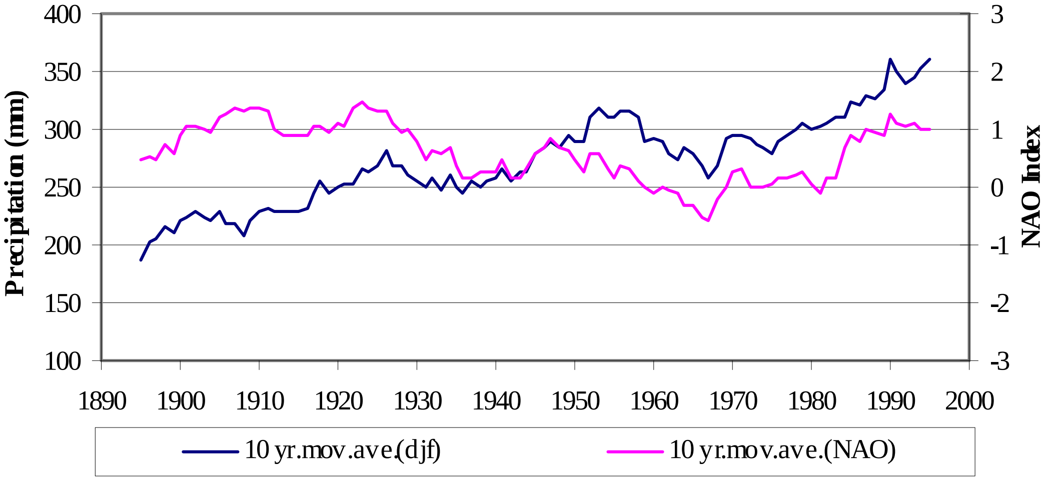

Figure 2.37. Malin Head Winter precipitation and the North Atlantic Oscillation Index (10yr.mov.ave., 10-year moving average; djf, December, January and February).

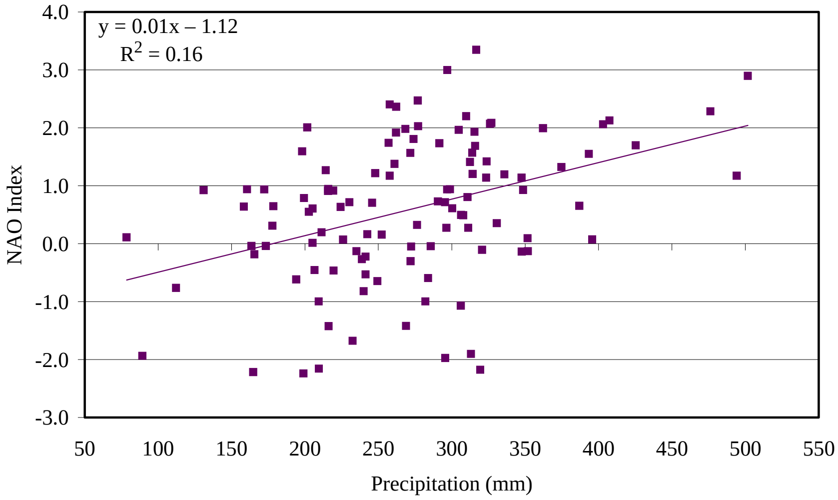

Figure 2.38. Linear regression by least squares fitting – Malin Head winter precipitation in relation to the NAO Index.

2.7 Conclusions

This chapter has presented an assessment of indicators of climate change from the meteorological record. A number of significant trends/indicators have been detected.

An average increase in annual temperature of 0.5°C overall has been observed over the course of the 20th century. This warming has been concentrated in two periods but most significantly in the last decade of the century.

On a shorter time scale, the seasonal maximum and minimum temperatures are increasing at a number of locations. Globally, it is minimum temperatures that are increasing most. This is also observed in Ireland, particularly for the summer months. Increases in both winter maximum and minimum temperatures mean that this season has experienced the greatest warming.

There has been a significant decrease in the frequency of frost days nationally and a general increase in ‘hot’ days and decrease in ‘cold’ days.

A significant increase in the annual precipitation level in the north of the country has been observed. The precipitation level in the south of the country has decreased but the statistical significance of this observation is low.

The critical precipitation indicators are the frequency of ‘rain’ and ‘wet’ days and the intensity of maximum 1-day precipitation events. This indicator shows increases in some months, in some stations, but no overall trend. However, winter increases in precipitation in north-western Ireland appear to be occurring. A decrease in summer precipitation in south-eastern Ireland has also been observed.

The changes outlined above thus appear to be in line with global trends. Given growing confidence that these global trends are driven primarily by anthropogenic influences, there must also be growing confidence that the indicators of climate change established for Ireland are probably also not driven by natural changes. That significant indications of changes in climate can now be detected in an oceanically dominated climatic regime is noteworthy and perhaps indicates that Ireland, while it may lag continental European trends somewhat, will ultimately be as affected as elsewhere by the changes associated with the enhanced greenhouse effect.

3 Secondary Indicators

Secondary indicators of climate change comprise phenomena that are likely to show responses to changes in primary climatic components. Secondary indicators that show a weak correlation with climate variables at present may show a strong correlation in future and *vice versa*. They may also vary spatially over relatively short distances due to prevailing localised considerations, which may subsequently be overwhelmed by regional considerations. For example, an increase in spring temperature is probably strongly correlated with the flowering of particular tree species earlier in the year and this is an indicator of climate change in itself. However, the earlier spring also has relevance to another potential indicator, namely human health, because earlier flowering implies that pollen release episodes will occur earlier, thus affecting pollen sufferers. This chapter assesses the significance of a selection of secondary indicators to climate change in Ireland. Examples of potential indicators are examined with reference to their degree of correlation with chosen climatic parameters.

As mentioned in Chapter 1 (Section 1.3), an indicator describes the state of a phenomenon with a significance extending beyond that directly associated with a parameter value. Indicators considered here include agricultural, biological, social and economic factors.

3.1 Agriculture

Crop model predictions suggest that increases in temperature in the mid-latitudes will increase potential crop yields if the temperature increase is not more than a few degrees centigrade and adequate moisture is available (IPCC, 2001). However, if the temperature increase is more than a few degrees centigrade the potential crop yields will be reduced. Although an increase in temperature can stimulate crop production, the response will depend on the species and cultivar concerned, the soil properties, interaction with various pests and diseases and atmospheric CO_2 concentration. Advances in agronomy and husbandry have resulted in changes in plant breeding, planting dates, fertilisation rates and irrigation, making changes in crop production due to climate change difficult to isolate. Furthermore, market forces and the influence of the European Common Agricultural Policy also alter the nature of crop growing. In this section, an investigation is conducted of the indicator potential of aspects such as the use of irrigation in Irish agriculture, the introduction of new warm-weather crops, and grass and potato production in relation to temperature or rainfall.

3.1.1 Use of irrigation in agriculture

Artificial irrigation systems are not generally associated with Irish agricultural activity, as water is not perceived as a limiting factor to agricultural production. However, during the past 5–6 years, possibly initiated by the 1995 drought, large sprinkler systems have been used during the summer months to supply water, especially to the potato crop. Increases in summer temperatures may give rise to severe soil moisture deficits in summer, which adversely affect the potato crop. In particular, the amount of rainfall in August, when maximum leaf area is achieved, is critical to the development of high quality marketable tubers. As the introduction of irrigation is a relatively new phenomenon, there are no statistics on the type of crops that are receiving their water supply in this way nor are there any data on the area of crops that are irrigated. However, potato growers are increasingly using irrigation and an ‘experienced guess’ would suggest that a figure of 15% of the total main crop (i.e. not including early maturing varieties) is currently being irrigated (Burke, J. (2001) Teagasc, Oakpark Research Centre, Carlow, Ireland, personal communication).

3.1.2 Warm-weather crops

In future, the pattern of farming in Ireland may change due to the expansion of the production area of warm-weather crops such as maize, soybean and grapes. Forage maize has been grown in Ireland since the early 1990s and demand is expected to increase in order to supplement grass fodder for livestock. The establishment of the maize crop has not been specifically due to increases in temperature. Cold-tolerant strains have been successfully bred in order to survive the northern climate.

The data presented in Figure 3.1 are from the same cultivar grown throughout Ireland.

The area under forage maize has increased from 500 ha in 1992 to more than 12,000 ha in 2000 and this trend is expected to continue. Maize yields in 1995 and 1997 are higher than in the other years due to the exceptionally warm summers. The reduced yields in 1993 are due to difficulty in establishment that year.

According to Lister and Subak (1999a) maize yields in the UK will increase if temperatures increase. However, the increase in yield will be limited by the soil moisture content. If soil moisture is reduced, the benefit of increased temperatures will be lost and the crop is not valuable enough to justify the use of irrigation. However, the area under maize production would be expected to expand if temperatures in Ireland increase and this expansion could provide an indicator of climate change.

Currently, there are two commercial vineyards in Co. Cork. Although this shows that it is possible to produce wine in this country, spring frosts and high summer rainfall have the potential to limit production. In future, it may be possible to establish large-scale production of wine if temperatures increase sufficiently. Such increases in the production area of warm-weather crops in Ireland could be used to indicate increasing temperatures.

3.1.3 Grass production in late summer

The production of hay and silage from grass in Ireland is important for supplying winter fodder for livestock. In the UK, in years when the summer temperatures are high, soil moisture is generally low and hay production is adversely affected (Sparks and Potts, 1999). A 1°C increase in the July to August temperature could result in a loss of 0.33 t/ha (Sparks and Potts, 1999). These authors concluded that grass production in late summer could have reduced yields if the temperature increases with no change in rainfall patterns. Conversely, if both rainfall and temperature increase, production could be maintained or increased. However, Jones and Jongen (1997) and Jones and Brereton (1992), using both experimental and model simulation techniques, suggest an increased yield of agricultural grasses in Ireland as a direct fertilising effect of increasing concentrations of atmospheric CO_2 coupled with increasing temperatures. They also point out that interaction with water supply and other environmental variables are unknown at present. These results reveal the complex nature of a changing environment on crop production and the difficulties of predicting future responses to climate changes.

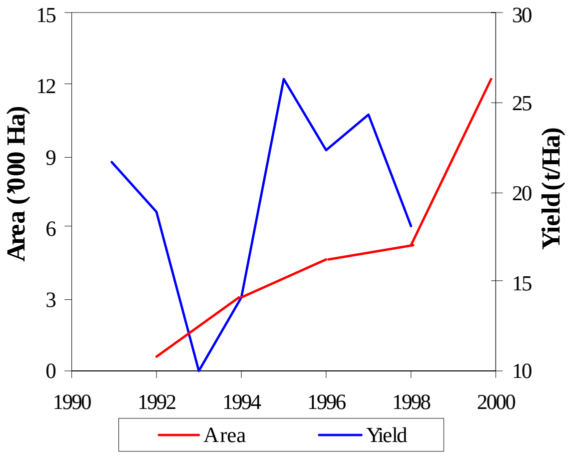

Figure 3.1. Area and yield of forage maize in Ireland.

3.1.4 Potato yields

Potatoes are one of the most important economic crops grown in Ireland. The area for potato production has decreased from 40,000 ha in the early 1960s to nearly half that by 2000 but the yields have increased from 22 to 26 t/ha over the same period (Fig. 3.2a). August rainfall is particularly important in producing high quality marketable tubers and the introduction of irrigation systems will influence the tuber size. Therefore, as regards using potato yields as an indicator of climate change, it is important to consider the non-irrigated main-crop potato yields.

Potato is a shallow rooting plant with a high water requirement for sufficient tuber filling to occur. This makes it particularly vulnerable to drought stress. In the UK, potato yields are strongly correlated to August rainfall and yields can be reduced by as much as 25% during dry summers (Lister and Subak, 1999b). The data presented in Figure 3.2 were taken from the Central Statistics Office Annual Reports and show the average annual yield of potatoes from 1960 to 2000 in relation to August rainfall.

Yields were reduced from an average of 24 t/ha in the 1960s, 1970s and 1980s and increased in the 1990s to 28 t/ha (Fig. 3.2a). It is clear that there is no correlation between main-crop potato yield and August rainfall in Ireland (Fig. 3.2b) unlike that reported for the UK (Lister and Subak, 1999b). In some years, yields were greater in years where August rainfall was high, but there are notable exceptions. In 1963 and 1985, when average August rainfall was relatively high, the yields were low and, conversely, in 1976 and 1995, when rainfall was low, yields did not appear to decrease proportionally. It is difficult to pick out a long-term trend in these data, as new varieties and crop management clearly help to increase yields. However, warmer and drier weather in Ireland during the late summer would be expected to adversely impact on main-crop potato yields if irrigation systems were not used.

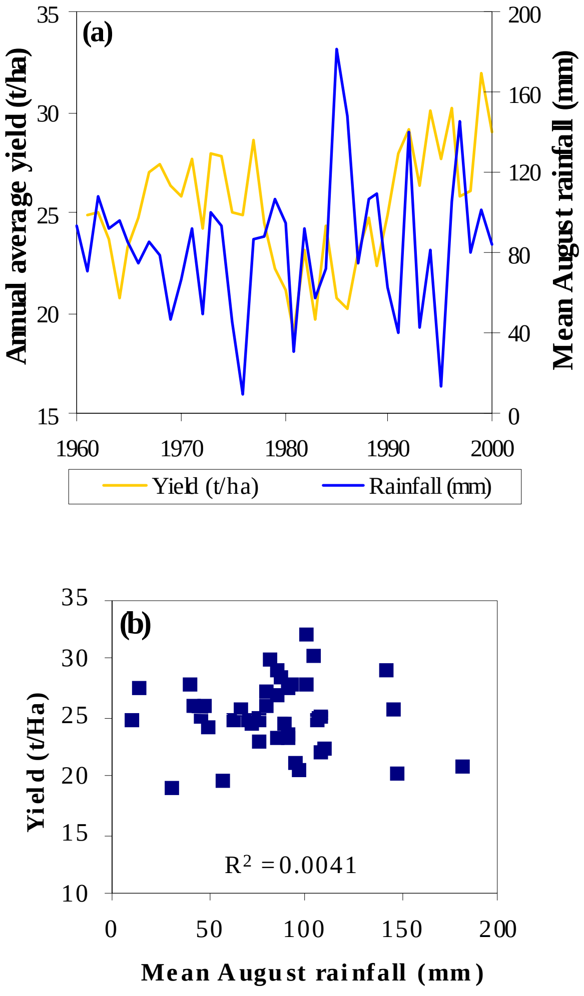

Figure 3.2. (a) Annual average potato yields (t/ha) and rainfall (mm) from 1960 to 2000, (b) yield in relation to mean August rainfall (mm).

During the summer months, weather conditions suitable for blight development are reported regularly in weather bulletins by Met Éireann. The two main climatic factors concerned are temperature and relative humidity. Therefore, any change in these two parameters will affect the conditions necessary for blight development and could be used in future as a possible indicator of climate change.

Conclusions

Agricultural data are influenced by factors such as management, market forces, subsidy payments and agricultural policy. It is, therefore, difficult to identify suitable agricultural indicators for climate change. Advances in science, in particular the breeding of new cultivars tolerant of adverse environmental conditions, make it difficult to isolate climatic influences on agricultural crops. The production area for warm-weather crops such as forage maize and vines may be expected to expand as temperature rises, as would the introduction of new warm-weather varieties. Also a reduction in crop yields of shallow rooting crops such as potato and grass may occur in non-irrigated farms.

In order to establish more suitable indicators of climate change in agriculture, the phenological stages, such as terminal spikelet, flowering and ripening of wheat and various other crops, should be assessed to investigate if they are changing. These data are not available for any long-term periods but would be a valuable climate change indicator.

3.2 Butterflies, Bats and Birds

The appearance, abundance and activity of insects are highly reliant on temperature. Warmer temperatures promote the early appearance of insects (Sparks and Woiwod, 1999). This will have implications for many aspects of human activity due to the effect insects have as pests of the agricultural, horticultural and forestry industries, as well as their effect on human health. However, as yet, there are no data available in Ireland on insect appearance and abundance. In this section, the possibility of using butterflies, bats and birds to indicate changes in temperature is examined.

3.2.1 Butterfly activity

Many species of butterfly in Ireland and Britain are at the limit of their European range and so are vulnerable to small changes in environmental conditions. As such, they may be used as valuable indicators of changes in climate (Asher *et al.,* 2001). There has been an increase in butterfly abundance in Britain in recent years with no apparent increase in habitat area (Asher *et al.,* 2001). Although there could be other causes also, this suggests that an increase in temperature due to climate change could be a contributing factor. During warm, sunny conditions, populations of certain species of butterfly may expand due to greater survival rates of larval and pupal stages. Other species expand their numbers due to high rainfall early in the preceding year. In recent years in the UK, the date of appearance of many butterflies has become earlier, coupled with longer flight times (Roy and Sparks, 2000).

In Ireland, there are few co-ordinated data collected on butterfly appearance, abundance or activity. However, regular pollard walks have been carried out for several years, from 1st April to 30th September, to count species present as well as abundance in the North Slobs, Co. Wexford. These data will be available in the near future (Wilson, C.J., Wexford Wildfowl Reserve, personal communication).

3.2.2 Bat activity

In Ireland, bats and their hibernation behaviour have received little attention. Accordingly, little data are available on their emergence dates (Kelleher, C., Cork County Bat Group, personal communication). In central England, bats hibernate in December and generally remain inactive until March or April. In Ireland, a study of bats in Co. Cork during the winter of 2000, showed that the bats were on the wing most evenings throughout the winter period (Kelleher, C., personal communication). A search of seven known hibernation sites, revealed only eight bats. The difference in behaviour between southern Ireland and central England may be related to the milder climate in southern Ireland resulting in an abundance of insects for food, even in January. However, it is difficult to say whether or not bats were always active in winter in Ireland or if this is a recent phenomenon. The pattern of bat species distribution appears to be changing with records of a northern extension of their range across Europe. Nathusius' pipistrelle (*Pipistrellus nathusii*) is one such bat whose breeding roosts have been recorded in Britain and in the north of Ireland.

3.2.3 Bird activity

Bird populations will be affected by climate change but the exact nature of the influence is difficult to determine (Furness *et al.,* 1993). The use of birds as indicators of climate change in Ireland is complicated by the many other natural and anthropogenic influences that determine their distribution and behaviour. For example, birds may migrate to Ireland if populations become very large elsewhere and they are forced to find new locations. Also, anthropogenic influences, such as changes in land use, the use of pesticides and hunting, have a strong impact on bird populations. Although bird numbers are not well documented in Ireland, BirdWatch Ireland is establishing a Common Bird Census whereby it is proposed to choose certain areas where all bird activity will be monitored on a regular basis. This will establish long-term records of bird activity in specific areas throughout the country.

It has been established that, since the 1980s, several bird species that were not previously recorded in Ireland are now found to be nesting here (Table 3.1). For example, the little egret, which is a Mediterranean species, has been recorded as nesting in Co. Cork since 1997. It should be noted that the habitats and food sources of the birds listed in Table 3.1 have always been present in Ireland. Clearly, it will be important to carefully monitor these birds in future in order to be certain that their move here is permanent and not temporary.

As well as investigating the gains in bird species to Ireland it is also important to examine the losses in species such as the twite (*Carduelis flavirostris*). However, not enough information is available at present to draw strong conclusions as to the reasons for bird species disappearing from Irish habitats.

Table 3.1. Bird species newly nesting in Ireland since 1980 (Cooney, T., personal communication).

Little egret (*Egretta garzetta*)
Reed warbler (*Acrocephalus scirpaceus*)
Pied flycatcher (*Ficedula hypoleuca*)
Bearded tit (*Panurus biarmicus*)
Mediterranean gull (*Larus melanocephalus*)
Goosander (*Mergus merganser*)
Lesser whitethroat (*Sylvia curruca*)
Blackcap (*Sylvia atricapilla*)

It may be more difficult to explain sightings of arctic birds such as species of golden-eye (*Bucephala clangula*), eider (*Somateria mollissima*) and the black-throated diver (*Gavia arctica*) as their distribution would be expected to decrease in warmer winters. Long-term records of behavioural patterns are required in order to draw any conclusions from bird distributions as indicators of climate change.

Monitoring bird species can give information with a significance extending beyond that directly associated with the particular species in question. For example, seabirds that feed off certain fish may be used as an indicator of the fish stocks. If the fish population changes its distribution or disappears then the birds too will seek another area to feed (Newton, S., BirdWatch Ireland, personal communication).

Other important aspects of bird behaviour as indicators of climate change are egg-laying dates and changes in small-bird populations. The egg-laying date of birds is an important parameter in determining the survival and productivity of the population (Crick, 1999a). Temperature and, to a lesser extent, rainfall influence egg-laying dates with higher spring temperatures resulting in earlier egg-laying dates. Resident small-bodied bird populations can be severely reduced during prolonged cold spells in winter due to their inability to gain access to food (Crick, 1999b). The population size is strongly influenced by winter temperature and in severe winters mortality is high. At present, there are no data available, in Ireland, on either egg-laying dates of birds or on small-bird population sizes, but the Common Bird Census should provide valuable information on these two parameters.

The arrival of the swallow (*Hirundo rustica*) is certainly an indication of spring to many people in Ireland. Many of the migratory birds are insectivorous and, therefore, arrive when insect numbers increase and leave when their numbers decline (Sparks, 1999a). Other common birds such as the cuckoo (*Cuculus canorus*), the swift (*Apus apus*) and the house martin (*Delichon urbica*) are associated with spring and together with the swallow are popularly recorded birds across Europe (Sparks, 1999a). The arrival date of these birds to Ireland may be an indicator of climate change, which is resulting in increases in spring temperature. Sparks (1999a) has clearly shown an earlier arrival of spring migrants in recent decades with a strong effect of temperature.

The arrival dates of the swallow and the house martin to the east coast of Ireland have been recorded since 1980 (Cooney, 1980–2000) providing a valuable dataset for examining a possible role of climate change. The arrival dates of these birds have been related to March temperatures at Dublin Airport (Fig. 3.3a–d). The most comprehensive dataset is that of the swallow and, in general, the arrival date was earlier when March temperatures were relatively high. However, there is one notable exception – in 1983 the March temperatures were among the highest in the recording period but the arrival date was the latest in the recording period (Fig. 3.3a). There are less data available for the house martin but the trends are similar (Fig. 3.3c and d). The data show that for every 1°C increase in March temperatures, the swallow and the house martin will arrive approximately 2 and 1 days earlier, respectively. These results suggest that there will be an earlier arrival of some migratory birds in spring with the predicted increase in temperatures. Sparks and Loxton (1999) found a negative relationship between spring temperatures and swallow arrival dates showing that with a 1°C increase in temperature, the arrival date of the swallow is expected to be 2–3 days earlier. Although the data provided thus far indicate that the migrant birds are arriving earlier, more data are needed from sites throughout Ireland to confirm similar patterns on a national scale.

Conclusions

The limited amount of data available on insect abundance and behaviour suggest that, in future, insects, butterflies

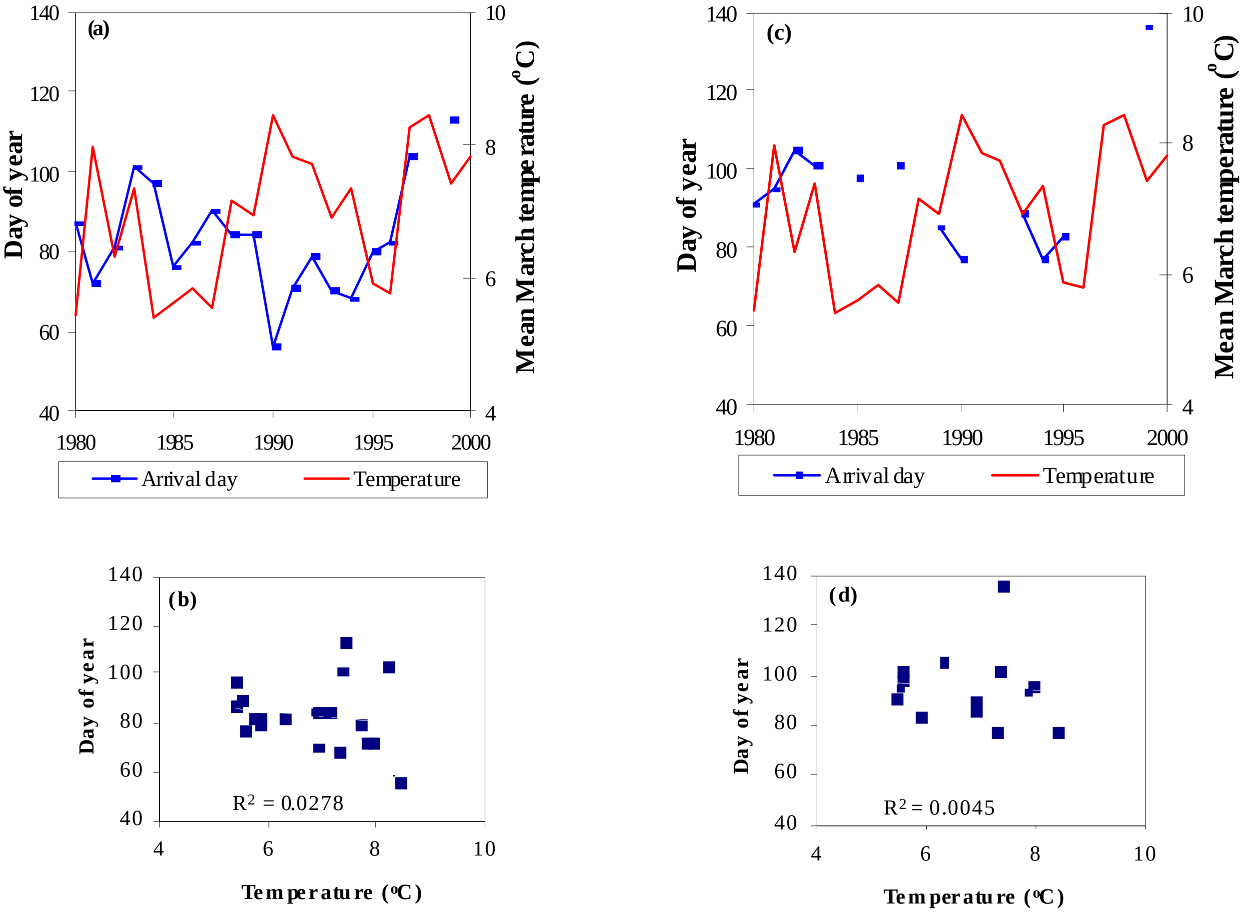

Figure 3.3. The arrival of (a) the swallow and (c) the house martin on the east coast of Ireland from 1980 to 2000, and the arrival of (b) the swallow and (d) the house martin in relation to mean March temperatures at Dublin Airport.

and bats could increase in abundance and activity, in Ireland, and extend their geographical range due to predicted increases in temperature. But in order to draw any firm conclusions in future, it is essential to collect and process more data.

Some migratory species of bird are arriving 1–2 days earlier in spring on the east coast of Ireland, associated with an increase in spring temperatures. The development of the Common Bird Census by BirdWatch Ireland will provide many more data on bird behaviour on a more national scale and add to the information already present. It will be important to monitor the nesting of alien species and the loss of more cold-adapted species.

3.3 Fish

If ocean temperatures around the Irish coastline change in future, this may impact on fish stocks and behaviour. This section will briefly examine the possibility that the appearance of new species of fish in the waters off Ireland might be indicative of climate change and also that changes in the salmon population might reflect an increase in temperature.

3.3.1 Fish stocks

An increase in sea temperature can cause a change in the species of fish that inhabit the waters around Ireland. Mediterranean species, such as red mullet, have been identified as residing off the coast of Co. Cork. In order to establish whether or not the move is temporary or permanent, careful monitoring of its habitat must be carried out.

3.3.2 Salmon run

The number of salmon returning to Irish rivers has been declining in recent years and it is known that salmon are highly sensitive to water temperature (McGinnity, P., Marine Institute, personal communication). Initially, it was thought that this resulted from a decline in the stock. However, when the data for the whole of Europe were examined it transpired that the number of salmon returning to rivers in Norway, and other Scandinavian countries was increasing. It could be hypothesised that changes in water temperature may be affecting the distribution of salmon in Europe, though other influences such as water pollution, fish farming and forestry practices may also be involved. Furthermore, changes to river-water temperature might be more important, as these are critical for breeding. Given such uncertainties it is unlikely that the salmon run is going to be a useful indicator of climate change.

Conclusions

There is limited research on the effect of increasing temperature on fish stocks and behaviour available for Ireland. It is clear that more data are required in this area to draw any reliable conclusions. However, the fact that fish are so sensitive to small changes in water temperature suggests that some aspect of their behaviour could be used as an indicator of climate change.

3.4 Trees

There are numerous ways in which we might expect to be able to infer recent climate change from observations of trees. Phenological observations of trees, such as the dates of leaf unfolding, flowering, leaf discoloration and leaf fall, provide an historical record which may indicate how plants respond to changes in climatic conditions. Trees may, therefore, be used as a secondary indicator of climate change as many developmental phases are strongly influenced by temperature. Changes in the growth rate of trees, crown density and timber production are other possible indicators of recent climate change.

A recent analysis of daily satellite images produced by NASA has shown that parts of the Northern Hemisphere are ‘greener’ for longer in the year than they were 20 years ago (Pearce, 2001). The suggested reason for this is that the increased length of the growing season produces denser forests. Other areas, such as northern Canada, Alaska and the east of Russia appear concurrently ‘browner’, possibly due to more frequent water stress.

Phenology is defined as the study of the relationship between developmental processes in living organisms and seasonal climatic variation. In the mid-latitudes, bud burst, leaf emergence and flowering of many species are dependent on spring air temperature. When spring air temperatures are increased these events occur earlier in the year. Numerous studies (Ahas, 1999; Beaubien and Freeland, 2000; Chmielewski and Rötzer, 2001; Menzel, 2000; Sparks *et al*., 2000) of different species, and at different locations throughout the world, have shown that the timing of spring events has become earlier, largely since the early 1970s. However, the timing of autumn events, such as leaf colouring and leaf fall, has shown less of a change. This suggests that the length of the growing season (LGS) (length of time between spring and autumn events) is increasing, mainly due to the earlier onset of spring and to a lesser extent to a delay in the timing of autumn events. In relation to trees, an increase in the LGS will lead to increased productivity (Myneni *et al.*, 1997) and will also increase the sink for carbon dioxide and help mitigate further increases in atmospheric CO_2 concentrations (White *et al.*, 1999).

The data presented in this section of the report were obtained from the four phenological gardens in Ireland, which are located at Valentia Island, Co. Kerry, the John F. Kennedy Arboretum, Co. Wexford, Johnstown Castle, Co. Wexford and the National Botanic Gardens in Dublin (Fig. 3.4). The data are collated by Met Éireann, and archived at the International Phenological Gardens (IPG) centre, at Humboldt Universität in Berlin.

The IPG network was established in 1959 to collect phenological data from sites across Europe (Chmielewski and Rötzer, 2001). Vegetatively propagated species of trees and shrubs were planted at each site in order to gain comparable results. There are 50 IPGs throughout Europe, recording data from 23 species. For the purpose of the present study, data collected from three of the nine recorded species in Ireland (Table 3.2) were used to demonstrate relationships between climate and phenology. The phenological stages, for each species, were the beginning of unfolding of the leaf (which is considered to be the beginning of the growing season) (BGS) and leaf fall (LF). The length of the growing

Table 3.2. Tree species on which observations were made at each of the four phenological gardens. A tick mark indicates the presence of a species.

Species	Valentia Island	John F. Kennedy Arboretum	Johnstown Castle	National Botanic Gardens
Betula pubescens	✓	✓	✓	✓
Fagus sylvatica				
‘Har’	✓	✓	✓	
‘Tri’	✓	✓		
‘Dud’		✓	✓	
Populus canescens	✓	✓	✓	✓
Populus tremula	✓	✓	✓	✓
Prunus avium				
‘Bov’	✓	✓	✓	✓
‘Lut’	✓	✓	✓	✓
Sorbus aucuparia	✓	✓		
Tilia cordata	✓	✓	✓	✓
Salix aurita	✓	✓		✓
Salix acutifolia	✓	✓	✓	✓
Salix x *smithiana*	✓	✓	✓	
Salix viminalis	✓	✓	✓	
Salix glauca		✓		
Ribes alpinum			✓	✓
Robinia pseudoacacia		✓		✓

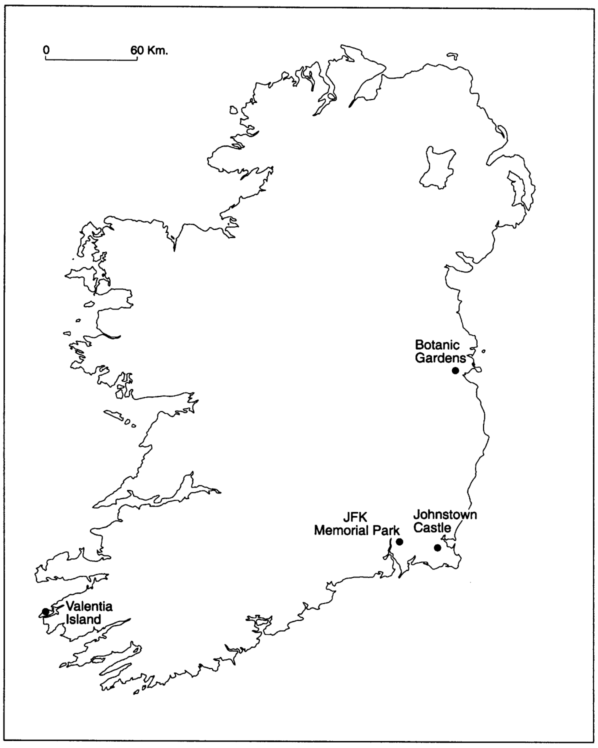

Figure 3.4. Location of the four phenological gardens in Ireland.

season (LGS) was determined by the number of days between the BGS and LF.

3.4.1 *Climatic data*

In order to establish the trends in phenological stages in relation to climate, air temperature data from synoptic weather stations close to each of the phenological gardens were examined. Daily data from synoptic stations at Valentia Observatory for Valentia Island, Rosslare, for both the John F. Kennedy Arboretum and Johnstown Castle, and Dublin Airport for the National Botanic Gardens, were used.

3.4.2 *Results*

Figures 3.5–3.11 show the beginning of the growing season (BGS), as determined by the unfolding of the leaves, leaf fall (LF) and the length of the growing season (LGS) for *Betula pubescens*, *Fagus sylvatica* ‘Har’ and *Tilia cordata* for the 30-year period from 1970 to 2000. These species were chosen as they are common to all sites (except for *Fagus sylvatica* ‘Har’ which was not grown in the National Botanic Gardens) and because the necessary phenological phases were already recorded. These data for the four phenological gardens are tabulated in Table 3.3.

3.4.3 Length of the growing season (LGS)

Over the period of observations, the average LGS as determined by the number of days between the BGS and LF, ranged between 168 (*Fagus sylvatica* 'Tri', Valentia) and 235 (*Prunus*, National Botanic Gardens, Dublin) reflecting the variation across the species range. On average, the LGS was longer at Johnstown Castle and the National Botanic Gardens than at the other locations.

At the Valentia garden, the length of the growing season has become significantly longer since 1970 for most of the species recorded (Table 3.3). However, there was largely no change in the length of the growing season at the other sites. However, the LGS decreased for at least one species at all other sites.

There was a strong positive correlation between length of the growing season and average annual temperature at Valentia (Table 3.4). Figures 3.5–3.7 show the length of the growing season for the three species being examined, at each of the four phenological gardens, in relation to annual air temperature. With an increase of 1°C in the annual temperature, the length of the growing season (averaged across the four sites) for *Betula pubescens*, *Fagus sylvatica* 'Har' and *Tilia cordata* is expected to be 9, 3 and 7 days longer.

The LGS is determined by changes to the BGS and LF. These phenological stages are now considered in more detail.

3.4.4 Beginning of the growing season (BGS)

The BGS data are presented in Table 3.3. A negative slope indicates an earlier beginning of the growing season. The slopes that are printed in 'bold' are significantly different from zero. Over the 30 years of observation, the BGS ranged between 81 (*Prunus avium*, National Botanic Gardens) and 139 (*Robinia pseudoacacia*, John F. Kennedy Arboretum), reflecting the variation across the range of species. The BGS for *Betula pubescens* (Fig. 3.8), *Prunus avium, Salix*, and *Robinia pseudoacacia* did not differ between the four sites. However, the BGS for the remaining species showed considerable variation. The BGS for *Fagus sylvatica* ($P < 0.01$) (Fig. 3.9) and *Sorbus aucuparia* ($P < 0.01$) was significantly later at the John F. Kennedy Arboretum, compared to the other sites, whereas, at Johnstown Castle, the BGS was earlier for *Populus* ($P < 0.01$) and *Ribes alpinum* ($P < 0.01$), and later for *Salix* ($P < 0.05$), than at the other sites. Finally, the BGS for *Tilia cordata* ($P < 0.01$) (Fig. 3.10) was later at the National Botanic Gardens in Dublin compared to the other sites.

The Valentia data in Table 3.3 show a significantly earlier beginning of the growing season between 1970 and 2000. An earlier onset in the BGS is also evident for a number of species at all other sites. However, the BGS was later for *Prunus avium* at the National Botanic Garden and for *Salix* at Johnstown Castle.

The rate of decline in the BGS varied significantly between the sites for most species (Table 3.3). However, for all species at Valentia Island, there was a faster rate of decline than observed at the other sites, as indicated by a larger negative slope value.

The beginning of the growing season was strongly influenced by spring-air temperature (February to April) (Table 3.5, Figs. 3.10–3.12). There was a strong negative correlation between the average (February to April) air temperature and the beginning of the growing season, at all sites, suggesting that as spring temperature increases the BGS is earlier in the year. The beginning of the growing season is largely influenced by average monthly temperature in March at all sites except the John F. Kennedy Arboretum where February temperatures show the strongest correlation (Table 3.5). Surprisingly, there is no correlation between average monthly temperature (January to April) and unfolding of leaves of *Salix* at Johnstown Castle and the pattern is also less clear at Valentia Island for this particular species. With an increase of 1°C in the spring temperature the beginning of the growing season (averaged across the four sites) for *Betula pubescens*, *Fagus sylvatica* 'Har' and *Tilia cordata* is expected to be 5, 6 and 8 days earlier, respectively. This is in agreement with Sparks (1999b) who reported a 6-day advancement in leafing of oak with an increase of 1°C in spring temperature.

Table 3.3. Average values, from start of recording, for the beginning of the growing season (BGS), leaf fall (LF) (day of year) and the length of the growing season (LGS) (days) at the four phenological gardens, with corresponding standard errors. Values printed in italics are significantly different from the other sites. Slopes printed in bold are significantly different from zero and slopes underlined are significantly different from the other sites. P values in ANOVA columns show significant differences between sites. n.s., not significant (n.a., data not available).

Species	Valentia Island			John F. Kennedy Arboretum			Johnstown Castle			National Botanic Gardens			ANOVA		
	BGS	LF	LGS	BGS	LF	LGS	BGS	LF	LGS	BGS	LF	LGS	BGS	LF	LGS
Betula pubescens	94 ± 2.0	295 ± 2.1	199 ± 3.1	98 ± 1.7	296 ± 1.9	198 ± 2.5	94 ± 1.8	301 ± 1.9	207 ± 2.7	100 ± 2.7	*324 ±1.0*	224 ± 3.2	n.s.	P<0.01	n.s.
Slope	–**0.44**	–0.02	0.55	–0.06	–**1.12**	–**0.95**	–**0.52**	0.14	**0.63**	–**0.38**	–0.05	0.37	n.s.	P<0.001	P<0.05
Fagus sylvatica															
‘Har’	110 ± 1.7	287 ± 2.7	176 ± 3.9	*116 ± 1.3*	293 ± 1.7	176 ± 2.0	110 ± 1.5	*305 ± 1.6*	*194 ± 1.9*	n.a.	n.a.	n.a.	P<0.01	P<0.01	P<0.05
Slope	–**0.72**	**1.68**	**2.52**	–**0.29**	–0.04	–0.12	0.06	0.26	0.32	n.a.	n.a.	n.a.	P<0.01	P<0.001	P<0.01
‘Tri’	116 ± 1.8	282 ± 3.7	168 ± 4.9	*126 ± 1.0*	302 ± 1.7	176 ± 2.1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	P<0.01	P<0.01	P<0.01
Slope	–**1.06**	**2.19**	**3.25**	–**0.34**	–0.04	–0.02	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	P<0.01	P<0.001	P<0.01
‘Dud’	n.a.	n.a.	n.a.	*121 ± 1.4*	297 ± 2.6	177 ± 2.1	114 ± 1.3	306 ± 1.5	*192 ± 2.0*	n.a.	n.a.	n.a.	P<0.01	P<0.01	P<0.01
Slope	n.a.	n.a.	n.a.	–**0.56**	–0.04	–0.07	–0.01	–0.05	0.15	n.a.	n.a.	n.a.	P<0.01	n.s.	n.s.
Populus canescens	114 ± 1.8	290 ± 1.1	179 ± 2.0	114 ± 1.6	290 ± 1.5	172 ± 2.0	*108 ± 2.3*	305 ± 2.2	*201 ± 3.2*	113 ± 1.1	*339 ±2.3*	226 ± 3.0	P<0.05	P<0.01	P<0.01
Slope	–**0.73**	0.29	**1.08**	–0.00	–**1.18**	0.14	–**0.95**	0.39	**1.14**	0.01	–**1.22**	–**3.80**	P<0.01	P<0.01	P<0.01
Populus tremula	116 ± 2.5	288 ± 1.2	179 ± 2.5	121 ± 1.8	298 ± 1.9	176 ± 2.5	*102 ± 0.8*	*310 ± 1.5*	*209 ± 1.4*	116 + 0.8	n.a.	n.a.	P<0.01	P<0.01	P<0.01
Slope	–**1.22**	0.32	**1.57**	–0.02	–0.13	0.04	0.30	**0.75**	0.43	0.23	n.a.	n.a.	P<0.01	n.s.	n.s.
Prunus avium															
‘Bov’	93 ± 1.8	287 ± 2.1	186 ± 3.1	97 ± 2.1	n.a.	n.a.	100 ± 1.9	301 ± 2.1	203 ± 2.7	81 ± 3.3	*315± 1.0*	*235 ± 3.4*	n.s.	P<0.01	P<0.05
Slope	–**1.27**	**1.18**	**2.63**	–**0.68**	n.a.	n.a.	–**0.93**	–0.01	0.52	**1.72**	0.18	–**1.54**	P<0.01	P<0.01	P<0.001
‘Lut’	95 ± 1.8	277 ± 2.9	183 ± 2.9	98 ± 1.9	n.a.	n.a.	97 ± 2.0	300 ± 2.2	206 ± 2.7	81 ± 3.3	*316± 0.6*	*235 ± 2.3*	n.s.	P<0.01	P<0.01
Slope	–**1.20**	**1.19**	**2.71**	–**0.40**	n.a.	n.a.	–**1.03**	0.22	0.82	**1.74**	0.20	–**1.54**	P<0.01	P<0.05	P<0.01
Sorbus aucuparia	104 ± 2.1	285 ± 2.2	186 ± 3.1	*112 ± 1.2*	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	P<0.01	n.a.	n.a.
Slope	–**1.02**	**1.11**	**2.07**	0.13	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	P<0.01	n.a.	n.a.
Tilia cordata	108 ± 1.9	*286 ± 2.9*	182 ± 4.6	116 ± 1.2	302 ±1.4	183 ±1.4	108 ± 2.1	302 ± 2.3	196 ± 3.3	*126 ± 0.9*	316 ±0.5	190±0.8	P<0.01	P<0.01	P<0.05
Slope	–**0.85**	**2.07**	**3.49**	0.19	–0.30	–0.32	–**0.95**	0.07	0.99	–0.18	0.12	0.47	P<0.01	P<0.01	P<0.001
Salix acutifolia	89 ± 1.8	303 ± 1.9	220 ± 1.9	n.a.	n.a.	n.a.	90 ± 1.4	307 + 1.5	220 + 1.9	n.a.	n.a.	n.a.	n.s.	n.s.	n.s.
Slope	–0.50	0.62	1.25	n.a.	n.a.	n.a.	0.62	**0.60**	–1.28	n.a.	n.a.	n.a.	n.s.	n.s.	n.s.
‘X smithiana’	83 ± 1.1	306 ± 1.9	225 ± 2.2	n.a.	n.a.	n.a.	*94 ± 1.7*	309 + 1.5	215 + 2.1	n.a.	n.a.	n.a.	P<0.05	n.s.	n.s.
Slope	–0.36	0.63	1.35	n.a.	n.a.	n.a.	**1.23**	0.70	–**1.91**	n.a.	n.a.	n.a.	n.s.	n.s.	n.s.
Ribes alpinum	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	*94 ± 1.5*	307 ± 1.7	214 ± 2.3	97 ± 1.4	*317 ±1.2*	221 ± 2.3	n.s.	P<0.01	P<0.01
Slope	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	–**0.55**	0.24	0.75	–**0.72**	0.12	0.47	n.s.	n.s.	n.s.
Robinia pseudoacacia	n.a.	n.a.	n.a.	139 ± 1.7	n.a.	n.a.	n.a.	n.a.	n.a.	137 ± 1.5	325 ±1.8	187 ± 1.3	n.s.	n.a.	n.a.
Slope	n.a.	n.a.	n.a.	0.19	n.a.	n.a.	n.a.	n.a.	n.a.	–**0.57**	–**0.45**	0.41	P<0.01	n.a.	n.a.

In summary, the beginning of the growing season can start as early as the end of March or as late as mid-May, depending on the species in question. Also, location can have an influence on the beginning of the growing season as not all leaf unfolding occurred at the same time at each site. However, the fact that the beginning of the growing season is occurring earlier is undisputed, as leaf unfolding has occurred earlier at all sites for at least some of the species. The rate of decline in the time to the beginning of the growing season was greatest at Valentia. Spring events are earlier throughout Ireland, but location will have a certain amount of influence on how early spring will begin. If spring temperatures increase by 1°C, the beginning of the growing season will be approximately 1 week earlier.

3.4.5 Leaf fall (LF)

Since recording began, the day of the year when LF occurred ranged between 282 (*Fagus sylvatica* 'Tri', Valentia, Fig. 3.11a) and 339 (*Populus canescens*, National Botanic Gardens, Dublin) reflecting the range between species. Within species, the day of the year on which leaf fall occurred was largely unchanged between 1970 and 2000 (Table 3.3, Fig. 3.11) as the slopes were not significantly different from zero. However, at the Valentia Island site, LF tended to occur later (from 1970 to 2000) for most of the species recorded. Valentia Island showed a faster rate of advancement in LF than the other sites, as indicated by steeper regression lines.

In general, LF was latest in the National Botanic Gardens compared to the other sites. Leaf fall became earlier in the year over the recording period at the John F. Kennedy Arboretum for *Betula pubescens* and *Populus canescens* and at the National Botanic Gardens for *Populus canescens* and *Robinia pseudoacacia*. LF was latest at Johnstown Castle for *Fagus sylvatica* 'Har' ($P < 0.01$) (Fig. 3.11c). At Valentia Island, LF for *Tilia cordata* ($P < 0.01$) was earlier than at the other locations (Fig. 3.11c).

Table 3.4. Correlation between the average annual temperature and the length of the growing season (LGS) at each site (numbers in bold indicate significance at 99% level; n.a., data not available).

Species	Valentia Island	John F. Kennedy Arboretum	Johnstown Castle	National Botanic Gardens
Betula pubescens	**0.38**	**–0.30**	**–0.31**	–0.02
Fagus sylvatica				
'Har'	**0.35**	0.03	**–0.29**	n.a.
'Tri'	**0.51**	0.01	n.a.	n.a.
'Dud'	n.a.	–0.20	**–0.13**	n.a.
'Danemark'	n.a.	–0.02	n.a.	n.a.
Populus canescens	**0.46**	**–0.45**	**–0.14**	n.a.
Populus tremula	**–0.37**	**–0.50**	–0.08	n.a.
Prunus avium		–	–	
'Bov'	**0.40**	–0.12	**–0.13**	n.a.
'Lut'	**0.34**	0.35	**0.15**	n.a.
Sorbus aucuparia	**0.25**	0.62	n.a.	n.a.
Tilia cordata	**0.47**	0.32	**–0.16**	**0.36**
Salix aurita	**–0.31**	n.a.	n.a.	n.a.
Salix acutifolia	0.08	n.a.	–0.21	n.a.
Salix x *smithiana*	**–0.35**	n.a.	0.02	n.a.
Salix viminalis	**–0.27**	n.a.	0.08	n.a.
Salix glauca	n.a.	n.a.	n.a.	n.a.
Ribes alpinum	n.a.	n.a.	0.04	**0.37**
Robinia pseudoacacia	n.a.	**0.88**	n.a.	0.02

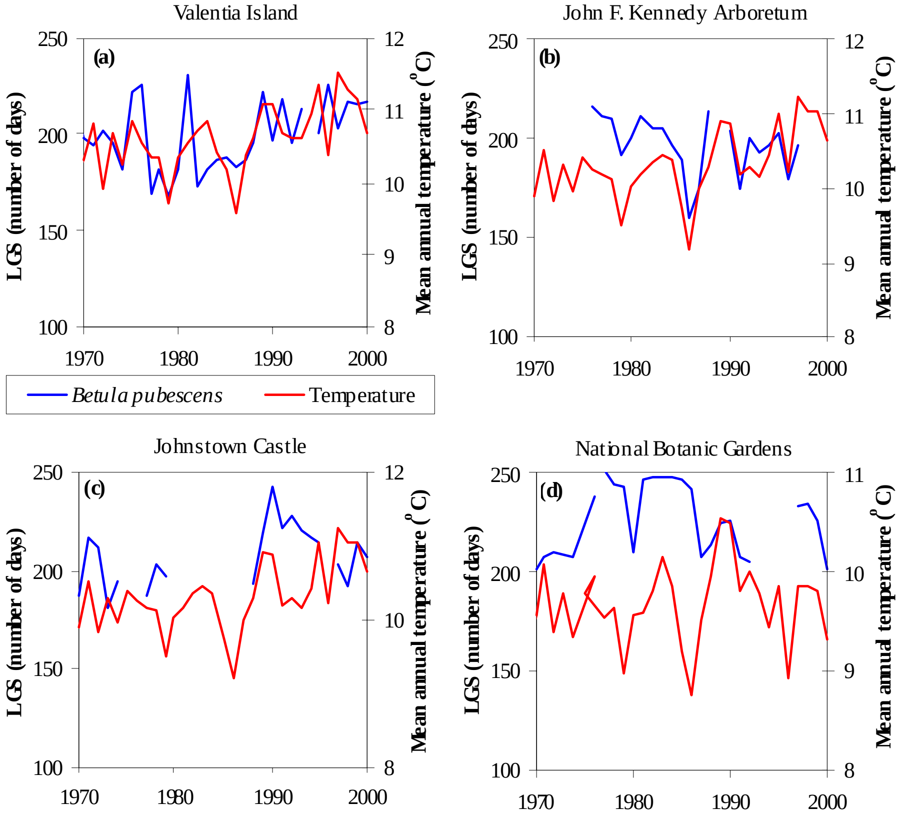

Figure 3.5. Length of the growing season (number of days per year) for *Betula pubescens*, in relation to annual air temperature at each of the four phenological gardens.

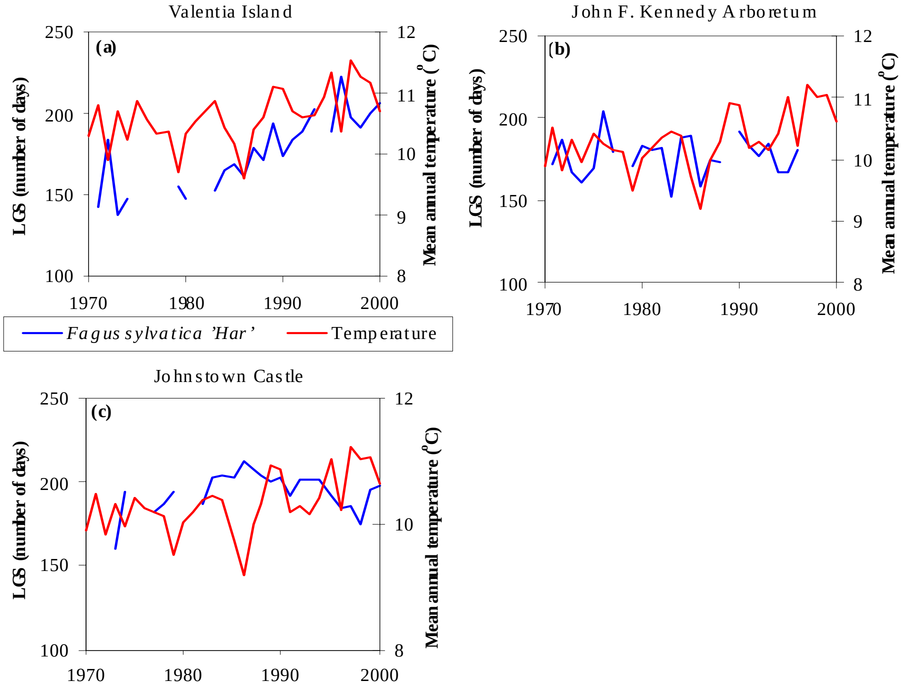

Figure 3.6. Length of the growing season (number of days per year) for *Fagus sylvatica*, at three of the phenological gardens in relation to annual air temperature at each site. This species was not recorded at the National Botanic Gardens.

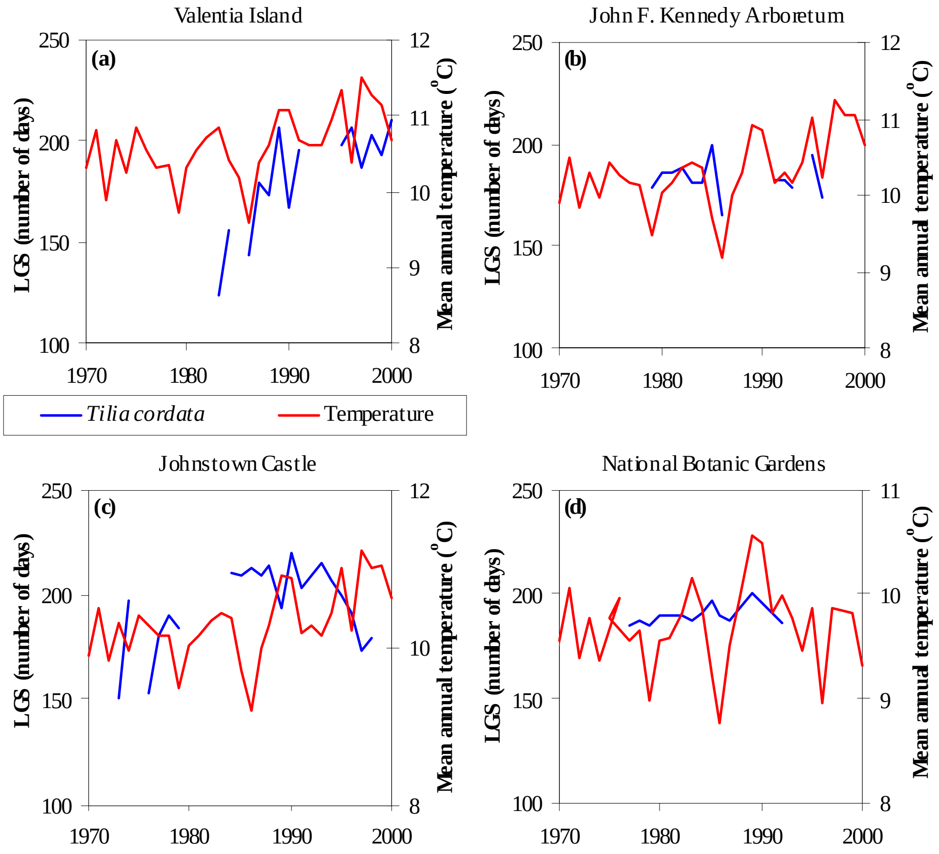

Figure 3.7. Length of the growing season for *Tilia cordata* (number of days per year) in relation to annual air temperature at each of the four phenological gardens.

In summary, LF can start as early as mid-October or as late as mid-November, depending on the species. Location can have an influence on LF as not all LF occurred at the same time at each site. The range within which LF occurred was less than that for the BGS. There is less evidence to suggest that LF is occurring later in the year although for most species at Valentia, (Fig. 3.11b and c) the trend for LF to be later in autumn is clear. Finally, air temperature during the growing season had very little influence on LF.

Conclusions

The use of phenological data as an indicator of climate change has proven to be extremely valuable. The historic nature of the datasets and the spread of sites across the country allow the indicators to be site specific. The Valentia phenological data show an increase in the LGS for a number of species. This is attributed to both an earlier onset of the BGS and a delay in LF. The increase in the LGS is correlated with annual average air temperature. At the other sites, the BGS data display greater variation than LF.

It is crucial to continue collection of these data, but as well as sending them to international data archives they should also be subject to analysis and interpretation in Ireland.

The significance of these data has been more appreciated recently and numerous European and global bodies are involved in setting up phenological networks. It is envisaged that additional data will be collected on the phenology of both plant and animal species in order to monitor the influences of possible climate change. It is anticipated that the data from Ireland, which provide information on the mid-latitude North Atlantic/European boundary will make an important contribution to such international efforts.

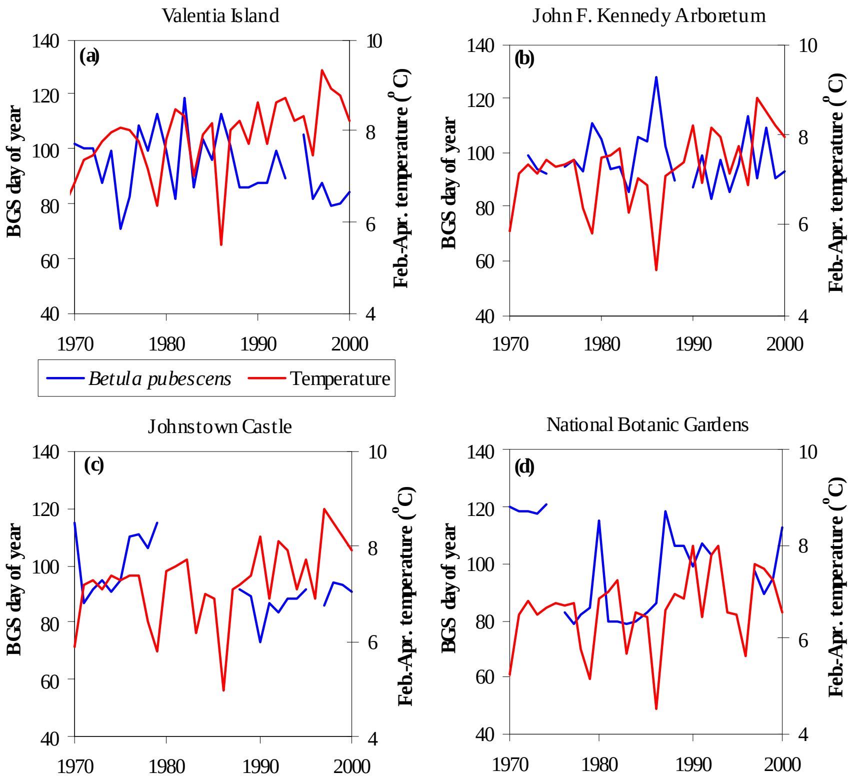

Figure 3.8. Day of the year when the beginning of the growing season occurred for *Betula pubescens*, at each of the four phenological gardens, in relation to February–April air temperature at each site.

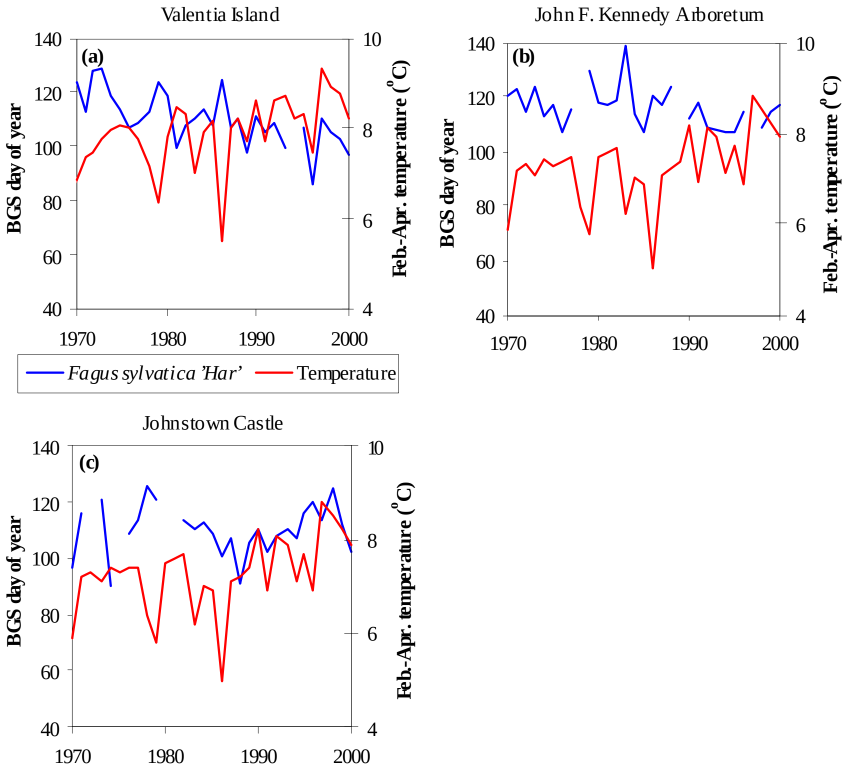

Figure 3.9. Day of the year when the beginning of the growing season occurred for *Fagus sylvatica* in relation to February to April air temperature at each site. This species was not recorded at the National Botanic Gardens.

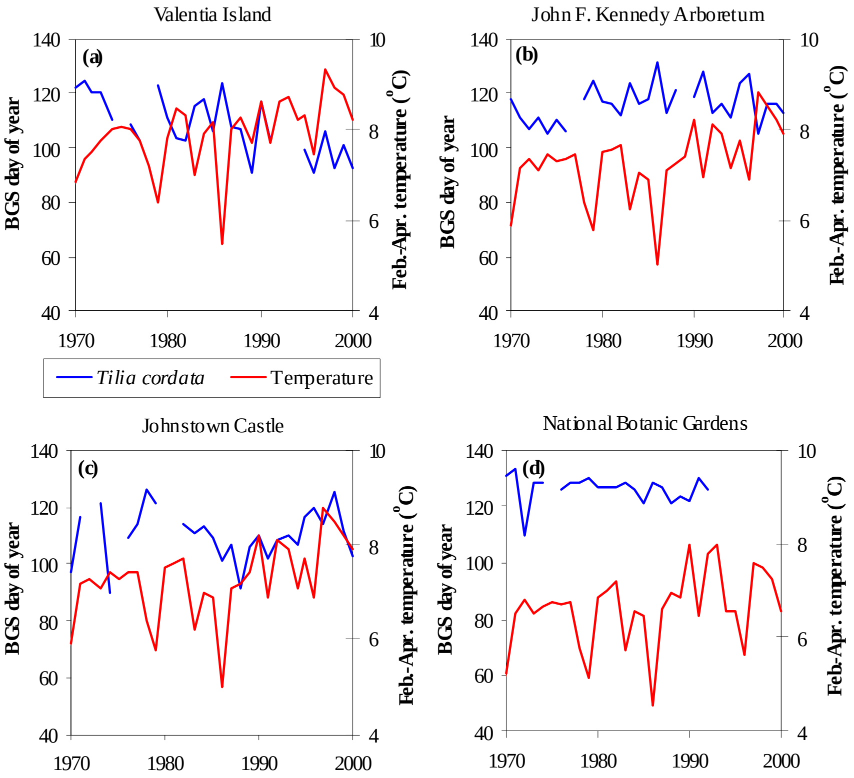

Figure 3.10. Day of the year when the beginning of the growing season occurred for *Tilia cordata*, at each of the four phenological gardens, in relation to February to April air temperature at each site.

3.5 Plant Distribution

The distribution pattern of plant species might be expected to change with predicted changes in climate. Some species might extend their range if temperature is increased while others may decrease in extent. Changes in rainfall pattern may also limit plant growth through alteration in soil moisture content. There may be losses of arctic/alpine species, increases in distribution of Mediterranean species, or changes in the distribution of current species. This section examines the use of plant distributions as a possible indicator of climate change.

3.5.1 Changes in the distribution pattern of plants

Given an increase in temperature it might be expected that the distribution and range of arctic/alpine plants on mountain tops and other sensitive habitats would be reduced. Arctic/alpine plants, such as *Dryasoctopetala*, *Alchemilla alpina* and *Salix herbacea*, have very restricted distribution patterns at present. These three species, when growing in upland areas, may be sensitive to changes in climate in these particular habitats. Other species with a strong south-west distribution may extend their range in a north-east direction to conform to newly drawn isotherms resulting from an increase in temperature (McWilliams, 1991). Species such as *Euphorbia hyberna*, *Rubia peregrina* and *Saxifraga spathularis* have a westerly distribution at present but this range may be expected to change in response to climate change. However, there are limited data available on changes in the distribution of these species. The problem associated with these datasets is that they are produced from short-term studies in a relatively small area and involve a small number of species; thus, no long-term trend data are available.

Conclusions

The distribution of some plant species may be expected to decrease in their range due to increasing soil moisture deficits – especially in the summer months. Arctic/alpine species may become more restricted in their distribution than at present whereas other species such as those having a south-western distribution may increase in extent. Therefore, it is important to select certain

Table 3.5. Correlation between the average monthly (January to April) air temperature and the average air temperature from February to April, at each site, and the beginning of the growing season (BGS) (numbers in bold indicate significance at 99% level; n.a., data not available).

Species	**Valentia Island**					**John F. Kennedy Arboretum**					**Johnstown Castle**					**National Botanic Gardens**				
	Jan.	**Feb.**	**Mar.**	**Apr.**	**Feb.–Apr.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**Feb.–Apr.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**Feb.–Apr.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**Feb.–Apr.**
Betula pubescens	**–0.51**	**–0.43**	**–0.52**	**–0.10**	**–0.49**	**–0.41**	**–0.45**	**–0.56**	**–0.24**	**–0.53**	**–0.56**	**–0.56**	**–0.58**	**–0.45**	**–0.66**	**–0.28**	–0.01	**–0.20**	**–0.11**	–0.05
Fagus sylvatica																				
‘Har’	**–0.29**	**–0.35**	**–0.46**	**–0.24**	**–0.47**	**–0.10**	**–0.53**	**–0.22**	**–0.51**	**–0.55**	**–0.14**	**–0.18**	–0.06	–0.07	**–0.14**	n.a.	n.a.	n.a.	n.a.	n.a.
‘Tri’	**–0.19**	**–0.41**	–0.32	**–0.14**	**–0.41**	**–0.19**	**–0.59**	**–0.36**	**–0.44**	**–0.56**	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
‘Dud’	n.a.	n.a.	n.a.	n.a.	n.a.	**–0.36**	**–0.51**	**–0.52**	**–0.46**	**–0.69**	**–0.13**	0.07	**0.11**	–0.08	**0.10**	n.a.	n.a.	n.a.	n.a.	n.a.
‘Danemark’	n.a.	n.a.	n.a.	n.a.	n.a.	**–0.18**	**–0.49**	–0.07	**–0.40**	**–0.43**	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Populus canescens	**–0.25**	**–0.66**	**–0.51**	**–0.45**	**–0.74**	**–0.48**	**–0.72**	**–0.47**	**–0.47**	**–0.73**	**–0.14**	**–0.26**	**–0.40**	**–0.30**	**–0.38**	n.a.	n.a.	n.a.	n.a.	n.a.
Populus tremula	**–0.09**	**–0.58**	**–0.59**	**–0.31**	**–0.68**	**–0.37**	**–0.54**	**–0.62**	**–0.46**	**–0.68**	0.01	**0.21**	0.32	**–0.36**	0.36	n.a.	n.a.	n.a.	n.a.	n.a.
Prunus avium																				
‘Bov’	**–0.21**	**–0.44**	**–0.58**	**–0.16**	**–0.54**	**–0.19**	**–0.28**	**–0.29**	**–0.32**	**–0.37**	**–0.26**	**–0.28**	**–0.52**	**–0.39**	**–0.47**	n.a.	n.a.	n.a.	n.a.	n.a.
‘Lut’	**–0.24**	**–0.62**	**–0.47**	**–0.18**	**–0.61**	**–0.42**	**–0.25**	**–0.34**	**–0.26**	**–0.37**	**–0.42**	**–0.42**	**–0.57**	**–0.33**	**–0.54**	n.a.	n.a.	n.a.	n.a.	n.a.
Sorbus aucuparia	–0.06	**–0.24**	**–0.65**	**–0.15**	**–0.46**	–0.04	**–0.09**	**–0.25**	**–0.28**	**–0.24**	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Tilia cordata	**–0.23**	**–0.54**	**–0.48**	**–0.23**	**–0.58**	**–0.26**	**–0.60**	**–0.20**	**–0.45**	**–0.54**	**–0.34**	**–0.22**	**–0.42**	**–0.29**	**–0.37**	**–0.09**	**–0.23**	**–0.24**	**–0.31**	**–0.35**
Salix aurita	**–0.37**	**–0.03**	**0.08**	**–0.25**	**–0.16**	n.a.	n.a	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Salix acutifolia	**–0.34**	**0.11**	**0.23**	**0.34**	**0.40**	n.a.	n.a.	n.a.	n.a.	n.a.	–0.13	–0.04	–0.16	–0.05	–0.12	n.a.	n.a.	n.a.	n.a.	n.a.
Salix x *smithiana*	**–0.16**	**–0.08**	**0.28**	–0.03	0.05	n.a.	n.a.	n.a.	n.a.	n.a.	**–0.36**	–0.05	–0.16	0.33	0.02	n.a.	n.a.	n.a.	n.a.	n.a.
Salix viminalis	0.20	**0.28**	**0.51**	**–0.14**	**0.33**	n.a.	n.a.	n.a.	n.a.	n.a.	0.09	–0.14	–0.09	–0.11	–0.01	n.a.	n.a.	n.a.	n.a.	n.a.
Salix glauca	n.a.	n.a.	n.a.	n.a.	n.a.	**–0.69**	**–0.50**	–0.12	–0.08	**–0.38**	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ribes alpinum	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	**–0.29**	**–0.29**	**–0.33**	**–0.37**	**–0.39**	**–0.21**	**–0.41**	**–0.68**	–0.16	**–0.53**
Robinia pseudoacacia	n.a.	n.a.	n.a.	n.a.	n.a.	**–0.45**	**–0.53**	–0.07	**–0.35**	**–0.46**	n.a.	n.a.	n.a.	n.a.	n.a.	**–0.17**	**–0.45**	**–0.51**	–0.07	**–0.61**

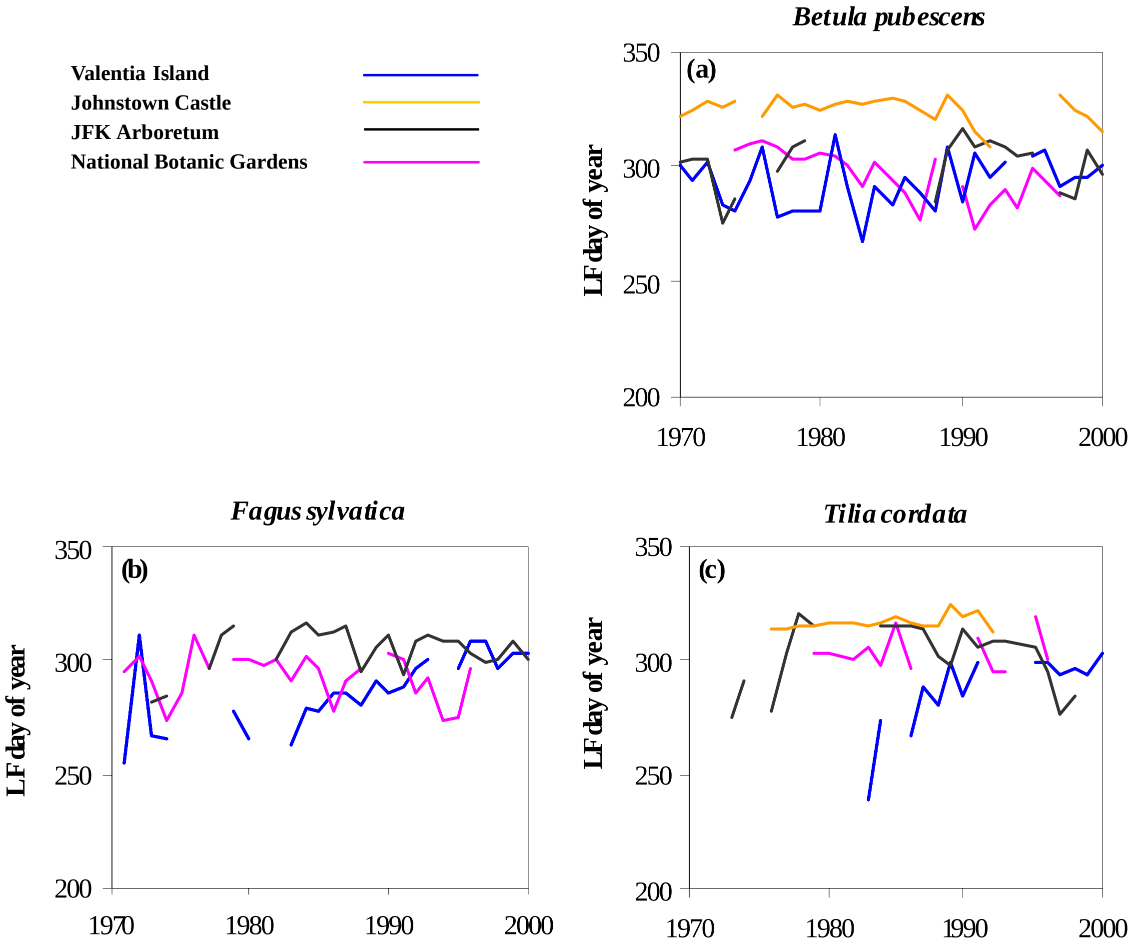

Figure 3.11. Day of year when leaf fall occurred for (a) *Betula* 'pubescens', (b) *Fagus sylvatica* and (c) *Tilia cordata* at each of the four phenological gardens.

indicative species and to monitor their distribution patterns to assess their usefulness as climate change indicators, but data availability is a restricting factor at present.

3.6 Palaeoecological Records

The use of palaeoecological records to reconstruct past climates is well established and events such as the Little Ice Age and the Medieval Warm Period can be clearly identified in both pollen records and tree-ring analysis. Analysis of stomatal densities of fossil leaf material can give an insight into past atmospheric CO_2 concentrations.

3.6.1 Dendrochronological data

Tree-ring analysis has been widely used to reconstruct changing environments of the past (Cherubini, 2000). However, more recently (since the industrial revolution) anthropogenic influences, such as increasing atmospheric concentrations of CO_2 and O_3, 'acid-rain' effects and increasing UV-B, have exerted both positive and negative pressures on the growth–climate response (Briffa *et al.*, 1998). Before the industrial revolution, changes in tree-ring parameters were largely due to natural processes. Since then the contribution due to human influences makes detecting climate change from tree-ring analysis more difficult.

Trees growing at the limits of their ecological tolerance are more sensitive to variations in climate. Summer temperatures are the most important determinant of tree growth at mid-high latitudes and, as most models predict an increase in summer temperatures, growth responses may be expected. An increase in forest growth rates and an advancement of the tree-line in a number of high-latitude and high-altitude locations is likely to occur due to climate change (Innes, 1991). A tree-ring chronology for Irish oak extends back 7000 years (Baillie and Brown, 1995), and shows some notable downturns in growth relating to catastrophic environmental events (Baillie, 1999). Recent increases in temperature are not clearly evident in the Irish oak chronology as the events are not severe enough or of long enough duration. Most trees in Ireland are not growing under any climatic stress conditions nor are they living at the extreme of their range and, therefore, are likely to easily adapt to subtle changes in climate. However, *Arbutus* (strawberry tree) is one tree that is living at the extreme of its European range and analysis of its tree rings could reveal some indications of recent changes in climate (Cherubini, P., Swiss Federal Research Institute, personal communication).

3.6.2 Bogs – pollen records

Cole (2000) carried out a palaeoecological study on three bogs in Ireland, Liffey Head Bog (Co. Wicklow), All Saint’s Bog (Co. Offaly) and Ballygisheen Bog (Co. Kerry), to investigate recent climate change. Various methods were used, such as regional pollen analysis, which clearly reflected mass clearance of trees from the landscape, the introduction of agricultural and exotic species, and the Great Famine. However, there was little evidence provided by the regional pollen record of the Medieval Warm Period or the Little Ice Age. There is some evidence from local pollen records and fungal spores to suggest an increase in dry conditions in the 20th century. However, this could be due to drainage of the bogs or peat cutting. Much of the palaeoecological research lacks the temporal resolution necessary to detect small changes in climate (Cole, 2000). Anthropogenic influences have dominated the regional pollen records in the past 1200 years, which renders it practically impossible to distinguish any recent climatic change.

3.6.3 Caves

Stalagmites and stalactites form on the floors and roofs of caves, respectively, by seeping water depositing layer upon layer of calcite. These structures develop over thousands of years and provide a chronology of past temperatures (McDermott *et al.*, 2001). Work carried out by McDermott *et al.* (2001) revealed evidence of a sudden and abrupt 40-year-long cooling period that occurred about 8200 years ago from analysis of the calcite layers in stalagmites from Crag Cave in Co. Kerry. However, to date there are no studies in Ireland at the appropriate spatial resolution in the recent calcite deposits to confirm whether or not recent climate change could be detected. In theory, it should be possible to detect a fraction of a degree change in temperature, and seasonal cycles of trace elements have been demonstrated from the Holocene speleothem deposits. This technique is currently being tested on more recent speleothem deposits, which may show signals of recent climate change (McDermott *et al.*, 2001).

Conclusions

It is currently unclear whether palaeo-records can be used to indicate recent climate change. It may be possible to find signals of recent climate change through analysis of the tree rings of certain tree species living at the extremes of their habitat and/or in analysing more recent speleothem deposits. Anthropogenic activity exerts a huge influence on the pollen records which is likely to make this method ineffective for such analysis. At present, with the data available, it is not possible to use palaeo-records as indicators of recent climate change, but the signs are encouraging that with more research it would be possible.

3.7 Human Health

The direct effects of climate change on human health are in relation to exposure to heat and cold, to extreme weather events, to the frequency of food- and water-borne illnesses and to the spread of vector-borne diseases (Wilkinson *et al.*, 2001). As Ireland has a very mild climate, at present, with air temperature rarely exceeding 25°C or falling below –5°C, and rarely remaining below freezing for more than 24 hours (Rohan, 1986), the climate does not impact greatly on human health. This situation is predicted to change in future. Therefore, statistics on deaths and illnesses related to heat and cold will need to be incorporated into the list of secondary indicators. Climate-sensitive diseases may also show changes in their seasonal pattern and/or in their geographical distribution. However, improvements in health care may mask the adverse effects of climate change on human health. In Ireland, collection of disease statistics is limited as it is dependent on the individual hospitals and many diseases are not notifiable. This has two major implications: the data are unrepresentative of both the population and of the disease. It is, therefore, necessary to develop a method of disease surveillance in order to provide early-warning mechanisms (Cullen, 2000).

Global climate model predictions suggest that climate change will be accompanied by an increase in heatwaves and humidity, and by increased urban air pollution (IPCC, 2001). This would increase the incidences of heat-related illnesses and deaths, with urban populations, the elderly and sick, being most vulnerable. An increase in temperature and humidity may lead to a change in timing of bronchial disease, as pollen episodes will be earlier in the spring, due to the earlier flowering of trees and grass species. Vector-borne diseases such as Lyme disease is spread by ticks and is associated with warm weather. Instances of Lyme disease have been positively correlated with summer temperatures in the UK, with a greater number being reported in south-western regions than in northern areas (Subak, 1999a). As this is not a notifiable disease these data are not available in Ireland (Lane, S., Adelaide and Meath, personal communication). Nevertheless, such diseases may become more common in Ireland in the future due to climate change and their occurrence should be monitored.

3.7.1 *Seasonal pattern of mortality rates*

The direct effect of increasing temperature on human health in Ireland may alter the seasonal pattern of mortality. As the greatest number of all cause deaths occur in January, fewer deaths due to cold-related illnesses may result, which would be particularity noticeable in the elderly.

Figure 3.12 shows the percentage of all cause deaths that occurred in January since 1980 in relation to average January temperatures. Obviously, the correlation is very weak (Fig. 3.12b), but as January temperatures for Ireland are expected to increase by 1.5°C by 2055, it might be expected that the proportion of deaths occurring in January would decline. For every 1°C increase in temperature, 30 fewer deaths are expected in the UK (Subak, 1999b).

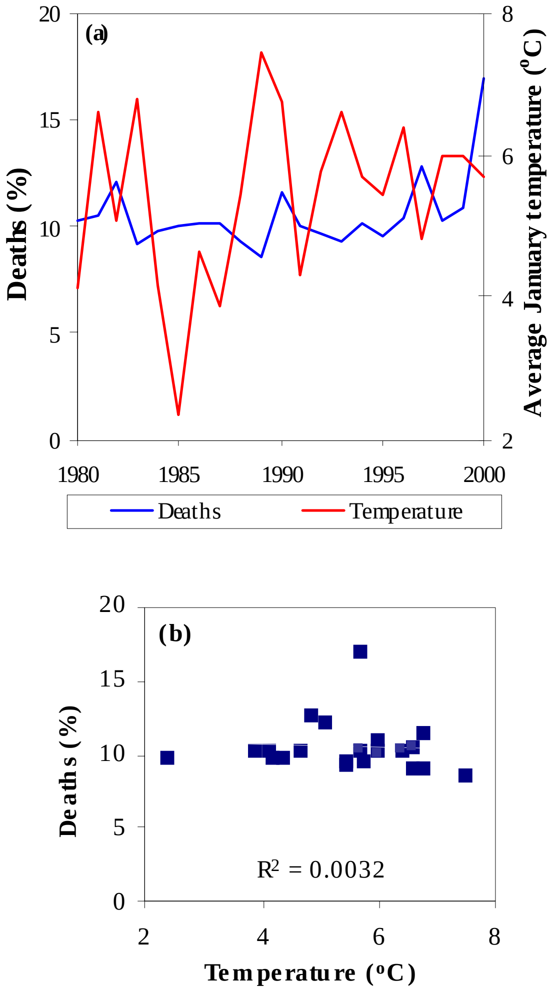

Figure 3.12. (a) The percentage of all cause deaths occurring in January from 1980 to 2000; (b) deaths in relation to average January temperatures.

Another possible indicator of climate change on human health might be to examine the incidences of skin cancers, on both the face and exposed limbs, in relation to summer temperatures. In theory, as the summer temperatures are predicted to increase, more people will spend long periods out of doors exposing their skin to the sun and so increase the risk of contracting melanomas. However, increases in skin cancers may also indicate that more people are taking holidays in hotter, sunnier climates. Therefore, a population could be targeted that spend a large proportion of their time outdoors, such as farmers, gardeners, fishermen. But, as people are becoming more aware of the harmful effects of the sun, they tend to use greater protection against any damaging effects. Any change in cloud cover would also be an important factor when dealing with this particular indicator.

Conclusions

Data on human health-related effects of climate change are difficult to obtain due to the lack of a co-ordinated programme for their collection. An indicator, such as changes in the pattern of mortality rates in January, is not necessarily transferable from one country to another even though the climates are similar. As regards mortality trends in winter, cold spells (periods of unseasonably low temperatures) from 10 days to 2 weeks increase the chance of high mortality rates. However, the use of mean monthly temperatures to assess these events is problematic, as extremes are masked in the averaging process. Similarly, increases in temperature can cause increases in mortality rates, but the duration of the heat wave (periods of unseasonably high temperatures) may only be 1–2 days.

These extreme events are not important factors for Ireland at present and Ireland will be used as a control for a European project examining the effects of extreme weather events on human mortality rates (Goodman, P.L., DIT, personal communication). It will be important to exclude certain types of mortality that are not climate related, such as car accidents and suicides, and to focus more on ‘natural’ cause mortality, such as cardiovascular and respiratory illnesses. However, in the 1990s, deaths from cardiovascular and respiratory illnesses decreased dramatically in Dublin city while winter temperatures increased over the same period. At least part of the reason for the decreased number of deaths was due to the introduction of a government ban on the sale of bituminous coal (Goodman, 1999). It is, therefore, important to investigate the specific causes of illnesses and deaths and their temporal pattern in order to find a connection to climate change (Staines, A., Dept. of Public Health, UCD, personal communication). In order to show direct effects of climate change on human health it is probably necessary to look more closely at areas such as vector-borne diseases and illnesses in relation to extreme changes in temperature. There is also a need to co-ordinate and develop methods of disease observation.

3.8 Tourism

As summer temperatures are predicted to increase, it may be expected that more people will holiday in Ireland, as was the case in the UK (Agnew, 1999). It is assumed that warmer weather in summer will lead to a growth in short-break holidays, thus boosting the tourist trade. In this section the propensity for tourists to take domestic short-break holidays in relation to an increase in mean July temperatures is examined.

3.8.1 Domestic holidays

In Ireland, since 1990, there has been a sharp decline in ‘home holidays’ and a sharp increase in ‘foreign holidays’. Figure 3.13a shows the number of non-business trips made by Irish residents since 1984. A ‘trip’ implies at least one night spent away from home. According to these data, supplied by Bórd Fáilte (the Irish Tourist Board), there is no correlation between the average July temperatures and the number of trips made (Fig. 3.13b). Prior to 1990, there was a visual correspondence between the two variables. In the mid-1980s, there was a tendency for the number of trips to increase when July temperatures were higher, but this pattern disappeared in the 1990s when the number of domestic trips declined dramatically and the number of trips abroad increased. This suggests that there is something other than July temperatures influencing the number of domestic holidays being taken by Irish residents. The growth in the economy during the 1990s is undoubtedly responsible for part of the decline seen in domestic holidays.

Conclusions

Given the lack of correlation and influences other than climate change acting upon this parameter, it is not possible to use the number of domestic-holiday trips as a secondary indicator of climate change, at least in Ireland. Therefore, greater consideration may be given to analysing increases in the number of foreign tourists coming to Ireland, but again this may be fraught with inaccuracy due to the influence of external factors such as global economic activity.

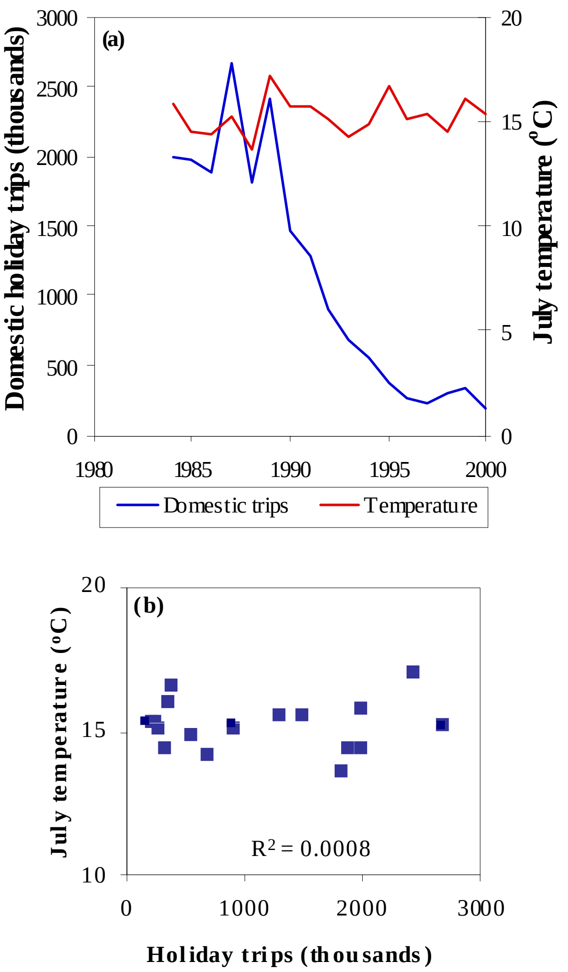

Figure 3.13. (a) Number of 'domestic holidays' taken in Ireland in relation to mean July temperatures from 1980 to 2000. (b) Relation between number of domestic holidays and July temperatures.

3.9 Economic

Changes in our climate may have economic implications. In this section, two areas of economic activity are considered – changes in energy consumption and insurance claims for storm damage.

3.9.1 Changes in energy consumption

It is anticipated that with an increase in winter temperatures energy consumption would decrease, but conversely, in summer with an increase in temperature the demand for energy might increase if use of air-conditioning units and fans for cooling purposes increased. Discerning a climatic signal from energy consumption data is, however, difficult due to the confounding effects of economic growth. However, due to the core role of energy consumption as a function of climate, change analysis of these effects is warranted.

3.9.2 Insurance claims for storm damage

It is predicted that there will be changes in the variability of climate with a change in the intensity and frequency of some extreme climate phenomena such as storms and flooding (IPCC, 2001). This could lead to an increase in the insurance claims for storm-damaged property. Insurance claims for damage to the foundations of buildings caused by hot dry-weather events, damage to roofs by excess winds and hail, or flood damage may be expected to increase. Analysis of insurance claims might be expected to show some relationship to climate change; however, insufficient data are available at present to draw any reliable conclusions.

Conclusions

Change in the pattern of energy consumption could be used as an indicator of climate change and monitoring types of fuel and their consumption could provide valuable information for this purpose. The insurance industry may expect more claims due to major weather events and monitoring of these data could be used as an economic indicator of the impact of climate change.

3.10 Conclusions on Secondary Indicators

In this chapter, a range of secondary indicators of climate change have been assessed. Secondary indicators are important as they provide valuable information for early warning on how climate change will affect important ecosystem, economic and social activities. By far the most valuable secondary indicators of climate change proved to be the phenological data on tree growth stages from monitoring carried out in the phenological gardens. The long historic record of tree phenology for a number of species and sites across Ireland has provided evidence of an increased length of growing season which is linked to temperature increase during the past 40 years. However, further analysis of phenological data is needed. There are fewer and less-defined data on birds, bats, insects and other plants. However, it is of note that new species of insects and birds have been observed in Ireland in recent times.

The most effective indicators of climate change in the agricultural environment are likely to be the increase in the area of production of warm-weather crops and the introduction of new varieties. The yield of potato and grass crops may be an effective indicator of climate change in future, even though the correlation with summer rainfall is weak at present. Finding suitable indicators of climate change from human-health issues proved difficult, as the datasets are not readily available. Changing social behaviour and economic development complicate analysis of data on energy and economic factors. These data require more in-depth analysis that was not possible under this study.

The palaeo-records are useful in reconstructing past climates but are not currently of use as indicators of more recent anthropogenic climate change. However, it is possible that research into more recent speleothem deposits will be effective as an indicator of recent climate change.

There are other datasets available in Ireland that require further analysis and interpretation. It was not possible to deal with river-flow data for which other analysis has indicated changes linked to climate change (Kiely, 1999). Also, tidal and ocean data have not been considered here. Therefore, it is important to continue analysis of these valuable data sources.

4 Conclusions and recommendations

4.1 Introduction

An assessment of a range of primary and secondary indicators for signals of climate change impacts in Ireland has been carried out. The main finding is that signals consistent with global warming/climate-change effects, due to the build-up of greenhouse gases in the atmosphere, are evident in the primary meteorological record and that there is evidence of linked ecosystem changes in secondary indicators. A summary is presented in this chapter. The challenges facing Ireland due to climate change are briefly considered and recommendations are given with regard to future work in relation to monitoring and understanding climate change in Ireland.

The main findings on indicators of climate change described in this study are as follows.

4.2 Primary Indicators

- An average increase in annual temperature of 0.5°C has been observed over the course of the 20th century. This warming has been concentrated in two periods but most significantly in the last decade of the century.

- Seasonal maximum temperatures are increasing and higher minimum temperatures are being recorded at a number of locations. Increases in both winter maximum and minimum temperatures mean that this season has experienced the greatest warming.

- There has been a significant decrease in the frequency of frost days/‘cold’ days nationally and a general increase in ‘hot’ days.

- The annual precipitation level in the north of the country has increased. The precipitation level in the south of the country has decreased but the statistical significance of this observation is weak.

- On a seasonal basis, increased winter precipitation in the north-west is evident. A decrease in summer precipitation in the south-east has also been observed. However, the occurrences of ‘rain’ and ‘wet’ days is erratic as is the intensity of maximum 1-day precipitation events. These data show increases in some months in some stations, but no overall trend.

The changes outlined above are largely in line with global trends. Given the growing confidence that these global trends are driven primarily by anthropogenic influences, these data indicate that changes to climate in Ireland are probably also driven by such influences.

4.3 Secondary Indicators

- The relatively long historic record of tree phenology from various species and sites across Ireland is the most valuable secondary indicator of climate change among the currently available dataset. Ecological changes have been principally seen in the increase in the length of the growing season, particularly at Valentia, but are also evident at other sites.

- The increased production levels of warm-weather crops, such as maize, and the introduction of artificial irrigation systems in the east of the country may point to a warmer and drier summer climate. The yields of potato and grass crops may be effective indicators of climate change in future, even though their correlation with summer rainfall is weak at present.

- There may be some changes to bird, bat and insect distributions as well as to distributions of plant species. However, the data considered were not yet of sufficient quantity or quality to provide firm indications of changes.

- Similarly, data on human health, energy and economic factors, are complicated by changing social behaviour and economic development. These data require more in-depth analysis than was possible under this study.

- The palaeo-records are useful in reconstructing past climates but are not yet of use as indicators of recent climate change. However, it is possible that research into recent speleothem deposits will provide effective indicator data on recent climate change.

4.4 Ireland: Climate and Climate Change

It is well known that Ireland's temperate climate is principally influenced by the North Atlantic Ocean and particularly the Gulf Stream circulation. The fact that significant indications of changes in climate can be detected in data from the west coast of Ireland in an oceanically dominated climatic regime is particularly noteworthy and is significant on a national and international level. Some of these changes could be regarded as being positive, i.e., higher minimum temperatures, decrease in occurrence of frost days and longer growing season. However, changes, such as increased winter-time precipitation levels and decreased sunshine levels, may not be regarded as beneficial developments. The build-up of greenhouse gases in the atmosphere is projected to lead to increased changes to our climate in future. There are very large levels of uncertainty as to what these changes will be (IPCC, 2001). What is certain is that the increased levels of greenhouse gases trap heat energy in our atmosphere. This more energetic atmosphere is likely to be more erratic and less predictable than today's with more extreme weather events occurring. If unchecked, long-term climate changes for Ireland may be extreme, for example, if oceanic heating is reduced due to the North Atlantic Drift circulation being reduced or halted. There may also be surprises, which have significant environmental, social and economic impacts that will be difficult to deal with. Ireland should, therefore, support efforts to understand the impacts of climate change through research and the further development of observational systems as required under the Kyoto Protocol. Some possible steps to do this are outlined in the following section.

4.5 Recommendations

It is important that further use is made of the data already in existence through more in-depth analyses and integration with other datasets. In order to optimise use of available data, it is essential to synchronise current and future monitoring and modelling activities. Greater focus should be given to national efforts in this area rather than being reliant on international analysis of Irish data.

There is also a need for increased co-ordination and commitment to long-term monitoring of primary (climatological) and secondary (ecological, health and economic) indicators in Ireland. In order to have an effective monitoring program it is essential to carefully consider the choice of measurements and sampling design. These must be linked to objectives to ensure that the results are useful, which would contribute to the development and implementation of environmental policy. Collaboration between the data-collecting organisations would be thereby ensured and volunteer groups would be given encouragement and guidance to collect data in a standardised manner. The collected data would then be more comparable and easier to process.

- It is, therefore, recommended that a national strategy for environmental observations centred on the issue of climate change is devised.

The present study can form a basis for devising this strategy. Such a strategy would serve to determine the requirements necessary to co-ordinate and integrate cross-sectoral work linked to primary and secondary observations of climate systems and climate change. Implementation of the strategy would aid analysis of climate-change effects in Ireland and would contribute to the fulfilment of national obligations under the UNFCC to generate and provide regular reports on Global Climate Observational Systems (GCOS) data.

4.5.1 Observational data

The Met Éireann observational network is the main source of primary meteorological data for Ireland. These data are of primary importance, without which research in this area would not be possible. The analysis of the Met Éireann dataset provided here can only be regarded as preliminary.

- A fundamental recommendation is that the existing observational network is maintained and that the investment in monitoring of climate parameters at the synoptic and climatological stations is continued.

- The integrity of the observational data may be threatened by housing or other developments close to the observational sites. An urgent assessment of this threat and how it may be avoided/managed is required.
- Further in-depth and ongoing analysis of these data should be carried out and sufficient national resources should be provided for this work.
- Following this assessment the network should be upgraded/modified if necessary and new sites developed.

The Valentia site is a Global Atmospheric Watch (GAW) regional station and is linked to one of the phenological gardens. This site provided key data used in this report. The further development of integrated analysis of data for Valentia should be an essential component of the climate change observational strategy.

4.5.2 Ecosystem monitoring

The value of long-term monitoring has never been more apparent. When the phenological gardens began collecting data in 1959, there was no mention of climate change but the importance of this dataset for climate-change studies is now been realised. This is an example of an historical dataset becoming a valuable tool and emphasises the need for rigorous data collection and design. The absence of other long-term datasets highlights the need for further long-term integrated ecosystem monitoring.

- It is recommended that data from the four phenological gardens be further analysed in Ireland as well as being submitted to international archives.
- Monitoring of the spatial changes in indicator species, particularly key Arctic–Alpine and also newcomers from more southern climes, is required.
- A network of long-term ecosystem monitoring sites should be established to select key indicators and collect data on various aspects of biological activity ranging from plant and animal phenology, to insect, butterfly, bat and bird behaviour.

Management and analysis of these data should be centrally co-ordinated and updated on a regular basis. Selected data should be published on a regular basis, i.e. annually or biannually.

4.6 Summary of Conclusions

There is evidence that anthropogenically induced climate change is influencing Ireland’s climate and ecosystems. However, analysis of the full impacts, particularly on ecosystems, is limited due to the absence of long-term monitoring sites or the development of systematic phenological observations beyond the phenological gardens. Climate-change impacts are projected to increase in future years which may result in major environmental changes as well as economic and social difficulties. It is therefore recommended that an integrated monitoring strategy focused on the observation of climate change should be devised and implemented. Other recommendations on ensuring the continuity and integrity of current observations and the development of new sites have been given. Immediate action is needed on these points.

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6 References

Agnew, M.D. (1999) Domestic holiday tourism. *In:* Cannell, M.G.R., Palutikof, J.P. and Sparks, T.H. (eds) *Indicators of Climate Change in the UK*. Centre for Ecology and Hydrology, UK, pp. 32–33.

Ahas, R. (1999) Long-term phyto-, ornitho-and ichtyophenological time-series analyses in Estonia. *International Journal of Biometeorology* **42,** 119–123.

Asher, J., Warren, M., Fox, R., Harding, P., Jeffcoate, G. and Jeffcoate, S. (2001) *The Millennium Atlas of Butterflies in Britain and Ireland.* Oxford University Press, Oxford, 343–344.

Baillie, M.L.G. (1999) John Jackson Lecture: Surprising things you can learn from tree-ring dating, O*ccasional Papers in Irish Science and Technology* **19,** 1–16.

Baillie, M.L.G. and Brown, D.M. (1995) Some deductions on ancient Irish trees from dendrochronology. *In:* Pilcher, J.R. and Mac an tSaoir, S.S. (eds) *Wood,Ttrees and Forests in Ireland.* Royal Irish Academy, Dublin, 35–50.

Balling, Jr., R.C., Vose, R.S. and Weber, G. (1998) Analysis of long-term European temperature records: 1751–1995, *Climate Research* **10,** 193–200.

Barry, R.G. and Chorley, R.J. (1998) *Atmosphere, Weather and Climate*. Routledge, New York.

Beaubien, E. G. and Freeland, H. J. (2000) Spring phenology trends in Alberta, Canada: links to ocean temperature. *International Journal of Biometeorology* **44,** 53–59.

Briffa, K.R., Schweingruber, F.H., Jones, P.D., Osborn, T.J., Harris, I.C., Shiyatov, S.G., Vaganov, E.A. and Grudd, H. (1998) Trees tell of past climates: but are they speaking less clearly today?, *Philosophical Transactions of the Royal Society of London, Series B – Biological Sciences* 353, 65–73.

Cherubini, P. (2000) Tree-ring research beyond the climate change: “Quo Vadis?” *Dendrochronologia* **18,** 91–93.

Chmielewski, F.-M. and Rötzer, T. (2001) Response of tree phenology to climate change across Europe. *Agriculture and Forest Meteorology* **108(2),** 101–112.

Cole, E. (2000) *Multi-proxy Evidence from Bogs for Environmental Change in Ireland over the last 1,200 years.* Ph.D. thesis submitted to the University of Dublin, Trinity College.

Cooney, T. (1980–2000) *Irish East Coast Bird Reports 1980–2000.* Environmental Consultant, 42 All Saints Rd., Dublin 5, Ireland.

Crick, H.Q.P. (1999a) Egg-laying dates of birds. *In:* Cannell, M.G.R., Palutikof, J.P. and Sparks, T.H. (eds) *Indicators of Climate Change in the UK*. Centre for Ecology and Hydrology, UK, 64–65.

Crick, H.Q.P. (1999b) Small bird population changes. *In:* Cannell, M.G.R., Palutikof, J.P. and Sparks, T.H. (eds) *Indicators of Climate Change in the UK*. Centre for Ecology and Hydrology, UK, 66–67.

Cullen, E. (2000) Possible adverse effects of global warming. *The Irish Medical Journal* **93(5),** 132–134.

Daultrey, S. (1994) Climate variability in Ireland: are there signals amongst the noise? *In:* Feehan, J. (ed.) *Climate Variation and Climate Change in Ireland.* Environmental Institute, University College Dublin, 37–52.

Easterling, D.R., Evans, J.L., Groisman, P.Ya., Karl, T.R., Kunkel, K.E. and Ambenje, P. (2000) Observed variability and trends in extreme climate events: a brief review. *Bulletin of the American Meteorological Society* **81,** 417–425.

European Environment Agency (1998) *Europe’s Environment: The Second Assessment.* Office for the Official Publications of the European Communities, Elsevier Science Ltd., Oxford, UK.

European Environment Agency (1999) *Environmental Indicators: Typology and Overview.* Technical Report No. 25. European Environment Agency, Copenhagen.

Folland, C.K. and Karl, T.R. (2001) Observed climate variability and change. *In:* Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J. and Xiaosu, D. (eds) *Climate Change 2001: The Scientific Basis.* Cambridge University Press, Cambridge.

Furness, R.W. and Greenwood, J.J.D. (1993) *Birds as Monitors of Environmental Change.* Chapman and Hall, London.

Goodman, P.L. (1999) *Particulate Air Pollution and Mortality in Dublin 1980–1996*. Ph.D. thesis, Department of Health Sciences, Trinity College, Dublin 2, Ireland.

Hays, J., Imbrie, J. and Shackleton, N. (1976) Variations in the Earth’s orbit: pacemaker of the ice ages. *Science* **194,** 1121–1132.

Hulme, M. (1999a) Air temperature in Central England. *In:* Cannell, M.G.R., Palutikof, J.P. and Sparks, T.H. (eds) *Indicators of Climate Change in the UK*. Centre for Ecology and Hydrology, UK.

Hulme, M. (1999b) Precipitation gradient across the UK. *In:* Cannell, M.G.R., Palutikof, J.P. and Sparks, T.H. (eds) *Indicators of Climate Change in the UK*. Centre for

Ecology and Hydrology, UK.

Hulme, M. and Jenkins, G.J. (1998) *Climate Change Scenarios for the UK: Scientific Report.* UKCIP Technical Report No. 1. Climate Research Unit, University of East Anglia, Norwich.

Hurrell, J.W. (1995) Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science* **269,** 676–679.

Hurrell, J.W. (1996) Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperature. *Geophysical Research Letters* **23,** 665–658.

Innes, J.L. (1991) High altitude and high-latitude tree growth in relation to past present and future global climate change. *The Holocene* **1,2,** 168–173.

IPCC (2001) WG2 Third Assessment Report. *Summary for Policymakers: Climate Change 2001: Impacts, Adaptation and Vulnerability.*

Jennings, E., Allott, N., McGinnity, P., Poole, R., Quirke, B., Twomey, H. and George, G. (2001) The North Atlantic Oscillation: implications for freshwater systems in Ireland. *Biology and Environment: Proceedings of the Royal Irish Academy* **100B(3),** 149–157.

Jones, M.B. and Brereton, A.J. (1992) Climate change prospects and consequences for Irish grasslands. *In:* Collins, J.F. (eds) *Future of Irish Agriculture – Role of Climate.* Agmet, Dublin, 28–37.

Jones, M.B. and Jongen, M. (1997) The effects of increasing CO_2 and climate change on European grasslands. *In:* Sweeney, J. (ed.) *Global Change and the Irish Environment.* Royal Irish Academy Dublin, 46–55.

Jones, P.D., Horton, E.B., Folland, C.K., Hulme, M., Parker, D.E. and Basnett, T.A. (1999) The use of indices to identify changes in climate extremes. *In:* Karl, T.R., Nicholls, N. and Ghazi, A. (eds) *Weather and Climate Extremes: Changes, Variations & a Perspective from the Insurance Industry.* Kluwer Academic Publications, The Netherlands.

Keane, T. (1986) Meteorological parameters in Ireland. *In:* Keane, T. (ed.) *Climate, Weather and Irish Agriculture*. Agmet, Dublin.

Kiely, G. (1999) Climate change in Ireland from precipitation and streamflow observations. *Advances in Water Resources* **23,** 141–151.

Lister, D.H. and Subak, S. (1999a) Warm-weather crops: forage maize. *In:* Cannell, M.G.R., Palutikof, J.P. and Sparks, T.H. (eds) *Indicators of Climate Change in the UK.* Centre for Ecology and Hydrology, UK, 50–51.

Lister, D.H. and Subak, S. (1999b) Potato yields. *In:* Cannell, M.G.R., Palutikof, J.P. and Sparks, T.H. (eds) *Indicators of Climate Change in the UK*. Centre for Ecology and Hydrology, UK, 46–47.

Mansell, M.G. (1997) The effect of climate change on rainfall trends and flooding risk in the West of Scotland. *Nordic Hydrology* **28,** 37–50.

McDermott, F., Mattey, D.P. and Hawkesworth, C. (2001) Centennial-scale Holocene climate variability revealed by a high-resolution speleothem ^{18}O record from S.W. Ireland, *Science* **294,** 1328–1331.

McWilliams, B.E. (1991) *Climate Change: Studies on the Implications for Ireland.* Department of the Environment, Dublin.

Menzel, A. (2000) Trends in phenological phases in Europe between 1951 and 1996. *International Journal of Biometeorology* **44,** 76–81.

Myneni, R.B., Keeling, C.D., Tucker, C.J., Asrar, G. and Nemani, R.R. (1997) Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature* **386,** 698–702.

OECD (1993) OECD core set of indicators for environmental performance reviews. *Environment Monographs* No. 83.

Osborne, T.J., Hulme, M., Jones. and Basnett, T. (2000) Observed trends in the daily intensity of United Kingdom precipitation. *International Journal of Climatology* **20,** 347–364.

Parry, M.L. (2000) *Assessment of Potential Effects and Adaptations for Climate Change in Europe: The Europe Acacia Report*. Jackson Environment Institute, University of East Anglia, UK.

Pearce, F. (2001) Global green belt, *New Scientist* 2308, 15.

Perry, A. (2000) The North Atlantic Oscillation: an enigmatic see-saw. *Progress in Physical Geography* **24(2),** 289–294.

Raper, S., Viner, D., Hulme, M. and Barrow, E. (1997) Global warming and the British Isles. *In:* Hulme, M. and Barrow, E. (eds) *Climates of the British Isles: Past, Present and Future*. Routledge, London, 326–339.

Rohan, P.K. (1986) *The Climate of Ireland*. Stationery Office, Dublin.

Roy, D.B. and Sparks, T.H. (2000) Phenology of British butterflies and climate change. *Global Change Biology* **6,** 407–416.

Sparks, T.H. (1999a) Phenology and the changing pattern of bird migration in Britain. *International Journal of Biometeorology* **42,** 134–138.

Sparks, T.H. (1999b) Date of leaf emergence on trees in spring. *In:* Cannell, M.G.R., Palutikof, J.P. and Sparks, T.H. (eds) *Indicators of Climate Change in the UK*. Centre for Ecology and Hydrology, UK, 54–55.

Sparks, T.H. and Loxton, R.G. (1999) Arrival date of the swallow. *In:* Cannell, M.G.R., Palutikof, J.P. and Sparks, T.H. (eds) *Indicators of Climate Change in the UK*. Centre for Ecology and Hydrology, UK, 62–63.

Sparks, T.H. and Potts, J.M. (1999) Late summer grass production. *In:* Cannell, M.G.R,, Palutikof, J.P. and Sparks, T.H. (eds) *Indicators of Climate Change in the UK.* Centre for Ecology and Hydrology, UK, 52–53.

Sparks, T.H. and Woiwod, I.P. (1999) Dates of insect appearance and activity. *In:* Cannell, M.G.R., Palutikof, J.P. and Sparks, T.H. (eds) *Indicators of Climate Change in the UK*. Centre for Ecology and Hydrology, UK, 58–59.

Sparks, T. H., Jeffree, E. P. and Jeffree, C. E. (2000) An examination of the relationship between flowering times and temperature at the national scale using long-term phenological records from the UK. *International Journal of Biometeorology* **44,** 82–87.

Stanhill, G. (1998) Long-term trends in, and spatial variation of, solar irradiances in Ireland. *International Journal of Climatology* **18,** 1015–1030.

Subak, S. (1999a) Incidence of Lyme disease in humans. *In:* Cannell, M.G.R., Palutikof, J.P. and Sparks, T.H. (eds) *Indicators of Climate Change in the UK*. Centre for Ecology and Hydrology, UK, 38–39.

Subak, S. (1999b) Seasonal pattern of human mortality. *In:* Cannell, M.G.R., Palutikof, J.P. and Sparks, T.H. (eds) *Indicators of Climate Change in the UK*. Centre for Ecology and Hydrology, UK, 40–41.

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

Tyrrell, J.G. (1994) Climate and Irish History. *In:* Climate variation and climate change in Ireland. *In:* Feehan, J. (ed.) *Climate Variation and Climate Change in Ireland.* Environmental Institute, University College Dublin, 25–32.

White, M.A., Running, S.W., Thornton, P.E. (1999) The impact of growing season length variability on carbon assimilation and evapotranspiration over 88 years in eastern US deciduous forest. *International Journal of Biometeorology* **42,** 139–145.

Wilby, R.L., O'Hare, G. and Barnsley, N. (1997) The NAO and British Isles climate variability, 1865–1996. *Weather* **52,** 266–275.

Wilkinson, P., Campbell-Lendrum, D., Kuhn, K., Menne, B., Haines, A., Parr, T. and Bertollini, R. (2001) Monitoring the impacts of climate change on health. *Detecting Environmental Change: Science and Society,* Conference 17–21 July 2001, University College London, Book of abstracts, 171.